AGROCLIMATOLOGICAL RISK ASSESSMENT OF RAINFED MAIZE PRODUCTION FOR THE FREE STATE PROVINCE OF SOUTH AFRICA

by

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Dedication

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“Robala ka khotso Mokoena”

Psalm 27:1 Morena ke leseli la ka le pholoho ea ka; nka tsaba mang? Morena ke sets’abelo sa bophelo ba ka; nka ts’oha mang?

Declaration

I declare that the dissertation hereby submitted by me for the Doctor of Philosophy in Agrometeorology at the University of the Free State is my own work except where acknowledged and has not being submitted by me for a qualification to another University/Faculty.

I further cede copyright of the dissertation in favour of the University of Free State.

Mokhele Edmond Moeletsi

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List of Abbreviations

ARC	Agricultural Research Council
ARC-ISCW	Agricultural Research Council-Institute for Soil, Climate and Water
C_H	Calibrated Hargreaves Coefficient
CSIR	Council for Scientific and Industrial Research
D	Drought index
DAFF	Department of Agriculture, Forestry and Fisheries
Dekad	Ten-daily period
DOA	Department of Agriculture
DST	Decision Support Tool
DRR	Directorate of Relief & Rehabilitation
ENSO	El Niño/La Niña-Southern Oscillation
ET	Evapotranspiration
ET_c	Crop Evapotranspiration
ET_H	Hargreaves Evapotranspiration
ET_{CH}	Calibrated Hargreaves Evapotranspiration
ETo	Reference Evapotranspiration/Penman-Monteith Evapotranspiration
FAO	Food and Agriculture Organization
FF	Probability of Frost-Free growing period
Fig	Figure
FS-Marct	Free State Agroclimatological Risk Tool
FSP	Free State Province
GDD	Growing Degree Days
GEOS	Goddard Earth Observation System
GIS	Geographical Information System
Kc	Crop Coefficients
K-S	Kolmogorov-Sminorv
IDW	Inverse Distance Weighting
LMS	Lesotho Meteorological Services
O	Probability that planting conditions are met
MAE	Mean Absolute Error
MBE	Mean Bias Error
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
PACSI	Poone AgroClimatic Suitability Index
UN	United Nations
r^2/R^2	Coefficient of Determination
RE	Relative Error
RMSE	Root Mean Square Error
SASAS	South African Society of Atmospheric Sciences
SAWS	South African Weather Service
SOI	Southern Oscillation Index
SST	Sea Surface Temperatue
T_{max}	Maximum Temperature
T_{mean}	Mean Temperature
T_{min}	Minimum Temperature
UK	United Kingdom
WMO	World Meteorological Organization
WRSI	Water Requirement Satisfaction Index

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ABSTRACT

The risks associated with climate and its variability over the Free State Province is the major determining factor for agricultural productivity, and has a major impact on food security across the province. To improve productivity of agricultural lands, producers and decisions makers have to be provided with relevant agrometeorological information that will enable them to make appropriate decisions. This has lead to the investigation of this agroclimatological risk assessment for maize production in the Free State. The ultimate goal was to characterize the agroclimatological risks impacting negatively on dryland maize production and develop a climate risk tool that will assist the stakeholders in their management of agricultural lands. First, meteorological data needed to perform this study was prepared by looking specifically at filling the missing data gaps and using alternative data in cases where measured data was not available to obtain good spatial distribution of weather stations.

Frost was identified as one of the climate hazards affecting the maize plant in the Free State. Three frost severity categories were analysed, namely 2°C, 0°C and -2°C representing light, medium and heavy frost respectively. The onset of frost for all the thresholds was earlier over the northern, eastern and far southeastern parts of the Free State province while places over the western and southwestern parts of the province the first frost dates are later. The northern and eastern parts are also marked by late cessation of frost giving a shorter frost-free period (220-240 days at medium frost severity). The western and southwestern areas mostly have earlier cessation of frost resulting in relatively long frost-free period with ranges from 241 to 300 days at medium frost severity level. Cessation of frost occurring later than normal over the Free State can impact negatively on the maize crop if planted in October and early November, especially over the highlands. Productivity of the crops can also be hampered by earlier than normal onset of frost that affects maize at silking and grain-filling stages.

The onsets and cessation of rains together with the duration of the rainy season also play an important role in agricultural planning. Over 300 stations across the Free State were analysed to characterize the rainy season. The onsets of rains were found to be early over the eastern parts of the province with median onsets on or earlier than 10 October. In most areas over the Fezile Dabi and Motheo districts, onsets are between 11 to 30 October while over the Lejweleputswa onsets are mostly between 21 October and 10 November. Most of the western parts of Xhariep experience later than 21 November at 50% risk level. The cessation of rains does not vary much over the Free State with most places having their median last rains between 21 April and 30 April. Rainy season lengths are longer over the Thabo Mofutsanyane district with over 200 days in some places. The ENSO episodes are related to Free State seasonal rainfall variability but only have slight effect on the cessation of rains while onsets of rains showed no differences between El Niño or La Niña phases as compared to all the years. In El Niño years the seasonal rainfall amount is lower than normal, being higher than normal in La Niña years which support findings from other studies. The cessation of rains occurs earlier in El Niño years and later than normal in La Niña years.

Agricultural drought is one of the most devastating hazards affecting maize production in most growing periods depending on the location. It is important to plant during periods which minimise drought conditions. In this study a simple water balance model developed by FAO called WRSI was used to quantify drought risk. When using the 120-day maize cultivar as a reference, drought index over most parts of the Lejweleputswa, Xhariep and eastern parts of the Motheo district show high vulnerability (WRSI<40) for October planting dates while other areas have relatively low risk of drought. In December and January planting dates drought index over most parts of the province showed much improvement but places that showed low risk are over the Thabo Mofutsanyane, Fezile Dabi and pockets of northern Lejweleputswa district.

Poone AgroClimatic Suitability Index (PACSI) was introduced to integrate all the climate hazards affecting maize production in the Free State. The index in made from the combination of frost probability over the growing period, non-exceedence probability of onset of rains and agricultural drought index. The index was further used to delineate the suitable areas across the Free State for planting maize variety requiring 1420 growing degree days (heat units) to maturity. The findings obtained from the resulting maps show areas of high maize production suitability over the Thabo Mofutsanyane district for mid-October to early November planting dates. Places over Fezile Dabi and northern parts of the Lejweleputswa district also showed high suitability of maize especially for planting from mid-November to end of December. The western and southern Xhariep district area is not suitable for planting maize while other marginal dryland maize production areas include western Motheo, southwestern Lejweleputswa and most parts of the central and eastern Xhariep.

To conclude the study, the Free State Maize Agroclimatological Risk Tool (FS-MACRT) was developed to provide agroclimatological risk information important to the production of rainfed maize in the Free State Province. The tool is to be used by the farmers, extension officers, policy-makers and agricultural risk advisors. The tool has two main parts, 1) climatological risk and 2) forecasting. The climatological risk enables the user to obtain drought stress risk for the 100-day, 120-day and 140-day maize cultivars for planting window starting in October to January. The best planting dates based on the risk associated with the climatology onset and cessation of both rains and frost can be determined. Using climate forecasts obtained from the national forecasting centres, drought index can be predicted for different planting dates giving the farmer valuable information when planning for the coming season. The tool also has the functionality of predicting onsets of rains using weather and climate forecasts.

Key words: Agroclimatological risk tool, Climate, Drought, Frost, Maize, Rainy season, WRSI

Agroklimatologiese risiko assesering van droëland mielie produksie van die Vrystaat provinsie in Suid Afrika

deur

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OPSOMMING

Die risikos wat geassosieer word met klimaat en die variasies in die Vrystaat provinsie is die hoof faktor wat landbou produksie beïnvloed en het ‘n groot impak op die voedsel sekuriteit. Om die produktiwiteit van die landbou produsente en die besluitmakers te verhoog moet die nodige agrometeorologiese inligting aan hulle verskaf word sodat die regte besluite geneem kan word. Dit het aanleiding gegee tot die ondersoek na die agroklimatologiese risiko assessering van mielie produksie in die Vrystaat. Die hoof doel was om die agroklimatologiese risiko te karakteriseer asook die negatiewe impak op droëland mielies en dan sodoende ‘n klimaat risiko instrument te ontwikkel wat kan help met die bestuur van hulle lande. Vir die studie is meteorologiese data voorberei deur die vermiste data te vervang met alternatiewe data waar geen gemete data beskikbaar was nie om die regte ruimtelike verspreiding van weerstasies te verkry.

Ryp is geïdentifiseer as een van die klimaats hindernisse wat mielies beïnvloed in die Vrystaat. Drie hewige ryp kategoriee is geanaliseer naamlik 2^{o}C, 0^{o}C en -2^{o}C wat ligte, medium en hewig ryp voorstel. Die eerste tekens van ryp begin in die noordelike, oostelike en ver suidoostelike dele van die Vrystaat waar ryp in die westelike en suidwestelike dele later voorkom. Die noordelike en oostelike dele word ook gekenmerk deur ryp op ‘n latere stadium wat aanleiding gee tot ‘n korter rypvrye periode (220-240 dae met medium ryp). In die westelike en suidwestelike dele vroeëre staking van ryp gee aanleiding tot in ‘n langer rypvrye periode wat wissel tussen 241-300 dae van medium ryp. Wanneer ryp later as gewoonlik voorkom in die Vrystaat het dit ‘n negatiewe impak op mielieproduksie in Oktober en begin November veral in die hooglande. Die produktiwiteit van gewasse kan ook gerem word deur ryp wat vroeër as gewoonlik plaasvind en dit kan die mieliebaard en graanvul period beïnvloed.

Die begin, einde en periode van reën speel ‘n belangrike rol in landbou beplanning. Oor die 300 weerstasies in die Vrystaat is geanaliseer om die reënseisoen te karakteriseer. Die begin van die reënseisoen is vroeër in die oostelike dele van die provinsie terwyl die middelste gedeelte se reën om en by 10 Oktober begin. In die Fezile Dabi en Motheo distrikte begin die reënseisoen gewoonlik tussen 11 tot 30 Oktober, terwyl Lejweleputswa begin tussen 21 Oktober en 10 November. In Xhariep se westelike areas kom reën gewoonlik later as 21 November voor met ‘n 50 % risiko vlak. Die einde van die reënseisoen wissel nie baie in die provinsie nie, maar die meeste reën kom voor tussen 21 April en 30 April. Die langste reënseisoen kom voor in die omgewing van die Thabo Mofutsanyane distrik met meer as 200 dae in sommige dele. Die ENSO episodes is verwant aan die wisselende

seisonale reënval maar het ‘n geringe effek op die einde van die reën periode terwyl die begin van die reënseisoen geen verskille toon tussen El Niño of La Niña tussen verskillende jare nie. Gedurende die El Niño jare is die seisonale reënval laer as normal, terwyl dit in die La Niña jare weer hoër is, wat verskeie studies ondersteun. Die einde van die reënseisoen is vroeër in El Niño years en later as normaal in La Niña jare.

Droogte is een van die mees verwoestend gevare wat mielie produksie gedurende die groeiseisoen kan affekteer afhangende van die lokaliteit. Dit is belangrik om te plant gedurende periods met minimum droeër kondisies. In die studie is gebruik gemaak van ‘n eenvoudige water model bekend as WRSI wat ontwikkel is deur FAO om droogte risiko te kwantifiseer. Wanneer die 120-dae mielie kultivar as verwysing gebruik word, dui die droogte indeks aan dat die meeste dele van Lejweleputswa, Xhariep en die oostelike dele van die Motheo distrik vatbaar is vir droogte (WRSI<40) gedurende Oktober se planttye terwyl ander areas ‘n laer risiko het. Gedurende Desember en Januarie is die droogte plant indeks beter oor die grootste gedeelte van die provinsie met laer risikos oor Thabo Mofutsanyane, Fezile Dabi en dele van die noordelike Lejweleputswa distrik.

Die Poone AgroClimatic Suitability Indeks (PACSI) is bekendgestel om alle klimaatsgevare te integreer wat mielie produksie in die Vrystaat kan beïnvloed.Die indeks bestaan uit ‘n kombinasie van die waarskynlikheid van ryp gedurende die groeiperiode, die waarskynlikheid van reën en die droogte indeks. Die indeks was ook gebruik om die regte areas oor die Vrystaat te skets om mielievariasies te plant wat 1420 dae (hitte eenhede) nodig het om volwassenheid te bereik. Die resultate toon areas met ‘n hoë mielie produksie oor die Thabo Mofutsanyane distrik van middel Oktober tot begin November. Dele van Fezile Dabi en die noordelike dele van Lejweleputswa distrik is ook hoogs geskik vir produksie van middel November tot einde Desember. Die westelike en suidelike Xhariep distrik is nie geskik vir mielie produksie nie terwyl matige droëland mielie produksie areas insluit die westelike dele van Motheo, suidwestelike Lejweleputswa en die meeste dele van sentrale en oostelike Xhariep.

Gevolglik is die Vrystaatse Mielie Agroklimaats Risiko Apparaat (VS-MAKRA) ontwikkel om agroklimaatsrisiko inligting te verskaf vir die produksie van droëland mielies in die Vrystaat. Die apparaat moet gebruik word deur boere, voorligtingsbeamptes, landboupolishouers en landbou risiko adviseurs. Die apparaat het twee hoof dele, 1) klimaatrisiko en 2) voorspelling. Die klimaatrisiko stel die gebruiker in staat om ‘n droogte stres risiko te bepaal vir 100, 120 en 140 dag mielie kultivars gedurende die plant periode vanaf begin Oktober tot Januarie. Die beste plant datums gebaseer op die risiko geassosieer met die klimatologiese begin en einde van reën en ryp kan voorspel word. Deur gebruik te maak van voorspellings kan die droogte indeks voorspel word vir verskillende plant datums, wat dan waardevolle inligting vir die opvolgende groeiseisoen gee aan die boer. Die apparaat kan ook die begin van die reënseisoen voorspel deur gebruik te maak van verskeie weer en klimaatsvoorspellings.

Chapter 1: General Introduction

Climate variability and climate hazards affect the livelihoods of people all around the world (Bharwani *et al*., 2005). Weather and climate variability is the major factor affecting inter-annual variability of crop production and yield in all the environments and thus climate information has to be considered in agricultural planning activities and decision making (Sreenivas *et al*., 2008; Das & Stigter, 2010). Weather and environmental conditions during the growing period have a direct bearing on the plant growth and development and ultimately affect the crop yield (Khushu *et al*., 2008). According to Reddy (1983a), improvement of farming systems and natural resource management requires a better understanding of climatology of a region. Climate data based on long-term seasonal or monthly averages often result in misleading agroclimatic classifications as compared with actual production pattern because they do not address risk at shorter time intervals (Reddy, 1983b).

1.1 Agrometeorological information

Agroclimatological information is important to improve the agricultural production as well as protecting the agricultural resources from deteriorating (Andre *et al*., 2007; Nadler, 2007). According to Stigter (2010) there is a need to continually review the farmers' needs for weather and climate information at every location and for each farming system. This is important because climate information needed for crop farming, livestock farming, forestry farming and fish farming is different for each region.

The aim of agricultural meteorology is to provide relevant information to farmers and decision makers on weather and climate affecting agricultural production. Agrometeorological services are important for sustainable agriculture especially for poor-resourced farmers who have scarce funds for obtaining the required agricultural inputs and where environmental conditions are a major determinant of agricultural yield (Rahimi *et al*., 2007). Rahimi *et al*. (2007) also stated that, information on occurrences of weather and climate events has to be combined with other information like soil and water to help farmers in managing their agricultural activities holistically and further decrease the impact of extreme weather in their farms. Wang *et al.* (2008) elaborated on the importance of using Agromet information in the choice of crop using the climate and soil conditions as well as using weather and climate forecasts to help dryland farmers to maximize their yield in favourable years and minimize costs in unfavourable years.

There is important agroclimate information which can be useful to improve the productivity of agricultural lands. Seasonal forecasts should be given to the farmers long before the season begins so that they can prepare the crop varieties in advance, which they have to use during the coming season. This can only be possible if the information provided by the meteorological services is downscaled to a community level and agrometeorologists properly interpret the information provided to the farmers (Nanja, 2010; Zuma-Netshiukhwi, 2010). The other information of use during the pre-season is the forecasting of onset of rains, which is important as farmers need to know probable dates in order to make informed decisions like ploughing just before the heavy rains as in some places ploughing and seeding is difficult when the soil is wet (Reddy, 1983a). But in South Africa forecasting of onset of rains has a very low skill (personal communication with WA Landman) but information about the climatology of the onsets indicating probabilities of onset per location can be very useful. Hence in Chapter 4 of this thesis, non-exceeding probabilities of the onsets of rain in the Free State province are investigated. It is also important to provide information about forecasting and climatology of frost in order for the farmers to plant their crops at times where the risk of frost is minimal. Crucial frost information includes the onset, cessation and probabilities of frost during the growing period (Rahimi *et al*., 2007). Information pertaining to probabilities of accumulated seasonal rainfall coupled with evapotranspiration is important in quantifying agricultural drought as they form the basis of most agricultural drought indices (Frere & Popov, 1979; Keyantash & Dracup, 2002). Farmers should be given dates on which drought frequency as well as severity is high in order for them to avoid coinciding most sensitive growing periods with those time periods. Information on probable occurrences of pests and diseases over the growing period is important for farmers for preparatory purposes.

Dissemination of agrometeorological services is of paramount importance to help in addressing food security (Balaghi *et al*., 2010). No matter how good the product is, if not passed on to the users in an appropriate manner the product will be defunct. For the climate information to be appropriate it has to be disseminated in the format that will be understood by the farmers. The information has to be in the language that the farmer is conversant with in order not to have false interpretation of the data or information (Walker *et al.*, 2001). In order to address farmers' needs the products that are developed should also be accompanied by training (Walker *et al.*, 2001; Mavi & Tupper, 2004). According to Rijks & Baradas (2000), agrometeorology information can make agriculture more profitable by reducing input costs and it can also reduce risks. In South Africa, the farmers are mostly in contact with the extension service workers who are mandated to give them guidance. Training of agricultural extension workers is also key to the success of the information passed to the farmers (Mavi & Tupper, 2004; Moeletsi *et al.*, 2009b). The advantages of involving the extension workers are as follows:

- They are easily trainable because in most cases their level of literacy is high
- They are mostly local inhabitants of the villages
- They speak local languages
- They can easily be reached by the farmers
- In cases of emergencies, they can react quickly to be of assistance to the farmers.

Weather and climate information in South Africa is mostly disseminated by the use of television, national and community radios and newspapers (Walker *et al*., 2001). However, this information is mostly general information and it is of little use to the farmers at their farm operational level. There is a need for the farmer-tailored information and this information should be passed directly to the farmers. The Agricultural Research Council together with EcoLink partnered on the Response Farming project which had pilot sites over the Limpopo and Mpumalanga provinces to develop farmer-tailored agromet service (Moeletsi *et al.,* 2009b). One of their objectives was to develop an efficient way of passing agroclimatology information to the farmers and their recommended method was through the use of mobile technology whereby they developed a coded SMS system.

1.2 Climate and crops

According to Hansen (2002) agriculture is the most weather dependent of human activities. Crop yield varies from one season to another owing to variation in climate during the growing season (Hansen & Jones, 2000; Hu & Buyanovsky, 2003; Kumar *et al.*, 2004). Hu & Bayanovsy (2003) further stated that climate affects yield but the yield potential is affected by both the crop genetics and nutrient availability during growth and development. The main weather parameters affecting crop growth are rainfall, temperature and solar radiation (Sreenivas *et al.*, 2008). There are also many non-climatic factors that influence yield like the cultivation techniques, fertilization practices, cultivars and farm management practices (Sun *et al.*, 2006; Zhang, 2004). Understanding how climate influences the yields can be helpful in designing policies that aim at reducing climate vulnerability and improving food security (Sun *et al.*, 2006).

The greatest risk concerning low temperature is frost, as it can cause severe reduction in productivity for fruits, vegetables and plants (Teitel *et al.*, 1996; Nadler, 2007). Andre *et al.* (2007) define frost as the occurrence of an air temperature of 0℃ or lower, measured at a certain height above ground mostly 1.2m. Frosts are mostly classified as either advective or radiative, depending on the atmospheric conditions under which they occur. An advective frost occurs when cold air from another region moves into an area and winds remain relatively strong. Radiative frosts are produced locally and occur only during clear, calm nights (Bootsma & Brown, 1985; Andre *et al.*, 2007). Frost critical temperature (minimum temperature which must be reached before damage occurs) depends on plant species, variety, growth or development stage, plant vigour, soil conditions, surface cover; frost intensity and duration (Bootsma & Brown, 1985). Frost affects crops differently, as some crops are more tolerant to frost than others. Due to the fact that Free State province is charecterized by uneven topography comprising mountain ranges and river valleys especially in the eastern parts, frost poses a serious threat to maize production.

Water is among the most important elements affecting agriculture as it is one of the limiting resources for crop growth in Southern Africa (Mukhala, 1998). This limiting factor is mostly caused by unreliable seasonal rainfall. Total seasonal rainfall amounts can be sufficient, but the distribution of rainfall throughout the season is mostly the cause of crop failure (Martin *et al*. 2000; Barron *et al.*, 2003; Nadler, 2007). This uneven distribution of rainfall exposes the crops to mild to severe intra-seasonal dry spells which decrease crop yields (Barron *et al.*, 2003). According to Walker & Tsubo (2003) it is important to use available water efficiently to improve crop production. Crop water requirements depend mainly on the nature and stage of growth of the crop together with the environmental conditions. These factors include soil characteristics, crop phenological stage and climate characteristics (Allen *et al.*, 1998; Sharma, 2006). The FAO definition of crop water requirement is the amount of water required to compensate the evapotranspiration loss from the cropped field (Doorenbos & Pruitt, 1977; Allen *et al.*, 1998). The crop evapotranspiration (ET_c) is usually estimated by a reference crop evapotranspiration (ETo) (Allen *et al.*, 1998; Shaozhong *et al.*, 2000; Sharma, 2006). Reference crop evapotranspiration can be calculated using different methods but the most common method is the Penman-Monteith equation (Doorenbos & Pruitt, 1977). The crop coefficient (Kc) changes as the crop develops and is ratio of potential crop evapotranspiration (crop water demand) to reference evapotranspiration i.e $Kc = ET_c/ET_0$ (Shaozhong *et al.*, 2000). Water deficit during the growing period develops when the crop water requirements are not realised, to an extent where the plant growth and yield are affected (Doorenbos & Kassan, 1979). When there is no water limitation, water demand can be achieved through precipitation or stored soil water (Allen *et al.*, 1998).

Drought is a natural hazard caused by lower than expected precipitation over a certain period of time such that it does not meet the demands of humans and environment (WMO, 2006). Precipitation is the primary factor controlling the incidence, formation and persistence of drought conditions, but evapotranspiration is also an important variable (Lloyd-Hughes & Saunders, 2002). There are four main types of drought namely: a) meteorological drought, b) hydrological drought, c) agricultural drought and d) socio-economic drought (du Pisani *et al.*, 1998; Loukas & Vasiliades, 2004). Agricultural drought occurs when there is a shortfall in the soil water supply to the crop (Wilhelmi *et al.*, 2002). Agricultural drought is the main cause of crop failure in most countries around the world including South Africa (Du Pisani *et al.*, 1998). The risk of agricultural drought is two-fold, the exposure to hazard (precipitation deficiency) and the response of different systems (cropping practices) to drought (Wilhelmi *et al.*, 2002).. The intensity and frequency of the hazard vary from year to year as affected by different climate scenarios but stabilizes over the long-term while vulnerability to drought is very dynamic because it is a combination of among others, land use and management, farm and government policies, societal wealth and many other factors (Wilhelmi *et al.*, 2002).

1.3 Maize crop

Maize is the third most important crop in the world after rice and wheat (Frere & Popov, 1986; Ofori & Kyei-Baffour, 2009). It is cultivated in different climates up to 55^{o}N latitude and at altitudes exceeding 2500m in Africa and America mainly for human consumption (Frere & Popov, 1986; Ofori & Kyei-Baffour, 2009). In South Africa, maize is the most important staple food crop of more than 40 million people (du Plessis, 2003; Ofori & Kyei-Baffour, 2009; DAFF, 2010). The average growing cycle of maize is between 120 and 140 days with exception of ‘ultra short’ early maturing cultivars which can take less than 100 days and others at high altitude take up to 300 days from sowing to maturity (Frere & Popov, 1986).

The main nutrients affecting crop growth and yield are nitrogen, phosphorus and potassium and other micronutrients like baron, calcium, magnesium, manganese and molybdenum (Reid *et al.*, 2006; Ofori

& Kyei-Baffour, 2009). For a farmer to maximize on productivity he is advised to assess of fertility of the soil every season in order to determine recommended amounts of fertilizer to apply (Ofori & Kyei-Baffour, 2009). Hu & Buyanosky (2003) stated that maize yield potential is the function of maize genetics and nutrient availability during growth and thus recent increased yields are attributed to introduction of inorganic fertilizers and improved maize varieties. But even if nutrients are available, the yields or productivity can also be affected by environmental conditions and well as the management of the pests and diseases (Ofori & Kyei-Baffour, 2009).

Maize plant growth and development ranges between 6℃ and 45℃ with an optimum temperature of 30℃ (Pannar, undated). But extremely high temperatures have the potential of reducing the yield because of the reduced pollination and poor seed setting (Ramadoss *et al*., 2004). Maize is also sensitive to extremely low temperatures (frost) and temperatures below 0^{o}C can have a damaging effect on the crop (Ofori & Kyei-Baffour, 2009; Trasmonte *et al.*, 2008). The other important temperature is the base temperature, which is the temperature below which the development of the crop stops (McMaster & Wilhelm, 1997; Pannar, undated). The rate of development for maize is zero at its base temperature of 10℃ and increases gradually peaking at 30℃ (Fig. 3.1) (Brown & Bootsma, 1993). Seasonal crops whether summer or winter crops respond to environmental conditions that regulate their growth and development (Agrawal & Updhyay, 2009; Wiebold, undated). Ransom *et al.* (2004) stated that the potential productivity of maize is directly related to the length of the growing season and the longer the growing season, the longer the maize plant has to photosynthesize and accumulate dry matter for grain yield.

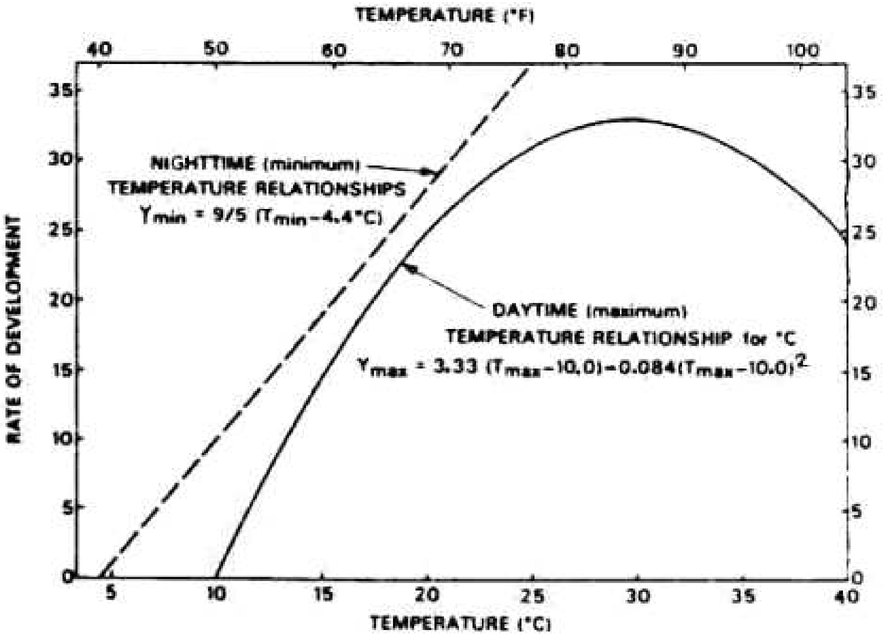


Fig. 1.1: Rate of development of maize in relation to temperature, source (Brown & Bootsma, 1993).

According to Neog *et al.* (2008) the period that a plant takes to complete a particular growth stage is directly related to temperature and particularly sums of daily temperatures above the base temperature. The effect of the temperature on the plant growth and development is known as thermal time and is commonly measured in growing degree-days (GDD) or heat units (Plett, 1992; Gordon & Bootsma, 1993; Ruml *et al.*, 2009). Heat units are mostly defined as the amount by which mean daily temperature exceed a certain base temperature (Bootsma & Suzuki, 1985; McMaster & Wilhem, 1997 Agrawal & Updhyay, 2009; Kumari *et al.*, 2009). The concept of a thermal time index or heat units was first introduced in 1730 by Reanumur (McMaster & Wilhelm, 1997; Ruml *et al.*, 2009). The thermal requirements of Pannar maize seeds in South Africa for reaching maturity for short, medium and medium-late varieties are 1340GDD, 1420GDD and 1470GDD respectively (Pannar, 2010; van der Walt(PANNAR SEED SA), personal communication, September 2010). These heat unit requirements are particulary for the selected Pannar cultivars. Since farmers in the Free State use seeds of different heat unit requirements, it was decided to use three cultivar season lengths in most parts of this study. It should be noted that 120-day maize cultivar has different heat unit requirements depending on the location. It is only in chapter 6 where an example of maize suitability for a medium season maize cultivar requiring 1420GDD is used.

Maize water requirements for South Africa are estimated at between 450mm and 600mm depending on the local environment (du Plessis, 2003). Even though maize is adaptable to adverse conditions, low rainfall and drought negatively affect the productivity (Akpalu *et al.*, 2006). According to Hu & Buyanovsky (2003) rainfall deficiency before anthesis and excessively high temperatures during anthesis have a great impact on the yield. On average South Africa produces 8 million tonnes of maize grain annually from over 3 million hectare but the yields are highly variable owing to changes in seasonal rainfall (du Plessis, 2003; USDA, 2007).

1.4 Climate risk assessment

Risk assessment of natural disasters according to Zhang (2004) is “the assessment of both the probability of natural disaster occurrence and the degree of the damage caused by the disaster”. DRR (2007) described risk assessment as the interaction of the hazard and vulnerability of the societal systems. Three major steps for risk assessment are (Ramesh & Stigter, 2010):

- Identification of hazards that may cause disasters;
- Estimation of the risks of the event
- Evaluation of the consequences of the risk

Risk identification includes defining the physical characteristics of the event likely to cause harm to society (DRR, 2007). Risk estimation is determining the magnitude and severity, probability and frequency of the hazard (DRR, 2007). Evaluation of the risk consequences entails determining the conditions of vulnerability causing threat to infrastructure, livelihoods and environment (Sonmez *et al.*, 2005; DRR, 2007). According to DRR (2007) climate risk can be identified by the natural characteristics of the hazard like the geographic extent, the time of the year in which it is likely to occur and its severity.

The main tools that are used for identifying and assessing climate risk are different depending on the area of concern. Some of the tools include climate risk maps, indices, probability graphs, historical transect, hazard Venn diagram and seasonal activity calendar (DRR, 2007; Zhang, 2004). The most common way of presenting the risk is through climate risk maps especially when considering districts, municipalities, counties, provinces, countries, regions or continents (WMO, 2006; DRR, 2007). According to Maths/Science Nucleaus (2000) maps are important tools for scientists investigating the spatial distribution of the effects of natural resources. Maps make it possible to visualize risks in relation to each other, gauge their extent, and plan what type of controls should be implemented to mitigate the risks (AuditNet, undated). It further stated that maps show likelihood of the risk events in a clear and effective manner. According to Wikipedia (2010), there is a saying that a “pictures is worth a thousand words” which means that a complex issue can be portrayed using one single image, or that visualization is a way for humans to absorb large amounts of data quickly.

1.5 Study area

This study was conducted in the Free State province of South Africa (Fig. 1.2). The province is situated between the latitudes 26.6 degrees South and 30.7 degrees South of the equator and between the longitudes 24.3 degrees East and 29.8 degrees East of the Greenwich meridian. It is the country's third-largest province making 10.6% of South Africa's land area with an area of around 129 825 square kilometres (FSP, 2002; Davis *et al.*, 2006). Cultivated land accounts for 3.2 million hactares while natural and grazing land area is around 8.7 million hectares of the total surface area (Maphalla & Salmon, 2002). There are around 2.9 million inhabitants in this province with over 60% of them being Sesotho-speaking (SA Info, 2010). The main economic activities contributing significantly towards the gross domestic product of the province are community service (24.7%), agriculture (20.1%), trade (10.7%) and mining (9.6%) (FSP, 2002). The Free State province is admistratively divided into five Municipal districts (Fig. 1.2) (Davis *et al.*, 2006):

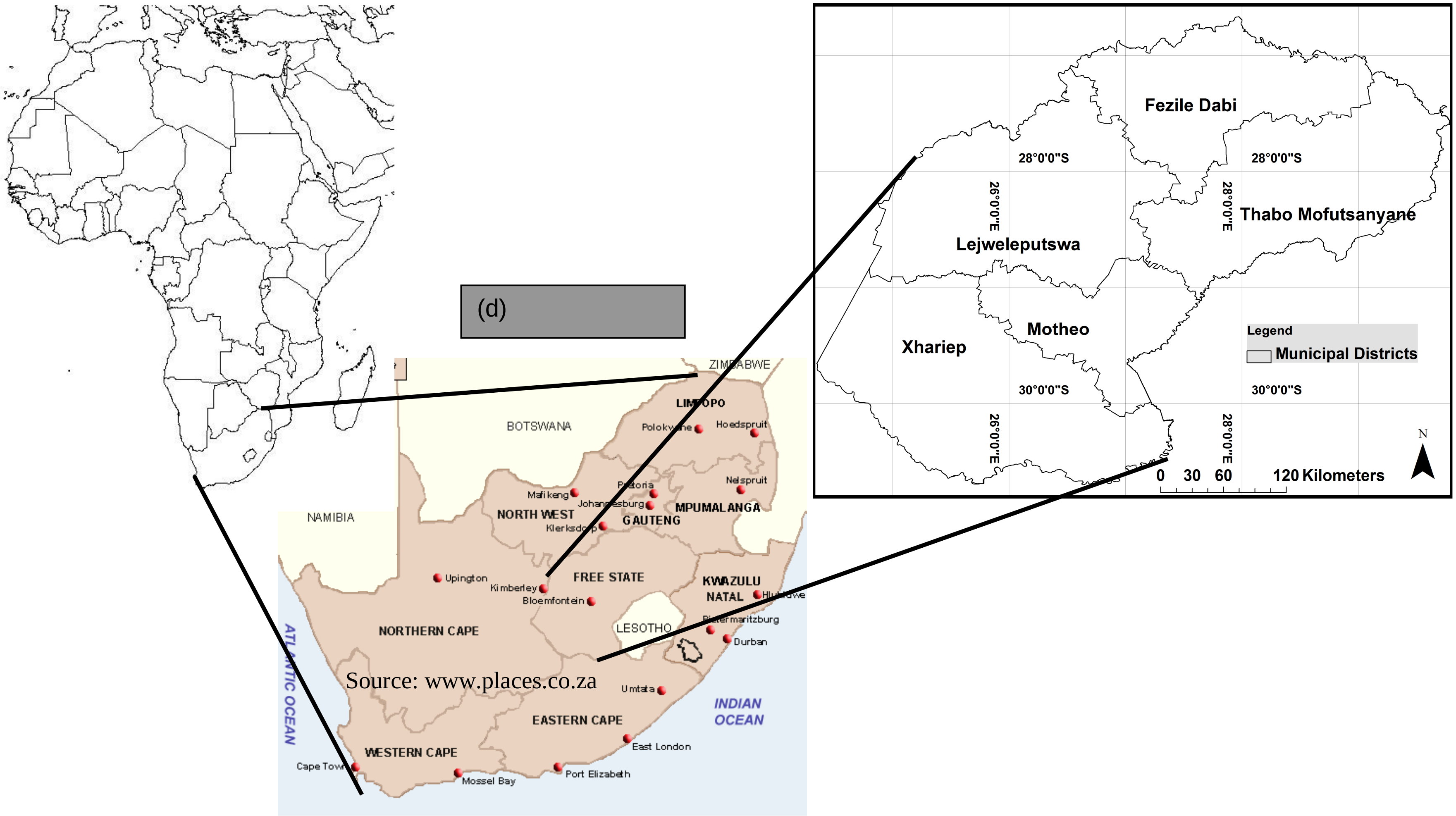
1. The Fezile Dabi district over the northern parts of the province
2. The Lejweleputswa district over the northwestern parts of the province
3. The Motheo district over the central extending to the eastern parts of the province
4. The Thabo Mofutsanyane district over the eastern and northeastern parts of the province;
5. The Xhariep district over the central and southern parts of the province.

The elevation of the Free State province varies a lot from lowest points over the southwestern parts with altitude below 1200m above sea level (Fig.1.3). The elevation increases eastwards with large parts of the province having elevation from 1200m to 1600m above sea level. The far eastern and northeastern parts are mostly mountainous with the altitude exceeding 1600m above sea level, peaking at the altitude of over 3000m above sea level in the mountains bordering Lesotho. The province is semi-arid with summer rainfall and cool temperatures according to Koppen Climate classification (Fig.1.4). The northeastern and eastern parts are mostly humid subtropical with summer rainfall and cool temperatures. There are a few small patches of semi-arid climate with summer rainfall and warm temperatures over the western parts. Some places over the south eastern parts experience humid subtropical temperatures with summer rainfall and cool temperatures.

Annual mean precipitation over the Free State varies from below 400mm over the western and southwestern parts to over 1000mm over the far eastern parts (Fig.1.5). Most places in the province receive annual mean precipitation of between 400mm and 700mm. The province has two seasons the rainy season (October to March) and the dry season (May to September). Over 70% of the rainfall over the Free State is received between October and April (ARC-ISCW Agroclimate database, 2010). Mean annual minimum temperatures is very low (< 5°C) over the high-lying areas in the eastern parts of the province (Fig.1.6). The temperatures increase westwards with most parts of the province having mean minimum temperature of between 7°C and 9°C. The western border of the province records relatively high minimum temperatures exceeding 9°C.

Figure 1.7 shows mean annual maximum temperatures over the Free State with the spatial distribution resembling that of the annual minimum temperatures. Mean annual temperatures over the high-lying areas in the eastern sides mostly have mean annual maximum temperatures of below 22°C. Most places over the Free State record mean annual temperatures of between 22°C and 26°C. Relatively high temperatures between 26°C and 28°C are experienced over the western parts of the province.

Accumulated heat units from November to March in cold seasons are shown in Figure 1.8. There are areas of less than 1250 GDD in the high-lying places over the eastern Free State. Most parts over the Thabo Mofutsanyane district (places surrounding Bethlehem, Ficksburg, Harrismith, Vrede and Warden) have their 50% cumulative heat units between 1251 to 1500GDD. In these areas there is a great chance of the growing period to go beyond March (after March rainfall diminishes and frost incidence increases) and thus short season maize varieties have a good chance of yielding better. Areas stretching from the northern tip of Free State to the far southern part of the Free State have their seasonal thermal units of 1501 to 1750GDD. This area includes areas surrounding Sasolburg, Parys, Koppies, Heilbron, Kroonstad, Senekal, Winburg, Brandfort, Dewetsdorp, Smithfield, Bethulie, Jagersfontein and Philipolis. There is a better chance that the maize crop to do well in these areas (provided other requirements like the water and nutrients are met) because the median heat units accumulated in main agricultural season exceeds the heat unit requirements for the short, medium and medium-late maize varieties. Areas with the highest median heat units is evident over most parts of the Lejweleputswa district, northwestern Xhariep and western Fezile Dabi districts with the excess of 1750GDD accumulated from November to March.



Source: www.places.co.za

Fig 1.2: Location of the Free State province in South Africa.

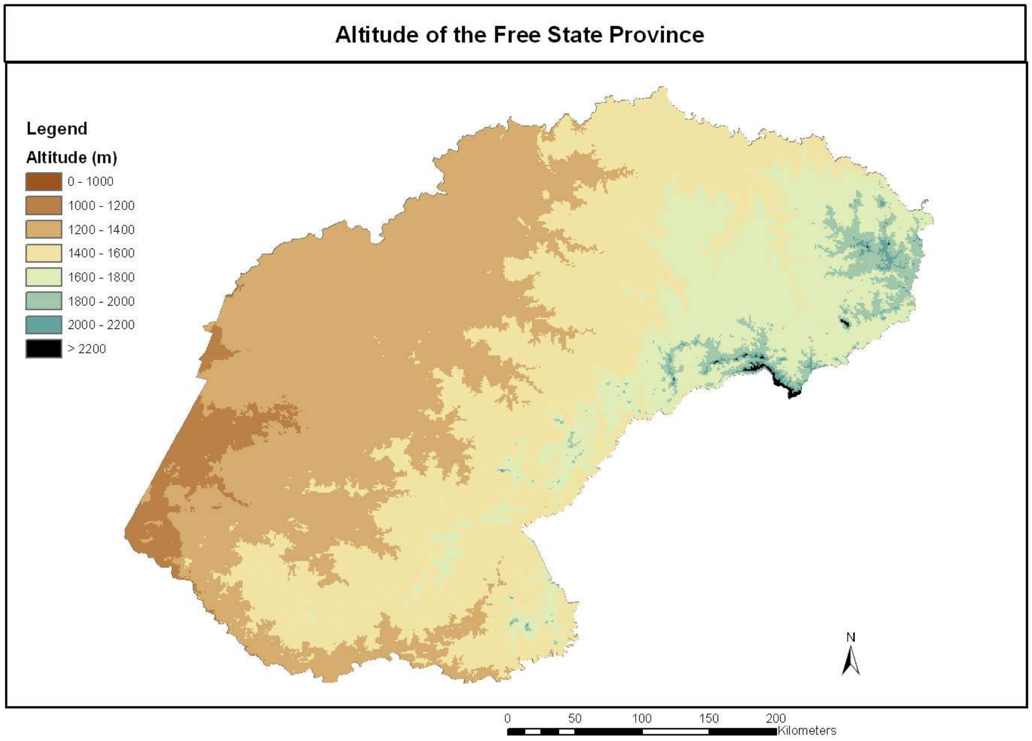


Fig. 1.3: Map showing altitude for the Free State Province (source: ARC-ISCW GIS database).

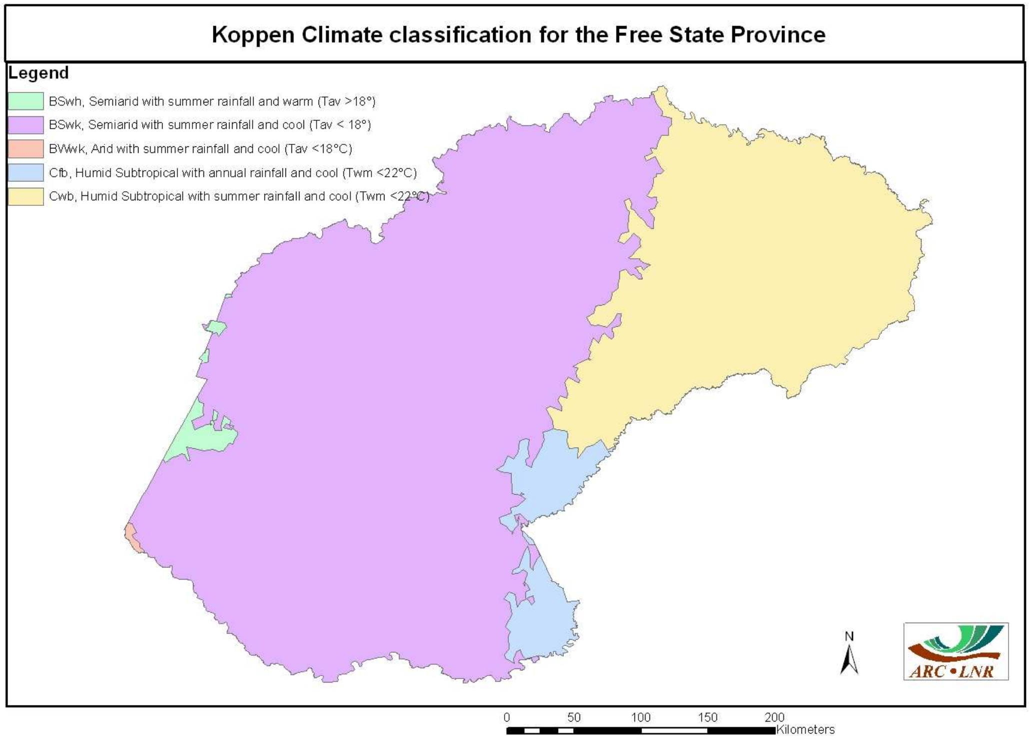


Fig. 1.4: Koppen climate classification for the Free State province (source: ARC-ISCW GIS database).

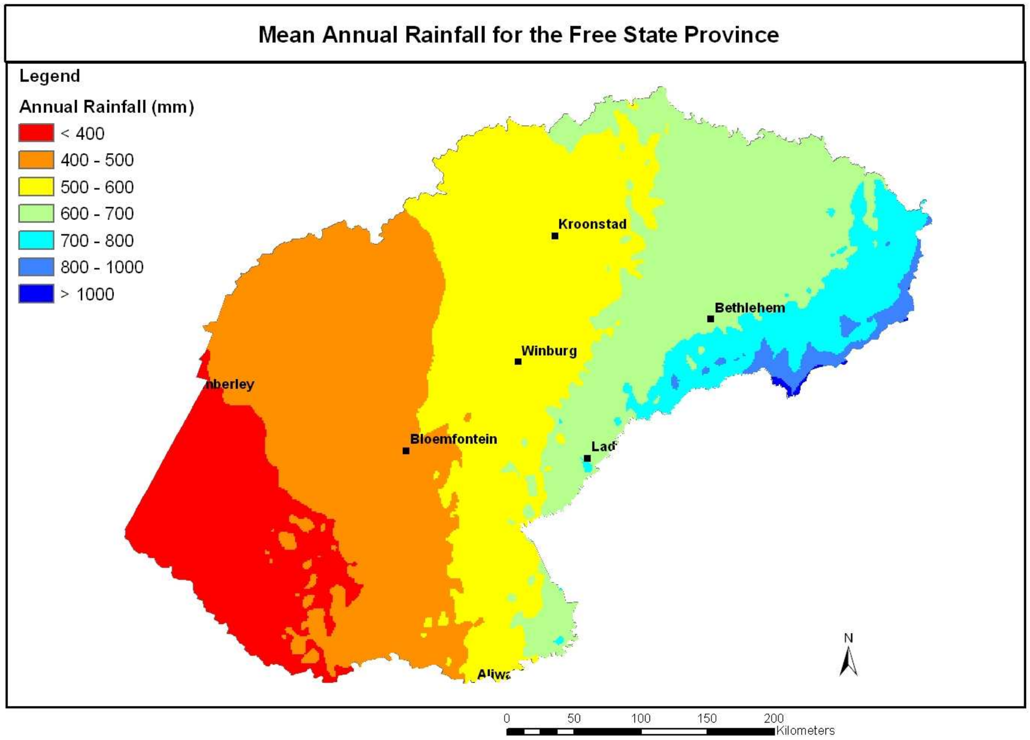


Fig. 1.5: Mean annual precipitation for the Free State Province (source: ARC-ISCW GIS database).

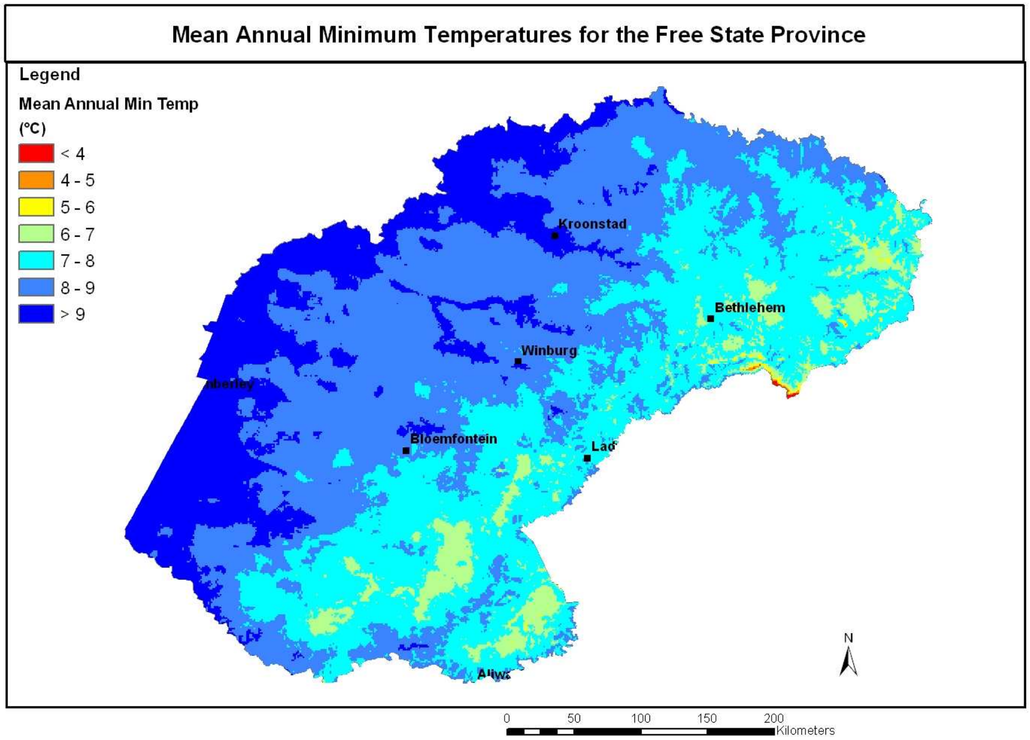


Fig. 1.6: Mean annual minimum temperatures for the Free State province (source: ARC-ISCW GIS database).

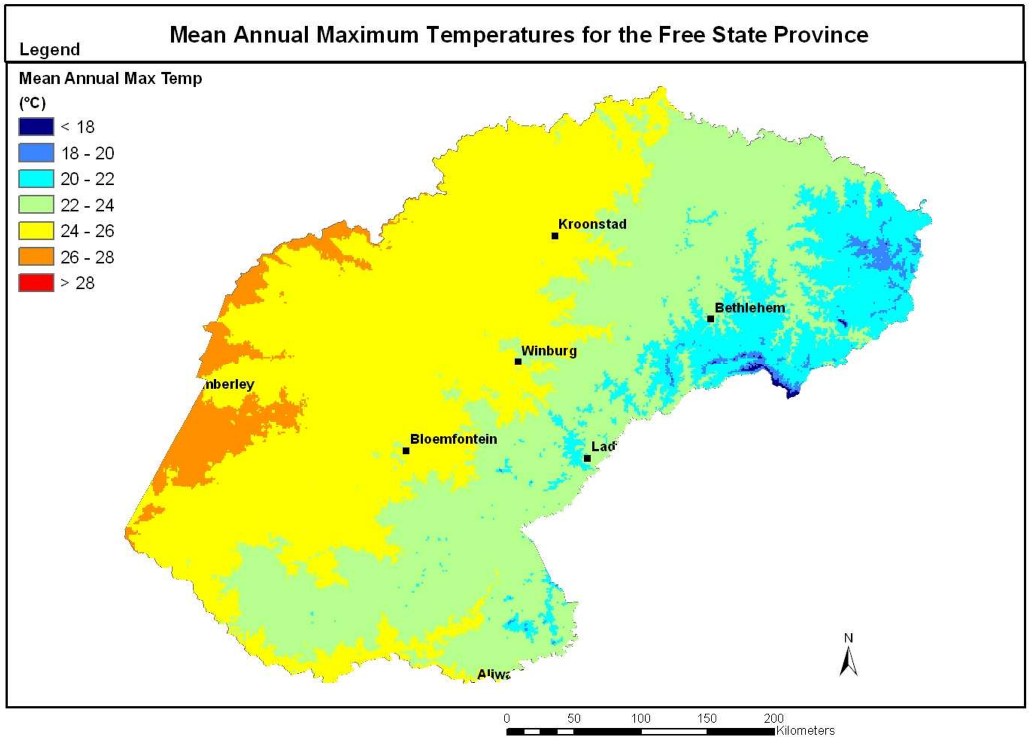


Fig. 1.7: Mean annual maximum temperatures for the Free State province (source: ARC-ISCW GIS database).

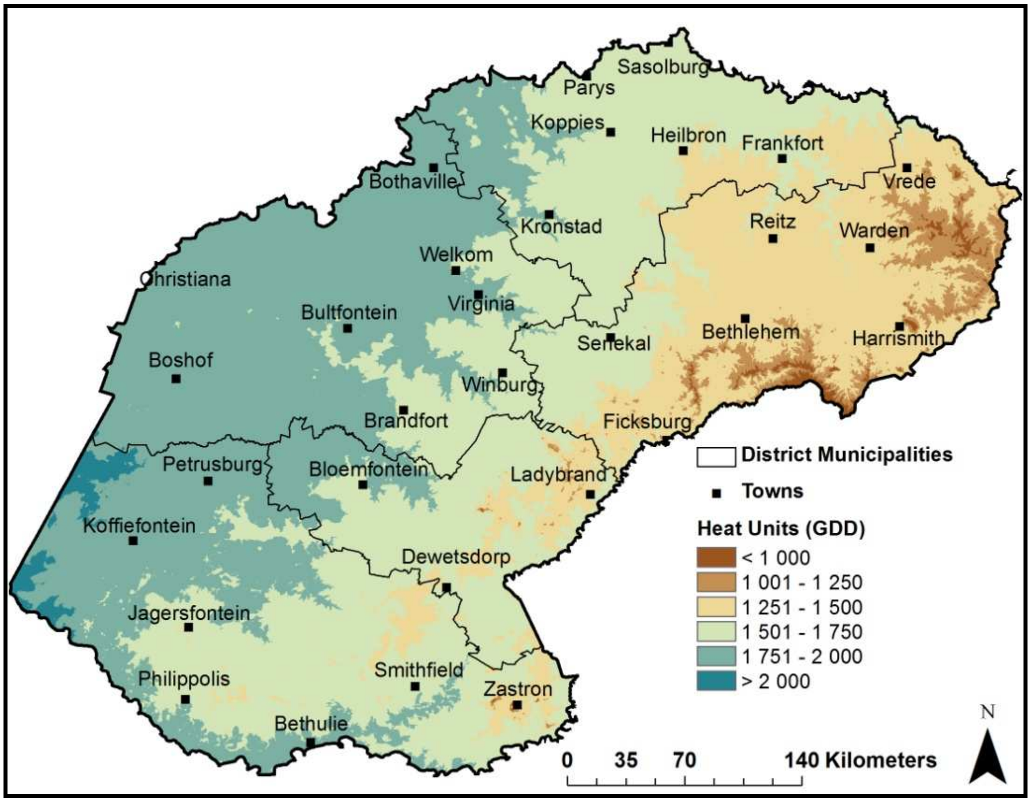


Fig.1.8: Median accumulated seasonal heat units (November to March) for the Free State Province.

Overall the climate of the Free State province has advantages for maize production but there are also disadvantages for agriculture in the province (de Jager *et al.*, 1998). These include: drought, late cessation of frost that damages early planted crops, early onset of frost affecting crops at late stages of their growth, sporadic hail occurrence and low temperatures during the growing period resulting in extended growing periods making crops vulnerable to agroclimatic hazards (Allemann, 1997; van der Berg *et al.*, 2002). Due to lack of instruments for the weather station network in South Africa, quantification of risk associated with hail cannot be done appropriately owing to lack of data. Other agroclimatological hazards (e.g frost and drought) affecting maize production over the Free State can be assessed with the data recorded at the weather stations supplemented by other sources like the satellite-derived datasets. Free State province produces over 30% of the maize in South Africa however the average maize yield over the province varies a lot from one year to another mainly owing to climate variability. Figure 1.9 shows variation of average annual yield for the Free State province from 1981 to 2004 agricultural seasons. Very low yields are evident during the 1982/83 and 1992/93 where average yield over the Free State is below 1 tonne per hectare. These years correspond to the El Niño years which were characterised by low rainfall and increased intensity of drought over Southern Africa. Hence there is a link between adverse weather conditions and maize yields over the Free State province.

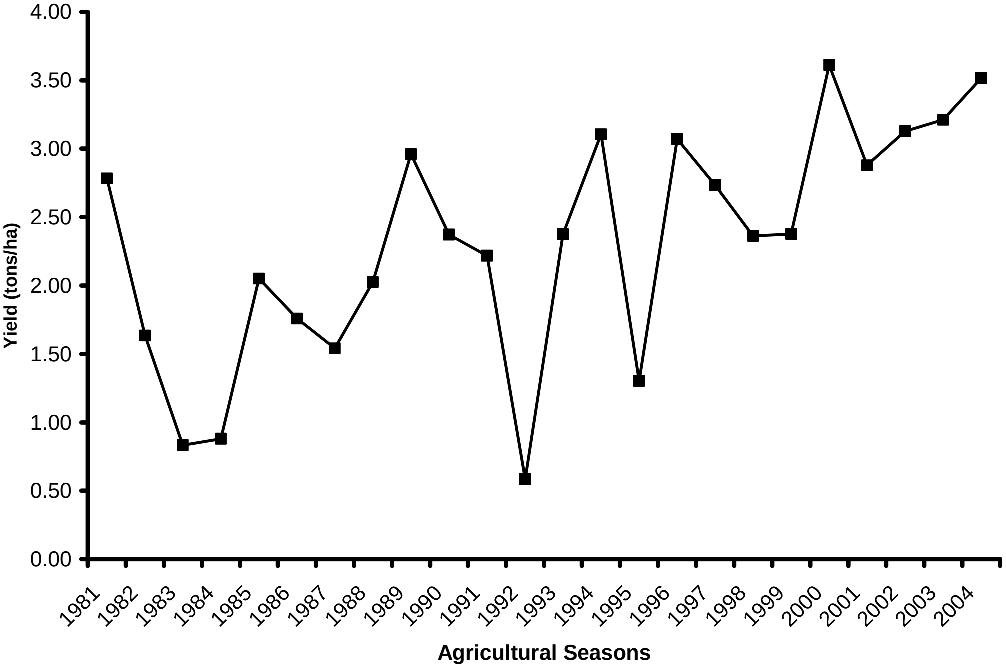


Fig. 1.9: Average yield for the Free State Province from 1980 to 2004 (Source: Grain SA, 2005).

1.6 Motivation

Agriculture is the one of the main economic activities in the Free State contributing significantly in the production of cereal in South Africa (van den Berg *et al.*, 2002). According to Martin *et al.* (2000)

maize is the most important crop in Southern Africa as it forms a staple food of most people. It is mostly planted under rain-fed conditions making it vulnerable to climate variability and change. The crop is grown in most parts of the country but the Free State province produces over 30% of the total maize production in South Africa (de Jager *et al.*, 1998). Recently maize cropping has been under intensive competition for land from other crops of higher returns or other biofuel crops. Thus, there is a great need to maximize production per area available for maize in order to feed the growing population of Southern Africa. Previous research (du Pisani *et al.*, 1982; du Pisani, 1987; Tsubo & Walker, 2007) shows that adverse weather phenomena like drought and frost hamper maize production and thus increase food insecurity in South Africa. Most of the research has been focused on drought effects disregarding other important agroclimatic hazards which are investigated in this study.

The most important way of ensuring that crop production remains sustainable is to ensure that crops and cropping systems match the climate of the location (Nadler, 2007). Maize production in SA fluctuates from year to year depending on the weather experienced during that particular growing season. Climate variability, often characterized by changes in the extreme weather events like El Niňo and La Niňa cannot be avoided; but through research on how different climate scenarios affect crop production, the negative impacts of climate variability can be minimized. Thus, more focus has to be directed towards climate variability research aiming at helping farmers and governments to cope with agroclimatic risks that are projected to escalate due to the effects of global warming (Jagtap and Chan, 2006; Reid *et al.,* 2007).

Agroclimatological information is important to improve the agricultural production as well as protecting the agricultural resources from deteriorating (Andre *et al.*, 2007; Nadler, 2007). The frequencies, means, extremes, deviations, exceedence of thresholds, spatial variability and trends of agroclimatological parameters are important for assessing and managing agricultural risk (Freisland & Lopmeier, 2006). Many practices like the use of irrigation, improved cultivation and improved crop varieties have been developed over the years to adapt agriculture to climate variability and climate change, but agricultural productivity can further be increased, costs of production reduced and crop failures avoided through use of weather and climate information (Basco, undated). Analyses of agrometeorological information can help the farming community in better planning, improving preparedness and adaptive capacity, risk assessment, evaluation of current climate and agricultural interactions and simulation of future trends (Freisland & Lopmeier, 2006). Extreme weather events like drought, floods, frost and heat-waves are the biggest risk factors impacting negatively on agricultural systems performance. Thus, knowledge of climate can become an important risk management tool for the agricultural sector (Meinke *et al.*, 2003). The main challenge we are facing is to use climate information for risk management strategies that increase preparedness and reduce vulnerability to climate variability (Meinke *et al.*, 2003).The planning and management of sustainable agricultural production systems requires detailed agroclimatological information that is presented in a clear manner. The lack of useful packaging for the agroclimatological information to help farmers and decision-makers has initiated this study of the climatic risk affecting maize production in the Free State province of South Africa.

1.7 General objectives

The objectives of the study are as follows:

1. To identify data needs required for proper agroclimatological risk assessment and devise ways of bridging the data gaps;
2. To identify and quantify the agroclimatological risk associated with dryland maize production in the Free State province of South Africa;
3. To develop a simple agroclimatic risk assessment decision making tool for dryland maize production over the Free State province.

1.8 Organization of chapters

The study resulted to eight chapters with two of the chapters being general chapters and six of the chapters being the research chapters. The general chapters are chapter 1 which is an introduction and chapter 8 giving conclusions. The research chapters are chapter 2 which explains the data manipulations, chapter 3 assessment of frost risk, chapter 4 assessment of the rainy season, chapter 5 assessment of agricultural drought, chapter 6 combined climate risk and chapter 7, the development of simple agroclimatic risk tool for dryland maize production over the Free State Province of South Africa.

Chapter 2 deals with the preparation of the agroclimatic data to be used to assess the risk associated with maize production. The main research topics are patching of meteorological data, determination of appropriate model to use for estimating evapotranspiration and lastly evaluation of NASA satellite-derived temperature data for modelling agricultural drought. Chapter 3 investigates the assessment of frost over the Free State using three thresholds representing light (2^{o}C), medium (0^{o}C) and heavy frost (-2^{o}C). Chapter 4 is addressing the rainy season characteristics paying attention to the onset, cessation and duration of the rainy season as well as the seasonal rainfall. Chapter 5 examines agricultural drought using maize water requirement satisfaction index (WRSI). In Chapter 6, the three climate risks are combined to obtain areas most suitable for maize production. While in chapter 7, the development of a simple agroclimatic risk tool for the Free State province is presented.

Chapter 2: Data Manipulations

For proper agroclimatological analyses to be performed it is imperative to have appropriate climate data in a format that is required by the investigator or researcher. The climate variables requirements that were considered important over the Free State are rainfall, minimum temperature, maximum temperature and evapotranspiration. These data is mostly recorded in weather stations that are manned by Agricultural Research Council (ARC) and South Africa Weather Service (SAWS) and they are measured inside the Stevenson screen at the elevation of between 1.20 - 1.5m above the ground. Some of the data recorded in the stations identified was missing and other stations don't have all elements required to estimate evapotranspiration. Thus alternative methods have to be considered to enable proper agroclimatological risk assessment over the Free State province. The time-scale that was used in the investigation was dekads (10 days) which is a recommended time step by FAO for crop production response to climate systems (Frere & Popov, 1979).

2.1 Estimation of meteorological data

2.1.1 Introduction

Measuring and archiving of different weather elements like rainfall, temperature, humidity etc. is important because long-term meteorological data can be used in many studies including modelling in the fields of agriculture, hydrology and engineering. Weather data in South Africa dates back to the 1800 with rainfall being the most common element measured. There are a few stations around the country which recorded temperature, humidity and wind in the early 1900 but the number increased significantly from 1950 onwards. With the improvement in technology, automatic weather stations were introduced in South Africa in the 1990s and this helped to address shorter time scale measurements like minute or hourly values. Increased frequency of measurements means better climate monitoring and understanding of weather occurrences with life-cycle shorter than a day.

Regardless of the technology used to take the recordings, whether manual measurements or the use of electronic sensors, some of the data stored is either faulty or missing. The gaps in the meteorological archives are caused mainly by absence of observers, vandalism, loss of records, data contamination, data processing error, effects of natural disasters like tornadoes or human-induced factors like wars, lack of funds for replacing broken instruments as well as instrument mulfunctioning (Tang *et al*., 1996; Elshorbagy *et al.*, 2000; Smithers & Schulze, 2000; Potgieter, 2008; Kim & Ahn, 2009; Villazon & Willems, 2010). Faulty data is mainly caused by observer's negligence, un-calibrated sensors and faultiness of the electronic sensors. Accurate and complete climatological data is important for the successful designing and operation of natural resource management systems (Gyau-Boaky & Schultz, 1994; Jeffery *et al.*, 2001).

Missing or faulty climate data have to be estimated in order to have a complete dataset especially for modelling purposes. The accurateness of the estimations is dependent on a number of factors including; the closeness of the stations used and the location of the patching stations in relation to barriers like mountains. There are three main techniques of estimating missing meteorological data namely: empirical methods, statistical methods and function fitting methods (Xia *et al*., 1999). The application of the patching method is dependent on the length of the gap, the season, the climatic region, the density of stations as well as data characteristics of the data archived (Gyau-Boaky & Schultz, 1994).

In most agricultural applications the effects of adverse weather events like drought are mostly seen not on daily basis but on the time scale of weekly to ten-day (dekadal) basis and some of the agrometeorological models run in Africa use dekadal values (Frere & Popov, 1979; Mukhala & Hoefsloot, 2004; Instat+, 2007). Long-term climate data measured using either mechanical weather stations or automatic weather stations contains a lot of missing values which need to be estimated in order to have a continuous dataset to be used for different purposes. These reasons led to this study, which aims at evaluating the use of the inverse distance weighting (IDW) method of estimating dekadal rainfall from daily data as possible method of patching missing or faulty rainfall measurements. The UK traditional method will also be evaluated for estimating minimum and maximum temperatures (see sub section 2.1.2.2.2).

2.1.2 Data and methods

2.1.2.1 Data

To assess the method of patching rainfall and temperature over the Free State, six weather stations were selected that are evenly distributed over the Province. The other criteria for selecting the stations was based on the percentage of missing data which had to be less than 10% and the stations should also have over 20 years of data records. Table 2.1 shows information about the stations used while Figure 2.1 shows the geographical distribution of the stations across the stations. Daily rainfall data was obtained from the ARC - Agroclimatology database and the SAWS.

Table 2.1: Geographical information of weather stations used in evaluating rainfall and temperature estimation methods.

Station Name	Latitude (^{o})	Longitude (^{o})	Altitude (m)	Data Range
Bethlehem	-28.1626	28.2953	1631	1951-2008
Bloemfontein-Glen College	-28.9500	26.3333	1304	1950-2008
Frankfort	-27.2667	28.5000	1502	1950-2001
Hertzorgville	-28.2000	25.3000	1326	1978-2000
Oukraal	-29.9333	24.6833	1143	1978-2002
Welkom	-28.1333	26.6833	1295	1964-2001

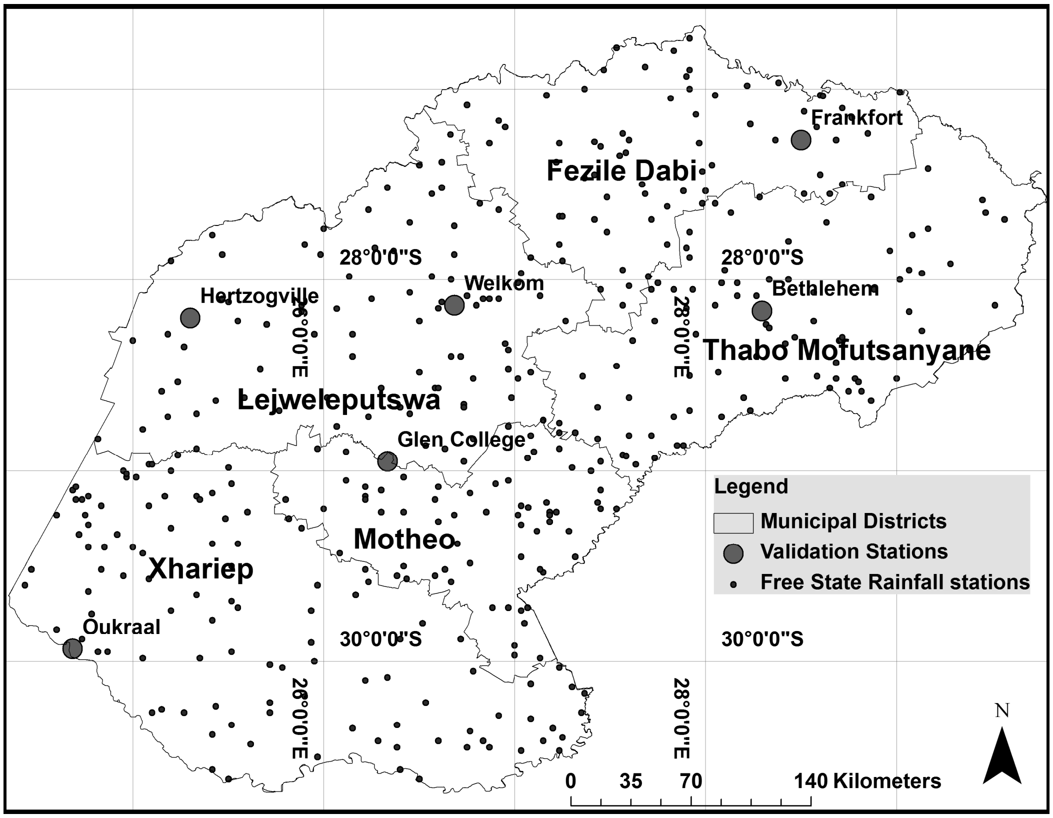


Fig. 2.1: Spatial distribution of weather stations used to evaluate rainfall estimation method.

2.1.2.2 Estimation methods

2.1.2.2.1 Rainfall

Before using IDW methodology of patching, first the accuracy of the method should be tested. The testing of the method is done by estimating daily rainfall data for the entire data range for each of the stations in Table 2.1 using IDW equation shown in equation 2.1 (Longley et al., 2001). The minimum of two to the maximum of five nearest weather stations with data in that particular day of estimation were used. The methodology also considered only nearby stations within the 50km radius of the target station. The method was chosen because it is one of the simple and recommended ways of filling the missing rainfall data (Moeletsi, 2004; Bennett *et al*., 2007; Teegavarapu *et al*., 2009). According to these researchers, the method performs best if the density of the stations is very high. In the Free State, there are over 500 rainfall stations with data within the 1950 to 2008 which makes it ideal to us IDW method. Data length of these stations varies from less than ten years to over 50 years.

$$y_t = \frac{\sum_{i=1}^{m} x_t^i \big/ D_i^2}{\sum_{i=1}^{m} 1 \big/ D_i^2} \tag{2.1}$$

where:

y_t is the estimated value of the missing data, x_t^i is the value of the ith nearest weather station, and D_i is the distance between the station of missing dataset and the ith nearest weather station.

2.1.2.2.2 Temperature

Patching minimum and maximum temperatures was performed using the UK traditional method. The methodology uses the differences in long-term monthly temperature values between the target station and the patching stations (Appendix 1) (Xia *et al.*, 1999; Moeletsi, 2004). These differences are then added to daily values for their corresponding months. As an example, Frankfort station daily minimum temperature value in January can be estimated by adding 0.2, 0.7, 1.0 and 1.3 to that day's minimum value at Villiers, Reitz, Bethlehem and Bethlehem-WK stations respectively (Appendix 1.3). These constant differences were added to the daily values of that particular station in order to estimate daily temperature values for the target station. The average of the estimated values from all the neighbour stations with data in that particular day was taken as the final estimated value for the target station. The neighbour stations were chosen based on the closeness to the target station and data efficiency of the station during the same period as the target station. As in the previous sub-section, daily estimates for all the data range were obtained for all the stations.

2.1.2.3 Statistical analysis

To analyse the performance of the methodology used at each climate station, daily values were aggregated to dekadal (10-day basis) values. First ten days of the month are grouped as the first dekad of the month, second ten days (11-20) of the month as the second dekad and last days (8 to 11 depending on the month and year) as the 3rd dekad of the month. All the data was aggregated into dekads because most of the analysis and models used in the investigation of agroclimatic risk affecting rainfed maize production over the Free State Province are based on dekadal data. The estimated dekadal values were then compared with the measured values in dekads where there were no missing values for the dataset. To find the correlation between the measured and estimated values, the coefficient of determination (r^2) was used; for determining the deviations of the estimated values from the measured values, the Mean Absolute Error (MAE) statistic was used and the Kolmogorov-Sminorv (K-S test) statistic was used to test the similarity of the estimated and measured values. The K-S test determines whether the two datasets differ significantly without making any assumption about its distribution (Van Bockstale *et al*., 2006). The decision is made using the D-value and the p-value which range from 0 to 1. D-value is the maximum deviation between the hypothesized cumulative distribution function (CDF) and the empirical CDF while p-value is the significance level (Wang *et al*., 2004). When D-value is very much greater than p-value then the statistics of the two datasets do not differ significantly and when D is less than p-value the two datasets differ significantly (Van Bockstale *et al*., 2006). The r^2 statistic was first determined by correlating all the dekadal values at each of the weather stations to the estimated values. The r^2 statistic was also determined on monthly basis (dekadal values grouped by months). The MAE and the K-S test of dekadal estimated values against the measured dekadal values were also performed on monthly basis. The r^2 at 95%

confidence interval was obtained using the Excel programme while the K-S test was done using the Past programme (Hammer *et al.*, 2001). The following is the formula for MAE (Jacovides and Kontoyiannis, 1995):

$$MAE = \frac{1}{N}\sum_{i=1}^{N}\left|d_i\right| \qquad (2.2)$$

where:

N is the number of data pairs, d^i is the difference between i^{th} predicted dekadal value and the i^{th} measured dekadal value.

2.1.3 Results and discussion

2.1.3.1 Evaluation of rainfall patching method

The results of the coefficient of determination (r^2) for the comparison of the measured dekadal rainfall and the estimated dekadal rainfall for the entire dataset are high in all the stations (Fig. 2.2). The r^2 values range from 0.776 in Frankfort to the highest of 0.90 in Bloemfontein (Glen College) with all stations having r^2 exceeding 0.75. These shows that the estimated dekadal rainfall using the IDW method over the Free State result to more than 75% of variation of measured dekadal values. Hence, the IDW method using values from the two to five nearest stations performs well in estimating actual dekadal rainfall amounts.

Looking specifically at the correlation of the patching method on monthly basis, one can see a lot of variation of r^2 from month to month and per station (Table 2.2). The values are still mostly above 0.70 in all the months for all the stations indicating a good performance with few exceptions. On average the r^2 statistic ranges from 0.71 to 0.88 and in 10 out of 12 months the average was exceeding 0.75. Bloemfontein show consistently high values with all the monthly correlations exceeding 0.80. The monthly r^2 vaues in Bethlehem also exceeds 0.75 showing good correlation except in December where the value is below 0.70. In contrast, Frankfort monthly r^2 values show a lot of variation with values between from 0.55 and 0.91. The results clearly show that, there is a good relation between estimated rainfall values and actual rainfall values.

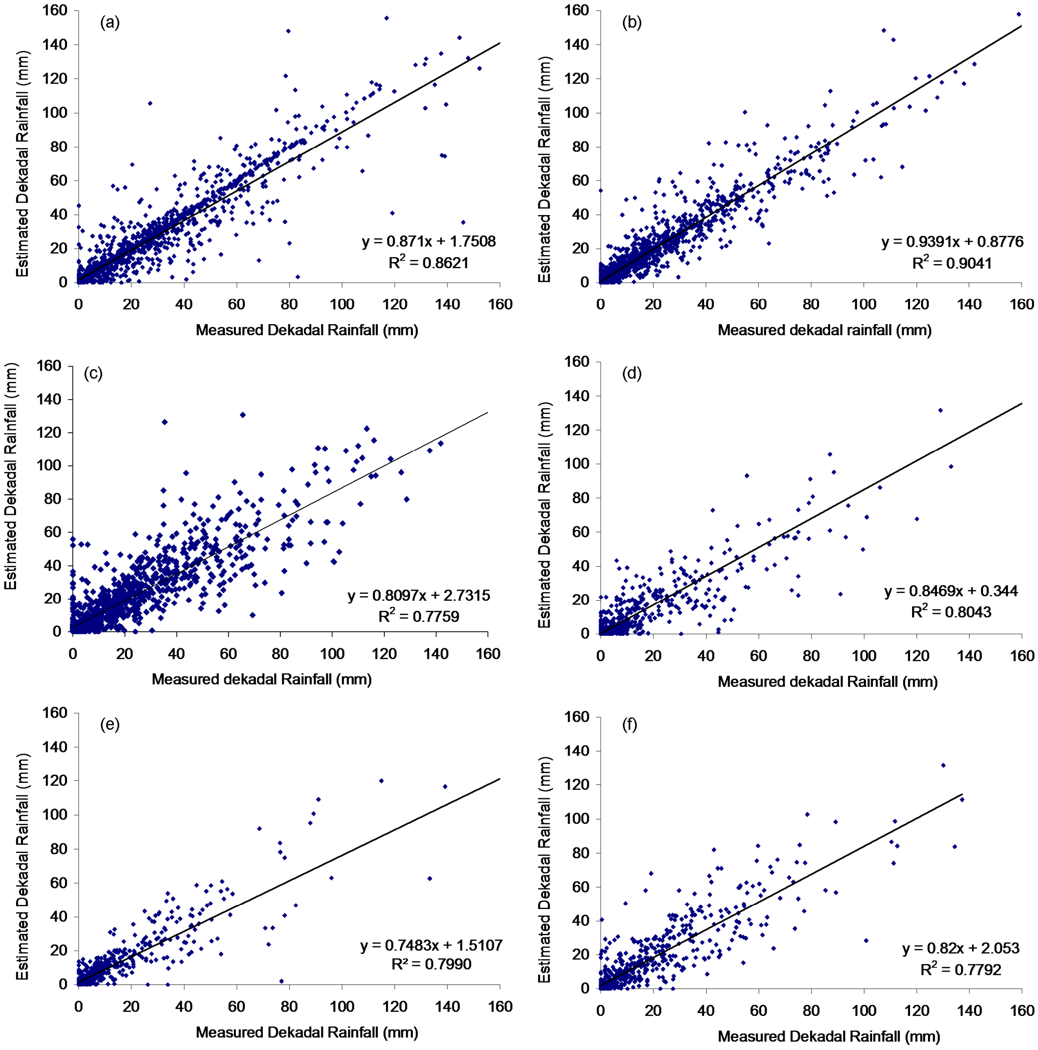


Fig. 2.2: Comparison between measured dekadal rainfall and estimated dekadal rainfall for (a) Bethlehem; (b) Bloemfontein (Glen College); (c) Frankfort; (d) Hertzogville; (e) Oukraal; (f) Welkom.

The deviations of estimated values compared to the measured values as well the similarity test using K-S test are also shown in Table 2.2. Small MAE values were obtained in the winter months due to the low rainfall recieved while in the other months the MAE values a relatively large. Bethlehem, Bloemfontein and Oukraal show low error with MAE of less than 10 mm/dekad for all the months. In Frankfort, Hertzogville and Welkom the errors obtained exceed 10mm/dekad mostly in December to March while in other months relatively low error of less than 10mm/dekad. In order for the estimated values to be statistically similar to the actual values, the D-statistic should be far less than the p value (Hammer *et al*., 2001; Van Bockstale *et al*., 2006). In all the months for every station, the D-statistic is far less than p value except for December month in Welkom whereby the P value is more than the D-statistic hence showing statistical difference between the estimated and measured values. In Frankfort, the D statistic is very close to the p value in January. Thus, the results show that IDW method used for estimating daily rainfall performs very well most of the times.

Table 2.2: The r^2, MAE and KS test value of the comparison between measured dekadal rainfall and IDW method estimated values.

Station		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
r^2													
Bethlehem		0.79	0.88	0.87	0.81	0.96	0.94	0.90	0.88	0.96	0.91	0.78	0.61
Bloemfontein		0.84	0.88	0.88	0.92	0.94	0.94	0.96	0.97	0.95	0.94	0.91	0.86
Frankfort		0.66	0.55	0.75	0.77	0.87	0.77	0.67	0.64	0.90	0.75	0.70	0.72
Hertzogville		0.70	0.85	0.87	0.88	0.53	0.73	0.63	0.95	0.71	0.79	0.73	0.83
Oukraal		0.58	0.89	0.81	0.83	0.82	0.92	0.95	0.98	0.86	0.95	0.71	0.80
Welkom		0.70	0.78	0.58	0.77	0.93	0.69	0.93	0.88	0.91	0.88	0.81	0.60
Average		*0.71*	*0.81*	*0.79*	*0.83*	*0.84*	*0.83*	*0.84*	*0.88*	*0.88*	*0.87*	*0.77*	*0.74*
MAE													
Bethlehem		7.4	5.4	5.1	3.3	1.2	0.7	0.8	1.4	2.0	4.3	5.9	7.5
Bloemfontein		7.8	7.3	5.9	3.7	1.3	0.8	0.6	0.8	1.4	3.5	5.3	5.4
Frankfort		14.5	11.9	8.1	5.3	1.9	1.0	1.0	2.6	2.8	7.0	9.5	11.2
Hertzogville		13.7	10.5	9.0	5.1	2.3	1.0	1.0	0.6	3.4	6.7	7.0	7.4
Oukraal		8.3	5.7	5.0	3.6	1.1	0.9	0.6	0.8	1.4	2.9	4.7	7.3
Welkom		11.9	10.9	10.6	5.2	1.3	0.9	0.4	0.8	2.4	6.3	7.3	8.3
Average		10.6	8.62	7.28	4.37	1.52	0.88	0.73	1.17	2.23	5.12	6.62	7.85
KS													
Bethlehem	D	0.09	0.04	0.06	0.06	0.05	0.08	0.07	0.05	0.06	0.05	0.06	0.05
	p	0.55	1.00	0.95	0.90	1.00	0.72	0.80	0.98	0.90	0.99	0.96	0.99
Bloemfontein	D	0.08	0.09	0.06	0.08	0.05	0.04	0.04	0.07	0.05	0.07	0.05	0.07
	p	0.77	0.64	0.96	0.75	1.00	1.00	1.00	0.84	0.98	0.79	0.99	0.86
Frankfort	D	0.15	0.10	0.08	0.07	0.07	0.07	0.05	0.06	0.04	0.10	0.09	0.10
	p	0.17	0.70	0.82	0.94	0.97	0.97	1.00	1.00	1.00	0.64	0.67	0.63
Hertzogville	D	0.16	0.13	0.18	0.13	0.12	0.09	0.04	0.09	0.09	0.12	0.10	0.12
	p	0.43	0.75	0.31	0.71	0.84	0.98	1.00	1.00	0.98	0.76	0.91	0.76
Oukraal	D	0.12	0.09	0.11	0.11	0.07	0.06	0.03	0.08	0.05	0.07	0.10	0.09
	p	0.76	0.98	0.89	0.85	1.00	1.00	1.00	0.98	1.00	1.00	0.92	0.97
Welkom	D	0.09	0.11	0.07	0.14	0.09	0.09	0.06	0.13	0.09	0.09	0.14	0.20
	p	0.97	0.94	1.00	0.61	0.98	0.97	1.00	0.73	0.96	0.98	0.69	0.19

2.1.3.2 Evaluation of minimum temperature estimation method

The results of the correlation of determination (r^2) for the comparison of the measured dekadal minimum temperatures and the UK traditional method estimated dekadal minimum temperatures for the entire dataset at all 6 stations have values exceeding 0.95 (Fig. 2.3). These generally show that, the UK method performs fairly well in estimating minimum temperatures at dekadal scale. Table 2.3 shows r^2 values for estimated dekadal values against measured values for all the months. The values obtained are still high with the minimum value of 0.69 being recorded in Welkom in January and the maximum value of 0.95 at Hertzogville in October. In all the months the average r^2 ranges from 0.75 to 0.85. r^2 values exceeding 0.75 clearly indicates good correlation between the measured and estimated dekadal minimum temperatures values.

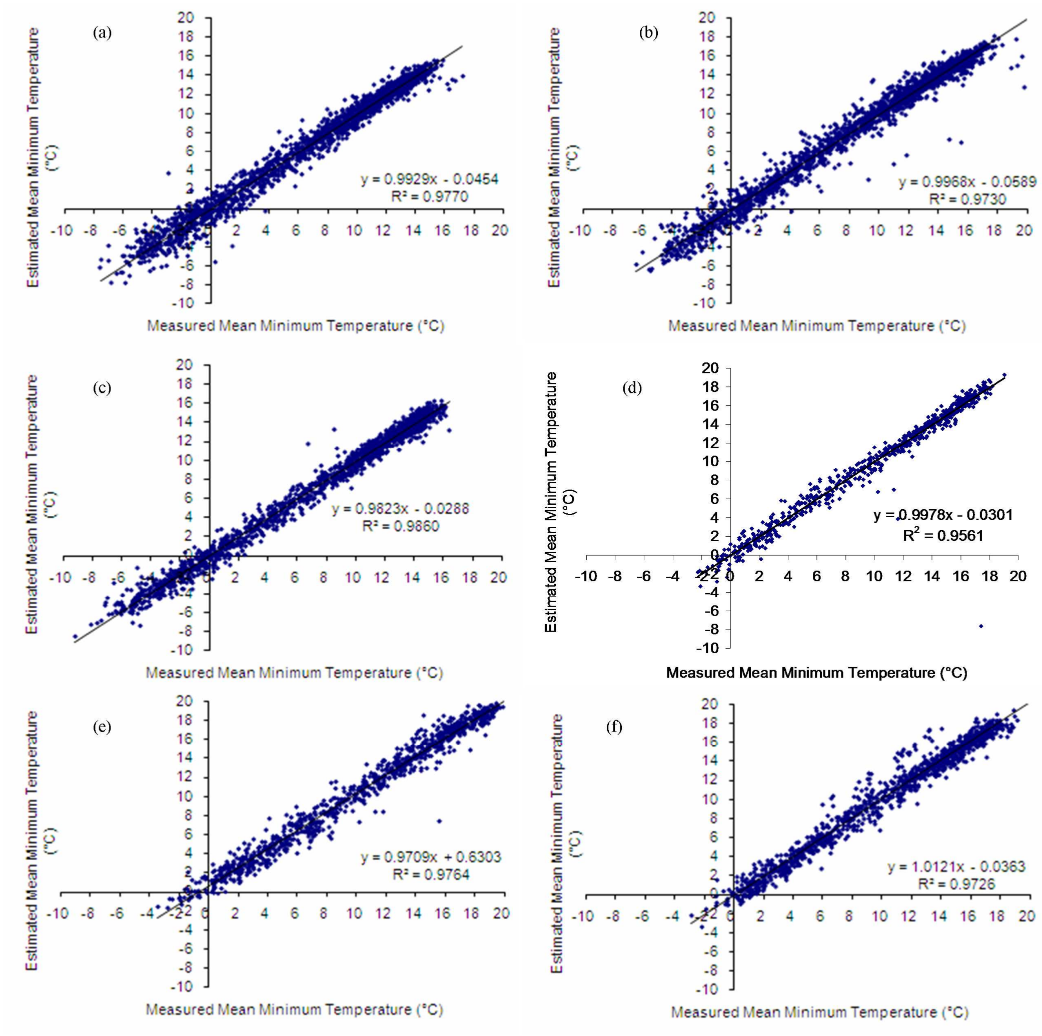


Fig. 2.3: Comparison between measured dekadal minimum temperature and estimated dekadal minimum temperature for (a) Bethlehem; (b) Bloemfontein; (c) Frankfort; (d) Hertzogville; (e) Oukraal; (f) Welkom.

The MAE values in Table 2.3 show that, the UK method performs best during the summer and transition seasons (Autown & Spring) with MAE of less than 0.8℃. In contrast, in winter months (June and July), the MAE are relatively high than in the other months with the highest values of around 1℃ in June and July in both Bethlehem and Bloemfontein. As compared with the average dekadal minimum temperatures, MAE in winter shows relatively high error while in the summer months MAE values compared with the long-term average show extremely low error. The KS test results for measured minimum temperatures versus the UK traditional method estimated values show low values of the D-statistic and high values of P values for most of the values with the few exceptions (February in Frankfort; February, July and December in Oukraal; February in Bloemfontein and January in Welkom) where p values are less than D. The relatively low D-statistics is an indication that the estimated minimum temperatures are statistically similar to the actual values hence the UK method performed well. In contrast, when D is greater than p then the estimated values are statistically different.

Table 2.3: The r^2, MAE and KS test value of the comparison between measured dekadal minimum temperatures and UK traditional method estimated values.

Station		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
r^2													
Bethlehem		0.72	0.77	0.84	0.85	0.78	0.61	0.55	0.79	0.82	0.81	0.83	0.64
Bloemfontein		0.81	0.83	0.90	0.85	0.85	0.70	0.76	0.84	0.78	0.71	0.86	0.70
Frankfort		0.72	0.82	0.82	0.92	0.87	0.78	0.81	0.93	0.91	0.88	0.70	0.85
Hertzogville		0.79	0.91	0.92	0.92	0.81	0.73	0.86	0.85	0.90	0.95	0.93	0.82
Oukraal		0.80	0.75	0.90	0.87	0.85	0.84	0.81	0.82	0.79	0.86	0.84	0.79
Welkom		0.69	0.80	0.84	0.63	0.90	0.84	0.80	0.86	0.86	0.86	0.89	0.79
Average		*0.76*	*0.81*	*0.87*	*0.84*	*0.84*	*0.75*	*0.77*	*0.85*	*0.84*	*0.85*	*0.84*	*0.77*
MAE													
Bethlehem		0.43	0.47	0.49	0.66	0.82	1.01	1.12	0.90	0.82	0.65	0.46	0.49
Bloemfontein		0.52	0.52	0.46	0.64	0.55	0.94	0.99	0.82	0.84	0.76	0.57	0.68
Frankfort		0.51	0.64	0.57	0.68	0.67	0.80	0.73	0.60	0.63	0.57	0.52	0.40
Hertzogville		0.43	0.38	0.45	0.52	0.67	0.60	0.57	0.60	0.61	0.42	0.35	0.44
Oukraal		0.58	0.62	0.63	0.83	0.65	0.71	0.83	0.91	0.90	0.67	0.58	0.62
Welkom		0.60	0.51	0.55	0.83	0.58	0.61	0.66	0.68	0.79	0.55	0.41	0.47
Average		*0.51*	*0.52*	*0.53*	*0.69*	*0.66*	*0.78*	*0.82*	*0.75*	*0.77*	*0.6*	*0.48*	*0.52*
KS													
Bethlehem	D	0.07	0.05	0.08	0.05	0.07	0.12	0.11	0.11	0.08	0.09	0.06	0.04
	P	0.73	1.00	0.72	0.98	0.83	0.22	0.30	0.39	0.71	0.46	0.90	1.00
Bloemfontein	D	0.09	0.13	0.08	0.07	0.12	0.11	0.13	0.09	0.09	0.09	0.08	0.11
	P	0.47	0.11	0.73	0.82	0.23	0.39	0.22	0.62	0.60	0.51	0.66	0.12
Frankfort	D	0.12	0.27	0.12	0.11	0.08	0.12	0.07	0.09	0.06	0.11	0.10	0.10
	P	0.37	0.00	0.29	0.53	0.80	0.37	0.94	0.69	0.96	0.47	0.58	0.67
Hertzogville	D	0.17	0.12	0.13	0.12	0.13	0.10	0.12	0.13	0.08	0.05	0.10	0.08
	P	0.32	0.77	0.74	0.77	0.71	0.95	0.85	0.70	0.98	1.00	0.92	0.98
Oukraal	D	0.06	0.18	0.13	0.09	0.14	0.13	0.18	0.17	0.06	0.13	0.13	0.21
	P	0.96	0.16	0.50	0.88	0.38	0.51	0.18	0.20	1.00	0.51	0.51	0.05
Welkom	D	0.19	0.08	0.09	0.14	0.13	0.08	0.10	0.09	0.13	0.10	0.04	0.10
	P	0.07	0.88	0.86	0.41	0.33	0.94	0.81	0.86	0.38	0.76	1.00	0.65

2.1.3.3 Evaluation of maximum temperature estimation method

The r^2 values for the UK tradional method estimated maximum temperatures versus the measured values are above 0.96 for all the 6 stations with the entire dataset (Fig. 2.4). The monthly r^2 values show a lot of variation with the lowest value of 0.61 being recorded in May at Oukraal and the highest value of 0.97 being obtained eight times at different stations. The average r^2 for all the months is over 0.90 excluding June and December where the average r^2 values are 0.86 and 0.89 respectively. The high r^2 values show that UK method of estimating maximum temperatures has a good relationship with actual values. The MAE values (Table 2.4) for the dekadal averages are below 0.80°C with lowest values in July and August around 0.28°C. The relative error (MAE over dekadal average) is less than 4% in all the months for all the stations. These clearly show that, UK method is a good method of estimating maximum temperatures. The KS test results for comparing measured maximum temperatures with estimated values reiterate the fact that UK method is the good estimator. The D-statistic is mostly far lower than P value with few exceptions in May and June at Frankfort and April at Welkom.

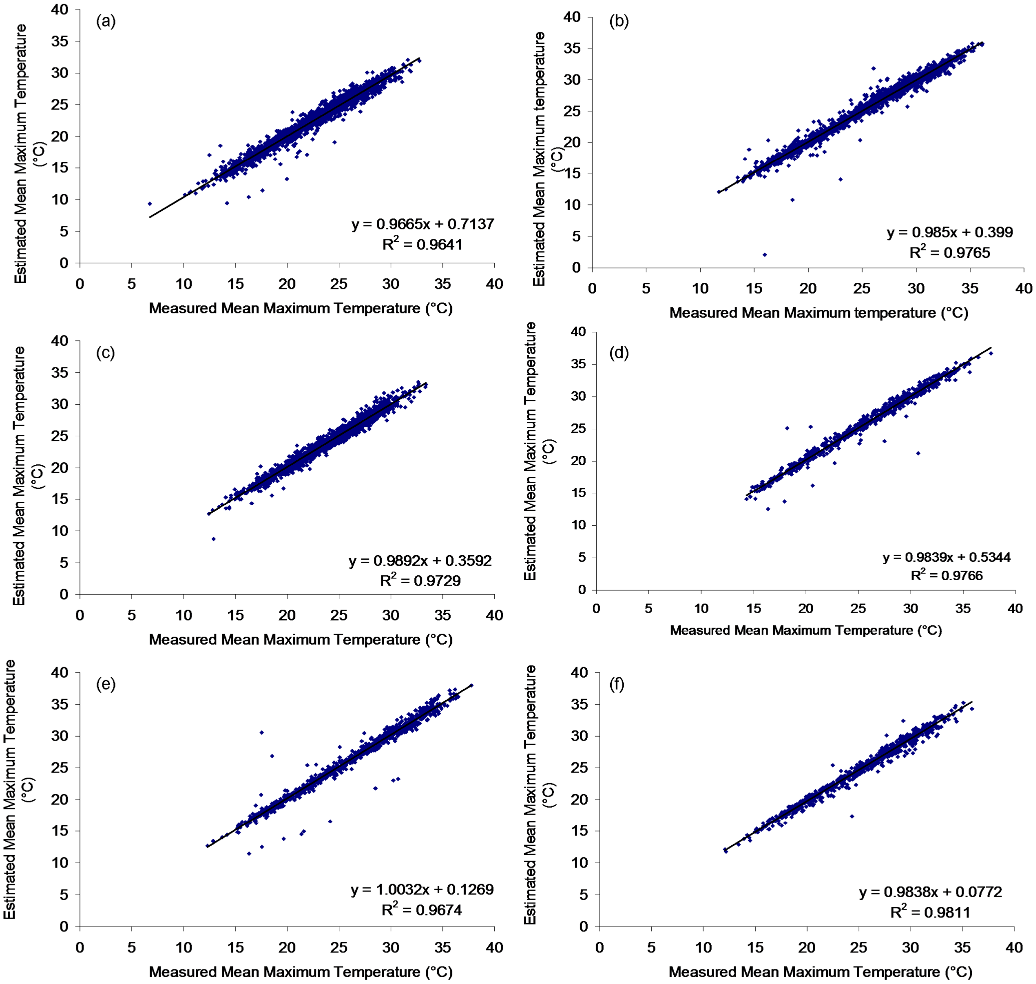


Fig. 2.4: Comparison between measured dekadal maximum temperature and estimated dekadal maximum temperature for (a) Bethlehem; (b) Bloemfontein; (c) Frankfort; (d) Hertzogville; (e) Oukraal; (f) Welkom

Table 2.4: The r^2, MAE and KS test value of the comparison between measured dekadal maximum temperatures and UK traditional method estimated values.

Station		**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
r^2													
Bethlehem		0.88	0.88	0.89	0.90	0.89	0.73	0.80	0.85	0.89	0.85	0.93	0.82
Bloemfontein		0.93	0.90	0.93	0.95	0.95	0.94	0.96	0.93	0.94	0.94	0.92	0.87
Frankfort		0.92	0.92	0.88	0.93	0.94	0.85	0.91	0.94	0.97	0.92	0.92	0.88
Hertzogville		0.93	0.97	0.95	0.95	0.97	0.74	0.97	0.97	0.87	0.95	0.96	0.94
Oukraal		0.93	0.93	0.96	0.96	0.61	0.70	0.94	0.97	0.97	0.95	0.94	0.91
Welkom		0.94	0.94	0.95	0.94	0.93	0.96	0.93	0.96	0.94	0.96	0.97	0.76
Average		*0.92*	*0.92*	*0.93*	*0.94*	*0.88*	*0.82*	*0.92*	*0.94*	*0.93*	*0.93*	*0.94*	*0.86*
MAE													
Bethlehem		0.62	0.56	0.51	0.59	0.53	0.59	0.47	0.50	0.65	0.68	0.48	0.66
Bloemfontein		0.54	0.53	0.46	0.38	0.33	0.35	0.29	0.39	0.45	0.44	0.52	0.55
Frankfort		0.69	0.51	0.59	0.59	0.46	0.50	0.45	0.49	0.43	0.56	0.48	0.51
Hertzogville		0.56	0.50	0.46	0.50	0.67	0.63	0.24	0.28	0.54	0.40	0.35	0.51
Oukraal		0.48	0.76	0.54	0.55	0.78	0.60	0.33	0.36	0.40	0.46	0.44	0.48
Welkom		0.48	0.72	0.45	0.79	0.45	0.53	0.28	0.29	0.44	0.55	0.43	0.73
Average		*0.56*	*0.60*	*0.50*	*0.57*	*0.54*	*0.53*	*0.34*	*0.39*	*0.49*	*0.52*	*0.45*	*0.57*
KS													
Bethlehem	D	0.08	0.08	0.06	0.08	0.04	0.04	0.05	0.05	0.07	0.05	0.07	0.10
	P	0.64	0.72	0.95	0.64	1.00	1.00	0.98	0.98	0.82	0.99	0.83	0.44
Bloemfontein	D	0.08	0.06	0.09	0.04	0.04	0.06	0.05	0.05	0.06	0.07	0.05	0.08
	P	0.67	0.96	0.56	1.00	1.00	0.95	0.99	0.98	0.92	0.86	0.97	0.66
Frankfort	D	0.13	0.08	0.07	0.08	0.14	0.14	0.13	0.16	0.07	0.05	0.05	0.07
	P	0.22	0.80	0.88	0.78	0.14	0.16	0.22	0.07	0.90	1.00	0.99	0.95
Hertzogville	D	0.12	0.15	0.07	0.09	0.18	0.12	0.11	0.09	0.10	0.11	0.08	0.16
	P	0.76	0.48	1.00	0.98	0.29	0.77	0.87	0.97	0.91	0.81	0.98	0.36
Oukraal	D	0.09	0.18	0.16	0.13	0.08	0.12	0.10	0.08	0.10	0.14	0.06	0.08
	P	0.88	0.14	0.25	0.48	0.96	0.63	0.87	0.96	0.78	0.38	1.00	0.97
Welkom	D	0.07	0.16	0.10	0.04	0.11	0.17	0.14	0.08	0.07	0.12	0.12	0.12
	P	0.99	0.32	0.84	1.00	0.83	0.29	0.60	0.98	1.00	0.70	0.72	0.69

2.1.4 Conclusions

The accuracy of the patching methods used in the Free State study area was evaluated using 6 selected stations. The rainfall values were estimated using the Inverse distance weighting method. The correlation of determination (r^2) for rainfall for all the stations shows a good correlation with values mostly exceeding 0.75. The monthly r^2 values are also high in most stations clearly showing that ID method resulted in good estimates of rainfall. The KS test results at 95% confidence interval also show that there is no significant difference in the measured and IDW estimated dekadal rainfall values. Minimum and maximum temperatures were estimated using the UK taditional method. The overall r^2 results for minimum and maximum temperatures are over 0.90 for all the stations. The MAE error estimates are less than 0.80℃ for all 6 stations in most months for the comparison of both minimum and maximum temperatures. The KS test results for the measured minimum/maximum temperatures versus the UK traditional method estimated values show that D-value is significantly lower than P-value hence the two datasets are statistically similar. These means both the IDW and UK traditional method can be used to patch missing values over the Free State.

2.2 Evaluation of the Hargreaves Evapotranspiration Empirical Model

2.2.1 Introduction

Accurate estimation of evapotranspiration (ET) is important for modelling water use and for agricultural/ecological applications, natural resource management and other planning activities (Chiew *et al.*, 1995; Tilahun, 2006; Fooladmand & Haghighat, 2007; Nova *et al*., 2007; Suleiman & Hoogenboom, 2009). ET is dependent on the supply of heat energy, vapour pressure gradient and movement of air (de Jager & van Zyl, 1989; Allen *et al*., 1998; Xu & Singh, 1998). It can be estimated either by using earth-atmosphere energy balance and aerodynamics principles or by empirically determined models (Samani, 2000; Garcia *et al*., 2004; Berengena & Gavilán, 2005; Bautista *et al*., 2009).

According to the UN - Food and Agriculture Organization (FAO), the most reliable way to estimate ET from meteorological data involves use of the Penman-Monteith method (ETo) which couples earth-atmosphere energy balances and the aerodynamic transport properties of water vapour (Allen *et al*., 1998; Popova *et al*., 2006; Suleiman & Hoogenboom, 2009; Liang *et al*., 2010). Although this method is widely accepted because of its accuracy, its utility is constrained by dependence on numerous parameters, i.e. maximum and minimum temperature, vapour pressure, net radiation and wind speed (Allen *et al*., 1998; Tilahun, 2006; Foolandmand *et al.,* 2008). This limitation has substantial implications for data-scarce areas like South Africa and other African countries which therefore have to depend on other methodologies to estimate ET. In most places the most commonly measured weather parameters are rainfall, minimum and maximum temperatures, while wind and relative humidity measurements are unreliable and scarce. Although data from South Africa's automatic weather stations can be used with the ETo method, temporal coverage is restricted to the period after 1995. Thus, another method which has lower data demands for estimating ETo is required to generate ETo from long-term climate records.

Three different types of empirical models (temperature-based models, radiation-based models and mass-transfer-based models) are commonly used to determine ET depending on the meteorological data available (Chiew *et al.*, 1995; Xu & Singh, 2002; Berengena & Gavilán, 2005). Temperature-based models include the Thornthwaite, Hargreaves and Blaney-Criddle models; radiation-based models include the Makkink, Ritchie-type and the Priestley-Taylor equations; whilst the Dalton and Rohwer equations are two examples of mass-transfer-based models (Thornthwaite, 1948; Xu & Singh, 1998; Xu & Singh, 2002; DehghaniSanij *et al*., 2004; Pereira & Pruitt, 2004; Berengena & Gavilán, 2005). Other empirical models (the Copais equation for example) need relative humidity, mean temperature and solar radiation as inputs and are run by combining radiation and temperature (Alexandris *et al*., 2006). Due to the lack of models designed specifically for estimating ET in semi-arid areas like the Free State Province of South Africa, any empirical model developed elsewhere will have to be calibrated per location/region against the Penman-Monteith equation (DehghaniSanij *et al*., 2004; Gavilán *et al*., 2006; Jabloun & Sahli, 2008).

In this study, the use of Hargreaves equation to estimate the ET because of their exclusive use of temperature data which is commonly recorded at the majority of South Africa's weather stations will be evaluated over the Free State Province using the Penman-Monteith equation. Research from other semi-arid conditions showed that, ET values obtained from this emperical equation has a good agreement with the Penman-Monteith equation values (e.g Gavilán *et al*. (2006) in southern Spain; Popova *et al*. (2006) in southern Bulgaria; Fooladmand & Haghighat (2007) in Iran).

2.2.2 Data and methods

2.2.2.1 Data

The study area is located in the Free State Province of South Africa. The climate of the province is mostly semi-arid except the eastern and northeastern parts where humid-subtropical climate is experienced according to the Köppen climate classification. Average annual rainfall ranges from 300 mm to over 900 mm with more than 70% of the rainfall occurring in September to April. The topography of the province is diverse with altitudes of <1200 m in the southern part and >1800 m in the eastern Free State. Table 2.5 shows coordinate locations and altitudes of the eight selected weather stations used in this study and the temporal coverage of data that was used from each weather station for the evaluation exercise. Figure 2.5 shows the locations of these stations in the Free State Province.

Table 2.5: Coordinate locations and altitudes of weather stations used in the study and temporal coverage of data by each weather station.

Station Name	**Latitude (^{o})**	**Longitude (^{o})**	**Altitude (m)**	**Data Range**
Bleskop	-29.8781	24.5831	1224	1999-2008
Bloemfontein(UFS)	-29.1058	26.1850	1417	2000-2008
Bothaville	-27.3034	26.6822	1315	2000-2008
Gladdedrift	-26.9955	28.9582	1521	2001-2008
Senekal	-28.3889	27.5866	1487	2000-2008
Welkom	-28.1773	26.4162	1293	1999-2008

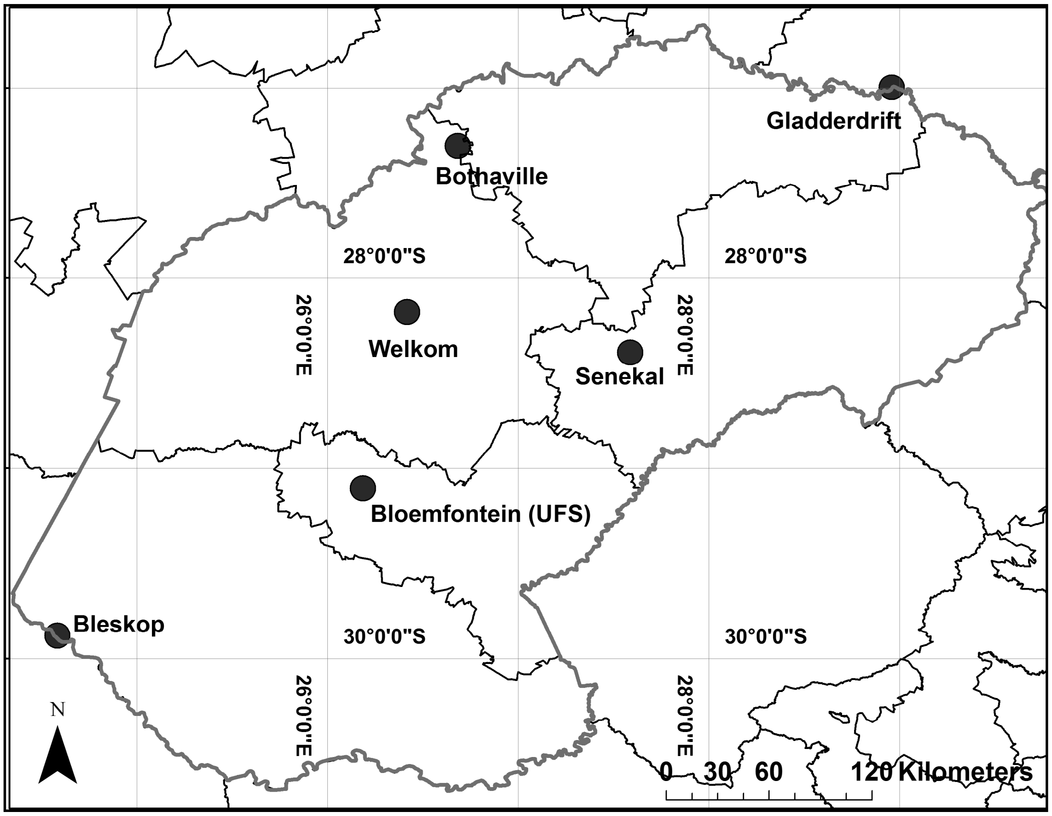


Fig. 2.5: Locations of weather stations in the Free State Province used in the evaluation of Hargreaves evapotranspiration equation.

Selection of the six weather stations that provided data for this comparison of ET estimation methods was guided by the need for:

1. Near-even geographical distribution,
2. Availability of weather data for a minimum period of 6 years, and
3. Continuity of data.

Geographical distribution was purposefully structured to yield a sample that allowed different ecological regions of the province to be represented, with the eventual selection being determined by the combined influence of this criterion and the spatial distribution of operational stations with data in excess of the minimum 6-year temporal period. Continuity of data was objectively determined by analyzing station data for missing values and the 90% efficiency level (i.e. less than 10% missing values) used as the cut-off point for selecting the eight stations. All the data as per the equations in sub-section 2.2.2.2 were obtained from the ARC-ICSW Agroclimatology databank.

2.2.2.2 ETo estimation

The Hargreaves equation (equations 2.3), was used to estimate daily ET using daily minimum temperatures and daily maximum temperatures for each weather station. The daily ET values were then summed for each 10-day period (dekad) of every month from 1999 to 2008.

- Hargreaves equation (Hargreaves & Samani, 1985):

$$ET_H = 0.408 * 0.0023 * (T_{av} + 17.8) * (T_{\max} - T_{\min})^{0.5} * Ra \tag{2.3}$$

where:

ET_H is evapotranspiration in mm per day estimated using the Hargreaves equation; T_{av}, Tmax and Tmin are the daily mean, maximum and minimum air temperatures in ^oC; Ra is the extraterrestrial radiation (MJ m^{-2} per day); 0.408 is the constant for converting MJ m^{-2} per day into mm per day and 0.0023 is the original coefficient of the Hargreaves equation.

2.2.2.3 Calibration and validation

Data for all six stations were segregated into two groups comprising the calibration period and the validation period. The calibration period is from 1999 to 2004 while the validation period is from 2005 to 2008.

The Hargreaves equation was calibrated against the FAO-56 Penman-Monteith for estimating ET (Eq. 2.4). The equation for FAO-56 Penman-Monteith (ETo) is as follows (Allen *et al.*, 1998):

$$ETo = \left(\frac{0.408 * \Delta * (R_n - G) + \gamma(\frac{900}{T_{av} + 273}) u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34 u_2)} \right) \tag{2.4}$$

where:

ETo is in mm per day; R_n is the net radiation (MJm^{-2} per day); G is the soil heat flux (MJ m^{-2} per day); u_2 is the mean wind speed in ms^{-1}; $(e_s – e_a)$ is the saturation vapour pressure deficit (kPa); Δ is the slope of the vapour pressure-temperature curve (kPa^oC^{-1}) and γ is the psychometric constant (kPa^oC^{-1}).

To calibrate the equations, the slope of the regression between dekadal ETo and dekadal ET_H was forced to pass through the origin for each month per station for the calibration period. The calibration coefficient was then obtained by calculating the product of the slope of the regression lines (forced to pass at (0,0)) and the original coefficients (equations 2.5).

$$C_H = slope \times 0.0023 \tag{2.5}$$

where:

C_H is the new calibration constant for the Hargreaves equation.

The resultant calibrated equation for Hargreaves is shown in equations 2.6.

$$ET_{CH} = 0.408 * C_H * (T_{av} + 17.8) * (T\max - T\min)^{0.5} * Ra \tag{2.6}$$

where:

ET_{CH} is the calibrated Hargreaves estimate.

To validate the performance of the original equation (equations 2.3) and the calibrated equation (equations 2.6), climate data from 2005 to 2008 were used. The estimated dekadal ET values were compared with the Penman-Monteith estimates using statistical methods outlined in sub-section 2.2.2.4 below.

2.2.2.4 Statistical analysis

Performance of the original Hargreaves equation and its calibrated version versus the Penman-Monteith equation was determined by calculating the Root Mean Square Error (RMSE), Mean Bias Error (MBE) and relative error (RE) for the validation period (2005-2008). Since calibration had no effect on the coefficient of determination (r^2) between ET_H and ETo, r^2 was determined for the entire period (1999-2008) using 95% confidence limits. The following are the formulae for determining other statistical indicators (Jacovides & Kontoyiannis, 1995; Almorox *et al*., 2005):

$$RMSE = \left(\frac{1}{N} \sum_{i=1}^{N} d^2 \right)^{0.5} \qquad (2.7)$$

$$MBE = \frac{1}{N} \sum_{i=1}^{N} d_i \qquad (2.8)$$

$$RE = \frac{RMSE}{\overline{ETo}} \times 100 \qquad (2.9)$$

where:

N is the number of data pairs; d^i is the difference between i^{th} predicted ET and the i^{th} ETo value and $\overline{ETo}$ is the mean dekadal ETo.

2.2.3 Results and discussion

2.2.3.1 Correlation between ET_H and ETo

Figure 2.6 shows the regression between the dekadal ET estimated using the Hargreaves formula and the Penman-Monteith formula for 1999-2008 weather station data. The Hargreaves estimates have a close relationship with the Penman-Monteith method, the coefficients of determination (r^2) ranging from 0.85 in Bothaville to 0.95 in Bleskop and Bloemfontein. The general tendency of the Hargreaves equation to underestimate ETo is portrayed by regression slopes (range 0.77 to 0.87) for all the stations that are less than 1. The regression intercepts (range 4.49 to 8.63) are also not close to zero. Because of these characteristics, the Hargreaves equation cannot be used in its original form to estimate ET for the Free State semi-arid area. In the study done by Jabloun & Sahli (2006) in another semi-arid region in Tunisia, Hargreaves equation mostly overestimated Penman-Monteith ET which is contradicting with the results obtained from this study. Gavilán *et al.* (2006) found both underestimation and overestimation of the Hargreaves equation when compared to the Penman-Monteith in the semi-arid region over the southern Spain.

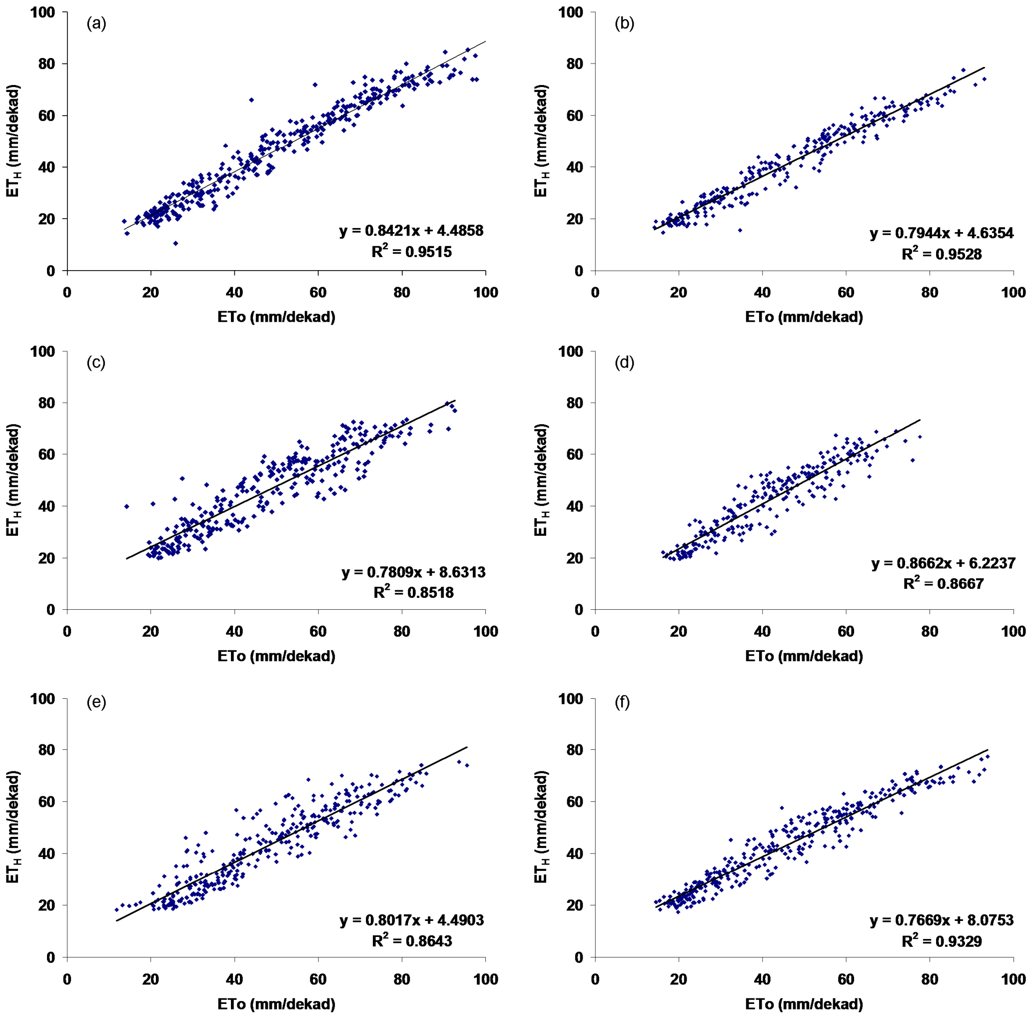


Fig. 2.6 Comparison between Penman–Monteith (Eto) and Hargreaves (ET_H) evapotranspiration models for (a) Bleskop; (b) Bloemfontein; (c) Bothaville; (d) Gladdedrift; (e) Senekal; (f) Welkom.

For better determination of the closeness of the Hargreaves equation to the Penman-Monteith equation, comparison was made on a monthly basis using r^2 statistics. Table 2.6 shows the r^2 values for dekadal estimates of all monthly datasets for each station. The correlation between Hargreaves and Penman-Monteith is high during the main maize growing season (October to April) with the values ranging from 0.52 to 0.95 and the average r^2 exceeding 0.70 for all the stations. The results are in agreement with research done in other environments which shows high correlation between the Hargreaves equation and the Penman-Monteith equation (Temesgen *et al.*, 2005; Trajkovic, 2007; Jabloun & Sahli, 2008). By contrast, the Hargreaves equation perfoms poorly in winter and the transition period (May to September) the Hargreaves estimates show low skill in estimating the ETo with the lowest values of r^2 being observed in June and May, averaging 0.24 and 0.46 respectively.

Table 2.6: The r^2 values of the regression between dekadal Penman-Menteith and Hargreaves evapotranspiration estimates in each month.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bleskop	0.66	0.90	0.52	0.77	0.60	0.29	0.42	0.66	0.67	0.87	0.83	0.74
Bloemfontein	0.88	0.95	0.89	0.62	0.49	0.03	0.65	0.74	0.71	0.76	0.92	0.81
Bothaville	0.84	0.85	0.72	0.77	0.39	0.17	0.57	0.86	0.61	0.81	0.91	0.83
Gladdedrift	0.89	0.84	0.94	0.68	0.26	0.57	0.54	0.79	0.60	0.69	0.85	0.75
Senekal	0.74	0.80	0.77	0.66	0.32	0.21	0.65	0.62	0.62	0.58	0.65	0.60
Welkom	0.78	0.87	0.75	0.81	0.69	0.17	0.40	0.58	0.44	0.56	0.93	0.92
Average	*0.80*	*0.87*	*0.77*	*0.72*	*0.46*	*0.24*	*0.54*	*0.71*	*0.61*	*0.71*	*0.85*	*0.78*

2.2.3.2 Calibration of Hargreaves

The slope of the regression between the ETo estimates to ET_H estimates was computed for the period 1999 to 2004 and their values for every month are presented in Table 2.7. The results of the calibrated coefficient (C_H), which is the product of slope and Hargreaves original coefficient (0.0023), are also shown in Table 2.7. At the eight weather stations that were investigated, the highest number of stations with the closest estimation to ETo occurs mainly from February to June with at least four stations having a slope between 0.95 and 1.05 (Table 2.8). During the months where there is a close estimation, the calibrated coefficient ranges from 0.0022 to 0.0024 (Table 2.7). From July to January the Hargreaves equation for the majority of the stations underestimates ETo with the average slope of ETo to ET_H being over 1.05. In the months of August, September and October, all eight stations underestimate ETo with the maximum slope of 1.27 (resulting in calibration coefficient of 0.0029) in September at the Koppies station. On average the underestimation in August and September is by 16% (calibration coefficient of 0.0027). Bloemfontein and Senekal stations, situated in the central parts of the Free State respectively, show a consistent underestimation throughout the year. Overestimation is at its peak in February and April with two out of 6 stations having a ratio of less than 0.90. The highest overestimation with a slope value of 0.88 for Bothaville during April and the corresponding calibration coefficient (C_H) is 0.0020 compared to the original 0.0023.

Table 2.7: The slope of the regression line between estimated dekadal Hargreaves (ET_H) and Penman-Monteith ET (ETo) and the calibration coefficient of the Hargreaves equation (C_H) for each station per month.

Station	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Slope of regression												
Bleskop	1.06	1.03	1.00	0.97	0.89	1.02	1.09	1.13	1.14	1.10	1.11	1.14
Bloemfontein	1.14	1.09	1.06	1.00	0.98	0.97	1.10	1.14	1.14	1.16	1.13	1.11
Bothaville	0.95	0.89	0.91	0.88	0.96	1.00	1.07	1.19	1.21	1.12	1.07	1.05
Gladdedrift	0.96	0.89	0.91	0.92	0.99	0.95	1.14	1.16	1.14	1.05	1.01	0.95
Senekal	1.07	1.06	1.04	1.07	1.14	1.16	1.21	1.25	1.19	1.05	1.02	0.98
Welkom	1.05	0.97	0.92	0.89	0.90	0.92	1.02	1.14	1.15	1.09	1.10	1.08
Average	*1.04*	*0.99*	*0.97*	*0.96*	*0.98*	*1.00*	*1.11*	*1.17*	*1.16*	*1.10*	*1.07*	*1.05*
Calibration coefficient												
Bleskop	0.0024	0.0024	0.0023	0.0022	0.0020	0.0023	0.0025	0.0026	0.0026	0.0025	0.0025	0.0026
Bloemfontein	0.0026	0.0025	0.0024	0.0023	0.0022	0.0022	0.0025	0.0026	0.0026	0.0027	0.0026	0.0026
Bothaville	0.0022	0.0020	0.0021	0.0020	0.0022	0.0023	0.0025	0.0027	0.0028	0.0026	0.0025	0.0024
Gladdedrift	0.0022	0.0020	0.0021	0.0021	0.0023	0.0022	0.0026	0.0027	0.0026	0.0024	0.0023	0.0022
Senekal	0.0025	0.0024	0.0024	0.0025	0.0026	0.0027	0.0028	0.0029	0.0027	0.0024	0.0023	0.0022
Welkom	0.0024	0.0022	0.0021	0.0020	0.0021	0.0021	0.0023	0.0026	0.0026	0.0025	0.0025	0.0025
Average	*0.0024*	*0.0023*	*0.0022*	*0.0022*	*0.0022*	*0.0023*	*0.0025*	*0.0027*	*0.0027*	*0.0025*	*0.0025*	*0.0024*

2.2.3.3 Statistical evaluation: ET_H vs ETo

Dekadal comparison of the Hargreaves and Penman-Monteith equations using RMSE, RE and MBE statistics shows a lot of variation from station to station and from month to month (Table 2.8). These values were determined for the period 2005 to 2008 (validation period). The RMSE values on average range from 3.5 mm/dekad in June to over 11 mm/dekad in December (Table 2.8). The RE values range from 8% to over 20% with the months of July, August having the highest average value of 20.7% while the lowest monthly average RE of 11.3% is obtained in March. The MBE values for January to July show a slight negative bias with values between -2 to -5 mm/dekad, with the exception of Bothaville and Gladderdrift which recorded positive bias (overestimation) during that period. In contrast, the months of August to December show high negative values (less than -5 mm/dekad), indicating the tendency of the Hargreaves equation to underestimate ETo.

Table 2.8: RMSE, RE and MBE between Penman-Monteith and Hargreaves evapotranspiration estimates for each station and month using data from 2005 to 2008.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
RMSE												
Bleskop	5.91	5.77	3.29	2.90	2.59	3.46	2.57	5.19	4.35	6.33	8.17	14.41
Bloemfontein	9.29	7.35	7.59	7.22	3.72	6.63	3.11	7.47	6.73	9.06	8.49	12.32
Bothaville	6.44	8.65	3.86	5.68	3.91	3.18	4.19	10.55	13.17	10.07	10.13	9.24
Gladdedrift	9.27	6.67	4.93	6.76	3.85	2.34	3.91	5.14	6.57	4.49	4.23	7.14
Senekal	8.16	8.42	9.09	5.43	5.53	5.08	6.14	10.90	13.73	11.93	11.47	12.42
Welkom	8.91	4.16	3.86	2.73	3.49	3.07	3.67	7.98	8.71	8.64	11.71	11.13
Average	*8.00*	*6.84*	*5.44*	*5.12*	*3.85*	*3.96*	*3.93*	*7.87*	*8.88*	*8.42*	*9.03*	*11.11*
RE												
Bleskop	7.81	9.54	6.28	8.16	9.90	16.52	10.49	14.89	9.39	10.06	11.10	17.11
Bloemfontein	13.22	13.80	15.58	21.59	15.37	34.43	13.40	22.08	15.01	15.16	13.36	17.06
Bothaville	10.34	18.40	8.18	17.26	13.55	13.67	14.91	24.96	23.08	15.29	15.30	13.29
Gladdedrift	17.95	16.05	11.91	21.85	13.87	11.07	15.35	13.81	13.05	8.09	7.64	12.39
Senekal	12.12	15.31	18.12	14.67	18.60	21.20	22.02	27.96	27.27	20.14	18.13	18.36
Welkom	13.33	8.29	8.53	8.64	14.39	15.25	14.51	20.52	16.71	14.16	16.86	15.56
Average	*12.46*	*13.57*	*11.43*	*15.36*	*14.28*	*18.69*	*15.11*	*20.70*	*17.42*	*13.82*	*13.73*	*15.63*
MBE												
Bleskop	-4.47	-2.21	-0.36	1.04	0.53	-0.46	-1.02	-4.58	-2.87	-5.90	-7.15	-11.93
Bloemfontein	-6.75	-4.80	-3.74	-3.48	-1.46	-2.21	-1.33	-7.02	-5.84	-8.38	-7.57	-10.90
Bothaville	3.72	6.50	2.92	4.72	1.25	-0.20	-0.72	-8.80	-10.82	-9.29	-7.76	-5.45
Gladdedrift	7.92	5.88	4.55	6.20	1.05	0.66	0.78	-3.41	-4.57	-0.52	1.16	4.50
Senekal	-5.91	-6.61	-3.89	-4.16	-4.23	-4.28	-5.47	-10.21	-12.23	-11.04	-10.52	-10.43
Welkom	-5.83	-2.46	-0.23	2.17	2.55	0.86	-0.85	-6.79	-8.34	-7.23	-10.29	-9.26
Average	*-1.89*	*-0.62*	*-0.13*	*1.08*	*-0.05*	*-0.94*	*-1.44*	*-6.80*	*-7.45*	*-7.06*	*-7.02*	*-7.25*

2.2.3.4 Statistical evaluation: ET_{CH} vs ETo

The calibrated Hargreaves equation was used to estimate dekadal ET from 2005 to 2008. The use of the new coefficient (C_H) improved the Hargreaves estimation at all the stations for most of the months. This is shown by the massive reduction in the RMSE, RE and MBE magnitudes (Table 2.9). The greatest improvements are in August to December where the average difference in RMSE for calibrated and uncalibrated exceeds 2.5 mm/dekad while the average RE in these months is between 5 to 11%, excluding cases when the calibrated coefficient is equivalent to the original coefficient. January, February and April also show a reasonable improvement with 1.1 to 1.7 mm/dekad average RMSE deviations. The RE reduction is between 2.5% and 5.2% on average. During the winter months there is little reduction in error owing to the poor relationship between Hargreaves and Penman-Monteith estimates in these months as shown in Table 2. The MBE also show a lot of improvement in most places especially in August to December with the average MBE reducing from around -10 mm/dekad to less than -2 mm/dekad. Gavilán et al. (2006), Fooladmand *et al*., 2008 and Bautista *et al*., 2009 recorded an improvement in the estimation of the Hargreaves equation after calibration. Incontrast, Xu & Singh (2002) recalibration of the constants didn't improve the relation between Hargreaves and Penma-Monteith ET.

Table 2.9: RMSE, RE and MBE between Penman-Monteith and calibrated Hargreaves evapotranspiration for each station and month using data from 2005 to 2008.

Station	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
RMSE												
Bleskop	3.77	5.20	3.43	2.74	3.42	3.44	2.56	2.52	4.77	2.20	3.64	7.94
Bloemfontein	5.95	4.89	6.44	7.16	3.96	6.78	2.99	3.72	3.26	3.01	3.18	6.68
Bothaville	5.49	6.38	11.12	3.13	3.68	3.18	4.38	5.22	7.21	4.20	6.90	7.63
Gladdedrift	7.50	3.23	2.29	4.48	3.75	2.32	5.84	3.76	5.08	4.92	4.40	5.90
Senekal	5.60	5.88	8.21	3.86	3.50	2.93	2.67	3.74	7.02	9.30	10.63	13.67
Welkom	6.67	5.38	5.74	2.44	2.24	3.04	3.55	4.07	2.61	4.98	6.83	6.99
Average	*5.83*	*5.16*	*6.21*	*3.97*	*3.43*	*3.62*	*3.67*	*3.84*	*4.99*	*4.77*	*5.93*	*8.14*
RE												
Bleskop	4.99	8.59	6.55	7.72	13.08	16.40	10.45	7.25	10.29	3.49	4.95	9.43
Bloemfontein	8.83	8.89	12.85	19.34	13.31	28.32	10.72	9.55	6.48	5.07	5.03	9.88
Bothaville	8.81	13.57	10.71	9.51	12.78	13.67	15.57	12.35	12.63	6.37	10.42	10.98
Gladdedrift	14.53	7.78	5.53	14.48	13.54	10.98	22.88	10.10	10.10	8.87	7.95	10.24
Senekal	8.31	10.69	16.38	10.42	11.79	12.23	9.56	9.60	13.94	15.70	16.80	20.21
Welkom	9.97	10.73	12.69	7.73	9.22	15.11	14.01	10.46	5.00	8.15	9.84	9.77
Average	*9.24*	*10.04*	*13.29*	*11.53*	*12.29*	*16.12*	*13.87*	*9.89*	*9.74*	*7.94*	*9.17*	*11.75*
MBE												
Bleskop	-2.02	-4.04	-3.83	-1.70	-0.02	-0.89	-0.33	-1.75	-0.70	-2.16	-4.32	-3.72
Bloemfontein	-1.88	-3.42	-1.99	-1.86	-0.54	-0.91	-0.48	-2.46	-3.92	-8.24	-9.62	-11.86
Bothaville	-0.08	-0.63	0.15	0.10	-2.37	-0.13	1.15	-0.46	3.22	-0.25	0.01	-1.09
Gladdedrift	1.53	-4.00	-1.56	-0.02	-1.08	-1.05	0.55	-2.26	-1.03	0.97	3.11	-1.56
Senekal	3.01	-1.78	-2.07	-1.11	-1.04	-2.76	1.48	-0.62	0.54	1.20	-0.51	-1.69
Welkom	-2.02	-4.04	-3.83	-1.70	-0.02	-0.89	-0.33	-1.75	-0.70	-2.16	-4.32	-3.72
Averarge	*-0.24*	*-2.99*	*-2.19*	*-1.05*	*-0.85*	*-1.11*	*0.34*	*-1.55*	*-0.43*	*-1.77*	*-2.61*	*-3.94*

2.2.4 Conclusions

In this study, ET was estimated using the Hargreaves equation and values were compared to the Penman-Monteith equation estimates. The estimated ET_H values showed a good correlation with ETo especially in the summer period but in winter (June and July) the correlation was poor. Thus Hargreaves estimates should be used with care in the winter months. Even though there is some relationship between ET_H and ETo, the actual values of dekadal ET_H underestimate ETo especially from July to December, making it necessary for coefficient adjustment. The calibrated coefficients have a minimum value of 0.0020 and a maximum of 0.0029. When using the calibrated coefficients the deviations between the two values were greatly reduced. Thus the use of the Hargreaves equation is favoured to estimate ET in the Free State when there is not enough data to adopt the Penman-Monteith equation, but the use of calibrated coefficients is adviced for months from August to December.

2.3 Evaluation of NASA Satellite-Derived Temperature Data

2.3.1 Introduction

Weather and climate information can be used in many applications ranging from agriculture, forestry, hydrology and engineering purposes (Trapasso, 1986). In the field of agriculture, yields of the crops are mostly affected by the weather conditions during the growing season and thus most of the modelling of crop performance or growth use climate data as their core inputs (Nonhebel, 1993; Peng *et al*. 2004). According to Porter & Semenov (2005) and Lobell & Field (2007) slight changes in the mean of a climate variable like temperature can affect growth and development and consequently yield. It is therefore important for governments and other institutions to invest in building a good weather station network in support of agricultural research. Proper maintenance (replacement of mulfunctional instruments on time & calibration of the sensors) of this infrastructure could result in good quality measured data with only isolated missing or faulty data. Accurate climate data enables the scientists to better understand local climatology, resulting in increased knowledge of critical factors limiting production.

Normally climate data used for modelling in areas without weather stations is taken from neighbouring stations. In some cases there is a small difference in climate between these areas especially when they are not far apart, but in other cases the distances is too large or topography drastically different for one to use neighbour station. In the latter case, the use of satellite derived dataset would help but this data has to be adjusted for the specific region as they can have tendencies of overestimating or underestimating depending on the variable and location. Satellite-derived weather data has been shown to be good enough to provide data in places where there are no weather stations (Chandler *et al*., 2010). However the accuracy of the satellite-derived data is still uncertain because it is affected by cloud cover, atmospheric aerosols and is of a course resolution (Wentz *et al*., 2000).

NASA has developed an online database of satellite and model-derived weather data at near real time (NASA, 2007; Chandler *et al*., 2010). According to White e*t al.* (2008), the data is obtained from the Goddard Earth Observation System (GEOS) assimilation model which is derived from land surface observations; ocean surface observations of surface pressure; ocean surface sea level pressure and upper winds; sea level winds from space-borne radars, upper-air rawisondes, upper-air drop sondes, pilot balloons and aircraft winds and lastly remote sensing data from satellites. The data from this web database is provided on a daily basis dating back to 1983 and weather elements include solar radiation at 2m, minimum and maximum temperatures at 2m, dew point temperature at 2m, relative humidity at 2m, rainfall and wind speed at 10m (NASA, 2007; NASA, 2010). The data provided is at the spatial resolution of 1x1 degree of latitude and longitude (NASA, 2007; Chandler *et al*., 2010). There has recently been work done on the evaluation or use of this NASA data in the modelling of wheat phenology (White *et al.,* 2008), in the simulation of maize yield potential (Bai *et al*., 2010) and for forecasting of extreme fires in Serbia (Westberg *et al*., 2010).

The main aim of this study is three-fold: 1) to compare the NASA satellite-derived minimum temperatures and maximum temperatures with the observed data; 2) to regionally calibrate the Hargreaves equation for estimating Penman-Monteith reference evapotranspiration (ETo) using NASA temperatures; 3) to evaluate maize water requirement satisfaction index (WRSI) based on calibrated NASA temperatures versus those obtained from measured meteorological data.

2.3.2 Data and methods

The study is deemed necessary because majority of the stations in the Free State only record rainfall and other agro-climate variables like temperature and evapotranspiration are important. NASA-derived temperature values will be evaluated in their original form and with the regional adjustments to determine their usage in places lacking data. Evapotranspiration is crucial in determining whether there is sufficient water for a crop to reach maturity and produce grain. The agrometeorology model mostly used for determining water requirements is FAO WRSI and this model will be used in chapter 5 to quantify drought risk. The WRSI model uses rainfall, evapotraspiration, soil water capacity, cultivar length and crop coefficients as the inputs (Frere & Popov, 1979; Allen *et al*., 1998; Senay & Verdin, 2003; Moeletsi *et al*., 2010). All the inputs are readily available except evapotranspiration which has to be estimated using the Penman-Monteith equation or any other empirical models. The Penman-Monteith equation is too data demanding and the previous subsection (2.2) shows that the Hargreaves equation has a good association with Penman-Monteith model hence this method will be used. The Hargreaves model has to be calibrated with the Penman-Monteith model according to recommended standards (Allen *et al*., 1998). NASA-derived temperature data will be used as input into the Hargreaves model. The data is easily downloaded from the NASA website (NASA, 2010). The values from the calibrated Hargreaves model will be used as input into WRSI model. The resulting WRSI values will be compared with the WRSI derived from the Penman-Monteith evapotranspiration.

2.3.2.1 Comparison of NASA satellite-derived data with weather station data

The stations used to demonstrate the comparison of the measured data and ones derived from the NASA website are same as pervious section (2.2) shown in Table 2.5 and Fig. 2.5. These stations were chosen on basis of data availability and also their spatial distribution. Stations should have over five years of data from 1999 to 2008 with less than 10% missing data and were chosen to be evenly distributed over the Free State to cover different climate and ecological zones. The correlation between the daily measured T_{min} and T_{max} and NASA derived T_{min} and T_{max} data was performed using Excel software.

2.3.2.2 Comparison of WRSI estimated using NASA satellite-derived data with WRSI fron measured data

Evapotranspiration data is an important intput to the WRSI model used to assess agricultural drought in chapter 5. In order to calculate WRSI at the stations with long-term rainfall data but with no measured temperature data (which forms bulk of the weather stations in the Free State), there has to an ET estimate. Evapotranspiration will be estimated by using the Hargreaves model using NASA satellite-derived temperature data as inputs. But this data has to be calibrated using Penman-Monteith (ETo) as in section 2.2. Due to the fact that weather stations targeted cannot estimate ETo, regional calibration of the Hagreaves model will be done using data from stations with relevant data to make ETo estimates. The selection of the stations used in the regional calibration was done as follows: weather stations which have over five years of Penman-Monteith evapotranspiration data with less than 10% of missing data were chosen. In total 36 weather stations were used in the determination of regional Hargreaves calibrations. Median coefficient adjustment was then obtained from all the 36 stations as shown in Table 2.10.

Table 2.10: Median Hargreaves coefficient adjustment and resultant Hargreaves coefficient across 36 stations for the Free State Province.

Variable	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Coefficient adjustment	1.3	1.2	1.2	1.3	1.3	1.5	1.4	1.6	1.4	1.3	1.4	1.4
Resultant Hargreaves coefficient	0.0030	0.0028	0.0028	0.0030	0.0030	0.0035	0.0032	0.0037	0.0032	0.003	0.0032	0.0032

For evaluating NASA WRSI versus WRSI calculated from weather station data, T_{min} and T_{max} values data from 1999 to 2008 were downloaded for all the stations shown in Table 2.5. The Penman-Monteith evapotranspiration data for the six stations were obtained the ARC-ISCW agroclimatology database. The NASA downloaded temperature data was used to estimate evapotranspiration using the regionally calibrated Hargreaves coefficient shown in Table 2.10 on a dekadal basis and these values were compared with the Penman-Monteith values. Maize WRSI was then calculated for 120-day maize cultivar from the planting window starting in October 1st dekad to January 3rd dekad using for both the Penman-Monteith ET and the regionally calibrated Hargreaves equation ET. Statistical parameters I sub-section 2.3.2.4 were used to evaluate the closeness of the WRSI derived from NASA adjusted Hargreaves to estimate WRSI calculated from the Penman-Monteith values.

2.3.2.3 Statistical analysis

The statistical analysis was done with the r^2, RMSE, RE, MBE and the Kolmogorov-Sminov (KS) similarity test to evaluate the performance of the NASA weather data to estimate maize WRSI. The r^2 is obtained from the linear regression imbedded in the Excel software. The KS test was perfommed using the “Past” program (Hammer *et al*., 2001).

2.3.3 *Results and discussion*

2.3.3.1 Comparison of NASA temperatures with weather station data

NASA dekadal minimum temperatures show a good correlation with the recorded data at the six weather stations (Fig. 2.7). The overall r^2 values for all the dataset ranges from 0.81 to 0.88 with average of 0.88. This high correlation clearly shows that the NASA minimum temperature data obtained can be used in the Free State in cases where minimum temperature data at the weather stations are missing or in places where there are no weather stations. The MBE at all the stations show positive bias implying that, the NASA minimum temperatures data tends to overestimate minimum temperatures (Table 2.11). The MBE is mostly more than 2°C with the months from April to September getting relatively high positive values of up to 8.4°C. The RMSE values are less than 4°C during the main rainfall season (October to March). The RMSE is mostly around 15% of the mean during the summer months while in winter the value can reach up to 400% due to low average minimum temperatures of around -0.8°C in places like Bloemfontein. The differences may be borne from the fact that, the resolution of the NASA data is 1° by 1° hence the data is an average of over a large area. Also, there is a great spatial difference in altitude over an area of 100 km by 100km in the Free State. The good correlation obtained in this study is comparable to the ones obtained in other areas which clearly show the world wide usability of the NASA satellite-derived weather data (White *et al*., 2008; Bai *et al.,* 2010). The comparison of NASA minimum temperature versus the ground data in China resulted in underestimation by NASA temperatures while the similar evaluation in the US showed overestimation by NASA minimum temperatures as compared with the measured weather data (White *et al.*, 2008; Bai *et al.*, 2010).

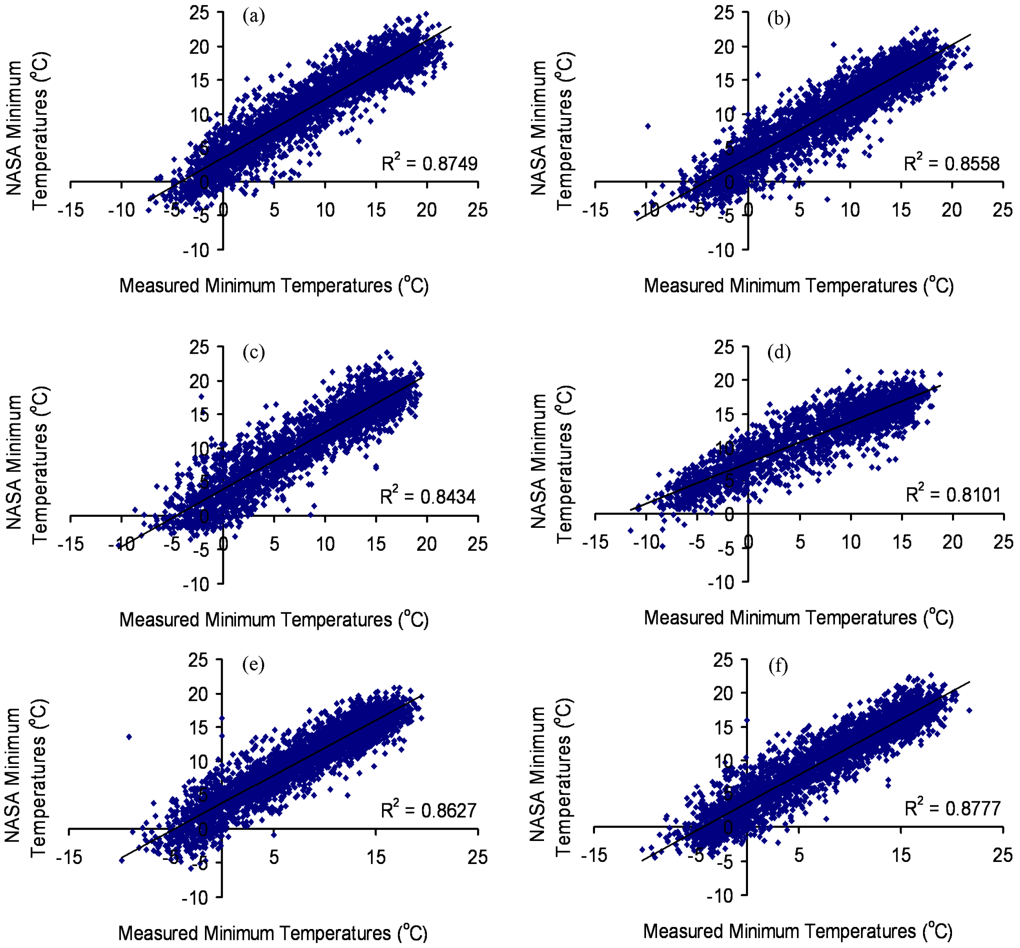


Fig. 2.7: Comparison between NASA minimum temperatures and measured minimum temperatures for (a) Bleskop; (b) Bloemfontein; (c) Bothaville; (d) Gladdedrift; (e) Senekal; (f) Welkom.

Table 2.11: MBE and RMSE for the NASA minimum temperatures compared with the recorded station data.

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
MBE												
Bleskop	2.0	1.3	2.0	4.8	3.2	2.2	1.9	2.5	3.4	3.0	2.6	1.6
Bloemfontein	1.6	0.9	1.4	2.4	2.6	1.9	2.2	2.8	2.9	2.6	2.3	1.7
Bothaville	2.0	2.0	2.0	2.5	3.7	2.5	2.8	3.4	3.3	2.7	2.5	1.6
Gladdedrift	1.9	2.1	3.0	5.2	8.4	7.5	7.9	7.2	7.4	4.5	3.3	2.4
Senekal	1.0	1.0	1.4	2.6	3.5	2.5	2.8	3.4	3.5	2.7	1.9	1.6
Welkom	1.3	1.0	1.4	2.6	2.9	2.4	3.0	3.7	3.5	2.6	2.1	1.1
Average	*1.6*	*1.4*	*1.9*	*3.4*	*4.1*	*3.2*	*3.4*	*3.8*	*4.0*	*3.0*	*2.5*	*1.7*
RMSE												
Bleskop	3.9	2.7	3.3	8.0	3.9	3.3	3.0	3.6	4.2	3.8	3.5	2.7
Bloemfontein	2.7	2.4	2.5	3.5	3.7	3.6	3.5	4.0	3.8	3.5	3.3	2.5
Bothaville	2.9	3.2	2.8	3.3	4.4	3.9	4.0	4.6	4.2	3.6	3.7	2.6
Gladdedrift	2.5	2.9	3.9	5.9	8.7	7.9	8.4	7.9	8.0	5.4	4.2	3.2
Senekal	2.1	2.3	2.3	3.6	4.1	3.6	3.8	4.3	4.2	3.8	2.8	2.4
Welkom	2.2	2.3	2.5	3.6	3.7	3.5	3.9	4.6	4.3	3.4	3.0	2.2
Average	*2.7*	*2.6*	*2.9*	*4.7*	*4.8*	*4.3*	*4.4*	*4.8*	*4.8*	*3.9*	*3.4*	*2.6*

Dekadal NASA maximum temperatures (T_{max}) also have a good agreement with the measured weather station recorded data with the r^2 ranging between 0.69 and 0.79 averaging 0.76 (Fig. 2.8). The MBE is mostly negative showing that NASA dataset underestimated the maximum air temperature in the perod 1999 to 2008. The MBE values are between -2°C and -4.3°C with the average exceeding -2.5°C for all the months with the exception of February, September and October (Table 2.12). The RMSE ranges from 2.5°C to 5.7°C with an average of around 4°C. Relative to the long-term mean, the RMSE is around 13% in the hottest months (December and January) while in the coldest months the RMSE makes around 25% of the mean maximum temperatures (Table 2.12). The results obtained from other areas also show good correlation between NASA maximum temperatures and ground data but NASA T_{max} had the tendency of underestimating by 2.4°C and 2.8°C in the US and China respectively (White *et al*., 2008; Bai *et al*., 2010).

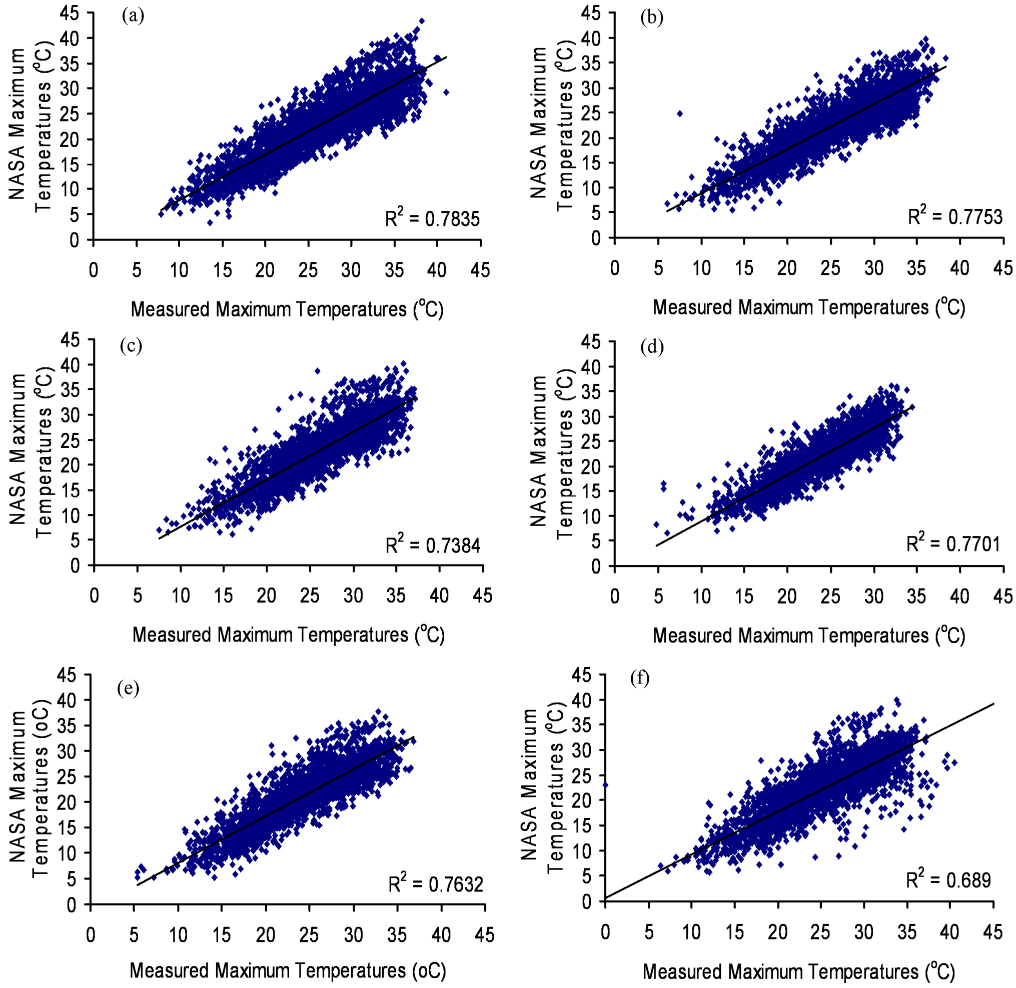


Fig. 2.8: Comparison between NASA maximum temperatures and measured maximum temperatures for (a) Bleskop; (b) Bloemfontein; (c) Bothaville; (d) Gladdedrift; (e) Senekal; (f) Welkom

Table 2.12: MBE and RMSE for the NASA maximum temperatures compared with the recorded station data.

Station	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
MBE												
Bleskop	-4.2	-4.2	-4.0	-3.5	-3.7	-4.2	-4.0	-3.1	-2.1	-2.5	-3.4	-4.4
Bloemfontein	-3.1	-2.9	-2.9	-2.1	-2.3	-3.4	-3.1	-2.5	-1.8	-2.3	-3.1	-3.7
Bothaville	-2.7	-2.3	-3.1	-3.2	-3.5	-4.3	-4.2	-3.5	-2.8	-2.4	-2.7	-3.4
Gladdedrift	-1.8	-1.2	-1.6	-2.0	-2.4	-2.9	-2.4	-2.1	-1.3	-1.3	-2.0	-2.5
Senekal	-3.4	-2.8	-2.8	-2.6	-3.1	-4.0	-3.8	-3.2	-2.2	-2.5	-3.1	-3.4
Welkom	-2.2	-1.7	-2.3	-2.5	-2.9	-3.7	-3.8	-3.4	-2.8	-2.7	-3.6	-3.6
Average	*-2.9*	*-2.5*	*-2.8*	*-2.7*	*-3.0*	*-3.8*	*-3.6*	*-3.0*	*-2.2*	*-2.3*	*-3.0*	*-3.5*
RMSE												
Bleskop	5.7	5.7	5.3	4.5	4.5	4.9	4.6	4.0	3.0	3.9	4.8	5.7
Bloemfontein	4.6	4.5	3.6	3.4	3.6	4.2	3.7	3.5	2.8	3.7	4.4	4.9
Bothaville	4.5	4.1	3.8	4.1	4.3	5.1	4.8	4.2	3.6	4.0	4.6	4.9
Gladdedrift	3.3	2.5	2.6	2.7	3.0	3.6	3.5	3.2	2.6	3.5	3.5	3.3
Senekal	4.7	4.5	3.9	4.0	3.7	4.7	4.3	3.9	3.0	4.0	4.5	4.5
Welkom	4.3	4.0	3.6	3.9	3.8	4.4	5.2	5.1	4.5	3.9	4.7	5.0
Average	*4.5*	*4.2*	*3.8*	*3.8*	*3.8*	*4.5*	*4.4*	*4.0*	*3.3*	*3.8*	*4.4*	*4.7*

2.3.3.2 WRSI derived from NASA data vs WRSI obtained from measured data

The NASA derived WRSI show a good linear correlation with the WRSI obtained from the measured meteorological data. The r^2 is lowest at Welkom with 0.78; average r^2 is 0.87 while the highest r^2 of 0.95 is obtained at Koppies (Fig. 2.9). The MBE values range from -0.3 to 5.4 with the average of less than 1.5 at all six stations for the entire year (Table 2.13). The average RMSE is less than 5 for all the months. The KS test at 95% confidence interval for the entire dataset show that the D-values is significantly less than the P-values and thus WRSI calculated from NASA data is statistically similar to the WRSI obtained from measured values for the planting dates of 1st dekad of October to 3rd dekad of January (Table 2.13).

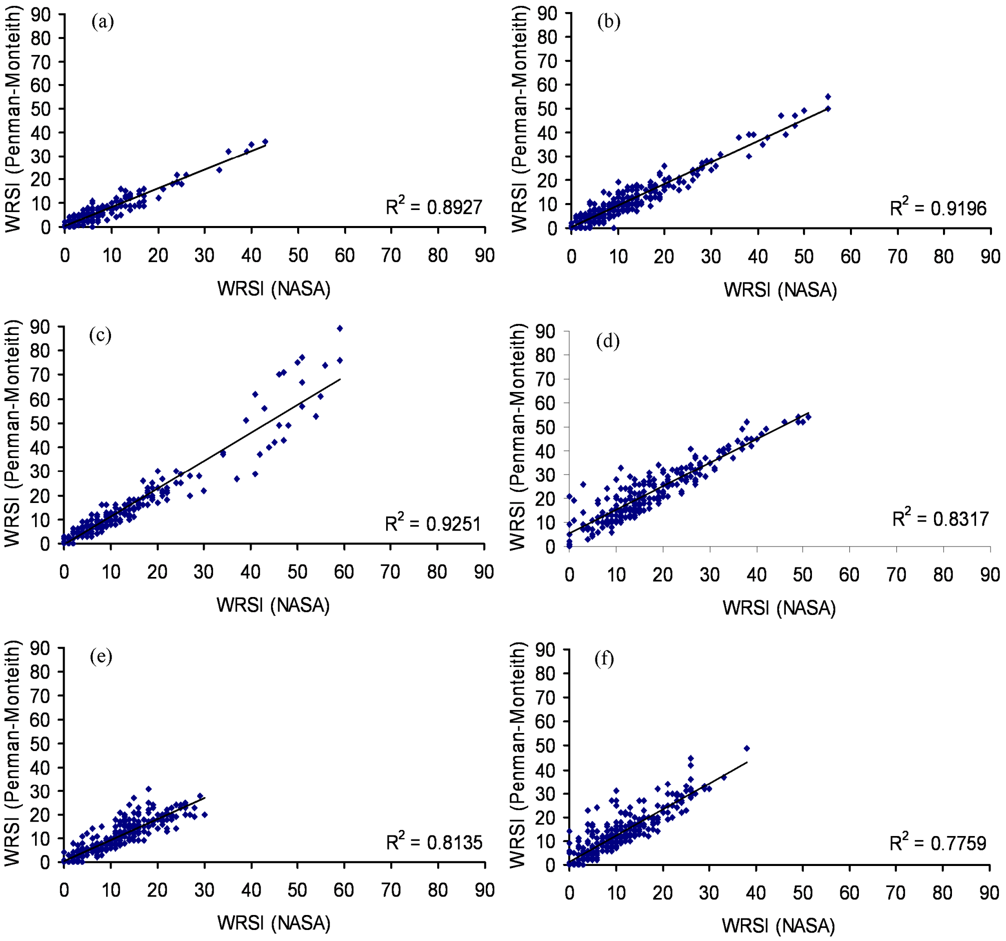


Fig. 2.9: WRSI obtained from NASA data (using Hargreaves Equation for estimating evapotranspiration) compared with the WRSI from measured data for (a) Bleskop; (b) Bloemfontein; (c) Bothaville; (d) Gladdedrift; (e) Koppies; (f) Senekal; (g) Thaba Nchu; (h) Welkom.

Table 2.13: MBE, RMSE and KS test results for the NASA WRSI compared with WRSI obtained from recorded station data.

Stations		**Oct 1dk**	**Oct 2dk**	**Oct 3dk**	**Nov 1dk**	**Nov 2dk**	**Nov 3dk**	**Dec 1dk**	**Dec 2dk**	**Dec 3dk**	**Jan 1dk**	**Jan 2dk**	**Jan 3dk**
MBE													
Bleskop		-0.3	-0.3	-0.4	-0.4	-0.9	-0.4	-0.7	-0.7	-0.7	-0.9	-0.7	-0.9
Bloemfontein		0.3	-0.2	-0.5	-0.6	-0.3	-0.7	-0.6	-1.1	-0.6	-1.0	-0.9	-1.6
Bothaville		2.5	1.3	1.4	0.5	0.0	0.0	1.2	2.1	1.2	3.8	4.2	2.1
Gladdedrift		3.3	3.4	4.2	4.6	4.7	4.6	3.9	5.4	3.9	3.8	5.2	4.6
Senekal		0.0	-0.1	-0.9	-0.2	-0.7	-0.6	-1.0	-0.2	-1.0	-0.7	-0.7	-1.7
Welkom		1.1	0.8	0.9	1.1	1.5	2.9	3.2	2.7	3.2	2.7	4.9	4.0
Average		*1.2*	*0.8*	*0.8*	*0.8*	*0.7*	*1.0*	*1.0*	*1.4*	*1.0*	*1.3*	*2.0*	*1.1*
RMSE													
Bleskop		1.2	1.7	1.9	1.9	2.3	2.0	2.7	2.7	2.7	2.8	2.1	2.8
Bloemfontein		2.6	1.7	2.6	3.0	2.3	2.3	2.3	3.2	2.3	3.3	2.8	3.7
Bothaville		4.8	3.5	3.4	3.4	3.9	2.4	2.5	3.9	2.5	7.5	8.3	5.8
Gladdedrift		4.0	4.7	5.6	5.5	5.5	5.8	5.6	6.8	5.6	4.7	6.1	5.7
Senekal		0.0	3.5	3.2	3.1	2.3	2.8	3.2	3.8	3.2	4.4	2.2	3.9
Welkom		2.7	3.2	3.7	3.9	4.7	5.4	5.4	5.0	5.4	6.0	8.0	6.0
Average		*2.6*	*3.1*	*3.4*	*3.5*	*3.5*	*3.5*	*3.6*	*4.2*	*3.6*	*4.8*	*4.9*	*4.7*
KS													
Bleskop	D	0.11	0.15	0.11	0.19	0.19	0.19	0.23	0.22	0.19	0.23	0.24	0.20
	P	0.99	0.91	0.99	0.70	0.67	0.70	0.44	0.47	0.70	0.44	0.41	0.65
Bloemfontein	D	0.07	0.04	0.11	0.11	0.11	0.11	0.11	0.07	0.07	0.11	0.11	0.15
	P	1.00	1.00	0.99	0.99	0.99	0.99	0.99	1.00	1.00	0.99	0.99	0.91
Bothaville	D	0.15	0.07	0.15	0.07	0.19	0.11	0.11	0.07	0.11	0.11	0.15	0.19
	P	0.91	1.00	0.91	1.00	0.70	0.99	0.99	1.00	0.99	0.99	0.91	0.70
Gladdedrift	D	0.11	0.07	0.07	0.07	0.19	0.07	0.22	0.22	0.11	0.11	0.15	0.11
	P	0.99	1.00	1.00	1.00	0.70	1.00	0.47	0.47	0.99	0.99	0.91	0.99
Senekal	D	0.20	0.13	0.13	0.13	0.17	0.08	0.17	0.17	0.25	0.17	0.17	0.08
	P	0.62	0.99	0.99	0.99	0.86	1.00	0.86	0.86	0.39	0.86	0.86	1.00
Welkom	D	0.24	0.28	0.22	0.21	0.27	0.29	0.21	0.27	0.27	0.27	0.42	0.26
	P	0.53	0.43	0.71	0.74	0.59	0.39	0.88	0.48	0.48	0.48	0.10	0.46

2.3.4 Conclusions

In this study minimum and maximum temperatures obtained from the NASA satellite-derived data and measured data were compared using 8 weather stations situated in the Free State Province of South Africa. NASA satellite-derived data showed a good correlation with the measured weather data. But, the NASA minimum temperatures had the tendency of overestimating measured values while NASA maximum data tend to underestimate as compared to recorded data at the weather stations. The regional calibration of the Hargreaves equation to estimate Penman-Monteith evapotranspiration also resulted in WRSI values that resemble WRSI obtained from the measured values.

2.4 Summary and conclusions for the data manipulations chapter

In this chapter, all the analyses which require data adjustments were investigated so that their usage in the later chapters is justified. All over the world recorded temperatures are bound to have missing values due to a number of reasons and hence this creates a gap in the measurements which makes it difficult for continuous analysis or utility of the data for any purpose. Patching of the missing data is therefore necessary to obtain a complete set of measurements and this exercise has to be performed using reliable methods. The main weather elements that will be used in the whole study are daily rainfall, daily minimum temperatures and daily maximum temperatures. The rainfall patching was done using the Inverse Distance Method (IDW) and its evaluation in section 2.1 showed that the estimated values are very close to the measured values and thus it is recommended that this method be used to patch daily rainfall. It should be noted that, patching rainfall is for circumstances where only one or two months are missing. The method used to patch both minimum and maximum temperatures is UK traditional method which also shows a good correlation as well as small error when comparing estimated values with the measured values. Hence the method is also recommended to patch missing temperature values in the Free State Province of South Africa.

In the Free State, the data available for most of the stations is the temperatures values and thus the Hargreaves equation which is a temperature dependent evapotranspiration model was evaluated. The results show that the Hargreaves equation has a good correlation with the Penman-Monteith ET values but it is still necessary to adjust the equation to yield smaller error.

Alternatively, there are over 200 stations over the Free State Province which only record precipitation. The usage of NASA satellite-derived temperature with the spatial resolution of 1 degree latitude by 1 degree longitude was investigated. The satellite-derived daily minimum and maximum temperatures were compared with the measured values. The comparison show that the NASA data has a good correlation with the measured values but NASA minimum temperatures overestimate the measured values while NASA maximum temperatures underestimate observed values. Due to the high correlation between the NASA satellite-derived and measured temperature data, this dataset can be used to estimate either minimum temperatures or maximum temperatures in places where there are no weather stations but the data has to be adjusted for bias. The accuracy of the NASA data to model Maize Water Requirement was also determined using the FAO Water Requirement Satisfaction Index. The results showed good agreement with the WRSI based on the measured weather data. Therefore, it is recommended to use NASA temperature data to estimate WRSI (using regionally calibrated Hargreaves equation) in places where there are no temperature measurements.

In the next chapter Frost risk over the Free State Province will be assessed using three minimum temperature thresholds (2°C, 0°C & -2°C).

Chapter 3: Frost-Free Period Assessment

3.1 Introduction

Frost is generally defined as the formation of ice crystals on exposed surfaces due to the drop in temperature at night, while the surrounding air temperature is at dew point (Hejazizadeh & Naserzadeh, 2007). Daily minimum temperatures measured at Stevenson screen level are normally used to assess the occurrence of frost in most places where ground or canopy level measurements are not recorded and the most common threshold value is temperature of 0℃ or less (Kalma *et al*., 1983; Nadler, 2007). The temperature at the ground is always a degree or two lower than the one recorded in the Stevenson/Gill screen at 1.2m above the ground (BOM, 2008).

In most literature, frost is categorized into two types of frost namely advective and radiative frost depending on the atmospheric conditions under which they occur (Laughlin and Kalma, 1990; Richards & Baumgarten, 2003; Nadler, 2007; Bootsma & Brown, 1985). Radiative frost on the other hand occurs mostly at night as a result of long wave radiative cooling under calm, clear and dry atmospheric conditions (Laughlin & Kalma, 1990; Francois *et al.*, 1999; Kassomenos *et al.*, 1997; Feldhake, 2002; Tait & Zheng, 2003). Advective frost occurs when there is a large scale influx of cold air during the day or night and is characterized by strong winds and well-mixed atmosphere (Laughlin & Kalma, 1990; Tait & Zheng, 2003; Schulze *et al.*, 2007). According to Peralta-Hernandez & Barba-Martinez (2009), advective frost is usually associated with a deep cyclones and cold fronts ahead of a strong anticyclone, while radiative frost occurs mostly with a slow moving anticyclone. The effects of these two types of frost differs, with advective frost normally resulting in little spatial differences in frost severity which are strongly related to elevation while radiative frost is mostly sporadic and localized over the landscape and more severe in low-lying areas (Tait & Zhang, 2003; Nadler, 2007; Schulze *et al.*, 2007; BOM, 2008). The other main difference between the two is the vertical temperature profile conditions, inversions occur during radiative frost formations while advective frost occurs under normal vertical temperature profile due to a well-mixed atmosphere (Nadler, 2007). Radiative frost is common on slopes with a southern aspect, at high altitudes and in valleys in association with cold air drainage (Lindkvist *et al.*, 2000; Richards & Baumgarten, 2003; Tait & Zheng, 2003). In advective frost, exposed hilltops are cooler than valleys while in radiative frost valleys and depressions are usually colder than hilltops (Laughlin & Kalma, 1990; Francois *et al.*, 1999). According to Schulze *et al.* (2007) radiative frost is common in the summer rainfall regions of South Africa which normally have long, dry, calm and clear nights occurring mostly during winter and transition seasons. Radiative frost causes severe damage to crops despite its restricted temporal and spatial distribution (Kassomenos *et al.*, 1997).

The extent of frost damage of a crop is dependent on plant type and variety, rate of temperature decrease, cloud and wind conditions during the freeze, soil type and water content, duration of frost and crop growth stage (Teitel *et al.*, 1996; Nadler, 2007; Bootsma and Brown, 1985; Oztekin, 2008). Many plants are more resistant to frost during their early development stage and less frost resistant during the late stages of the growth and development (Bootsma & Brown, 1985). Some plants are tolerant to frost in early vegetative and highly vulnerable at late vegetative, flowering and grain-filling stages (Alberta Atlas, 2003). Thus, farmers should manage their farms in a way such that the vulnerable stages of crop development such as flowering and grain-filling do not coincide with times of high frost incidences (Whaley *et al.*, 2004). Frost damage can reduce crop yield and quality and thus frost risk has to be considered in planning such things as selection of crop varieties and planting schedule (Sameshima *et al.*, 2007). Weak frost can cause damage to sensitive plants and fruit trees, moderate frost cause damage to semi-hardy plants and trees, while severe/hard frost usually damages all the crops and fruit trees (Kelleher *et al.* 2001). Different species have different tolerances to frost, fruit trees like apples and pears are said to be more frost resistant than peaches and apricots, while wheat is generally more frost-tolerant than maize and sorghum (Tait & Zheng, 2003). In fruits, the quality of the fruit is strongly affected by light frost while severe frost has a major impact on the final harvest (Cittadini *et al.*, 2006; Eccel, *et al.*, 2009).

Frost risk at regional scale is dependent on prevailing weather conditions, synoptic patterns and latitude while on local or farm level aspect, slope and altitude are major causes for variations in frost incidences (Kelleher *et al.* 2001). There are four main characteristics of frosts that are important in order to clearly understand frost occurrences: the onset of frost or first frost date, cessation of frost or last frost date, duration of the frost-free or frost period and the frequency of frosts. Studies by Tait and Zheng (2003) and Rahimi *et al.* (2007) emphasized the importance of frost analyses, especially how the knowledge about the frequency and timing of frosts will help reduce the risk of damage in frost vulnerable areas as well as minimizing future frost damages. Due to the inter-annual variability of frost, continuous updating of frost dates is necessary to reflect recent climatic events. Different temperature thresholds are used for determining frost, Zenoni *et al.* (2002) studied the risk related to late frost using five different thresholds (-1℃, - 2℃,-3℃,-4℃,-5℃). Hejazizadeh & Naserzadeh (2007) categorized frost as weak (0℃ to 2℃), mode rate (-2℃ to -4℃) or severe (less than -4℃). Trasmonte *et al.* (2008) studied the frost risk in the Mantaro river basin using the following limits: 5℃, 2.5℃, 0℃, -2℃ and -4℃. The threshold to use has to be specific according to a crop of interest but different thresholds can also be used to show severity of frost risk or to accommodate a variety of crops. Grain crops including maize freeze at temperature below 0℃, so a screen temperature 0℃ is a suitable indicator of damaging frost (Alberta Atlas, 2003). The critical temperature for maize is between -1℃ and -2℃ (Bootsma & Brown, 1985). Tras monte *et al.* (2008) used the 5℃ threshold to determine the frost risk analysis for the maize crop due to its sensitivity to low temperatures.

Based on the fact that maize crop is very sensitive to extremely low temperatures, temperatures of 2℃ on screen temperature relates to temperatures of around 0℃ on the ground. In this study, assessment of frost risk for dryland maize production in the Free State will be determined using three thresholds -2℃, 0℃ and 2℃. Three main indices will be determined for each threshold, onset of frost, cessation of frost and frost-free duration.

3.2 Data and methods

3.2.1 Data

The data used in the analysis was obtained from the ARC-ISCW, LMS and the SAWS. The stations used were chosen in the Free State province, as well as in neighbouring provinces and Lesotho, with at least 20 years of data records and over 70% data efficiency from 1950 to 2008. Figure 3.1 shows the spatial distribution of the stations that were used in the study while Table 3.1 and 3.2 show geographical information as well as data duration for stations in the Free State Province and surrounding provinces. The total of 36 weather stations was selected in the Free State and 19 weather stations were selected in the surrounding provinces including Lesotho. The daily minimum temperature dataset was used in the analysis for determination of frost risk assessment in the Free State. All the data used in the study is recorded inside the Stevenson screen elevated at 1.3-1.5 m above the ground. The data used in the analysis covers the period from 1950 to 2008. The data first went through a quality check and erroneous data was removed. Where necessary the data gaps were patched using the UK methodology evaluated in chapter 2.

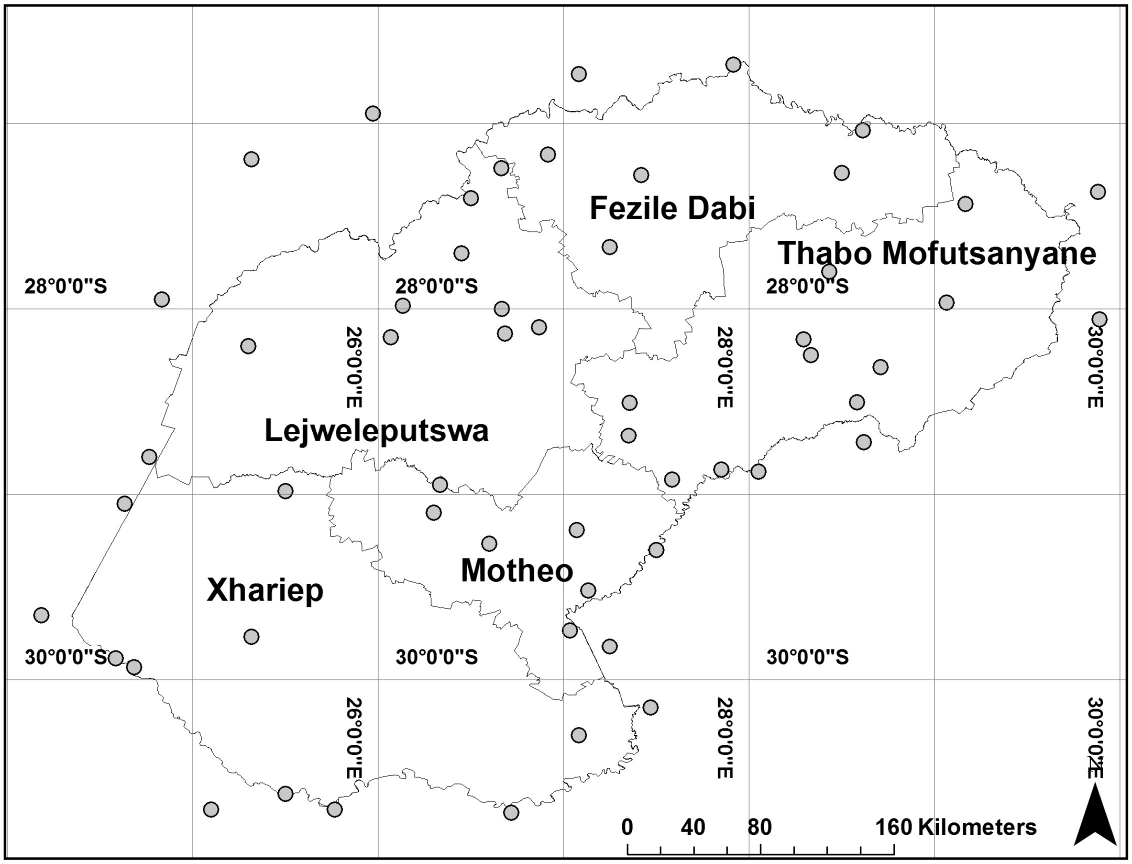


Fig. 3.1: Spatial distribution of climate stations used in frost risk analysis in the Free State Province of South Africa.

Table 3.1: Free State Province climate stations information used in the analyses of frost (from ARC-ISCW and SAWS).

Station	Latitude	Longitude	Altitude (m)	Start	End
Bethlehem	-28.2500	28.3333	1680	01/11/1980	31/03/2004
Bethlehem-ARC	-28.1626	28.2953	1631	01/01/1950	31/01/2006
Bleskop	-29.8833	24.5833	1145	01/06/1978	31/07/1996
Bloemfontein-Hertzog	-29.1000	26.3000	1351	01/01/1962	30/06/1992
Bothaville-Balkfontein	-27.4000	26.5000	1280	01/01/1960	31/12/2003
Bothaville-Nampo	-27.2389	26.6638	1300	01/10/1981	30/06/2005
Bultfontein	-28.1513	26.0672	1306	01/09/1978	31/10/2004
Clocolan	-28.9211	27.5841	1602	01/10/1979	31/12/2004
Faurismith	-29.7700	25.3200	1522	01/01/1960	31/07/2008
Ficksburg	-28.8667	27.8500	1829	01/01/1950	31/07/2001
Frankfort	-27.2667	28.5000	1502	01/07/1960	31/08/2001
Gariep Dam	-30.6167	25.5000	1324	01/03/1964	29/02/2004
Glen College	-28.9500	26.3333	1304	01/01/1950	29/02/2004
Golden Gate	-28.5037	28.5837	1846	01/05/1984	31/05/2004
Hertzogville	-28.2000	25.3000	1326	01/09/1978	28/02/1999
Hobhouse	-29.5167	27.1333	1448	01/08/1984	31/07/2008
Kestell	-28.3141	28.7086	1692	01/07/1980	31/12/2007
Koppies	-27.2778	27.4180	1401	01/07/1983	31/12/2007
Kroonstad	-27.6667	27.2500	1348	01/07/1967	31/07/1992
Marquard	-28.5044	27.3563	1447	01/11/1982	31/03/2004
Oukraal	-29.9333	24.6833	1143	01/05/1978	30/11/2002
Petrusburg	-28.9833	25.5000	1219	01/09/1978	30/06/2001
Plessis Draai	-27.9833	26.1333	1249	01/11/1974	31/01/2002
Reitz	-27.8000	28.4333	1615	01/07/1977	29/02/2004
Rietpan	-27.1667	26.9167	1321	01/10/1978	31/01/2004
Rusfontein Dam	-29.2667	26.6000	1382	01/01/1960	31/05/1993
Tweespruit	-29.1936	27.0696	1567	01/03/1981	31/12/2005
Villiers	-27.0368	28.6149	1493	01/08/1977	28/02/2003
Virginia	-28.1000	26.8667	1335	01/01/1960	31/12/2001
Vrede	-27.4333	29.1667	1670	01/07/1981	31/07/2008
Warden	-27.9700	29.0700	1770	01/07/1980	31/07/2008
Welkom	-28.1333	26.6833	1295	01/01/1975	31/03/2001
Welkom-AER	-28.0000	26.6667	1338	01/01/1964	30/11/1989
Wepener	-29.7333	27.0333	1438	01/01/1960	30/11/1996
Wesselsbron	-27.7000	26.4500	1325	01/09/1980	30/06/2001
Zastron	-30.3000	27.0830	1661	01/01/1959	31/07/2008

Table 3.2: Information for climate stations used in the frost assessment study from neighbouring provinces and Lesotho (from ARC-ISCW, LMS and SAWS).

Station	Latitude	Longitude	Altitude	Start	End
Eastern Cape					
Aliwal North	-30.7167	26.7167	1348	01/01/1974	31/12/1988
Oviston	-30.7000	25.7667	1294	01/01/1964	31/12/1980
Northern Cape					
Colesberg	-30.7000	25.1000	1328	01/01/1983	31/12/2001
Hope Town	-29.6500	24.1833	1143	01/01/1979	31/12/1995
Kimberley	-28.8000	24.7667	1198	01/01/1960	31/12/1991
Modder Rivier	-29.0500	24.6333	1120	01/01/1951	31/12/1991
Vaal Harts	-27.9500	24.8333	1175	01/01/1950	31/12/1998
Gauteng					
Vereeniging	-26.6833	27.9167	1440	01/01/1960	31/12/1985
Mpumalanga					
Volkskrust	-27.3667	29.8833	1652	01/01/1960	31/12/1985
KwaZulu Natal					
Ladysmith	-28.4615	29.6775	1191	01/01/1985	30/04/2008
Hazeldene	-28.0578	29.8907	1295	01/01/1975	30/04/2008
North West					
Ottosdal	-26.9465	25.9713	1494	01/01/1991	31/12/2002
Potchestroom	-26.7333	27.0833	1345	01/01/1950	31/12/2003
Schweizer Reneke	-27.1923	25.3176	1309	01/01/1981	31/12/2004
Lesotho					
Leribe	-28.8800	28.0500	1740	01/01/1967	30/04/2008
Mafeteng	-29.8200	27.2500	1610	01/01/1987	30/04/2008
Mejametalana	-29.3000	27.5000	1530	01/01/1968	30/04/2008
Mohales Hoek	-30.1500	27.4700	1620	01/01/1980	30/04/2008
Oxbow	-28.7200	28.6200	2600	01/01/1962	30/04/2008

3.2.2 Methodology

3.2.2.1 Determination of frost occurrences

3.2.2.1.1 Onset, cessation and frost-free duration

All the data was arranged according to the agricultural season from July to June of the following year. For each agricultural season the last day of frost in spring (cessation of frost) and the first day of frost in autumn (onset of frost) were determined for each of the stations and for each year. Screen temperatures of greater than 0℃ upper bounded by 2 ℃ are considered as light frost. Minimum temperatures recorded on the screen greater than -2℃ upper bounded by 0℃ are considered as medium frost while minimum temperatures of -2℃ or less represent heavy frost. The frost dates were converted to Julian days to facilitate statistical computations. The frost frost-free period for each agricultural season were then calculated for light, medium and heavy frost occurrences as the number of days between last and first frost. The frost-free period is the most important index which marks the length of the growing period for most crops in the highveld regions.

3.2.2.1.2 Frost within the growing periods

The number of frost days within the maize growing period was also determined for short season maize cultivar (100 days), medium season maize cultivar (120 days) and long season maize cultivar (140 days). The frequency of frost days was determined for light, medium and heavy frost for all the agricultural seasons for each station. For each station, the frequency was determined from the array of planting dates starting from the first dekad of September to through to the last dekad of February. The number of frost days per growing season for 100, 120 and 140day cultivars was determined for all the years and the absolute probability of a frost day per season was obtained from the ratio of years with frost over the total number of years.

3.2.2.2 Statistical analysis

Rainbow software was used to determine the appropriate probability distribution for all the variables (onset, cessation & frost period) for each station (Raes *et al*., 1996). The curve fitting was done using the maximum likelihood procedure (Raes *et al*., 2006). In this study, the Kolmogorov-Smirnov test and the closeness of linear relationship between the fitted line and data points were used to determine the distribution that best resembles the datasets from each station (Raes *et al*., 2006). The datasets which do not conform to a Normal distribution were transformed using four methods: a) square root, b) logarithmic, c) square method, d) cube root method. Different probability levels (20%, 50% & 80%) were determined using the Weibull method (Raes et al., 2006).To clearly show the risk associated with the onset of frost, cessation of frost, frost period and frost-free period, the exceedence probability was used for the cessation of frost while the non-exceedence probability was used in the other frost indices.

3.2.2.3 Mapping

All the interpolation of the frost indices was done using the ArcGIS 9.3. The inverse distance weighting model imbedded in Spatial Analyst was used for interpolation of all the indices.

3.3 Results and discussion

As there is much data generated with this type of analysis, only some of the more critical and useful information will be shown. Details are shown in Appendices. Appendix 3.1 shows the 20%, 50%, 80% probability and standard deviation for the cessation, onset and frost-free period at light, medium and heavy frost thresholds for the 36 stations in the Free State Province.

3.3.1 Cessation, onset and frost-free duration

3.3.1.1 Light frost

The cessation of frost in Southern Africa marks the beginning of the growing period which occurs mostly during months of September and October while the onset of frost indicates that the growing period of most summer crops is coming to an end and this normally occurs in April, May and June.

The length of the frost-free period denotes the growing period and is mostly between 160 to over 330 days depending on the temperature threshold and locality. Fig. 3.2 shows the cessation of frost for different probability levels (20%, 50% and 80%) at the 2°C temperature threshold. There is a 20% chance of light cessation of frost occurring on or after the 1st dekad of October for the far northeastern Thabo Mofutsanyane district (in the vicinity of Warden and Vrede), most parts of the Fezile Dabi district, northern and western parts of the Lejweleputswa district (including Bothaville, Welkom, Boshof and Virginia areas) (Fig. 3.2 (a)). In areas surrounding places like Frankfort, Reitz, Winburg, west and north of Bethlehem, Bulkfontein, Petrusburg, Koffiefontein, Bethulie and Phillipolis there is a 20% chance that the cessation of frost can be on or after 2nd dekad of October. Places of later cessation (on or after 1st dekad of November) occur along the border with Lesotho where the topography is the contrast of high altitude and valleys along the rivers making the area very prone to frost. Most parts of the Motheo, southwestern Xhariep district and southern Thabo Mofutsanyane district have their 20% non-exceeding probability in the 3rd dekad of October. Most parts of the Lejweleputswa, western and central Xhariep as well as the whole Fezile Dabi district have their median cessation (50%) of frost on or after the 3rd dekad of September with few pockets in areas like Bothaville, Welkom and eastern part near Vrede which have their 50% chance of cessation of light frost 10 days earlier (Fig. 3.2 (b)). Most parts of the Motheo, western Lejweleputswa, central and southwestern Thabo Mofutsanyane district and southwestern Xhariep area have their 50% chances of light frost during or after the 1st dekad of October with few patches occurring during or after the 2nd dekad of October. The 80% chance denotes the high risk category and in places surrounding Koppies, Sasolburg, Parys and Heilbron over the Fezile Dabi district, Vrede and Warden (in Thabo Mofutsanyane district), Bothaville, Welkom, Viginia and Kroonstad (in Lejweleputswa district) and Phillipolis, west of Jagersfontein and Koffiefontein (across Xhriep district) have this category occurring on or after the 11th September (Fig. 3.2 (c)). In areas of high risk like the Motheo district, southern Thabo Mofutsanyane and southwestern Xhariep have 80% chance of the cessation of light frost occurring mostly on or after the 3rd dekad of September.

Onset of the light frost period (2°C) also varied widely throughout the Free State province. Fig. 3.3 (a) shows that most places over the Free State have their 20% chance of frost occurring on or before the 20th April (2nd dekad of April). The few exceptions are along the Lesotho border where onset of frost occurs on or before the 10th April for most places. The other exceptions are over the Welkom and Kroonstad area and other patches over the Xhariep and Fezile Dabi district where 20% chance of onset occur on or before 3rd dekad April. 50% probability of the onset of light frost occurs early along the borders with Lesotho and southern Thabo Mofutsanyane district occurring mostly on or before the 2nd dekad of April (20th April) (Fig. 3.3 (b)). In most places over the Free State, the median onset of light frost occurs on or before 30th April (during 3rd dekad of April). There are areas along the western and southwestern Free State border as well as Bothaville, Welkom and Virginia (in the Lejweleputswa district) and Kroonstad, Parys and Sasolburg (across Fezile Dabi district) where onset occurs later on or before 10th May (1st dekad of May). The relatively high risk (80% chance) of light onset of frost occurs mostly by the 1st dekad of May over most places in the Free State (Entire Motheo, most parts of Thabo Mofutsanyane, and eastern Xhariep) and thus crops that are not matured by this time face a high risk of frost damage (Fig. 3.3(c)). In other areas over the southwestern Xhariep, western Lejweleputswa and northern parts of the Fezile Dabi can have 80% chances of onset of frost as late as 31st May. In these areas, crops have an extended growing period before being highly vulnerable to frost.

The frost-free period spatial pattern follows that of the onset and cessation of frost (Fig. 3.4). There is a 20% chance that the length of the frost-free period can be 180 days or less for most parts of the Motheo, Thabo Mofutsanyane and southeastern Xhariep district. These areas have the 50% and 80% chances of length of the growing period of 200 days and 220 days respectively. The short length of the Frost-free period at 20% probability level is caused by either or both the earlier than normal onset of frost and later than normal cessation of frost. The reduced length of the frost-free period restricts planting of high yielding long-season maize cultivars. In contrast, the areas with a longer length of the growing period are in a strip from Virginia, Welkom in north easterly direction through Kroonstad to Koppies, Parys and Sasolburg as well as Boshof and Christiana where the frost-free period at 20%, 50% and 80% probability level is mostly 220 days, 240 days and 260 days respectively. Most parts of the Xhariep and Lejweleputswa districts as well as Fezile Dabi and northeastern Thabo Mofutsanyane have 20%, 50% and 80% chance of the length of the frost-free period being shorter than 200 days, 220 days and 240 days.

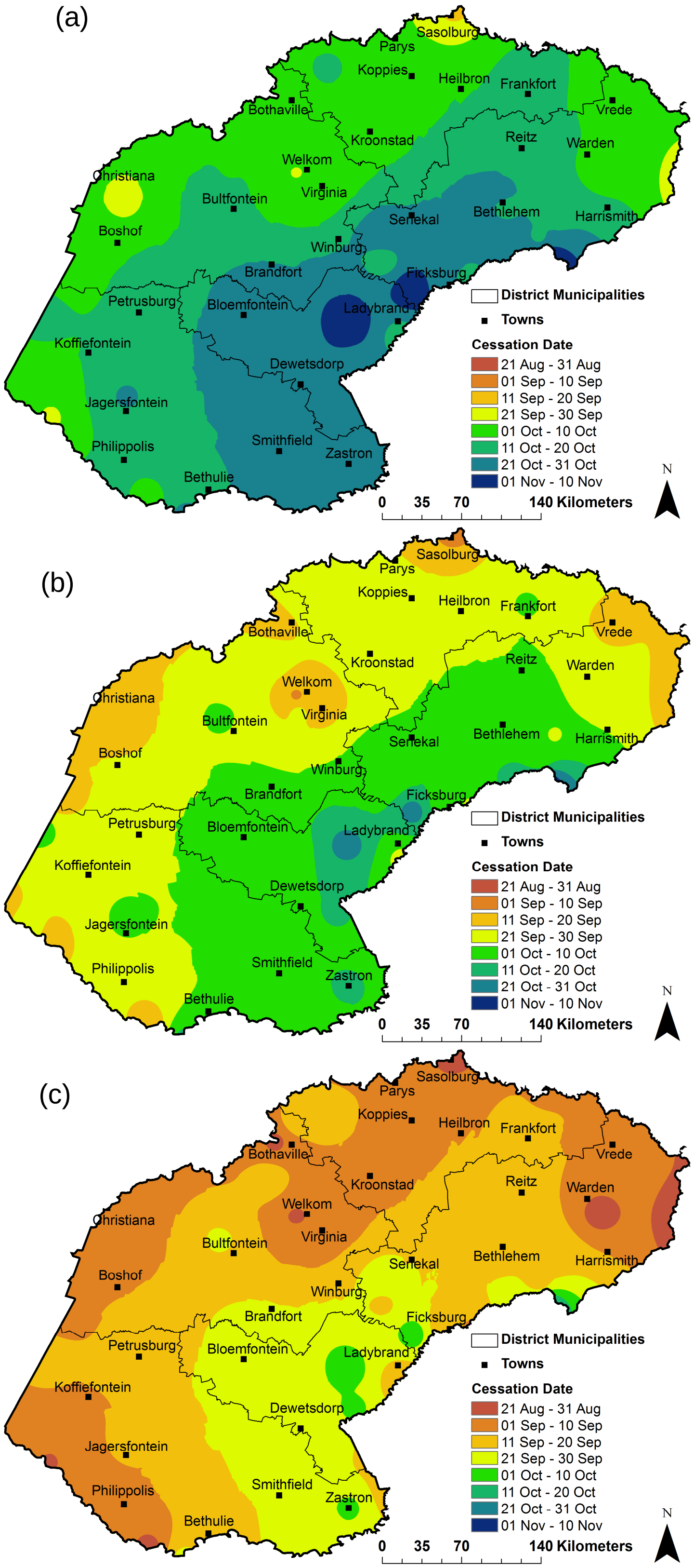


Fig. 3.2: Date at which cessation of light frost (2°C) at (a) 20%; (b) 50% and (c) 80% exceeding probabilities is achieved in the Free State Province.

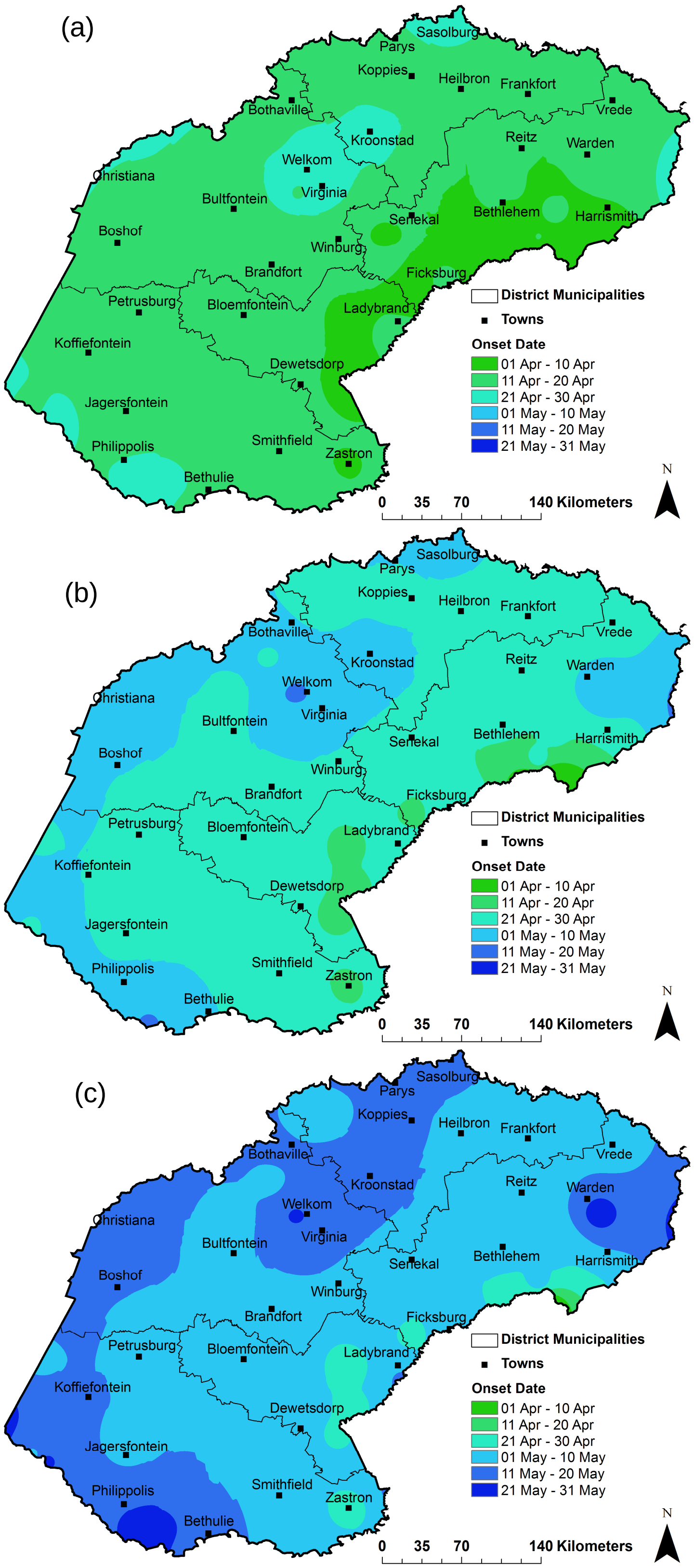


Fig. 3.3: Date at which onset of light frost (2°C) probability at (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities is achieved in the Free State Province.

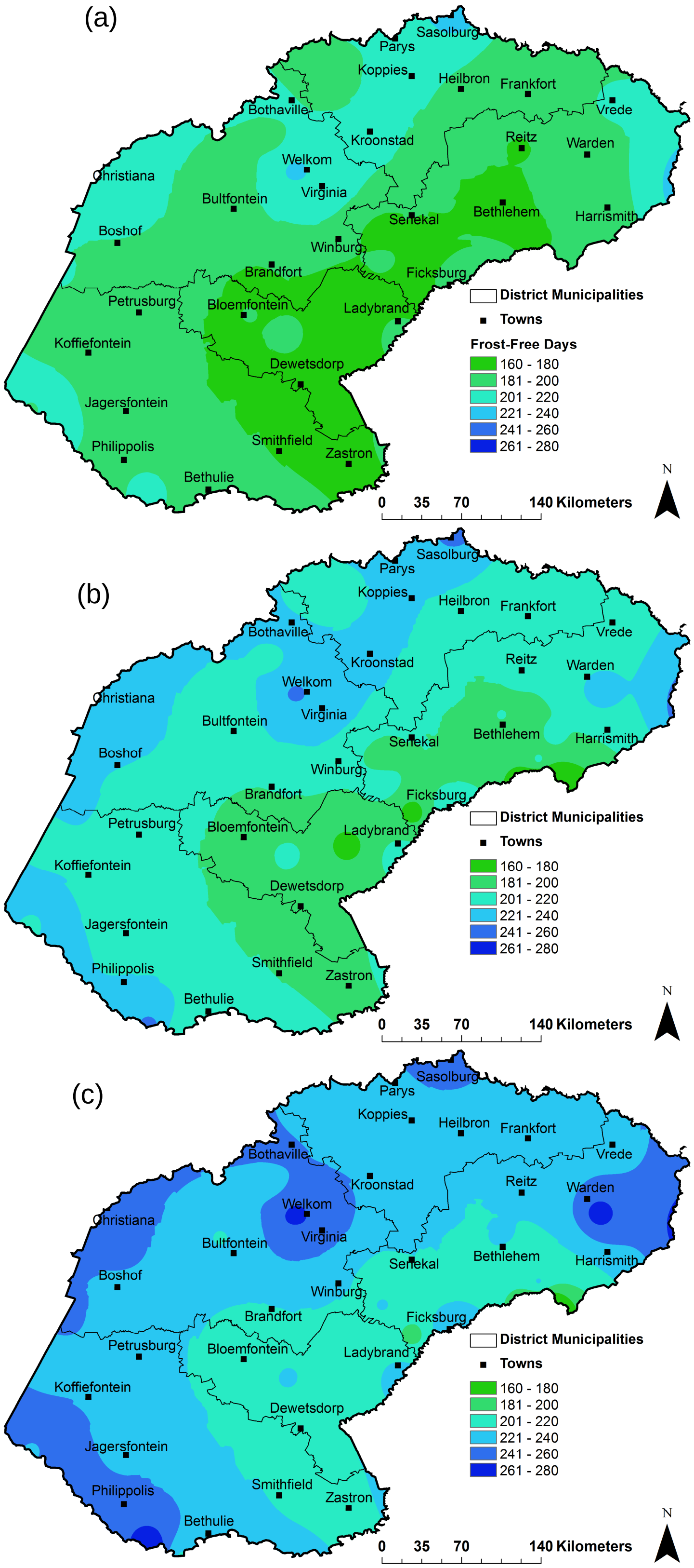


Fig. 3.4: Frost-free duration of light frost (2℃) at (a) 20%; 50% and 80% non-exceeding probabilities in the Free State Province.

3.3.1.2 Medium frost

Cessation of medium frost (0^oC threshold) was earliest over western areas like Sasolburg (in Fezile Dabi district), Bothaville, Boshof, Chistiana, Welkom and Virginia (in Lejweleputswa district), Koffiefontein, Jagersfontein and Phillippolis (in Xhariep district) and eastern part like Warden and Vrede (in Thabo Mofutsanyane district) where 20%, 50% and 80% chance of cessation of medium frost occurs on or after 20th September, 31st August and 20th August respectively (Fig 3.5). Earlier cessation of frost implies that crops can be planted earlier giving them a better chance of surviving the season. But most places over the Fezile Dabi, Lejweleputswa and Xhariep districts have their 20%, 50% and 80% probability of frost cessation on or after 30th September, 10th September and 31st August respectively. The majority of the Motheo district, central and western Thabo Mofutsanuane district and southeastern Xhariep have 20%, 50% and 80% chances of the frost cessation on or after the 10th October, 20th September and 10th September respectively. The latest cessation of frost is evident over the western and southern Thabo Mofutsanyane, eastern Motheo and southeastern Xhariep where the 20%, 50% and 80% non-exceeding probabilities are on the 20th October, 30th September and 20th September respectively. These places are more vulnerable to frost especially if planting is early and thus forcing farmers to delay their planting resulting to shorter growing periods suitable for short or medium cultivars.

Onsets of medium frost is relatively early over a few patches in the Motheo and Thabo Mofutsanyane district where 20%, 50% and 80% non-exceeding probability occurs before 20th April, 30th April and 10th May respectively (Fig. 3.6). Late planted crops in these areas are in danger of not achieving full maturity before suffering from damage resulting in poor quality yield or production loss in extreme cases. Most parts of the Lejweleputswa and Xhariep districts, central Fezile Dabi have 20%, 50% and 80% chances of onsets on or before 10th May, 20th May and 31st May (Fig. 3.6). Most parts of the Motheo and Thabo Mofutsamyane districts have their 20%, 50% and 80% onsets on or before the 30th April, 10th May and 20th May respectively. The other areas have relatively late onsets especially western Lejweleputswa, southwestern and western Xhariep as well as northeastern Thabo Mofutsanyane districts with 20%, 50% and 80% onsets being on or before 20th May, 30th May and 10th June respectively (Fig. 3.6). The dates for these three probability levels are 10 days apart for almost the entire province and hence showing low variability implying high predictability. Places with very late onsets are desirable for crop production such that the threat of crops not maturing is minimal. This means that they have a wider choice of planting dates and cultivar combinations and also possible staggering of plantings to spread the risk.

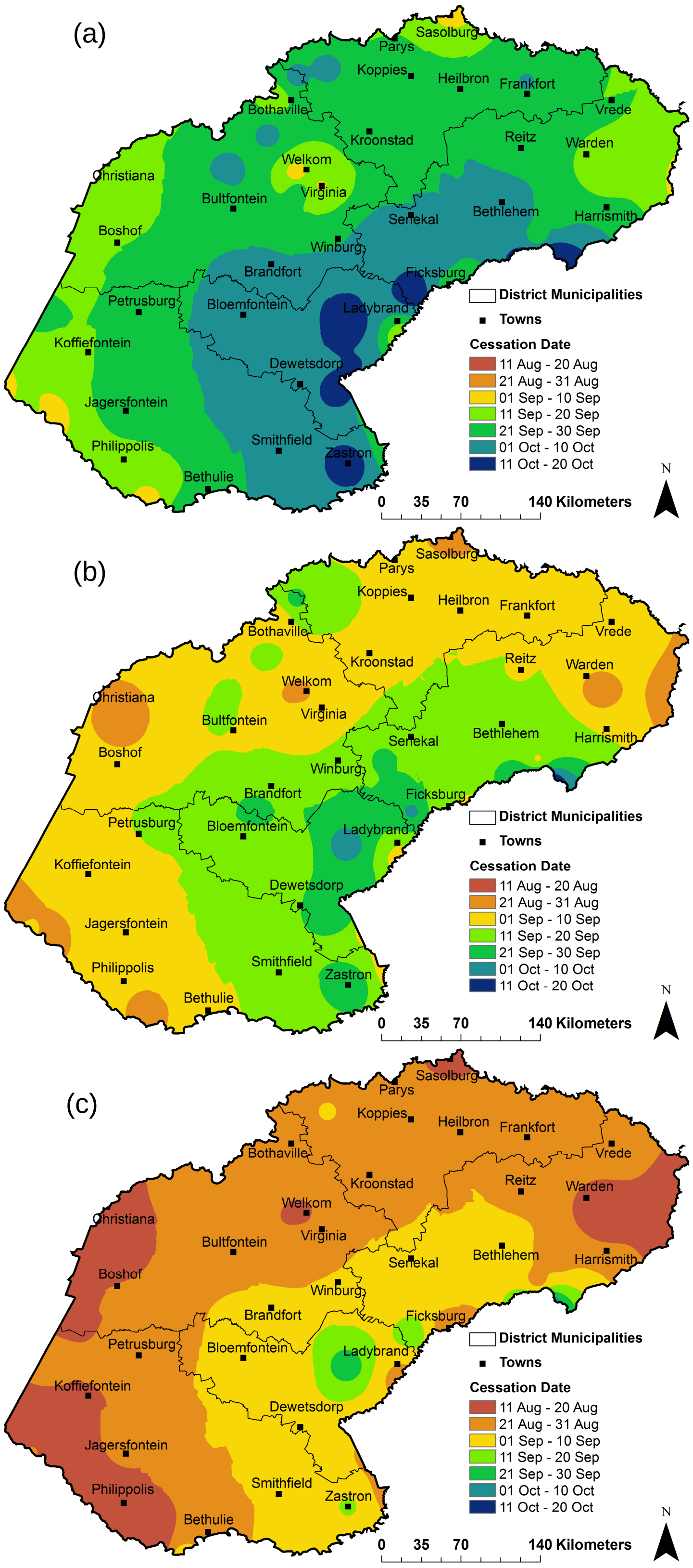


Fig. 3.5: Date at which cessation of medium frost (0°C) at (a) 20%; (b) 50% and (c) 80% exceeding probabilites is achieved in the Free State Province.

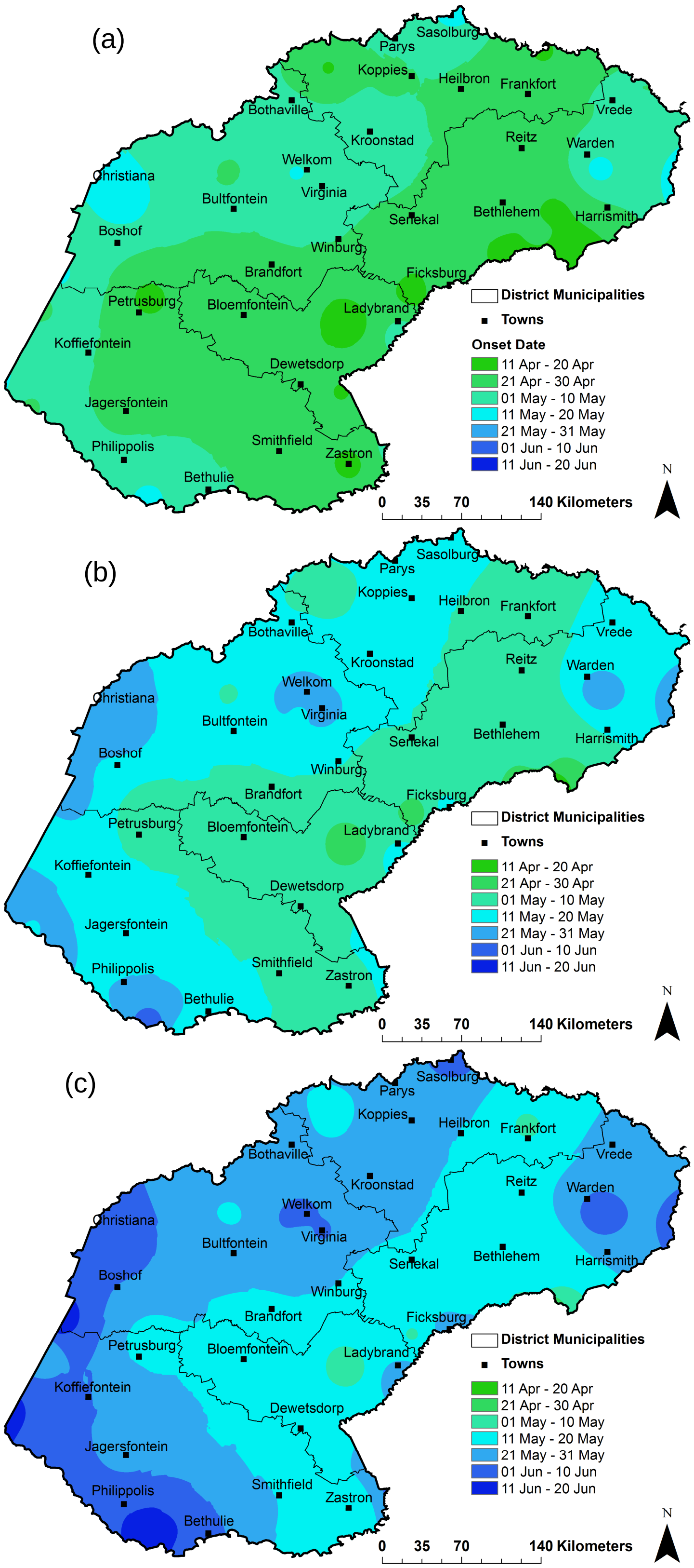


Fig. 3.6: Date at which medium frost (0°C) at (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities is achieved in the Free State Province.

Frost-free period for medium frost is equal or less than 200, 220 and 240 days for 20%, 50% and 80% probability for few patches in highlands near the border with Lesotho (Fig. 3.7). In these areas, the growing period is shortest and planting of medium-late or late season crop varieties which mature after a long period should be avoided. Over the entire Motheo district and central and southwestern Thabo Mofutsanyane district, the frost-free duration is equal or shorter than 220, 240 and 260 days for the 20% (low risk), 50% (medium risk) and 80% (high risk) probabilities. Over most parts of the Lejweleputswa, Fezile Dabi and western Xhariep districts the 20%, 50% and 80% frost-free period is equal or less than 240, 260 and 280 respectively. Patches in the far eastern Thabo Mofutsanayane, far northern Fezile Dabi, central and western Lejweleputswa and southwestern Xhariep have longest frost-free period of 280, 300 and 320 days for the 20%, 50% and 80% non-exceeding probability. The areas where there is longer frost-free period are mostly suitable for planting crops of varying cultivar length while places like the eastern Motheo and southwestern Thabo Mofutsanyane are more vulnerable to frost and thus short-season cultivars have to be planted.

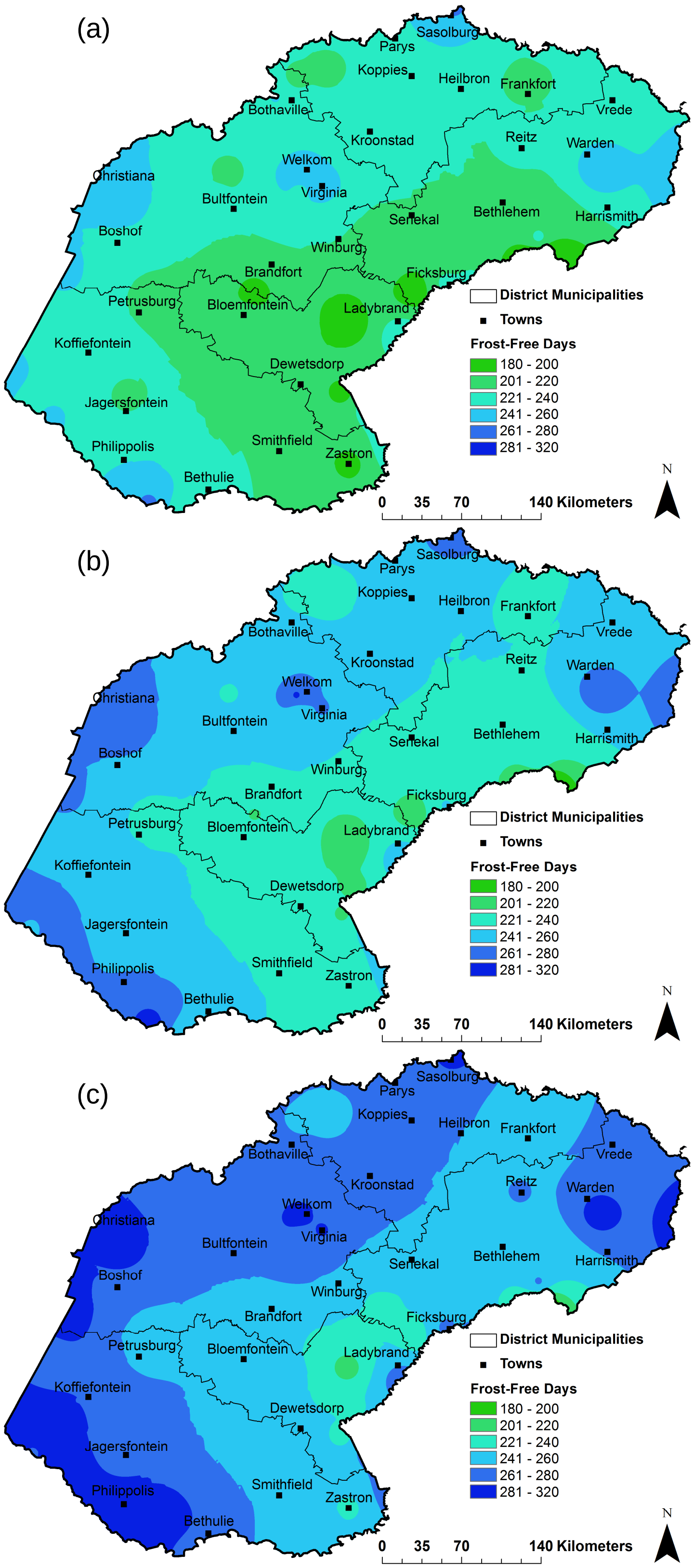


Fig. 3.7: Frost-Free duration of medium frost (0°C) at (a) 20%; 50% and 80% non-exceeding probabilities in the Free State Province.

3.3.1.3 Heavy frost

Cessation and onset of heavy frost (temperature threshold of -2°C) for the 20%, 50% and 80% probability levels are presented in Figure 3.8. The cessation of heavy frost at low frost risk (20%) probability is earlier in patches over the far eastern Free State (east of Warden), patches around Welkom, Virginia and western and southern parts of the Xhariep district occurring on or after 31st August (3rd dekad of August). There are a few patches close to these places with no frost risk at 50% and 80% non-exceeding probability. In other areas the 50% and 80% probability of cessation of heavy frost occurs on or after the 20th August and 31st July respectively. Most parts of the Fezile Dabi district and the northern and central Xhariep district have 20%, 50% and 80% chances on or after 10th September, 31st August and 20th August. The Motheo district, southern, central and southwestern Thabo Mofutsanyane district and southeastern Xhariep have their cessation of heavy frost for 20%, 50% and 80% being on or after the 20th September, 10th September and 20th August. Cessation of frost is very late for some places over the eastern Motheo and southern Thabo Mofutsanyane districts with the 20%, 50% and 80% non-exceeding probability occurring on the 30th September, 20th September and 31st August.

The 20% probability of onset of frost is earlier (21-30 April) over the sweep from Frankfort down thru central Thabo Mofutsanyane to the border with Lesotho down to southeastern Xhariep then stretching northwestwards to cover most parts of Motheo. This “M” shaped feature is mostly common at 20% and 50% probability for onset, cessation as well as frost-free duration. The feature breaks at 80% probability and in some 50% probability level to form a dipole with centres at Bethlehem and southwest of Ladybrand. The onset of heavy frost 50% and 80% chances in the southern Thabo Mofutsanyane, eastern Motheo, eastern Fezile Dabi district (areas surrounding Frankfort) and southeastern Xhariep districts occurs on or before 20th May and 31st May (Fig. 3.9). The Motheo district also have relatively early onset of frost with the 20%, 50% and 80% occurring on the 30th April, 10th May and 10th June. Onsets of heavy frost over the Thabo Mofutsanyane district is mostly on or before the 30th April, 31st May and 10th June for the 20%, 50% and 80% respectively. Apart from the southern parts which have relatively early onsets, the eastern Thabo Mofutsanyane especially around Warden have no heavy frost risk at 50% and 80% probability. Most parts of the Fezile Dabi district have the onset at low, medium and high risk on or before 10th May, 31st May and 10th June. Over the Lejweleputswa, areas around Welkom, Virginia, Christiana and Boshof show late onsets occurring on the 20th May, 10th June and 30th June for the 20%, 50% and 80% non-exceedence probability. The remainder of the district have their 20%, 50% and 80% heavy onsets on or before 10th May, 31st May and 10th June. The Xhariep district has early onsets over the southeastern parts while the western parts have no risk at 50% and 80% probability while the other parts mostly have 20%, 50% and 80% chances of heavy onsets on or before 10th May, 31st May and 10th June.

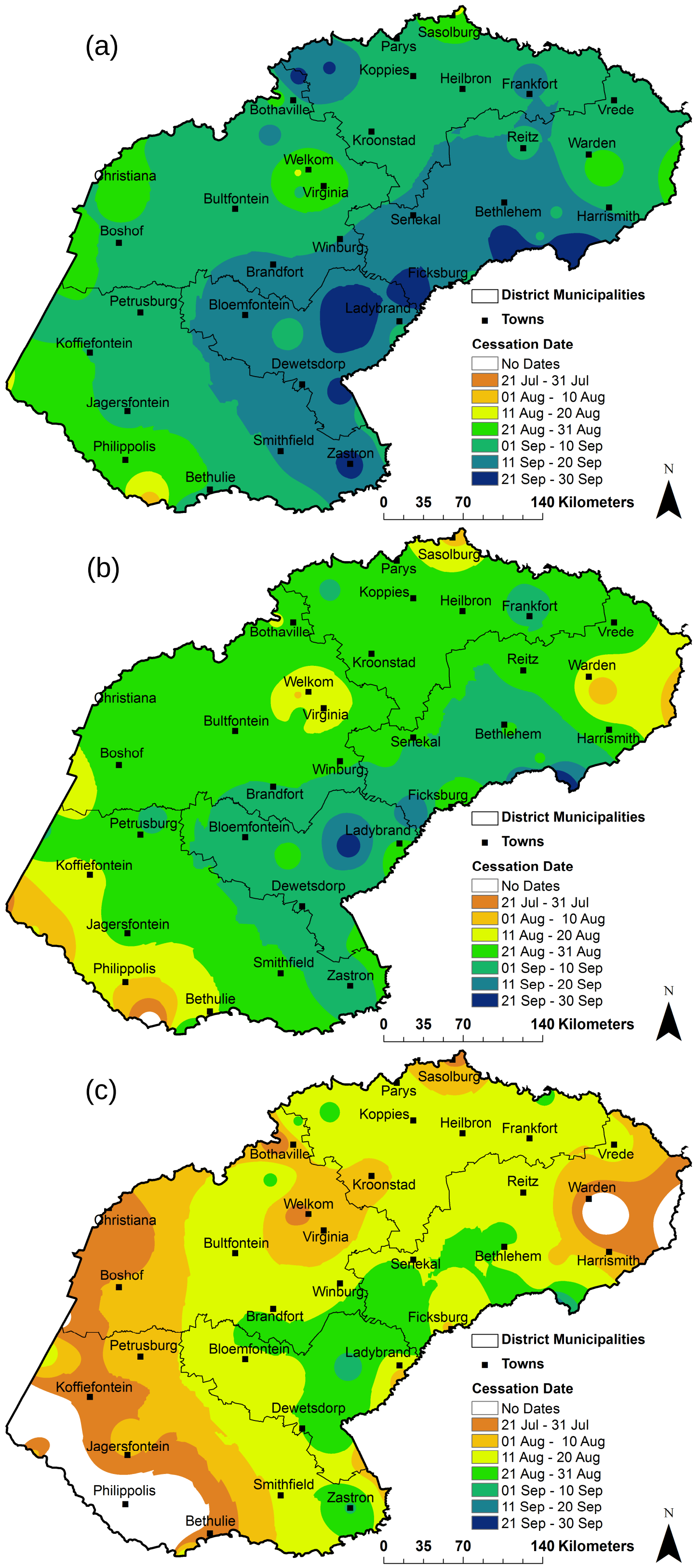


Fig. 3.8: Date at cessation of heavy frost (-2°C) at (a) 20%; (b) 50% and (c) 80% exceeding probabilities is achieved in the Free State Province.

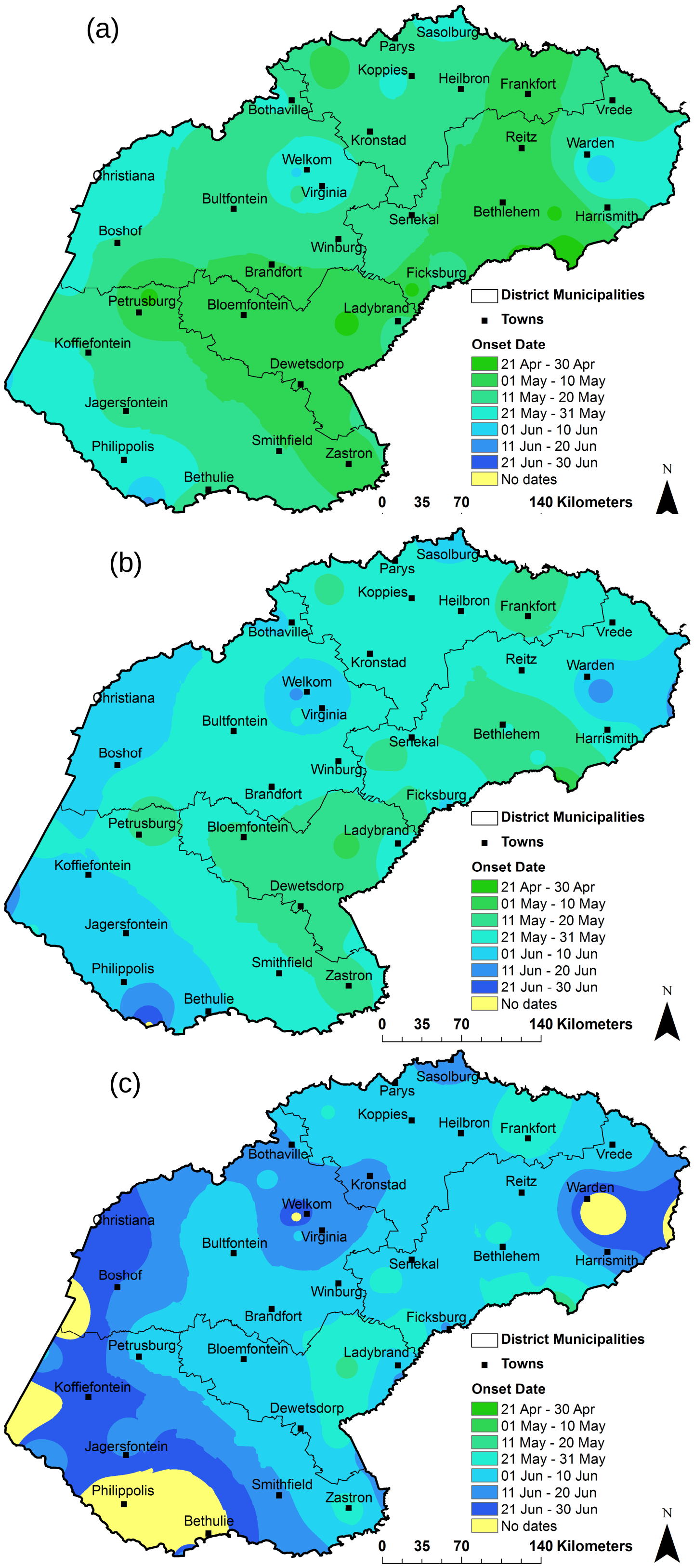


Fig. 3.9: Date at which onset of heavy frost (-2°C) at (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities is achieved in the Free State Province.

The frost-free duration for the heavy frost is shorter over the eastern Motheo, central and southern Thabo Mofutsanyane and southwestern Xhariep with the 20%, 50% and 80% chances of having 240, 260 and 280 or less growing period days respectively (Fig 3.10). Most parts of the Fezile Dabi (except Sasolburg and Kroonstad where the frost-free days are relatively high), most parts of the Thabo Mofutsanyane, most parts of the Motheo district and places around Winburg, Brandfort and Bultfontein over the Lejweleputswa have frost-free days of 260, 280 and 300 days for the 20%, 50% and 80% non-exceeding probability (Fig 4.11 to Fig. 3.13). The other places like Welkom, Virginia, Boshof and Bothaville mostly have their 20% probability of frost-free period of 280 or less with few patches with frost-free period of up to 330 days. The medium and high risk frost-free period for these places is 300 and 320 respectively with other areas of no frost risk (up to 365 frost-free days). The western parts of the Xhariep, far eastern Thabo Mofutsanyane and western Lejweleputswa have places which have the 50% and 80% chances of having the entire year without a heavy frost. These does not mean they are the most desirable places for planting maize as there are other climate risks like rainy season length (chapter 4) and agricultural drought (chapter 5) that also have to be considered.

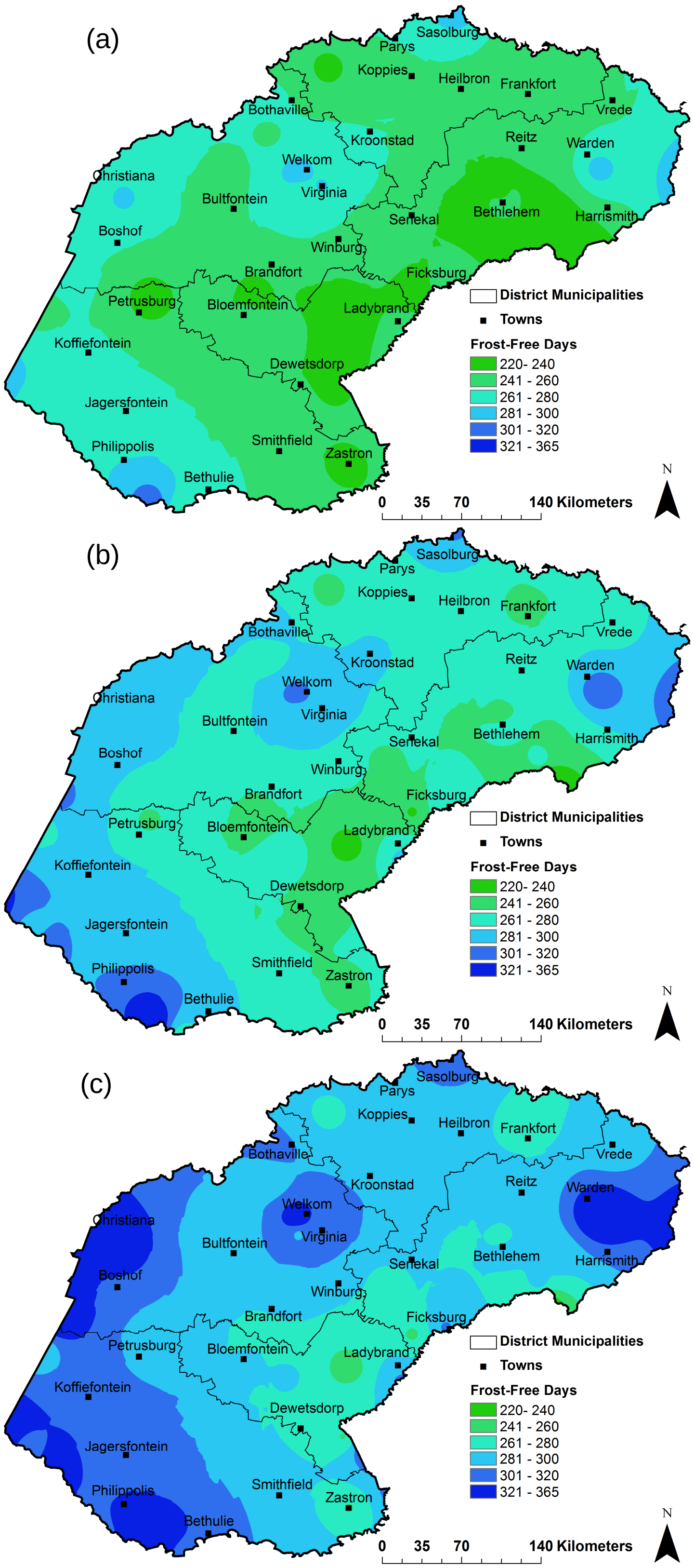


Fig. 3.10: Frost-Free duration of heavy frost (-2°C) at (a) 20%; 50% and 80% non-exceeding probabilities in the Free State Province.

3.3.2 Frost within the growing periods

The typical curves for frost probability (a frost incidence occurring) during different growing periods for light, medium and heavy frost are shown for relatively high frost prone place (Bloemfontein) in Figure 3.11. It can be depicted from the graphs that, frost risk during September and October for all the maize varieties is the same because late frost risk is high during these months while when planting in November onwards, the length of the growing period determines the risk. The longer the growing period the chances earlier the chances of reaching high frost risk zone in the months of April, May and June. Thus the maps for the frost probability will be the same in October and November planting periods while from December onwards every maps will be produced foe every cultivar. The frost of medium frost will be mapped in the up coming section because it is regarded as the most appropriate threshold for determining maize frost risk damage. The other thresholds are relevant to the maize production (Carter & Hesterman, 1990). Persisitent temperatures below 2°C have negative impact on growth and productivity of the maize crop because what is important is the canopy temperature not weather station temperature (Trasmonte *et al.* 2008; Rebbeck & Hayman, 2009). Due to shorter frost-free period for the light frost threshold, it is expected that its probability for frost during the season to higher in most planting dekads than in the medium threshold illustrated below (subsections 3.2.2.1 to 3.2.2.8) while the heavy frost probability is expected to be lower resulting in longer periods of frost free period within the growing periods (Fig. 3.11).

3.3.2.1 October 1st, 2nd and 3rd dekad planting

Probability of frost (0°C) during the growing period for the 100-day, 120-day and 140-day maize cultivars is shown in Fig. 3.12. Planting maize in the 1st dekad of October results in high risk over patches in the eastern Motheo district and eastern Thabo Mofutsanyane district where probability exceeding of up to 80% is possible (Fig. 3.12a). During the second dekad of October the risk at these places is reduced to mostly less than 40 (Fig.3.12b) while in the 3rd dekad the risk is mostly up to 20% (Fig. 3.12c). In these places, planting over the 1st dekad of October is not recommended because the likelihood of the crop failing due to frost damage is high. During the 3rd dekad of October planting maize of any cultivar is subjected to low frost (0°C) risk hence planting in this period is recommended. The area extending from far southeastern parts of Free State to Bultfontein and towards the north to Bethlehem have up to 40% chances of obtaining frost when planting in October 1st dekad. Hence these areas are slightly vulnerable to frost damage. The vulnerability is reduced during the 2nd dekad and 3rd dekad of October where less than 20% (October 2nd dekad) and less than 10% (October 1st dekad) chances are evident. The remainder of the Province have less frost risk (<10%) for all the October plantings. In these areas the likelihood of frost damage during the growing period starting in October for all the three cultivars is minimal.

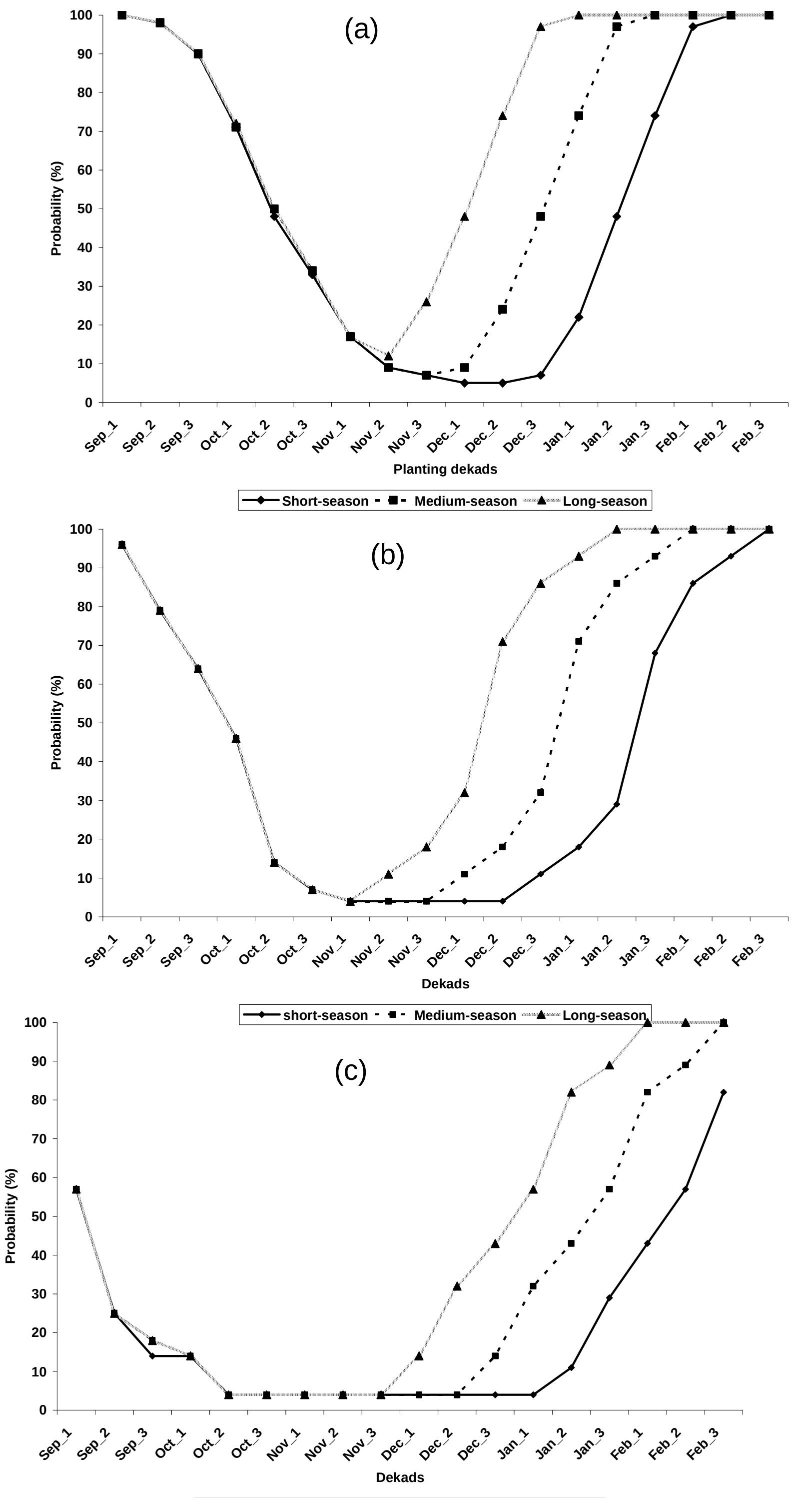


Fig. 3.11: Variation of frost probability during different planting periods for a) light frost, b) medium frost and c) heavy frost.

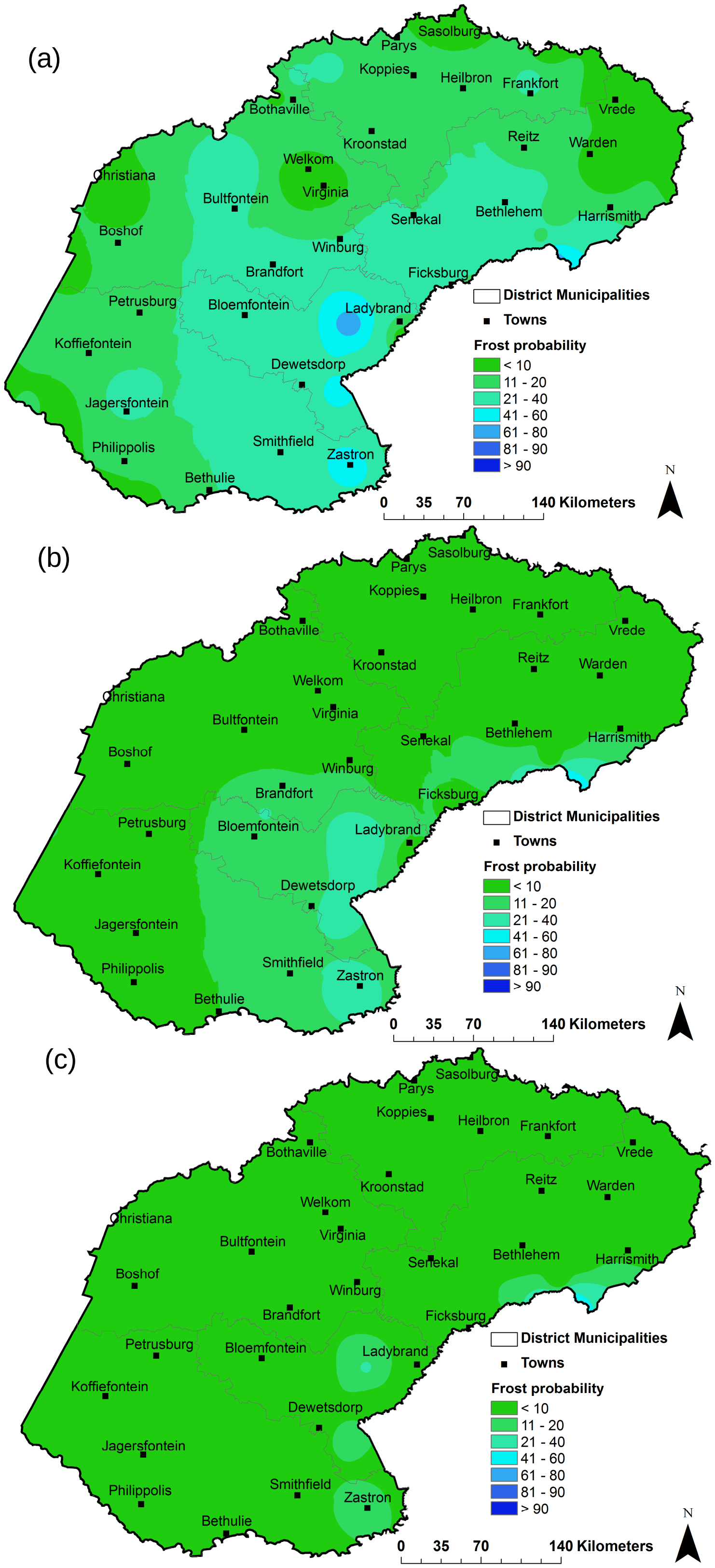


Fig 3.12: Probability of frost (0°C) within growing period of 100, 120 and 140-day maize cultivars planted in a) October 1st dekad, b) October 2st dekad and c) October 3rd dekad.

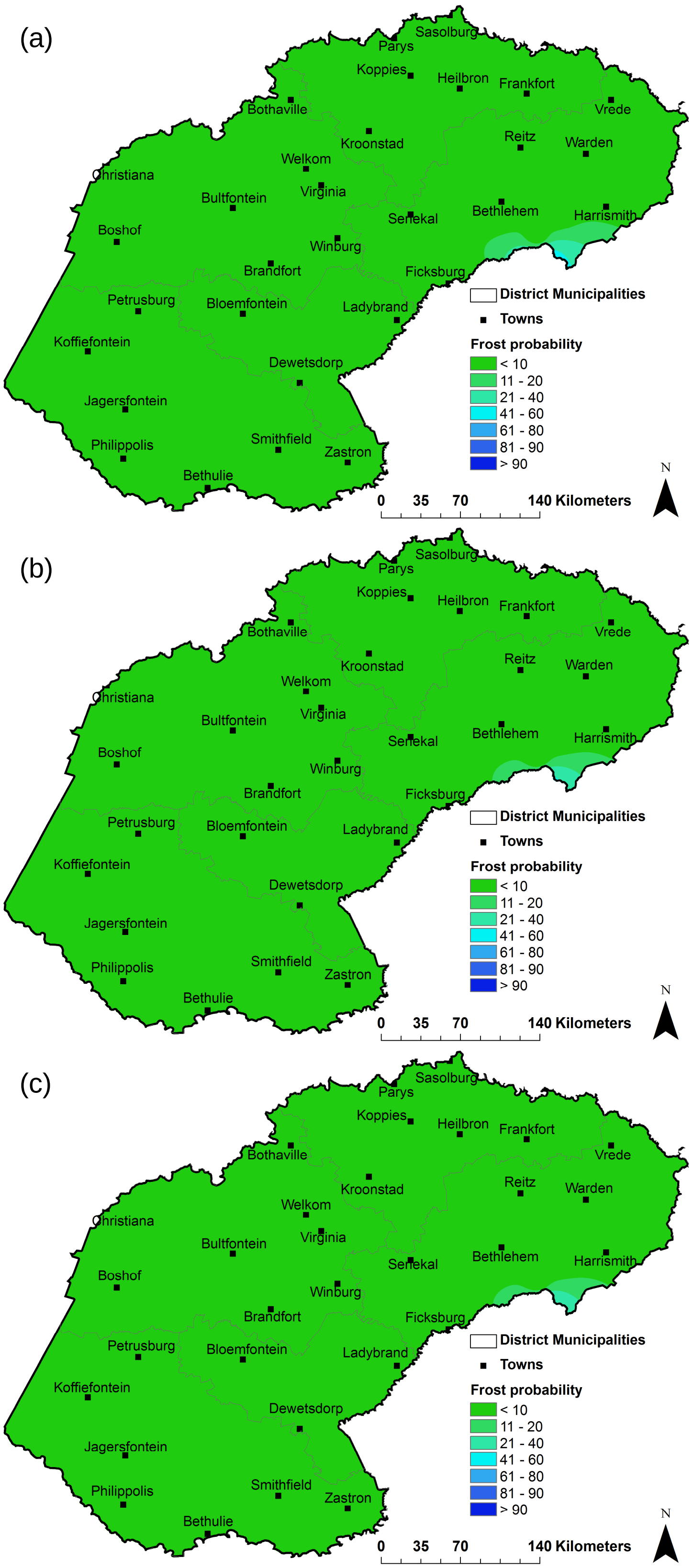


Fig 3.13: Probability of frost (0˚C) within growing period of 100, 120 and 140-day maize cultivars planted in a) November 1st dekad, b) November 2nd dekad and c) November 3rd dekad.

3.3.2.2 *November 1st, 2nd and 3rd dekad planting*

During the November planting period (1st, 2nd & 3rd dekad) the risk of frost damage over the entire Free State is minimal with most places having less than 10% chances of frost when planting their maize (100-day, 120-day & 140-day) over these planting dates (Fig. 3.13).

3.3.2.3 *December 1st dekad planting for 100-day, 120-day and 140-day maize cultivar*

If a farmer decides to plant a 100-day maize cultivar during the first dekad of December, the crop development is not likely to be affected by frost because of the low frost risk (<10%) for almost the entire Free State Province (Fig. 3.14a). The planting of the 120-day maize cultivar in 1st dekad of December is subjected to frost risk of less than 10% (Fig. 3.14b). In contrast, planting relatively long season cultivar (140-day) result in slightly increased risk of frost damage (21 to 40%) mostly over some pockets of eastern Motheo and eastern Thabo Mofutsanyane district (Fig. 3.14c).

3.3.2.4 *December 2nd dekad planting for 100-day, 120-day and 140-day maize cultivar*

When planting 100-day and 120-day maize cultivars in the 2nd dekad of December, the crop is still expected to have no developmental hinderance caused by frost damage because of low risk of frost (< 10%) almost the entire Province (Fig. 3.15a & Fig. 3.15b). The 140-day maize cultivar planted on this dekad could be affected by frost especially over the Motheo, eastern Thabo Mofutsanyane, southeastern Xhariep and patches over Fezile Dabi didtrict in the northern Free State. The frost risk is mostly between 41% and 60% with pockets of values exceeding 60% evident over the eastern parts of the Free State.

3.3.2.5 *December 3rd dekad planting for 100-day, 120-day and 140-day maize cultivar*

The 100-day cultivar planted in the 3rd dekad of December is still exected to grow well in most places over the Free State due to low frost risk (<10%), but the 120-day maize cultivar can be subjected to relatively high frost risk (21% - 40%) especially over the eastern Motheo and eastern Thabo Mofutsanyane districts (Fig. 3.16a & Fig. 3.16b). When planting the 140-day maize cultivar the frost risk increases drastically in this planting dekad. The area stretching from Frankfort thru to Bethlehem and Bloemfontein and southwards to Zastron have between 61% and 80% chances of frost (0°C) during the growing period starting in the 3rd dekad of December (Fig. 3.16c). Some parts of the Province have 41 % to 60% of frost risk chances, with places around Bothaville, Welkom, Virginia, Kroonstad, koppies, Sasolburg and places over the southwestern Free State having less than 40% chances of frost damage. These places can be suited to planting maize of this (140-day) length.

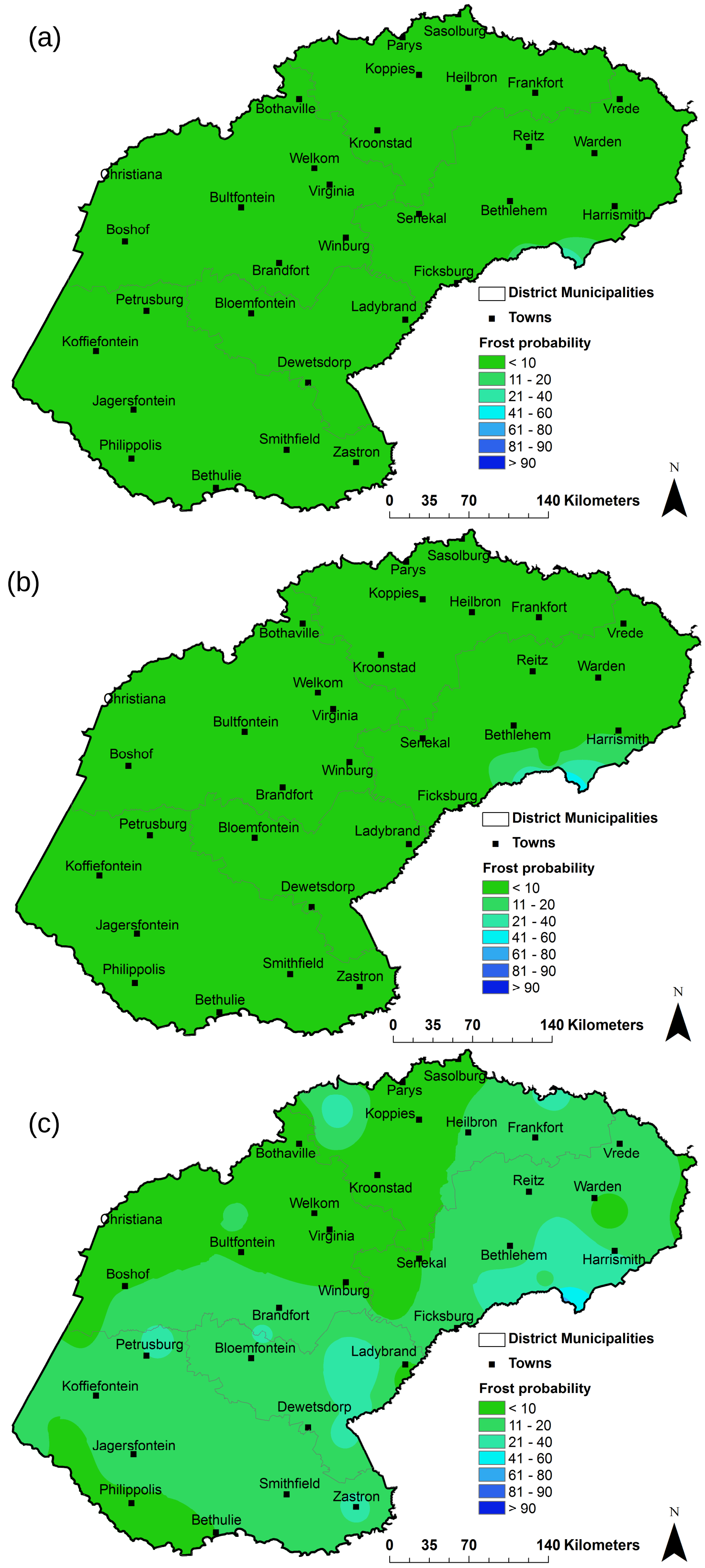


Fig 3.14: Probability of frost (0°C) within growing period of a) 100-day , b) 120-day and c) 140-day maize cultivars planted in December 1st dekad.

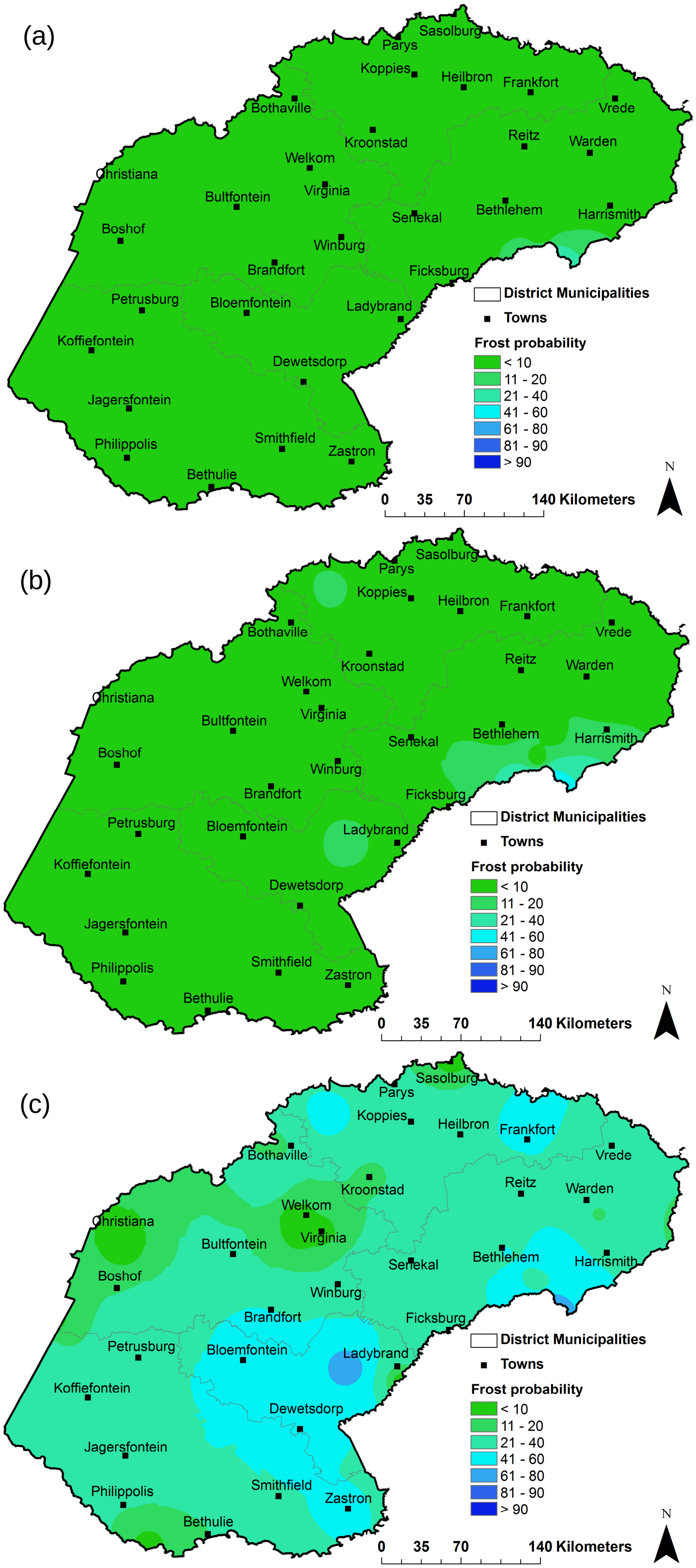


Fig 3.15: Probability of frost (0°C) within growing period of a) 100-day , b) 120-day and c) 140-day maize cultivars planted in December 2nd dekad.

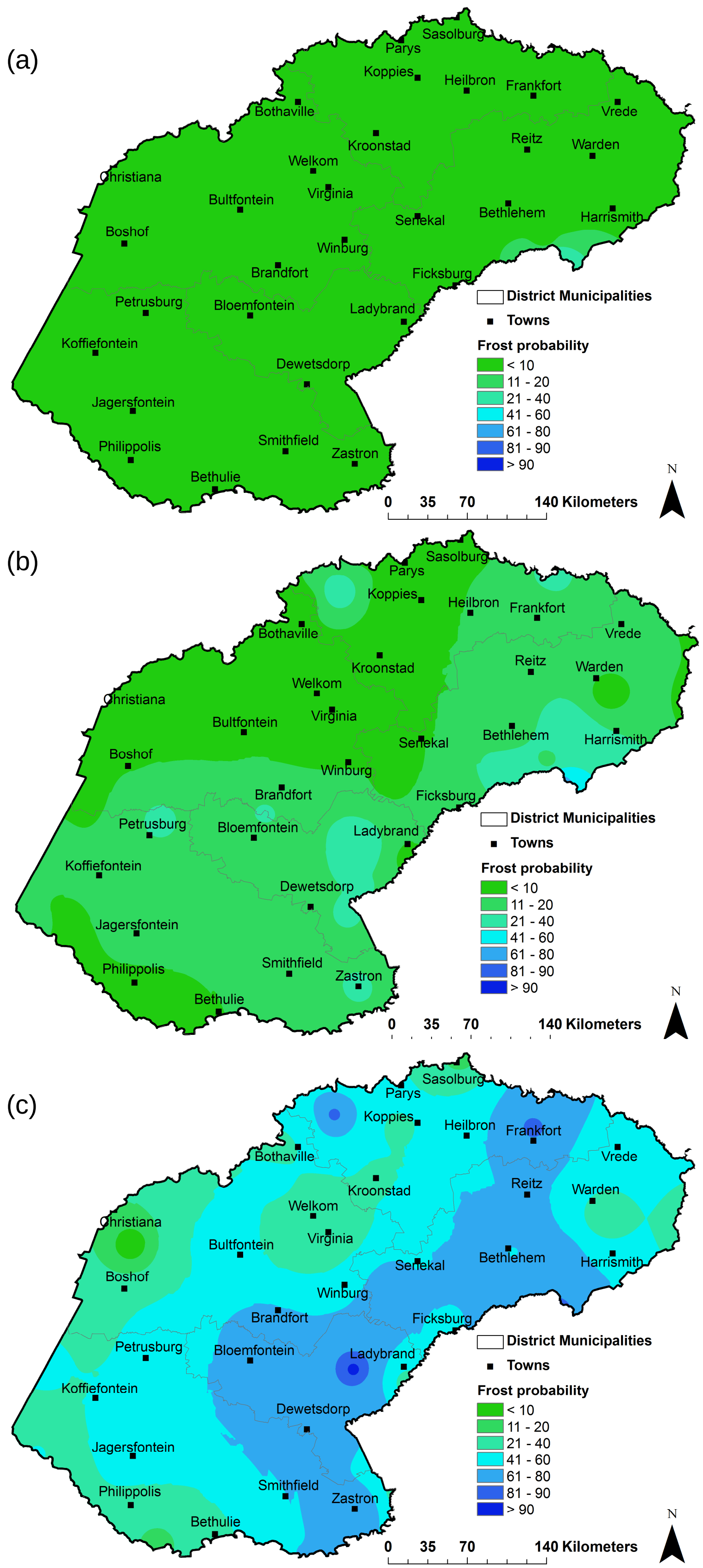


Fig 3.16: Probability of frost (0°C) within growing period of a) 100-day , b) 120-day and c) 140-day maize cultivars planted in December 3rd dekad.

3.3.2.6 *January 1st dekad planting for 100-day, 120-day and 140-day maize cultivar*

Planting 100-day maize cultivar during the 1st dekad of January is still expected to experience low risk of frost during the growing period for the entire province according to long-term climate data (Fig. 3.17a). But when planting of 120-day maize cultivar in this dekad one would expect relatively high frost risk damage over the Motheo and Thabo Mofutsanyane district with mostly up to 60% chance (3.17b). The other places still show relatively low (<40%) frost risk. Planting 140-day maize cultivar is not recommended in most parts of the Free State except in patches over the Lejweleputswa, far eastern Thabo Mofutsanyane and southwestern Xhariep (Fig. 3.17c). In most parts of the Province the frost risk probability ranges from 61% peaking at over 90% over pockets in the Motheo, Fezile Dabi and Thabo Mofutsanyane district.

3.3.2.7 *January 2nd dekad planting for 100-day, 120-day and 140-day maize cultivar*

The entire Province shows low risk (mostly below 10%) of frost for the growing period of the 100-day maize cultivar planted in the 2nd dekad of January (Fig. 3.18a). As for the 120-day maize planted in the same dekad, high frost risk is evident over the Motheo, southeastern Xhariep, Central and western Thabo Mofutsanyane and eastern Fezile Dabi district where values exceeding 60% are experienced (Fig. 3.18b). Places of low frost risk (< 40%) are over western and eastern Lejweleputswa, southwestern Xhariep and few patches over the Fezile Dabi and Thabo Mofutsanyane district. 140-day maize cultivar is not suitable during the 2nd dekad of January planting for the entire province because frost risk damage probability is in the excess of 80% for most parts of the maize growing area (Fig. 3.18c).

3.3.2.8 *January 3rd dekad planting for 100-day, 120-day and 140-day maize cultivar*

Planting 100-day maize cultivar during the 3rd dekad of January show frost risk damage chances of between 21% and 40% for most parts of the Province (Fig. 3.19a). The relatively high risk areas are over the Motheo and patches over the eastern Thabo Mofutsanyane and Fezile Dabi districts where the probability can reach up to 80%. Very low risk areas are over the over the western and eastern Lejweleputswa and patches over the northern tip of Fezile Dabi district and southern Xhariep. The 120-day maize cultivar planted in the 3rd dekad of January show frost risk probability exceeding 60% in their growing period for the entire Province with few exceptions (Fig. 3.19b). The 140-day maize cultivar has over 90% chances of being damaged by frost during the growing period starting in the 3rd dekad of January (Fig. 3.19c).

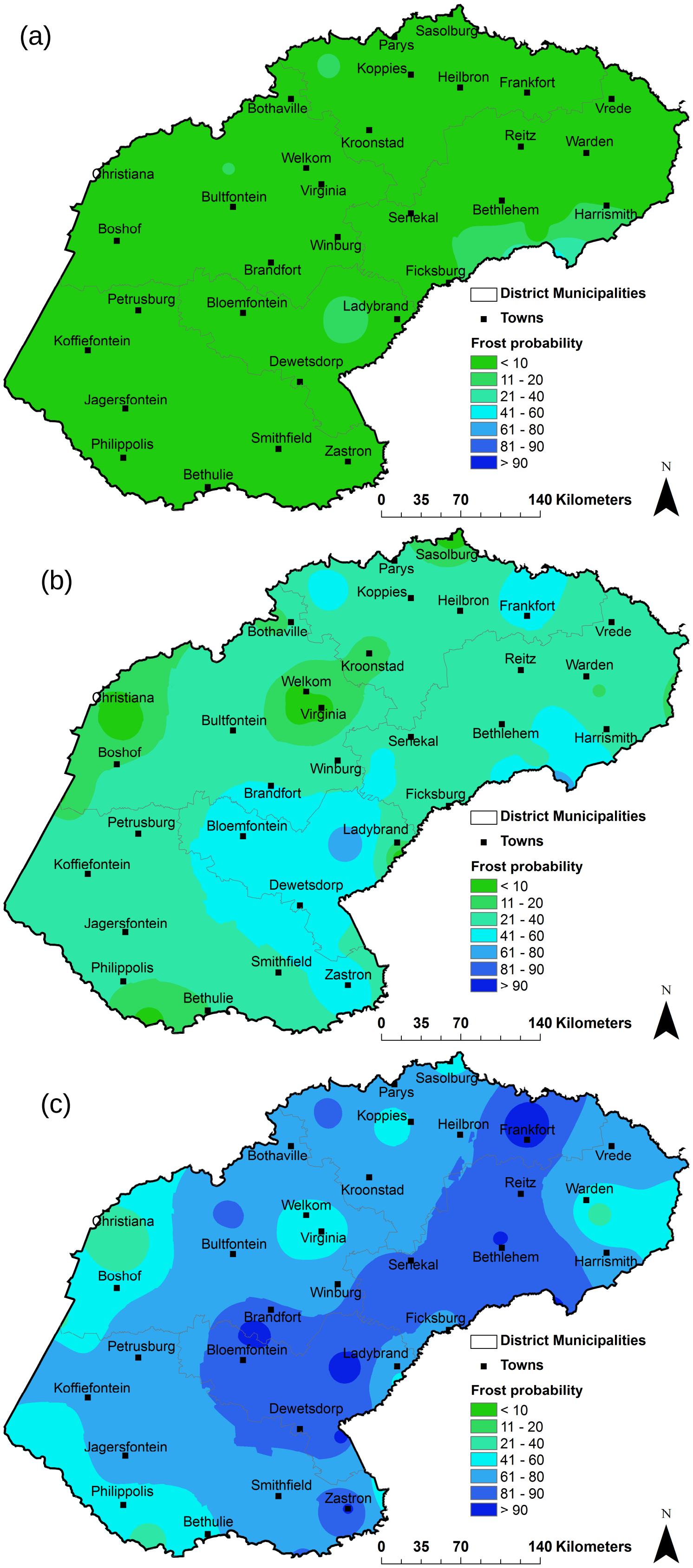


Fig. 3.17: Probability of frost (0°C) within growing period of a) 100-day , b) 120-day and c) 140-day maize cultivars planted in January 1st dekad.

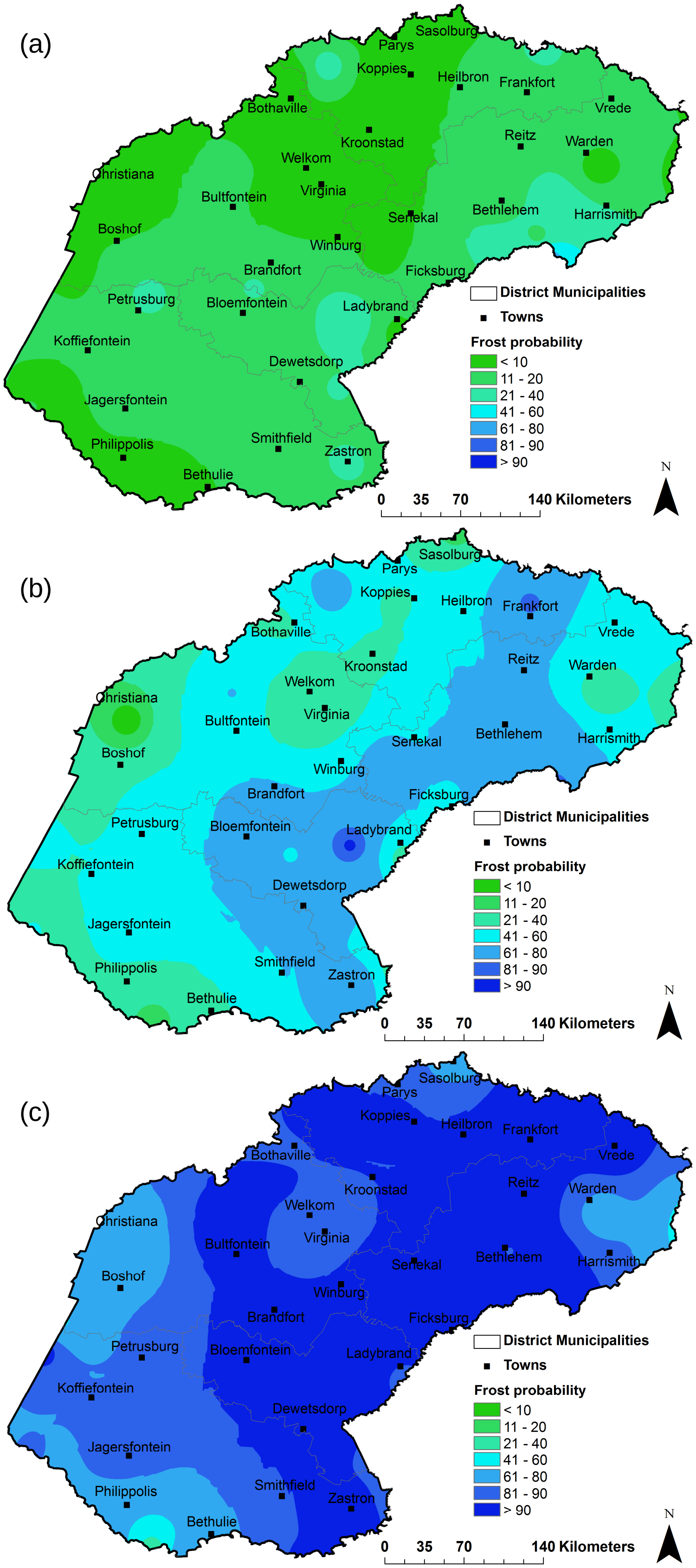


Fig. 3.18: Probability of frost (0°C) within growing period of a) 100-day , b) 120-day and c) 140-day maize cultivars planted in January 2nd dekad.

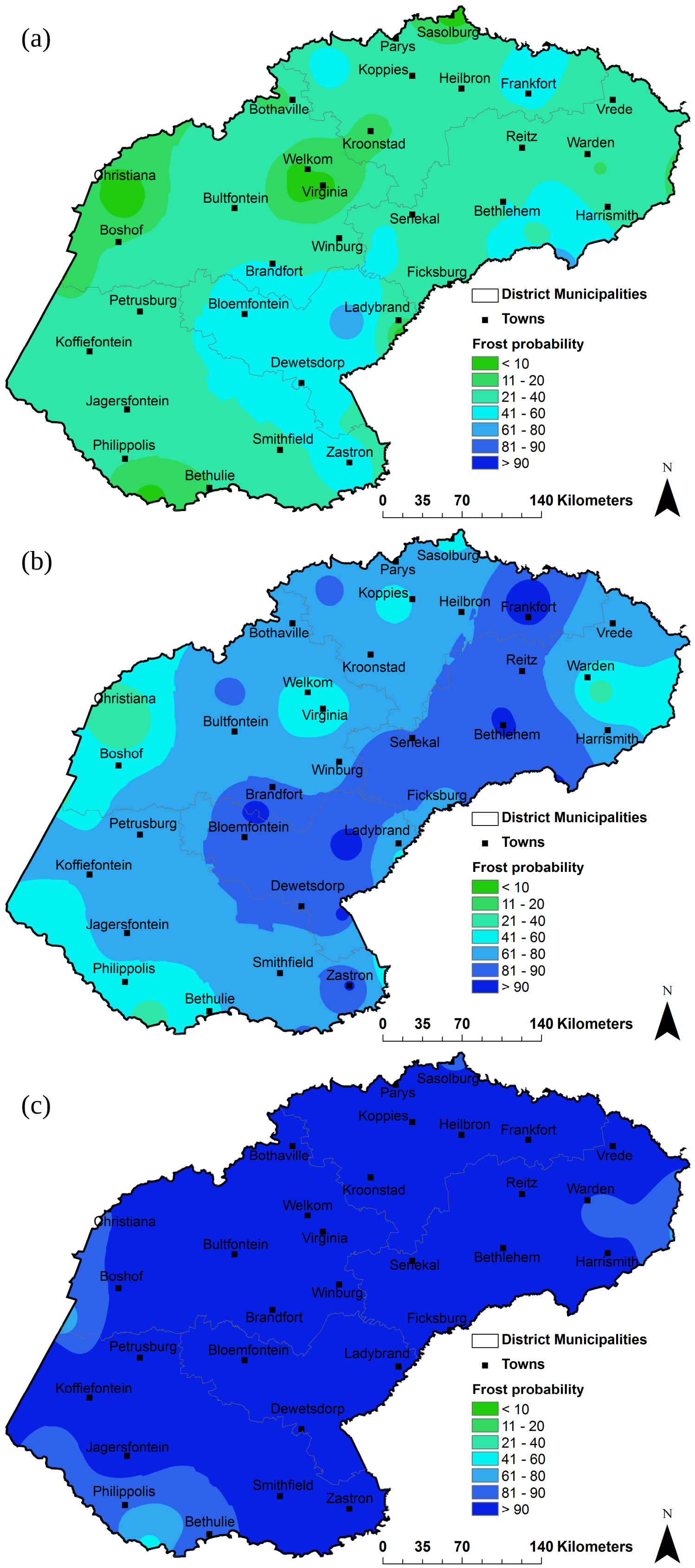


Fig. 3.19: Probability of frost (0°C) within growing period of a) 100-day , b) 120-day and c) 140-day maize cultivars planted in January 3rd dekad.

3.4 Conclusions

The assessment of frost occurrence over the Free State Province showed a lot of variation from one place to another owing to the vast differences in topography over the Province. The interpolated maps should be used with care because of the sparsity of weather stations in the Free State making the maps miss some topographical influences in some places in this province. Thus in places lying in the valleys or highlands, the onsets of frost might be earlier than shown while the cessation of frost is expected to be later resulting in shorter frost-free period.

Overall very late cessation of frost occurs over the southern Thabo Mofutsanyane and eastern Motheo district as well as patches of the Southeastern Xhariep. These areas are also characterized by very early onsets resulting in shorter frost-free period as compared to other regions. In these places planting early would definitely harm the seedlings while planting very late would result in crops not attaining their full maturity before the risk of frost increases. The window for planting is therefore relatively short in these places. In contrast, most parts of the Fezile Dabi, Lejweleputswa and western Xhariep experience relatively long growing periods. The eastern, northern and northeastern Lejweleputswa, eastern Xhariep and northeastern tip of Thabo Mofutsanyane have very long growing periods making them ideal for planting long-season crops provided other climate requirements in the coming chapters have low risk in those areas.

Absolute probability of frost within the growing period for the medium frost ($0^{\circ}C$) showed suitability for 100-day maize crop from planting in the 2nd dekad of October until the 2nd dekad of January with less than 10% chance of frost in the growing period. The 120-day maize showed low frost risk for planting from the 2nd dekad of October to 3rd dekad of December. While planting the 140-day maize cultivar has low chance of frost risk damage from the 2nd dekad of October to 2nd dekad of December for most parts of the Province.

The next chapter looks specifically at the rainy season characteristics over the Free State Province. The main characteristics of concern are the date for the onset of rains to help in the initiation of planting, cessation of rains and rainy season duration which are important to determine the right cultivar lengths for a location. The seasonal cumulative rainfall amounts also important in the cultivar selection.

Chapter 4: Rainy Season Characteristics

4.1 Introduction

Free State province contributes significantly to the agricultural economy of the country with over 30% of the national maize production (DAFF, 2010; de Jager et al., 1998). Agriculture in the Free State is mostly rainfed with less than 10% of the arable land being under irrigation. This, together with high climate variability associated with rainfall onsets, cessation and duration of rainy season emphases the importance of studies of the behaviour of the rainy season in the Free State Province.The main rainy season in the Free State starts in September/October and ends in March/April. Water is one of the most limiting factors for agriculture in the Free State and water shortages due to high climate variability and increased frequencies of dry spells are the cause of recent food insecurity concerns in most semi-arid climates over Southern Africa (Tadross *et al.*, 2003). Rainfall is one of the weather elements which is very complex and varies greatly on a spatial and temporal basis (Mwale *et al.*, 2004; Tveito *et al.*, 2005). This emphasizes the need for rainfall studies to assist the farming communities. According to Sivakumar (1990) and Mugulavai *et al.* (2008), it is important to determine at a reasonable accuracy the probability levels of the onsets of rain, cessation of rain and length of rainy period as well as their inter-relationships in order to plan dryland farming appropriately. Tadross *et al.* (2003) stated that knowledge of the probable dates of the onset and cessation and length of the rainy season can help farmers choose the right cultivar suitable for their particular location or region. Farmers are interested in obtaining the dates on which they can start planting knowing that the likelihood of crop failure is minimal (Ati *et al.*, 2002). Sivakumar (1990) discovered in West Africa that having early onset of rain can enable farmers to have an opportunity of planting a second crop not necessarily for grain but can be used as forage for animals and thus minimizing agricultural costs by maximizing on the increased length of the growing period. This can apply in South Africa especially in areas having long frost-free and long rainy season periods.

Maize production in SA fluctuates from year to year depending on the weather experienced during that particular growing season (DAFF, 2010). Climate variability, often characterized by changes in the extreme weather events like El Niňo and La Niña cannot be avoided; but through research on how different climate scenarios affect crop production, the negative impacts of climate variability should be able to be minimized. The El Niño-Southern Oscillation (ENSO) phases play an important role in the climate variability of most Southern African regions and better understanding of the teleconnections between the ocean and atmospheric conditions is of great importance (Reason & Mulenga, 1999; Ropeleskwi, 1999; Tyson & Preston-Whyte, 2000; Mason, 2001). The widely used indices for monitoring the El Niño or La Niña events are the sea-surface temperatures (SSTs) and Southern Oscillation Index (SOI) obtained from the surface pressure differences between Darwin and Tahiti (Richard *et al.*, 2000; Nicholson *et al.*, 2001; Nash *et al.*, 2008). During El Niño, the SSTs over the eastern Pacific Ocean are anomalously high and the SOI value is negative while during La Niña the SSTs over the eastern Pacific are anomalously low and SOI value positive (Vogel & Drummond, 1993; Zebiak, 1999). In El Niño years, the rainfall season is less favourable for crop production and in contrast, La Niña years are characterised by better yields in most semi-arid places in South Africa (Landman & Mason, 1999; Nicholson & Selato, 2000; Landman *et al.*, 2001; Fauchereau *et al.*, 2003; Rouault & Richard, 2003; Tsubo & Walker, 2007). However, there are a few exceptions during El Niño events which are expected to bring drought and famine in Southern Africa but instead it result in excessive rainfall and floods (Tumbare, 2000; Richard *et al.*, 2001).

During spring farmers are always anticipating the coming of the first rain for them to make preparations for the season. Onset of rainfall is one of the most important occurrences to the farmer. Earlier onsets allow them to plough land and plant earlier and benefit from the lower evaporative demand. Later onsets can cause the plant critical stages that are sensitive to water stress to be aligned with months of lower rainfall and higher evaporative demand. If the farmer is able to time his/her planting in such way to avoid false onsets of rain and the plants' crop water requirements are met at critical stages of development then that season's productivity will be increased. In the semi-arid areas like in the Free State, it is impossible to ensure perfect timing of planting every year, but when agrometeorological information about the behaviour of the rainy season is available, crop losses should be minimized (Sivakumar, 1990; Raes *et al.*, 2004).

In other case studies, the researchers used different approaches to determine the onset, cessation and consequent length of the growing period. Bello (1996) defined an onset as the time when the cumulative rainfall exceeds half the potential evapotranspiration, together with the condition that there is an absence of a dry spell of 5 days or more after that date. Others used the cumulative rainfall approach like de la Casa (2009), who used 30mm accumulative rainfall over 3 successive days plus no 7-day period without precipitation in the next 30 days. Still, others used the soil water balance method like Raes *et al.* (2004) and Mugulavai *et al.* (2008) who used cumulative rainfall over the 4 days that can bring the top 25cm of soil profile to field capacity as the their onset criteria. Kasei & Afuakwa (1991) also used the soil water balance method in their study in North Africa. Odekunle (2006) stated that the combination of both rainfall amount and rainy days to determine the onset and cessation of rainy season is better than the normally used rainfall amounts because it eliminates the false dates. The use of the condition that caters for false starts in the definition of the beginning of the rainy season is found as an integral in most applications (Stern *et al.*, 1982; Ojonigu *et al.*, 2008). Aviad *et al.* (2004) used multiple thresholds starting from 0.1mm to 200mm for determining the onset and cessation of rain to be applied for different geomorphical processes. Beniot (1977) used the evapotranspiration to rainfall ratio proposed by FAO to determine the onset of growing season with a condition that there is no dry spell within the 5 days after onset date.

The determination of the end of rains is as important as the onset because this will enable proper determination of the length of the rainy season and thus enable decision makers to make good choice of the type of plant or cultivar to plant for that particular location. The definitions for the end of rains mostly use the last date on which a certain threshold amount is exceeded or the dry spell of certain length after a specified date or the use of the soil water storage values reaching a certain minimum value (Stern *et al.* 1982; Oladipo & Kyari, 1993). In some cases, they use the difference between cumulative rainfall and half potential evapotranspiration as the criterion (Bello, 1996).

Just like most of the semi-arid places, agricultural production in the Free State province is affected by high climate variability which causes the dates for the onset, cessation rain and length of the rainy season to be highly uncertain (Camberlin and Diop, 2003; Usman & Reason, 2004; Mugulavai *et al.*, 2008). It has to be noted that, most southern African economies are dependent on rainfed agriculture and thus unfavourable weather conditions result in low economic performance while seasons that are characterized by favourable weather conditions for crop production result in widespread economic recovery (Unganai, 1994; Tsheko, 2003). The agricultural losses due to climate variability and climate change impacts are mostly felt by the poor-resourced farmers whose livelihoods depend solely on agriculture (Tadross *et al.*, 2003). Rural areas are the most vulnerable places and should be given priority in cases of food relief or any other social assistance after the occurrence of adverse weather conditions that have hampered agricultural productivity (Vogel & Drummond, 1993; Reason *et al.*, 2005).

In this study, the rainy season characteristics over the Free State province were investigated. The risk or probability levels of onset, cessation and duration of the rainy season were determined as well as the seasonal rainfall, probabilities of onset failure and rainy season of less than a specific duration. The effects of the El Niño and La Niña phenomena on the rainy season characteristics will be evaluated to determine risk associated for dryland maize production. The study was initiated because of the high risk that is associated with the rainfall season characteristics for dryland maize production in the Free State.

4.2 Data and methodology

4.2.1 Data

Rainfall data used in this study was obtained from the ARC, LMS and SAWS. Rainfall stations with 30 or more years of data and over 90% data records (i.e. less than 10% missing daily values) were selected for the analysis. However, where the spatial network of stations was sparse, stations with 20 or more years of data were used as complementary stations to aid in obtaining better interpolated surfaces. Daily rainfall data was used in all the analyses of the rainfall season charecteristics of the Free State province. The analyses start in 1950 and uses data up to and including 2008. However there are very few stations which have data starting in 1950 and also many of the long-term stations do not have data for years beyond 2000. In some cases the automatic station data was merged with the long-term manual station data when their location is within 2km. There were 309 stations that qualified to be used in this study, Fig.4.1 also shows the spatial distribution of all the 309 weather stations. All the missing values at the selected stations were estimated by using the IDW methodology outlined in chapter 2. For the analysis, the data was arranged in years starting from July to next June to make the summer rainfall season to fall in one continuous dataset.

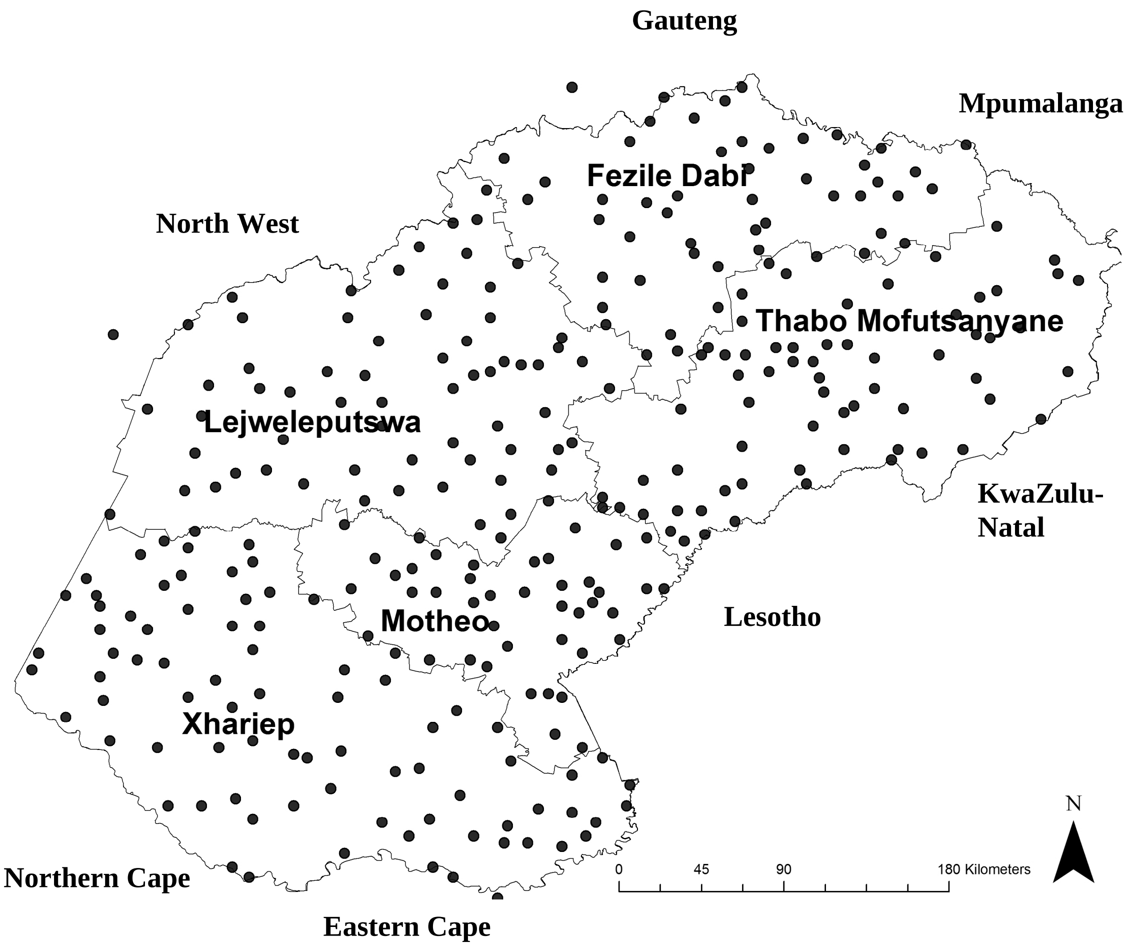


Fig. 4.1: Distribution of rainfall stations used in the analysis of rainy season characteristics over the Free State Province showing districts and neighbouring provinces (ARC-ISCW climate database).

4.2.2 Methodology

4.2.2.1 Onset of rain, cessation and rainy season duration

In this study the onset is defined as the last day in which rainfall of 25mm or above has been accumulated over the previous ten days and also at least 20mm accumulated in the subsequent 20 days (Tadross *et al*., 2003; Reason *et al*., 2005). This is the criterion commonly used to determine the beginning of the rainy season is most semi-arid areas in Southern Africa for dryland maize production (SADC-RRSU, 2004; FEWSNET, 2009). The additional 20mm of cumulative rainfall over the next two dekads ensures that there is enough moisture not only for germination but also to sustain the crop through the early development stage. The onset of rain was determined for all the agricultural years at all 309 stations. The end of the rainy season is obtained by searching for the last day on which the cumulative 25mm over ten days occurs. The length of the rainy season is calculated by subtracting the starting date of the rain in Julian day from 365(366 for leap years) and adding the number of Julian days for end of the rain if the start of the season is before 31 December. If the start of rain is in

January onwards, the rainy season length is obtained by subtracting the start date of rains (Julian days) from the end date of rains (Julian days).

The data was tested for Normality using the Rainbow software as indicated in the statistical subsection below. The onset and duration of the rainy season are presented with the non-exceeding probability while the cessation of rain is presented using exceeding probability. The 20% probability level value for the onset implies that 20% of the values occur on or before that value. The 20% probability value for the duration of rainy season means that 20% of the values are equal or less than that value. For the cessation of rain, 20% probability value implies that 20% of the values are on or later than that value.

4.2.2.2 Probability of onset failure, rainy season of less than 50, 100,120 and 140 days

The number of years in which the onset criteria was not obtained was recorded and the ratio of onset failure to the total number of years was obtained. This probability indicates the chances of not being able to get adequate rain to commence with planting. The probability of less than 50,100,120 or 140 days of growing period was also obtained for each station as the ratio of the number of years with rainy season duration of less than 50 or 100 or 120 or 140 days and the total number of years with data. These probabilities are important for choosing the right cultivar to be planted at a particular place. The probability for the 50 days criterion represents the occurrences whereby the onset of rainfall enables the farmers to plant but the rainy season becomes too short for a maize cultivar to reach full maturity without any water stress. The 100, 120 and 140 days thresholds stand for short season, medium season and long season cultivars respectively.

4.2.2.3 Seasonal rainfall

The rainfall season over the Free State is unimodal, mainly occurring in the summer months. The accumulated rainfall for the agricultural season was obtained by summing daily rainfall from 1st November to 31st March for each of the stations for all the years. The data was tested for Normality using the Rainbow software as indicated in the statistical sub section below. The non-exceeding probability was then determined. In the analysis only the 20%, 50% and 80% non-exceeding probabilities will be discussed. The 20% probability level denotes the seasonal rainfall accumulated during the dry seasons, 50% probability level is the median or average seasonal rainfall while the 80% level denotes the accumulated rainfall in very wet seasons.

4.2.2.4 Determination of the effects of El Niño and La Niña

To determine the association of rainy season characteristics with ENSO episodes, the dates for the onset, cessation, duration of the rainy season and seasonal rainfall were divided into two groups according to the El Niño and La Niña years using the SOI whereby negative values (average monthly SOI from June to November of less than -4) denote El Niño and positive SOI values (average monthly SOI from June to November exceeding 4) denote La Niña year (Table 4.1). The average onset, cessation, rainy season length and seasonal rainfall were determined for each of the stations for the El Niño years, La Niña years and all the years. The overall mean of onset date, cessation date, duration of rainy season and seasonal rainfall was compared with mean values during the El Niño and La Niña years.

Table 4.1: El Niño and La Niña years from 1950 to 2008.

El Niño years	La Niña years
1951/52; 1953/54; 1957/58; 1963/64; 1965/66; 1969/70; 1972/73; 1976/77; 1977/78; 1982/83; 1986/87; 1991/92; 1992/93; 1993/94; 1994/95; 1997/98; 2002/03; 2004/05; 2006/07	1950/51; 1954/55; 1955/56; 1956/57; 1962/63; 1964/65; 1970/71; 1971/72; 1973/74; 1974/75; 1975/76; 1984/85; 1988/89; 1996/97; 1998/99; 2000/01; 2007/08; 2008/09

Source: NOAA, 2010; Null, 2010; Thinkquest, undated

4.2.2.5 Statistical analysis

The dates for the onset and cessation of rain, length of the growing season and seasonal rainfall were analysed for each station using the Rainbow software to test distribution of the data. The curve fitting was done using the maximum likelihood procedure while the probabilities were estimated using the Weibull method (Raes *et al*., 2006). In this study, the Kolmogorov-Smirnov test and the closeness of linear relationship between the fitted line and data points were used to determine the distribution that best resembles the datasets from each station (Raes *et al*., 2006). The datasets which do not conform to a Normal distribution were transformed using four methods: a) square root, b) logarithmic, c) square method, and d) cube root method. Different probability levels (20%, 50% & 80%) were determined for both non-exceedence and exceedence probability.

4.2.2.6 Mapping

All the interpolation of the rainy characteristics indices was done using the ArcGIS 9.3. The inverse distance weighting model was used for interpolating all the indices. The maps for onset and cessation of rain are presented in dekads (ten-day periods for the month) whereby 1st dekad is from 1st to 10th day of the month, 2nd dekad is from 11th to 20th day of the month and 3rd dekad is from 21st to end of the month.

4.3 Results and discussion

4.3.1 Onset of rain

Dates for the onset of rain for the 20%, 50% and 80% non-exceeding probabilities are shown in Figure 4.2. The earliest 20% probability (1 in 5 years) onsets are mostly found in the east over the Thabo Mofutsanyane district occurring on or before the 3rd dekad of August while the western Xhariep experience latest onsets during the 1st dekad of November (Fig. 4.2a). At most places over the Free State, the onset of rain with the return period of 1 in 5 years occurs between 11th and 30th September. Most parts of the Thabo Mofutsanyane and Motheo districts have their 20% probability level onset of rain on or before the 2nd dekad of September. Over the Fezile Dabi district, 20% probability beginning of the rainy season occurs in the 3rd dekad of September with small pockets occurring later on the 1st dekad of October. The area stretching from Bothaville in the northern part of Lejweleputswa to Brandfort over the southern Lejweleputswa including Winburg, Virginia, Welkom experience 20% probability onsets on or before the 3rd dekad of September. The western parts of the Lejweleputswa have their 20% probability onset of rain in the 1st dekad of October. As for the Xhariep, most parts, especially the northern, central and southern, experienced onsets on the 3rd dekad of September. The 20% probability onsets are associated with high risk of plant loss due to insufficient water during the early stages of the maize crop. Farmers aiming at planting maize for early markets can utilize earliest onsets of rains occurring in September or October depending on the locality of the farm. But it should be enthasized that the chances of experiencing false start of the season in the 20% probability period are high (80%).

The Free State median (50% probability) onsets of rain are mostly in dates ranging from 11 October to 10 November (Fig. 4.2b). Synoptically, rainfall over the Free State area is mostly enhanced when there are consistent northerly winds bringing moisture from the tropics (Tyson & Preston-Whyte, 2000; Dube & Jury, 2002). During these months the rain producing systems like sub-tropical lows causing cloud bands that extend southward from the Tropics are frequent (Tyson & Preston-Whyte, 2000; Hachigonta et. al., 2008).The other important atmospheric circulation types significantly inducing rainfall to Southern Africa are the westerly waves and cut-off lows (Tyson & Preston-Whyte, 2000). The westerly waves occur frequently between October and April while the cut-off lows are most frequent September to November. Median onsets of rain over the Thabo Mofutsanyane district are earlier than in the remainder of the province with the dates from 3rd dekad of September to 2nd dekad of October (Fig. 4.2b). Fezile Dabi median onsets of rain is mostly between 11 October to 31 October with the eastern parts having ealier onset of between 20 September and 20 October while the western parts of the district experiences later onsets of rain occurins in the 3rd dekad of October. The Lejweleputswa median beginning of the rainfall season starts on 11th October over the far eastern parts and ends on 20 November over small sections in the far western parts. Motheo median onset of rain also shows east to west gradient with the dates starting from 2nd dekad of October with small parts in the west as late as 1st dekad of November. The Xhariep district shows great spatial variation of the median onset of rain with the far eastern parts experiencing early onsets in mid-October while the far western parts show very late onsets in December. 50% probability level is mostly used by the farmers as there is a 50/50 chance of the onsets being significant to support a maize crop at the early vegetative stage. Utilization of this probability level for producers aiming at introducing green miellies is recommended in preference to the 20% probability unless there are supplemenatry irrigation facility available.

The spatial distribution of the 80% Probability (4 in 5 years) onsets resembles that of the 50% probability with early onsets on or before the 1st dekad of November for the Thabo Mofutsanyane and Fezile Dabi districts. In most parts of the Lejweleputswa district, 80% probability onsets occur on or before 10 December. The Motheo district onsets are before the 2nd dekad of December and Xhariep experiences late onset dates of up to 2nd dekad of February (Fig 4.2c). Thus early onsets are experienced mostly in the whole of the Thabo Mofutsanyane district, eastern parts of the Motheo and Xhariep districts while late onset of rain is mostly in the western Xhariep district. Planting maize in the first dekad of November over the Thabo Mofutsanyane district is less risky, but the ultra short season and to a less extent the medium season varieties are recomemended because of the high risk associated with frost during the months of March and April as outlined in the chapter 3. The same recommendation applies to the eastern Motheo district where the onset of frost is earlier than other palces like the Lejweleputswa. Over most parts of the Lejweleputswa planting before the 1st dekad of December ensures support of the maize crop at its early stages of growth and this planting dekad is not associated with high risk of frost because of later onsets of frost in these areas.

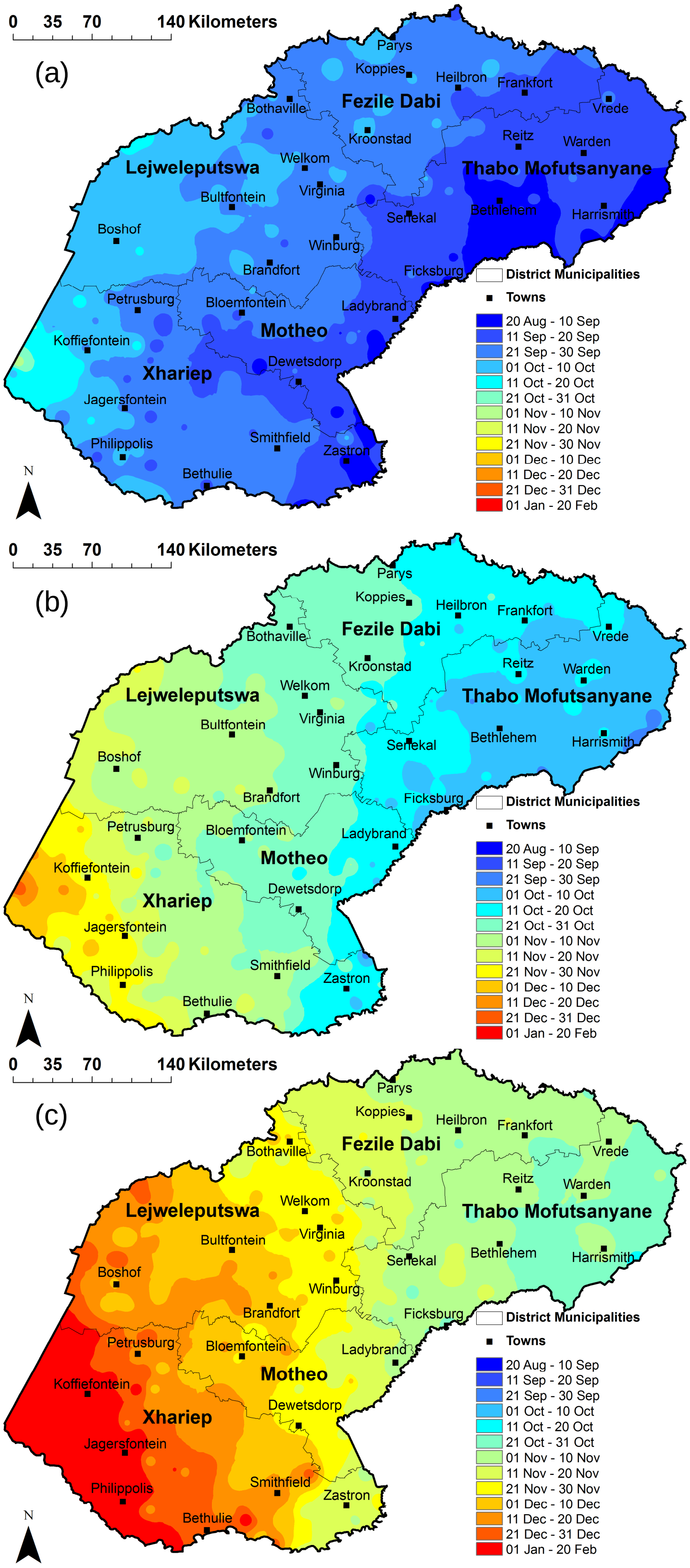


Fig. 4.2: Date of onset of rainy season over the Free State Province at a) 20%, b) 50% and 80% non-exceeding probabilities.

4.3.2 Cessation of rain

Cessation or retreat of rain dates for the 20th, 50th and 80th exceeding probability, representing return period of 5 years, 2 years and 4 in 5 years respectively (Fig. 4.3). For the Fezile Dabi and Thabo Mofutsanyane districts, the northern and eastern parts experience 10 days earlier cessation of rain as compared to the other areas. In contrast, for the Lejweleputswa, Motheo and Xhariep districts the cessation of rain is early for the western parts and late for the far eastern parts. At the 20% probability level, the cessation of rain occurs on or after the 2nd dekad of May for the eastern parts of the Fezile Dabi and northeastern part of Thabo Mofutsanyane districts, while the remainder of the two districts mostly have 20% chance that the rain will end on or after the 3rd dekad of May (Fig. 4.3a). The earliest 20% probability of cessation of rain in Lejweleputswa and Xhariep is by the 2nd dekad of May in the western parts while in the Motheo district it is in the 3rd dekad of May. There are patches especially over the eastern Xhariep, Motheo and Thabo Mofutsanyane districts where 20% chances of end of rain can occur as late as 10 June. If maturity of the maize crop coincides with the 20% probability of the cessation of the rainy season the crop can suffer high risk of water stress because at this probability level the chance of ealier end of rain is higher (80%). As the dry season approaches the rain-producing systems are replaced by the continental High Pressure System causing low-level divergence and upper-air convergence (Tyson & Preston-Whyte, 2000). The frequency of this system is high from April to October peaking in June and July and precipitation is significantly reduced in this period especially over the Free State province.

As for the 50% probability level, most parts of the Fezile Dabi, Lejweleputswa and Thabo Mofutsanyane districts cessation of rain occurs on or after the 3rd dekad of April with small patches occurring between a dekad earlier and later (Fig. 4.3b). Over the Motheo district, the eastern, western and far southern parts records 50% probability of cessation of rains occurring on or after the 1st dekad of May while in other parts it occurs earlier by the 3rd dekad of April. In the Xhariep district, the eastern and most parts of the central area mostly have their 50% probability of end of rainy season by the 1st dekad of May, while in the western and some parts of central area 50% cessation is in or after the 3rd dekad of April.

The 80% probability for the end of the rainy season for the Fezile Dabi, Lejweleputswa and Thabo Mofutsanyane districts is mostly on or after 3rd dekad of March while for the Motheo district it is mostly a dekad later by the 1st dekad of April (Fig. 4.3c). For the eastern and central parts of the Xhariep district 80% cessation of rain probability is by the 1st dekad of April while other parts are mostly on or after the 3nd dekad of March. The spatial variation of the cessation of rain dates is less than that of the onsets of rain. If the planting of maize is planned in a way that the maturity coincides with these 80% probability last rain dates, the loss due to lack of water to support the maize crop can be minimized. Maturity dates occurring later on induce high climate risk to the crop resulting in potentially high crop losses.

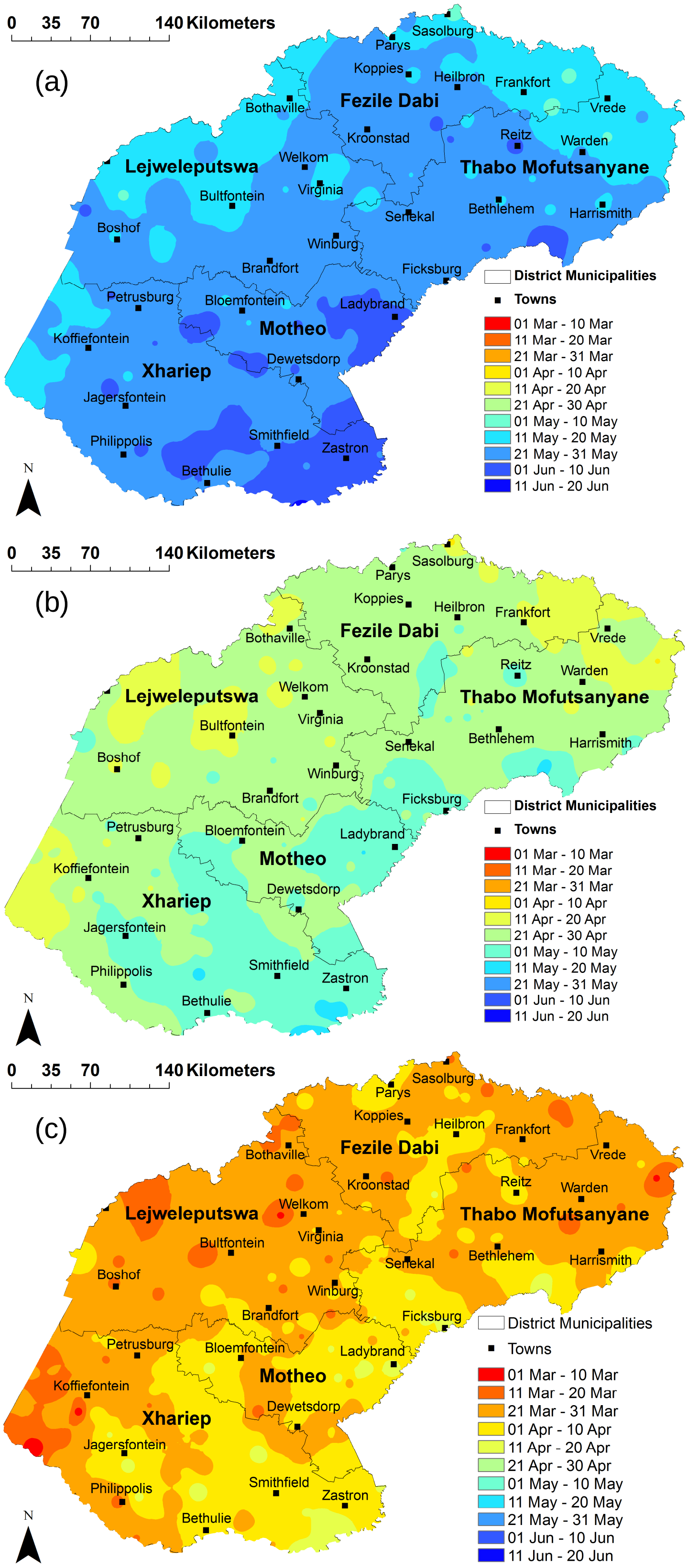


Fig. 4.3: Date of cessation of rainy season over the Free State Province at a) 20%, b) 50% and 80% exceeding probabilities.

4.3.3 Duration of the rainy season

The duration of the rainy season for the 20%, 50% and 80% non-exceeding probabilities are shown in Figure 4.4. The Fezile Dabi and Thabo Mofutsanyane districts show high rainy season duration at 20% probability with most places recording over 160 days at the 20% probability level (Fig. 4.4a). Over the Lejweleputswa district, most places record the 20% probability of rainy season between 121 to 140 days with some places towards the western sides with rainy days between 101 and 120. Planting of long season maize varieties at these places can result in excessive drought conditions in 1 in 5 years return period because the later stages of the growing period of the crop would be subjected to insignificant rains. For the Motheo district rainy season duration is low over the western parts with 121 to 140 days and increases moving eastwards reaching the maximum over Ladybrand vicinity with over 160 rainy season duration days. At 20% probability level, the duration of the rainy season is lowest over the western parts of the Xhariep district with less than 80 days (Fig. 4.4a). In this district, rainfall period increases gradually towards the southeast peaking over Zastron area with over 160 rainy season days.

At 50% probability, most parts of the central Thabo Mofutsanyane district and area along the southern border extending from south of Ficksburg to the northeast of Harrismith record over 200 rainy season duration days (Fig. 4.4b). The remainder of the district has 181 to 200 days at 50% probability. The Fezile Dabi district mostly has 181 to 200 days rainy season period with small pockets of less than 181 days over the western part and over 200 days south of Heilbron. The Lejweleputswa district rainy season duration at 50% probability is between 161 and 180, except for patches over the western part where the period was less than 161 and the eastern parts around Winburg where the period was between 181 and 200. Over the Motheo district, the lowest period of 161 to 180 days is northwest and east of Bloemfontein and peaking over the far eastern border at over 200 days around Ladybrand. As for the Xhariep, it increases from less than 140 days (west of Koffiefontein) in the far western part to over 200 days in the southeastern part near Zastron.

At 80% probability level, most places over the Fezile Dabi, Motheo and the Thabo Mofutsanyane districts have rainy season duration between 221 and 240 days (Fig. 4.4c). The exceptions in the Fezile Dabi district are over the western parts, where the period is between 201 and 220 days, while in the Motheo and Thabo Mofutsanyane districts exceptions are obtained along the eastern and southern borders of the districts respectively where favourable rainy season duration of more than 240 days is recorded. The rainy season duration increases from less than 180 days over the western part of Xhariep to over 240 days in the southeast.

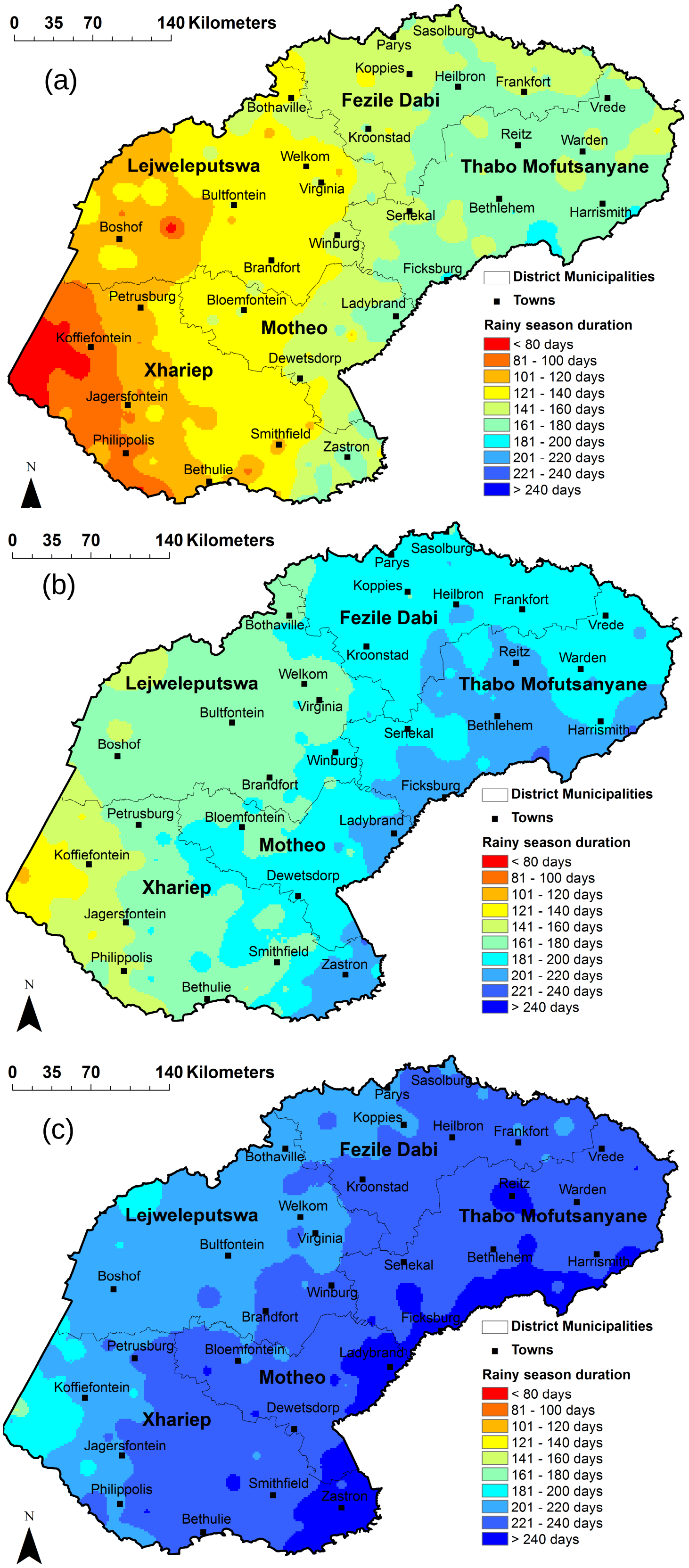


Fig. 4.4: Rainy season duration over the Free State Province at a) 20%, b) 50% and c) 80% non-exceeding probabilities.

4.3.4 Probability of onset of rain failure

Assessment of the number of years in which the onset criterion is not met is an important risk index (Fig. 4.5). The chances of onset failure are zero over most parts of the Thabo Mofutsanyane district This means that the onset criteria (over 25mm accumulated in the previous 10 days and over 20mm in the following 20 days) is realized at all times in these places making them less vulnerable to crop failure due to inadequate rains to support early stages of maize growth and development. The other places of no chances of onset failure are patches over the southeastern Xhariep, eastern Motheo, western Fezile Dabi and pockets over the eastern and western Lejweleputswa (Fig. 4.5). Most parts of the Free State Province have less than 2% chances of onset failure implying very low risk of crop failure. The Xhariep district has a relatively high risk of onset failure especially over the southern and western parts where the ratio of agricultural seasons with no onset date over the total number of agricultural seasons is up to 0.08. Up to 8% chances of not obtaining significant rains to start soil preparation and planting implies relatively high risk of crop failure due to false onsets because at times the rainfall received does not stretch to the early vegetative stage.

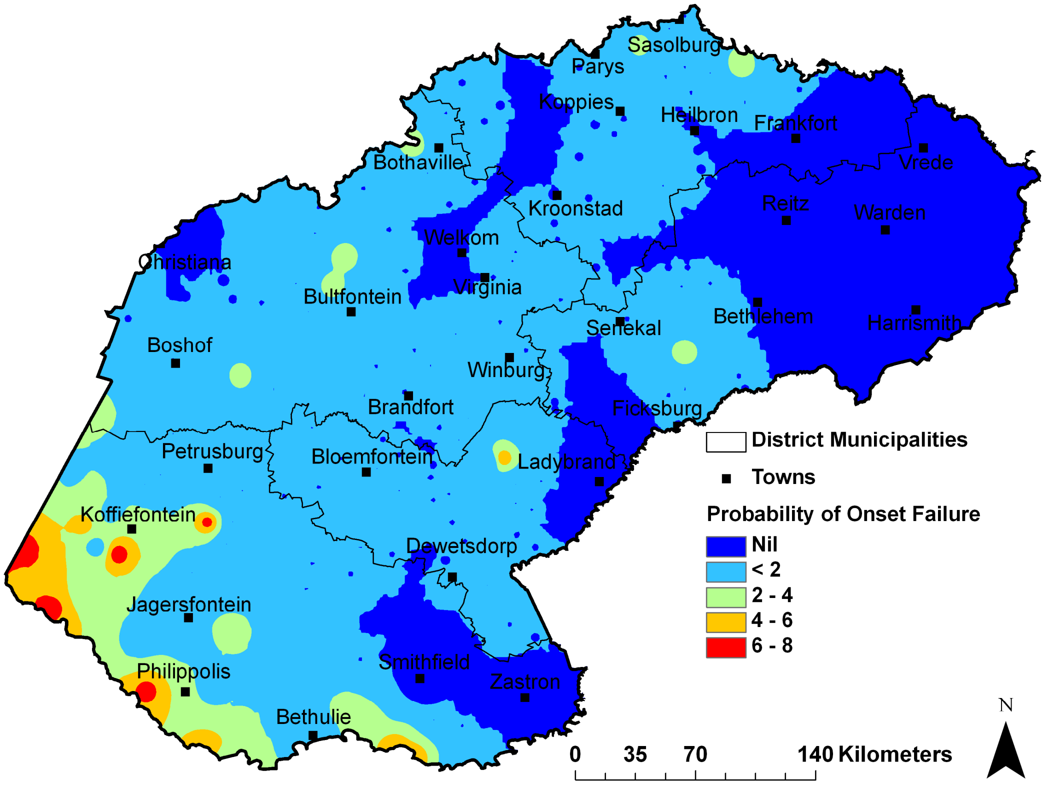


Fig. 4.5: Probability of onset rain failure over the Free State Province.

4.3.5 Probability of rainy season of less than 50, 100, 120, 140 days

The absolute probability of having a rainy season of less than 100, 120 and 140 days are shown in Figure 4.6. The probability of obtaining a rainy season of less than 50 days is less than 6% for the Fezile Dabi, Lejweleputswa, Motheo and Thabo Mofutsanyane districts with the eastern parts of the Thabo Mofutsanyane district having zero chance (Fig.4.6a). Over the Xhariep district, the eastern and southeastern parts experience low risk of rainy season of less than 50 days with values of less than 6%. The risk increases when moving southwestwards reaching a maximum of 30% over the western parts (west of Koffiefontien). These areas of high risk can not be used for maize crop farming unless under irrigation.

The chances of the rainy season being less than 100 days, as shown in Figure 4.6b, are low over the Fezile Dabi, Thabo Mofutsanyane district and eastern parts of the Motheo have less than 5% probability. In these areas, planting of short season maize varieties (<100 days) is subjected to low risk of failure due to inadequate rainfall to support plant growth and development. As for the Lejweleputswa district, the risk is slightly higher for most places with probability values between 11 and 20%. The highest chances of rainy season of less than 100 days are over the Xhariep especially in the west where probability values of up to 40% are realized. The lowest risk of planting a 100-day maize crop in this district (Xhariep) is obtained over the southeast (east of Smithfield) with probability of less than 10%, while the central parts experience relatively moderate risk of between 11 and 20%.

The chances of rainy season duration of less than 120 days (growing period of medium season maize cultivar) are less than 6% for most parts of the central and eastern Thabo Mofutsanyane district and patches over the Fezile Dabi district (Fig. 4.6c). Low probability at these areas indicates that 120-day maize cultivars' growth at these areas would not be hampered by a short growing period. Most parts of the Fezile Dabi have between 6 and 10% probability of a rainy season of less than 120 days. Less than 10% probability shows high suitability of planting a medium season maize crop. Most areas over the Lejweleputswa and Motheo districts have probability values between 11 and 20%. The western parts of the former have relatively high risk with patches of 21 to 30% values while over the north and eastern Lejweleputswa there are pockets of less than 11% values. Over the Xhariep, the area around Zastron has relatively low values while for the western parts risk is higher with up to 50% probability of rainy season of less than 120 days.

The risk of obtaining less than 140 days rainy season duration occurs over patches of the Thabo Mofutsanyane district with less than 6% probability (Fig.4.6d). Most parts of this district record between 6 and 10% chances of rainy season length of less than 140 days (growing period for long-season maize cultivar). Over most parts of the Fezile Dabi, the risk is lower than 20% in all the places while in Lejweleputswa most parts have a risk of between 21 and 30%. The area extending from Bothaville to Brandfort in the Lejweleputswa district has probability ranging from 11 to 20%. In the Motheo and Xhariep, the risk is low over the eastern parts, increasing towards the west with the highest risk of up to 60% over the western Xhariep. High probability at 140 days threshold shows unsuitability for the long season varieties.

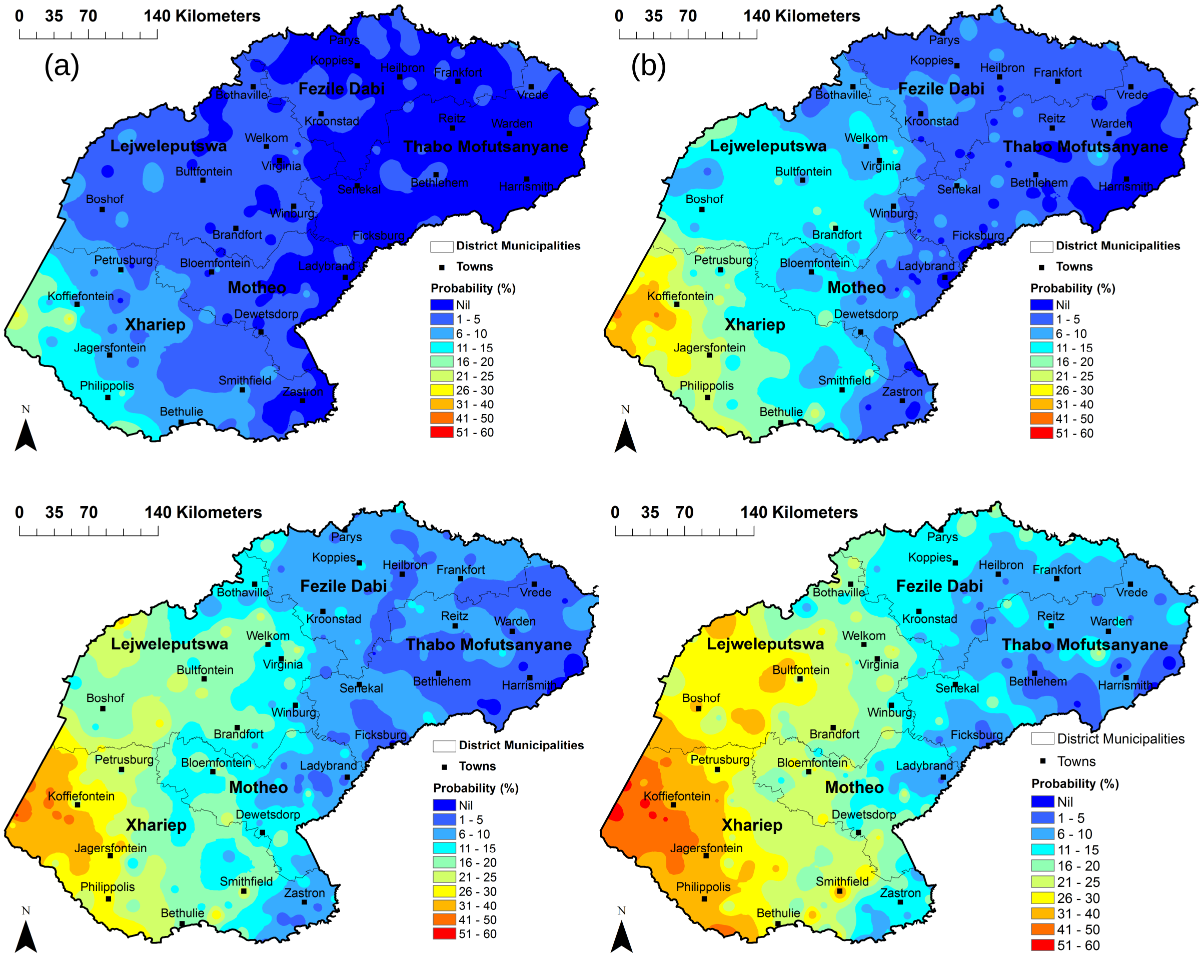


Fig. 4.6: Probability of rainy season over the Free State Province of less than a) 50 days, 100 days, 120 days and 140 days.

4.3.6 Seasonal rainfall

Seasonal rainfall varies a lot over the Free State province (Fig. 4.7). The eastern Thabo Mofutsanyane district shows relatively high rainfall accumulated in the period November to March with between 351 and 450 mm at 20% probability level (Fig. 4.7a). The 20% probability level can also mean that there is an 80% chance of seasonal rainfall to exceed 351 mm in this region. These areas stand a better chance of yielding better because the maize water requirements are likely to be satisfied even in the driest (20% probability) seasons. Most parts of the district (including Bethlelhem, Reitz, Vrede, Warden and Harrismith) mostly record 351 to 400 mm of seasonal rainfall at 20% non-exceeding probability. The highest values exceeding 400mm are accumulated over the far eastern parts of the province. As for the Fezile Dabi, the 20% non-exceeding probability ranges from 251mm over the southwestern parts (including places in the vicinity of Kroonstad) to 400mm in the far eastern and northern parts (including places around Sasolburg and Frankfort). Most parts of the district record 20% probability of between 350mm and 400mm (Fig. 4.7a). Over the Lejweleputswa district, there are a few patches of below 200mm over the southwestern parts of the district. Most parts of the western and southern accumulate 200mm to 250mm during dry agricultural seasons. The northern, eastern and southeastern parts (Bothaville, Welkom, Virginia, Winburg and Brandfort) accumulate relatively high seasonal rainfall (251 to 300mm) than the rest of the Lejweleputswa district. Spatial distribution of 20% seasonal rainfall shows low values over the far western and northwestern parts (201-250mm). Most parts of the district including Bloemfontein have 20% probability of seasonal rainfall of between 251 and 300mm in dry seasons while the eastern parts have relatively high seasonal rainfall mostly ranging from 301 to 350mm. The Xhariep district is the driest district with most places (area extending from Petrusburg to Bethulie) having less than 200mm in the dry seasons. The relatively high seasonal rainfall is evident over the far southeastern parts (near Zastron) with between 251 and 300mm.

The 50% non-exceeding probability (median value) for rainfall accumulated from November to March over the Thabo Mofutsanyane district ranges mostly from 401 to 500mm (over Senekal, Ficksburg, Bethlehem, Reitz, Vrede, Warden and Harrismth) with a few patches of below 400mm over the far southwestern parts and areas exceeding 500mm over the far eastern parts of the district (Fig. 4.7b). Over the Fezile Dabi district, median seasonal rainfall is relatively low over the southwestern parts (351-400mm) with most places having 50% probability of seasonal rainfall of 401 to 450mm. There are a few patches of seasonal rainfall of between 451 and 500mm over the eastern parts of the district. Median rainfall is relatively low over the southwestern Lejweleputswa (251-300mm) increasing to between 301 to 350mm over the western, southern and central parts with the highest values over the eastern parts (351-400mm). Seasonal rainfall over the Motheo district also increases from west to east with most parts over the west having between 301 to 350mm and the far eastern (especially along the border with Lesotho) parts with up to 500mm median rainfall. Over the Xhariep, the western parts have the lowest median rainfall (<250mm) with most parts over the central and southern recording median seasonal rainfall of between 251 and 350mm while the far eastern parts can have seasonal rainfall of up to 450mm. Places of less than 400mm in median category are likely to have soil water deficits impacting negatively on maize production and thus the use of high soil water use efficient cultivars will be advisable for these areas.

The 80% non-exceeding probability of seasonal rainfall ranges from 451mm over the southwestern parts of the Thabo Mofutsanyane district with the highest values over the southern and eastern border with over 600mm of seasonal rainfall expected in wet seasons (Fig. 4.7c). The western parts mostly have 501 to 550 of seasonal rainfall while places over the central, eastern and along the southern border with Lesotho have between 551 to 600mm of rainfall at 80% non-exceedence probability. Most parts of the Fezile Dabi district (places in the vicinity of Parys, Koppies, Frankfort and southern parts) have seasonal rainfall in wet seasons mostly between 501 and 550mm. Places over the southwestern part have relatively low seasonal rainfall at 80% non-exceeding probability between 451 and 500mm while a few patches of values exceeding 550mm are evident around Sasolburg (far northern part) and Heilbron (eastern part). Over the Lejweleputswa district, most places have between 451 to 500mm of rainfall in wet seasons with exceptions over the southwestern parts with relatively low rainfall of less than 450mm. As for the Motheo district, the far western parts have 450 to 500mm at an 80% non-exceeding probability level with most places having 500 to 550mm. The far eastern parts seasonal rainfall ranges from 501 to 600mm over the border with Lesotho. Over the Xhariep, seasonal rainfall in wet seasons also shows west to east gradient with below 350mm over the western parts to amounts ranging from 501 to 550mm over the southeastern parts (vicinity of Zastron).

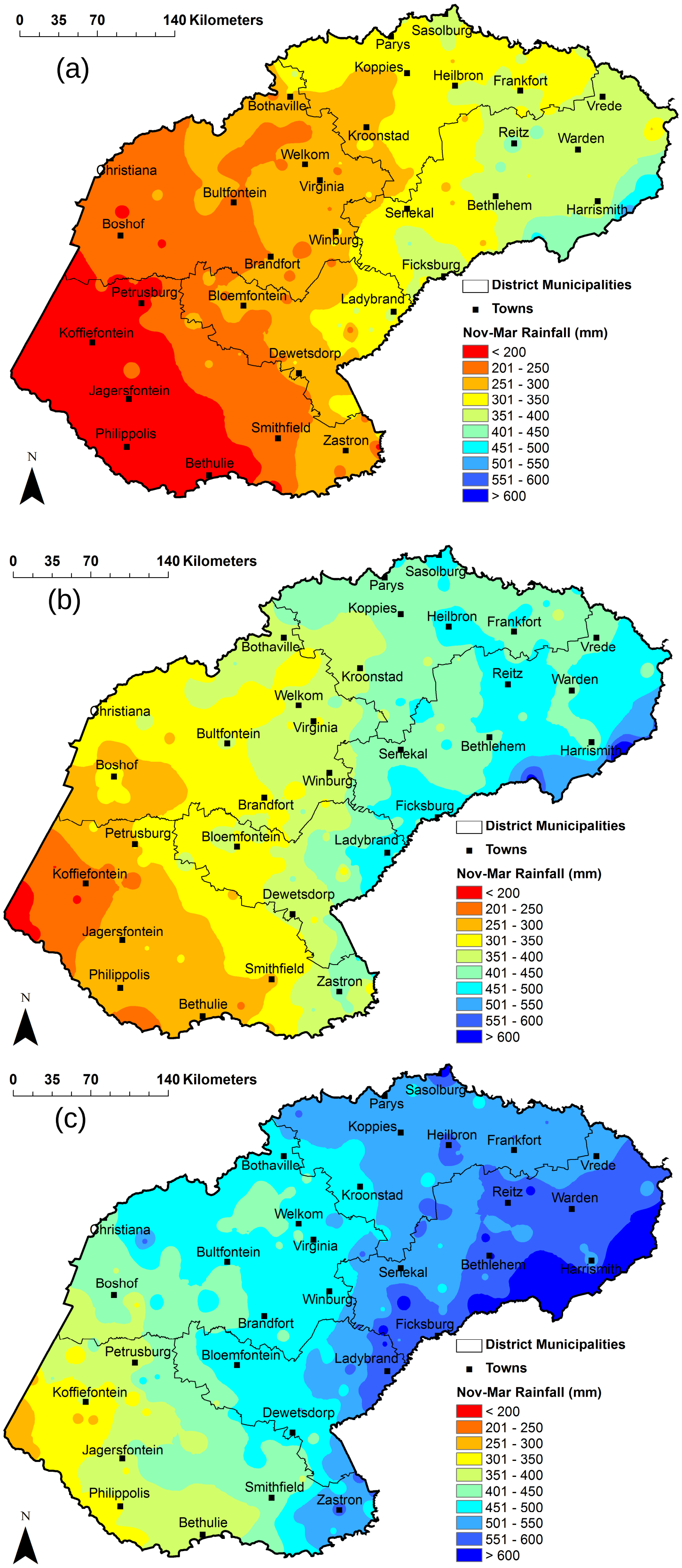


Fig. 4.7: Seasonal rainfall (November to March) amount over the Free State at a) 20%, b) 50% and c) 80% non-exceeding probabilities.

4.3.7 The effects of El Niño and La Niña on rainy season characteristics

The effects of El Niño and La Niña episodes on the onset, cessation and the length of the rainy season as well as their effects on seasonal rainfall will be discussed.

4.3.7.1 Onset, cessation and duration of rainy season

The expectations borne from previous research in southern Africa are as follows (Tadross *et al*., 2003; Reason *et al*., 2005; Hachigonta *et al*., 2008):

a. Onset of rain in El Niño years is later than normal
b. Onset of rain in La Niña years is earlier than normal

This means that the difference between mean onset in El Niño years (in Julian days) and overall mean onset date is expected to be positive in order to reflect late onset which is mostly unfavourable for seasonal crops. As shown in Fig. 4.8a, the difference in onset dates over the Thabo Mofutsanyane district is mostly positive (0 to 9 days) except in the western parts of the district where positive bias is recorded. Negative bias means that onset in El Niño years is earlier than normal. Over the Fezile Dabi district, most places show a positive bias with the far eastern parts having greater area where average onset date in El Niño years is later than normal by 5 to over 10 days. There are a few patches where average onset date in El Niño years is early by up to 5 days over the central and southwestern parts. As for the Lejweleputswa district, the central and southern parts show delay in onsets by values of up to 10 days. In contrast, the western, eastern and southeastern parts show a slight negative bias indicating early onset of rains over these parts. Over the Motheo district, the western parts clearly show late onsets (by up to 10 days) in El Niño years as compared to the normal while the eastern parts mostly show early onsets (by over 10 days in some places) in El Niño years. Over the Xhariep district, the most places show early onsets (by over 10 days in some places) with sporadic cases of late onsets. The results over the whole Free State Province show a lot of variation with some places experiencing earlier than normal onsets while in others later than normal onsets are evident. The results defy the overall assumption that in El Niño years onsets become very late in some areas but in the south it is the opposite.

The difference between mean onset in La Niña years (in Julian days) and overall mean date is expected to be negative in order to reflect early onset which are mostly favourable. Over the Thabo Mofutsanyane district, onset of rains is slightly early (0 to -5 days) as compared with the normal over the northern, eastern and northeastern parts of the district (Fig. 4.8b). The central, southern and western parts show slightly late onsets (0 to 4 days). Different scenario occurs over the Fezile Dabi district with the western (west of Koppies) and eastern parts (Heilbron and Frankfort) having early onsets while the northern and southern parts have a negative bias (late onsets by over 10 days in other places). Situation over the Lejweleputswa show positive bias over most parts (areas surrounding Bothaville, Bultfontein, Christiana, Boshof and Brandfort) of the district except an area extending from southwest of Bothaville and northeast of Christiana stretching to the southeast. As for the Motheo district, slightly negative (early by up to 5 days) bias is obtained over the western parts and few patches in the east. Most parts experience a delay in onsets in La Niña years with some places over the northern and southern parts having delay of over 10 days. Over the Xhariep, the onset is early for most parts with pockets of late onset scattered all over the district. The results clearly show that in La Niña years it is not always the case that the onsets are early with other places having late onsets and thus the assumption that in La Niña years onsets are late in overall does not apply to the entire Free State.

The scenario for the end of the rainy season for this region is expected to be as follows (Reason *et al*., 2005; Hachigonta *et al.,* 2008):

a. Cesstion of rain in El Niño years is earlier than normal
b. Cesstion of rain in La Niña years is later than normal

The difference between overall mean cessation of rain date in El Niño years (in Julian days) and mean cessation of rain date is expected to be negative in order to reflect early cessation of rains which is mostly unfavourable for seasonal crops. The cessation of rains over the Thabo Mofutsanyane district is earlier than normal in El Niño years for the whole district with most places cessation of rain occurring 11 to 20 days earlier than normal (Fig. 4.9a). The Fezile Dabi ditrict also have early cessation El Niño years of between 11 to 20 days with few exceptions. Over the Lejweleputswa district, most places also have their cessation of rains occurring earlier than normal by 11 to 20 days except over the southern part where the cessation is early by up to 10 days. The Motheo district also has early cessation (11 to 20 days) except the western sites (including Bloemfontein) where cessation of rains occurs at most 10 days earlier. The Xhariep district has a great portion where cessation is early by up to 10 days especially over the central and southern parts but the western and eastern areas have very early cessation in El Niño years. In most places over the Free State, the assumption that in El Niño years the cessation is mostly early is supported by the results.

The difference between mean cessation of rain date in La Niña years (in Julian days) and overall mean cessation of rain date is expected to be positive in order to reflect late cessation of rains which are mostly favourable. Over the Thabo Mofutsanyane district, the entire district has later than normal cessation with most places recording between 5 to over 15 days delay (Fig. 4.9b). Over the Fezile Dabi and Lejweleputswa district late cessation (5 to over 15 days) are also observed. As for the Motheo district, the cessation of rains is late by up to 9 days in most places. Even though cessation of rains is mostly late by up to 9 days over the Xhariep district, there are places (southern and central) where the cessation is earlier than normal.

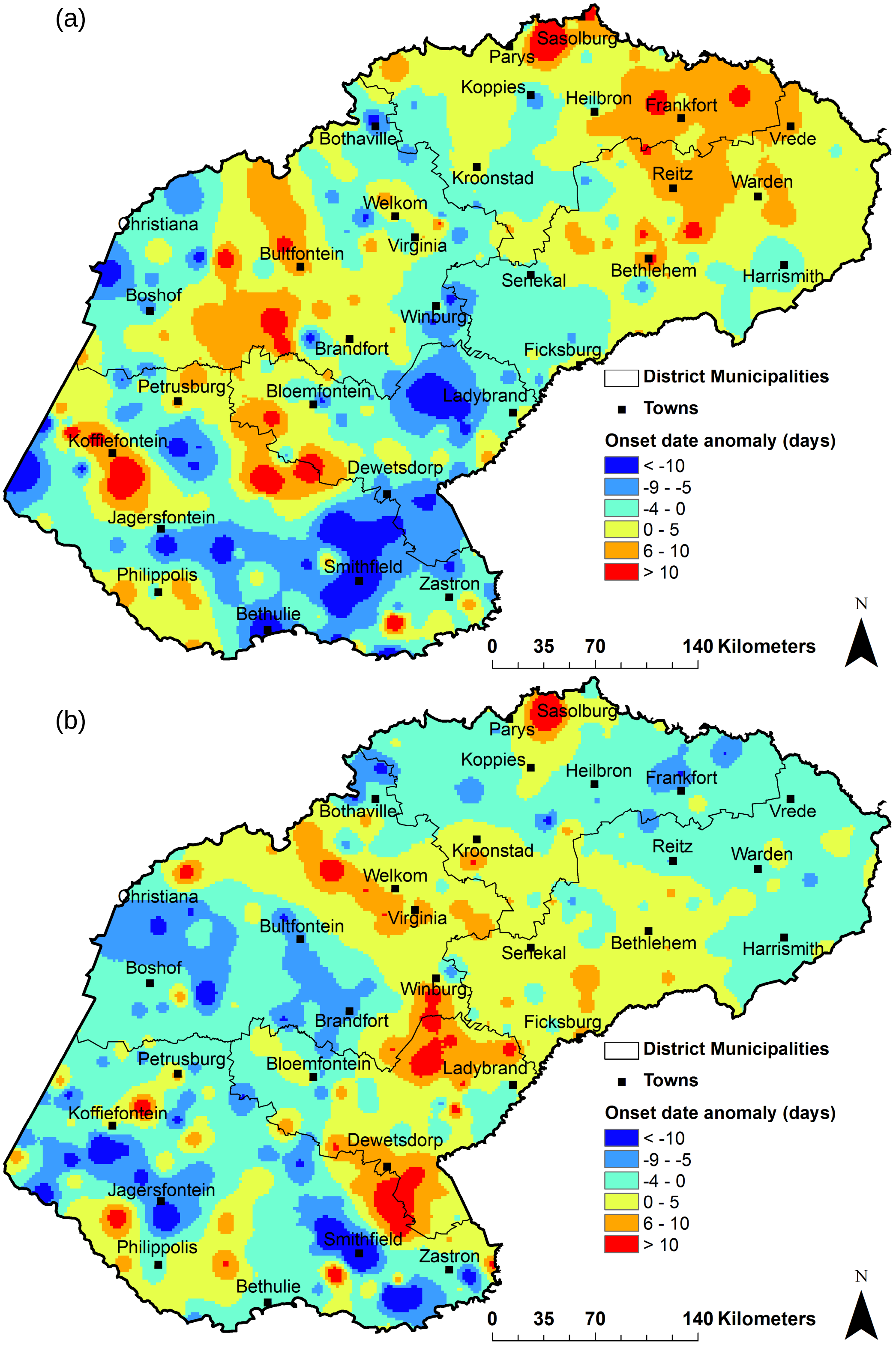


Fig. 4.8: The difference between a) mean onset date in El Niño years and overall mean onset of rain date (all data) and b) mean onset date in La Niña years and overall mean onset of rain date.

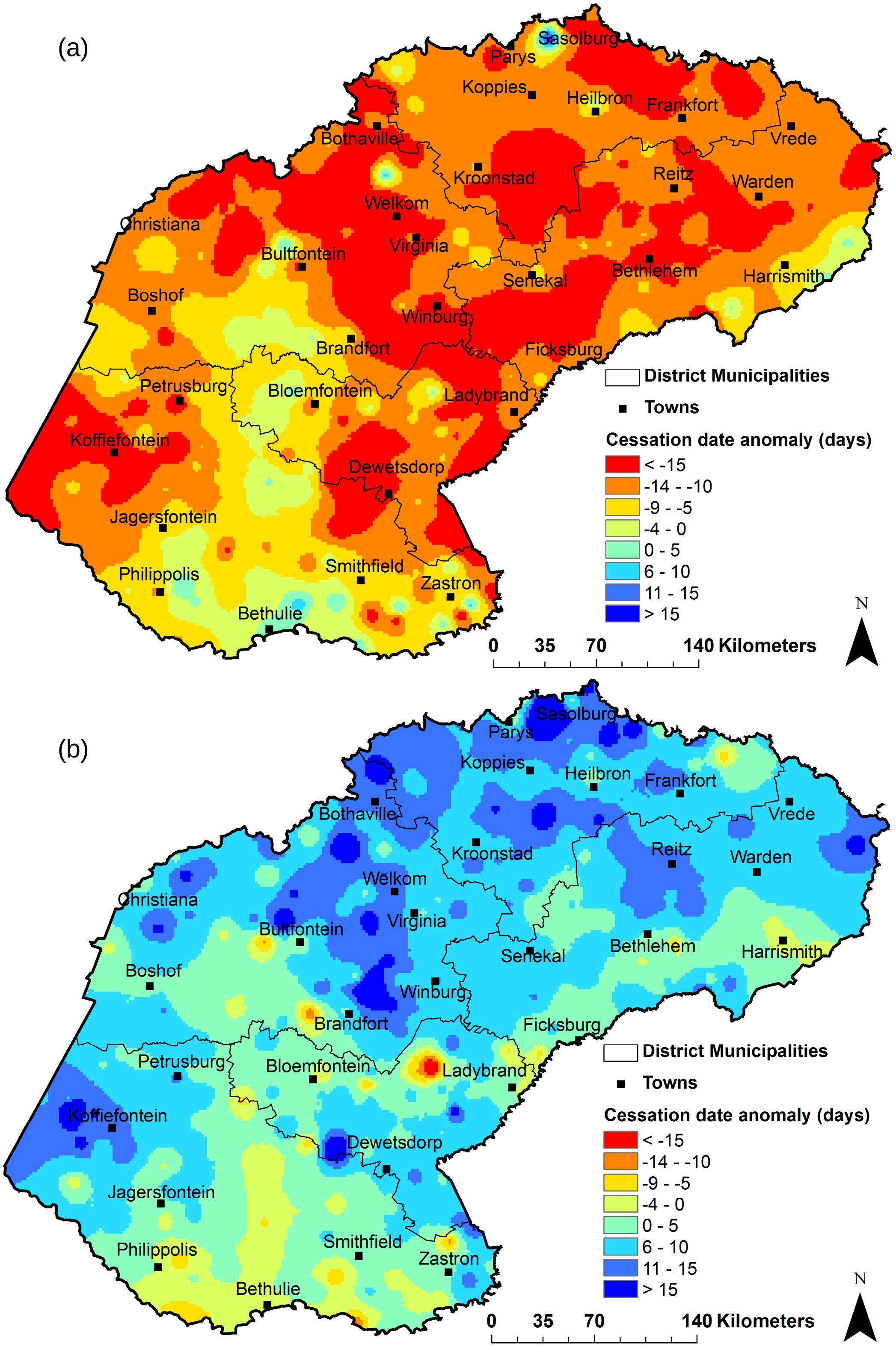


Fig. 4.9: The difference between a) mean cessation of rain date in El Niño years and overall mean cessation of rain date (all data) b) mean cessation of rain date in La Niña years and overall mean cessation of rain date.

The scenario for the duration of the rainy season for this region is expected to be as follows (Tadross *et al*. 2003; Reason *et al*., 2005; Hachigonta *et al*., 2008):

a. Duration of rainy season in El Niño years is shorter than normal
b. Duration of rainy season in La Niña years is longer than normal

The difference between mean duration of rainy season in El Niño years and overall mean duration of rainy season is expected to be negative in order to reflect short rainy season which is mostly unfavourable. The results of the difference between duration of rainy season in El Niño years and normal (mean) duration of rainy season over the Thabo Mofutsanyane district show a decrease in the length of rainy season by between 11 and 20 days in most places with few patches of over 20 days (Bethlehem, Reitz and surroundings of Warden) and less than 11 days decrease (patches over the western and eastern Thabo Mofutsanyane) (Fig. 4.10a). Over the Fezile Dabi district, most places have shorter than normal length of the rainy season by 11 to 20 days except the eastern parts where over 20 days decrease in duration of the rainy season is evident. Over Lejweleputswa the duration of rainy season in El Niño years is mostly short by 11 to 20 days as well with a few exceptions of below 11 days (sporadic over the whole district) and above 20 days (mostly over the central part). Over the Motheo district, the rainy season is shorter in El Niño years by up to 10 days in most places with a large area of between 11 to 20 days difference. Over the Xhariep district, most places also have the duration of the rainy season in El Niño years being up to 10 days shorter than normal. Overall the assumption that the duration of the rainy season is shorter in El Niño years than normal is true hence in El Niño years crop production can be affected negatively by relatively short growing periods.

The difference between mean duration of rainy season in La Niña years and overall mean duration of rainy season is expected to be positive in order to reflect longer than normal rainy period which is mostly favourable for rainfed agriculture. The difference between average length of the rainy season in La Niña years and the normal (mean) length of the rainy season over the Thabo Mofutsanyane district is mostly longer by up to 9 days (Fig. 4.10b). There are patches of slightly shorter rainy season duration over the southern parts and much longer (10 to 19 days) over the northern and northeastern parts. The Fezile Dabi district mostly has duration of rains longer by 10 to 20 days with some places (southern and patches over central and eastern sites) having up to 9 days longer season. The Lejweleputswa district has mostly longer season by up to 9 days with places around Christiana, Boshof, Bothaville, Brandfort and Bultfontein having a rainy season in La Niña years being longer by over 10 days. The Motheo district rainy season in La Niña years is also mostly up to 9 days longer with exceptions over the northeastern and southern parts with slightly shorter (up to 10 days) rainy season. Over the Xhariep district, most parts have slightly longer season (up to 9 days) with the eastern parts having an extremely long season (up to over 20 days longer) in La Niña years while southern and patches over the central and eastern parts have slightly short (up to 10 days shorter) length of the rainy season.

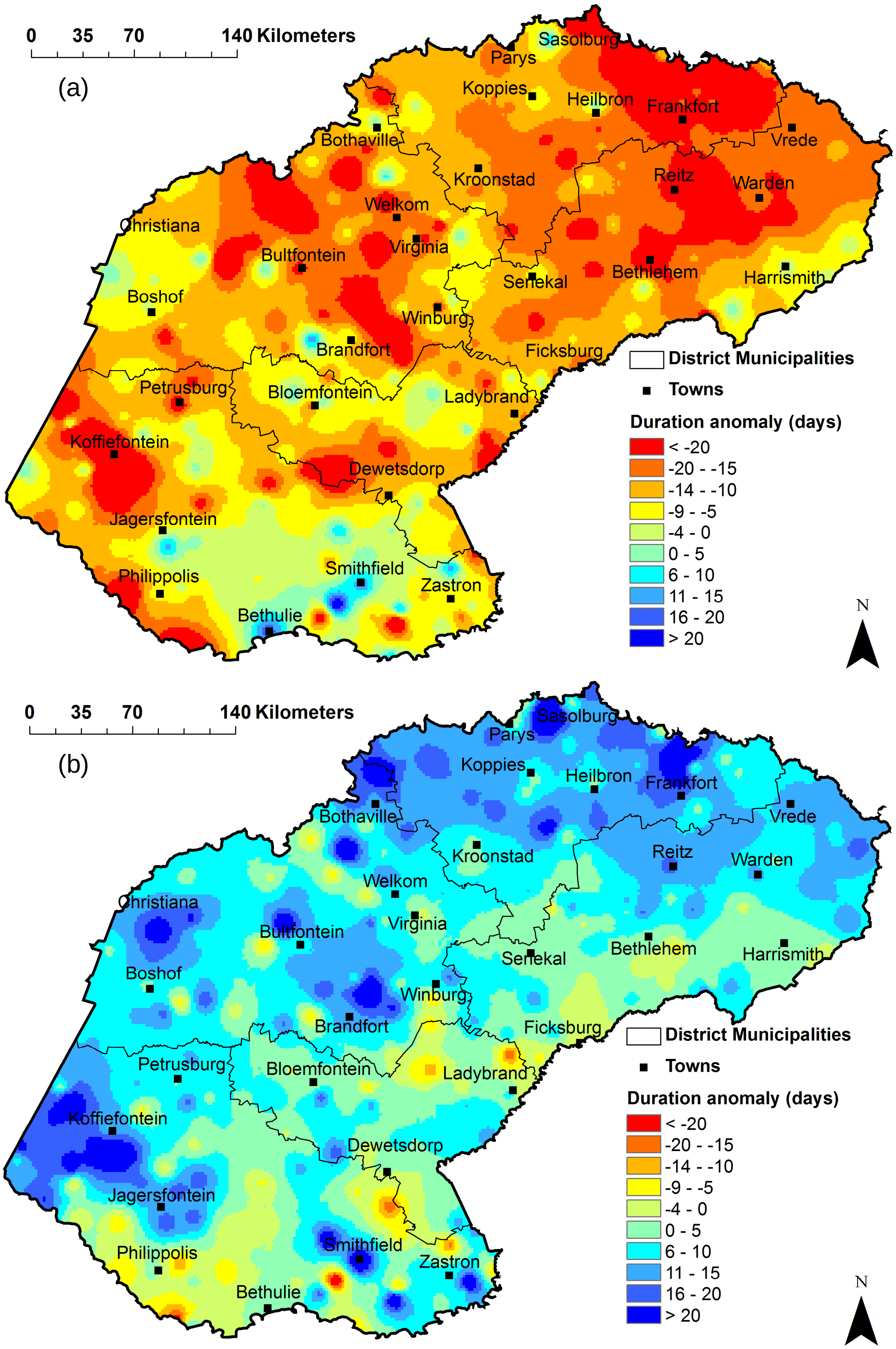


Fig. 4.10: The difference between a) mean rainy season duration in El Niño years and overall mean rainy season duration and b) mean rainy season duration in La Niña years and overall mean rainy season duration.

4.3.7.2 Seasonal rainfall

The expectation for seasonal rainfall during El Niño and La Niña years as compared with all the years data is as follows (Vogel and Drummond, 1993; Phillips et al., 1998; Landman and Mason, 1999; Nicholson et al., 2001; Fauchereau et al., 2003):

a. Seasonal rainfall in El Niño years is lower than normal
b. Seasonal rainfall in La Niña years is higher than normal

The difference between overall mean of seasonal rainfall and mean seasonal rainfall in El Niño years is expected to be positive in order to reflect lower seasonal rainfall in El Niño years which is mostly unfavourable. Figure 4.11a presents actual interpolated surface of the difference between mean seasonal rainfall in El Niño years and overall mean seasonal rainfall over the Free State Province. It is evident that during El Niño years accumulated seasonal rainfall is below normal as shown by negative values all over the province. Far below normal rainfall in El Niño years is an indication that crop water requirements are likely to be severely affected. The deviation from the overall mean is below 25mm for a few pockets situated in different parts of the Free State. But over 80% of the province records deviations from 51mm up to 100mm. There is sporadic occurrence of deviations exceeding 100mm especially over some patches of the Xhariep district. The percentage deviations from the overall mean to mean in El Niño years over the whole Free State Province ranges from 2% to 41% with an average of 20% deviation. Over the Thabo Mofutsanyane district, the difference is mostly between -50 to -74mm in most places over the central, southern and western parts. This makes 15 to 20% deviation from the mean. The northeastern Thabo Mofutsanyane district records differences of mostly between 26 to 50mm making a 6 to 15% deviation from the mean. The negative differences exceeding 74mm are evident over the central part of the district making over 25% deviations in other areas. Over the Fezile Dabi district, most parts have -50 to -74mm difference equivalent to 12 to 20% deviation from the mean. Places over the northern and eastern parts have less than 10% deviations from the mean. Over the Lejweleputswa district the difference is mostly between -50 to -74mm or between 5 to 15% deviation from the mean. Other places over the southwestern parts can have over 30% deviation from the mean. Over the Motheo district the western parts record the highest negative anomalies exceeding 76mm on average. The percentage reduction in seasonal rainfall in these places is mostly around 20% in El Niño years. The Xhariep district has the highest negative difference with some places having negative below -100mm differences. The percentage deviations from the mean are mostly over 20% with some places with over 40% reduction in rainfall in El Niño years. Places with more than 15% deviations or rainfall deviations below -50mm from the mean are more vulnerable in El Niño years hence crop production can be affected by reduction in rainfall.

The difference between mean seasonal rainfall in La Niña years and overall mean of seasonal rainfall is expected to be positive in order to reflect higher than normal seasonal rainfall which can denote good rains and hence successful dryland crop production. Over the Free State most places record a difference of 51 to 75mm with some patches above 75mm and below 51mm (Fig. 4.11b). Over the Thabo Mofutsanyane district, most central and western places record differences between 51mm and

75mm with their percentage deviations ranging from 5 to 20%. As for the Fezile Dabi district, most places show differences of between 26 to 50mm with percentage deviations from 2% to 15%. The southern Fezile Dabi district show high positive anomalies above 50mm. Over the Lejweleputswa and Motheo districts most parts have differences mostly between 51 and 75mm except the northern, western and southeastern parts of Lejweleputswa; northeastern Motheo where differences below 51mm are evident. In these two districts there is sporadic occurrence of le more 75mm differences. Over the Xhariep district, the differences are mostly between 51 to 75mm with other parts showing even greater differences (76 to 100mm). The percentage deviations over the Xhariep district are mostly over 30% showing that in La Niña years seasonal rainfall is significantly higher than normal.

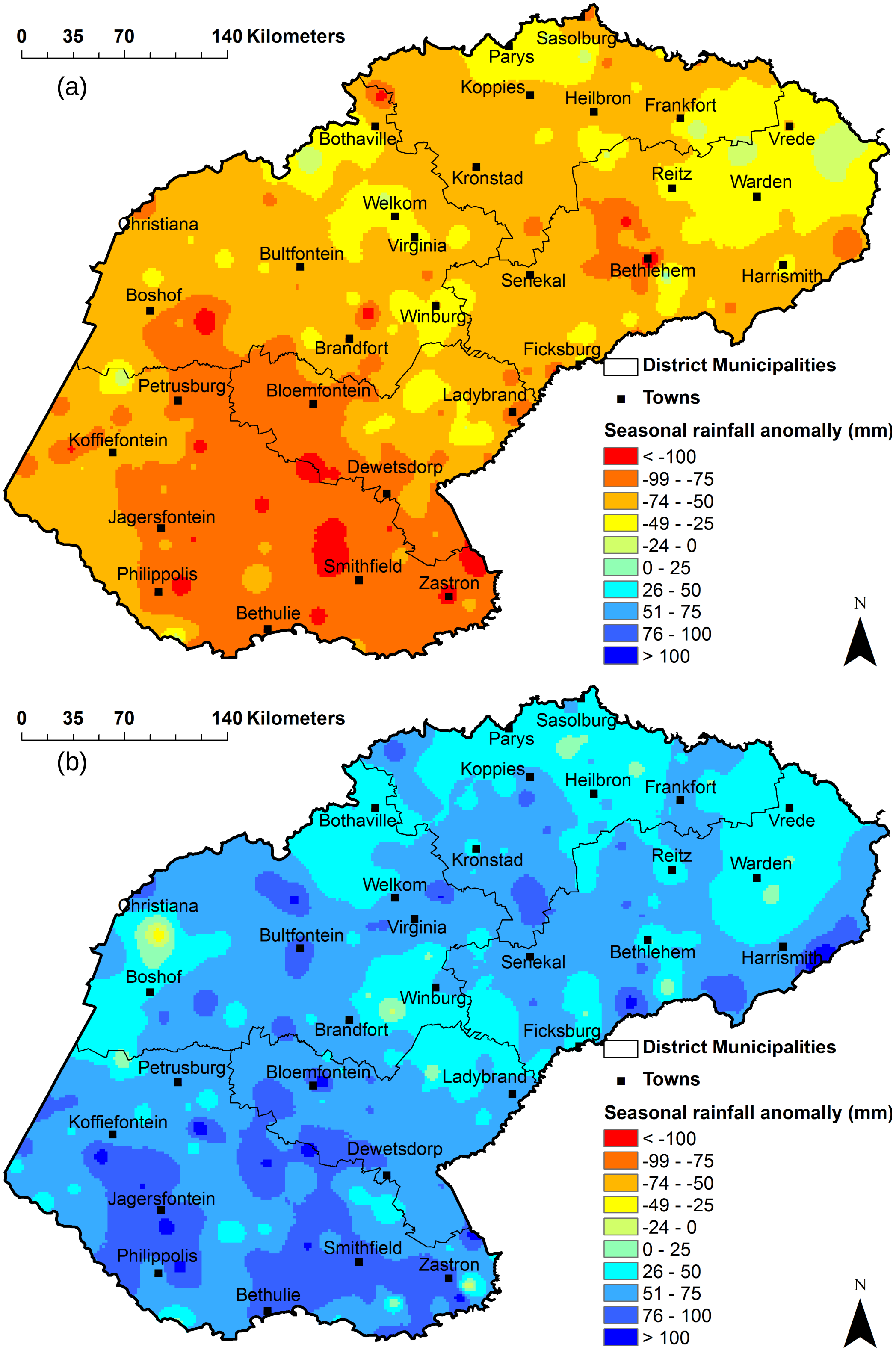


Fig. 4.11: The difference between a) mean seasonal rainfall in El Niño and overall mean seasonal rainfall and b) mean seasonal rainfall in La Niña and overall mean seasonal rainfall.

4.4 Conclusions

The onset of rains results clearly show that, for the Thabo Mofutsanyane, eastern parts of Fezile Dabi and far eastern parts of Motheo and Xhariep districts planting can be done early with 4 out of 5 years onset occurring on or before the first dekad of November. The cessation of rains in these places is also relatively late. For the western parts of Fezile Dabi, eastern parts of Xhariep and most parts of Motheo and Lejweleputswa, the onset of rains is not as early as the above regions and the cessation of rain does not vary a lot over the Free State. The duration of the rainy season over the Free State varies significantly for all the probability levels owing to great variation in the onset of rain. The spatial variation of the 20%, 50% and 80% probability level is more or less similar. Generally, the rainy season duration for all the probability levels is short over the southwestern Free State (west of Koffiefontein) and increases gradually moving eastwards or northeastwards and peaking over the southeastern, eastern and far northeastern parts of the province. A shorter growing period is evident over the western parts of the Xhariep district being less than 80 days, 140 days and 200 days recorded for the 20%, 50% and 80% probability levels respectively. In most places the 20%, 50% and 80% probability duration of the rainy season is over 120 days, 140 days and 200 days. At 20% probability, the risk of total failure of maize is high over Xhariep and the western parts of the Lejweleputswa district especially for the medium and long season cultivars. The risk at other parts of the province is relatively low. At 50% probability, the risk of crop failure due to water stress is high for long season maize cultivars over the far western parts of the Xhariep district. At 80% probability, the risk for crop failure caused by water shortages over the Free State is minimal due to very long growing periods especially over the central, northern and eastern parts of the province. Seasonal rainfall is lowest over the southwestern parts of the Free State. In these regions accumulated rainfall is less than 350mm even in very wet seasons (80% non-exceedence probability). The central and western parts obtain moderate seasonal rainfall with median rainfall between 300 and 400mm. Highest accumulated rainfall from November to March is recorded mostly in the northern and eastern parts of the province with the median rainfall exceeding 400mm. These places are expected to have a relatively low risk of crop failure due to crop water deficiency. The results of the analysis for all the indices show vulnerability of maize production over the western, southern and southwestern parts of the Free State. The rainy season is favourable for all maize cultivars over the Thabo Mofutsanyane district due to early onsets of rain resulting in a long rainy season and high seasonal rainfall especially in the northeastern parts. The northern parts (Fezile Dabi district) also show a relatively long rainy season as well as less risk of onset failure. It is thus expected that maize should flourish in those areas of low risk if rainfall were the only determinant of the success of the maize production. The western Xhariep and some pockets over the western Lejweleputswa have the highest risk of onset failure and probabilities of rainy season being less than 100, 120 and 140 days. Planting of maize of any cultivar length is not advisable under dryland conditions in these areas.

The comparison of overall mean onset dates with the onset dates during El Niño years does not show any consistency, with some areas having later than normal onsets (northern and northeastern Free

State) in El Niño years while others have earlier than normal onsets (eastern Motheo and most parts of Xhariep). The comparison with the onsets in La Niña years showed slight nagative bias over most parts of the northern, far eastern, western and southern parts of the province with mostly up to 5 days earlier than normal onsets. There are also a lot of places where the onsets in La Niña years is later than normal. One can thus conclude that the links between onset and ENSO episodes are not clear for the whole Free State. In contrast, the ENSO episodes have a good association with the cessation of rains in most parts of the province. Cessation of rains in El Niño years is very much earlier compared to the normal for the Free State mostly by 11 to 20 days, while in La Niña years cessation of rains is later by more than 5 days over most parts of the province. The study clearly shows that ENSO episodes have an influence in seasonal rainfall amount accumulated from November to March. The differences from mean in El Niño years and the overall mean seasonal rainfall are highly negative all over the Free State hence the seasonal rainfall is reduced in El Niño years. The most affected areas are in the Xhariep district where percentage deviations exceed 30% in some places. As for the difference between mean seasonal rainfall in La Niña years and overall mean in most places records positive values with a few exceptions indicating that rainfall is more than normal in La Niña years. The Xhariep district shows more places with percentage positive deviations of more 30%. There is also evidence that ENSO episodes influence productivity over the Free State Province with low production being linked to El Niño years and relatively higher maize production associated with La Niña years.

Chapter 5: Assessment of Agricultural Drought

5.1 Introduction

Drought is one of the most disastrous climate-related hazards in the world that has significant impact on agriculture, environment, infrastructure and socio-economic activities (Finan & Nelson, 2001; Keyantash & Dracup, 2002; Bhuiyan, 2004; Loukas & Vasiliades, 2004; Msangi, 2004; Sonmez *et al.*, 2005). Drought is mostly defined as a deficiency of precipitation over an extended period, usually over a period of a week to a month or more, resulting in a water shortage causing adverse impacts on vegetation, animals, and people (Rouault & Richard, 2003; Msangi, 2004; NOAA, 2006). Precipitation is the primary factor controlling the incidence, formation and persistence of drought conditions (Lloyd-Hughes & Saunders, 2002; Msangi, 2004; Sonmez *et al.*, 2005). Some describe drought as a sustained and extensive occurrence of below average natural water availability, and can thus be characterized as a deviation from normal conditions of variables such as precipitation, soil moisture, groundwater and streamflow (Runtunuwu, 2005). It is a recurring and worldwide phenomenon, with spatial and temporal characteristics that vary significantly from one region to another (NOAA, 2006; Runtunuwu, 2005; Loukas & Vasiliades, 2004; Wilhelmi & Wilhite, 2002). The impacts of drought depend on its intensity, duration, frequency and the affected area (du Pisani, 1987; Rouault & Richard, 2003; Tadesse *et al*., 2004). Its effects are also recorded even in following periods when precipitation occurs normally.

Drought differs according to the way water is used and its impacts also differ depending on the economy, social and environmental characteristics (Sonmez *et al.*, 2005). There are four main types of drought, namely: a) meteorological drought, b) hydrological drought, c) agricultural drought and d) socio-economic drought (Lourens, 1995; Keyantash & Dracup, 2002). The first three categories are referred to as environmental or physical droughts whilst the socio-economic drought is considered a water resources systems drought (Keyantash & Dracup, 2002; Loukas & Vasiliades, 2004). Figure 5.1 shows the interaction of these types of drought and the progression of drought from meteorological to socio-economic drought.

Meteorological drought occurs when there is a lack of precipitation over a large area and for an extensive period of time and is usually defined in comparison to “normal” or average rainfall at that particular place (Lourens, 1995; NOAA, 2006). Definitions of meteorological drought must be considered as region specific since the atmospheric conditions that result in deficiencies of precipitation are highly variable from region to region (Runtunuwu, 2005). Some definitions of meteorological drought identify periods of drought on the basis of the number of days with precipitation less than some specified threshold, while other definitions may relate actual precipitation departures to average amounts on monthly, seasonal, or annual time scales (Keyantash & Dracup, 2002).

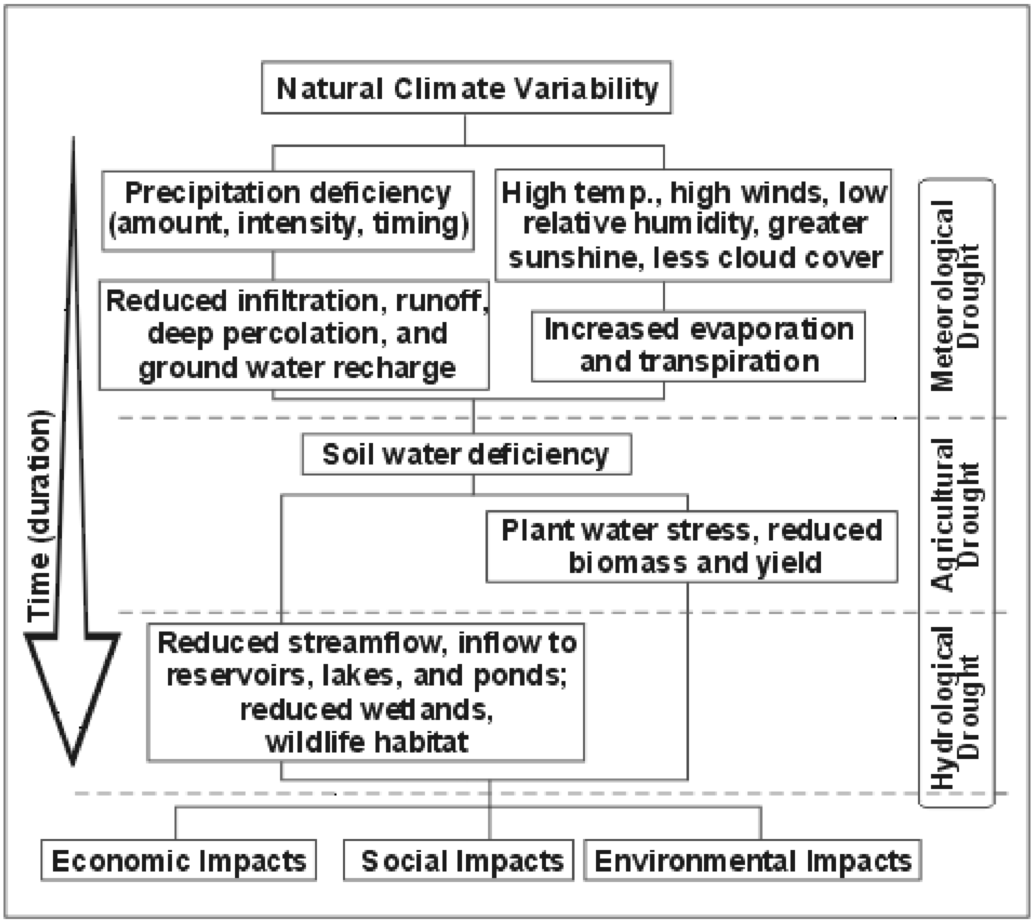


Fig. 5.1: Flow chart showing progression of meteorological drought to agricultural drought, hydrological drought and Socio-economic drought (National Drought Monitoring Center, 2006).

Hydrological drought on the other hand is defined as less than normal amounts of water in the different types of water bodies, represented by low water levels in streams, reservoirs and lakes as well as a low groundwater level (Lourens, 1995; Keyantash & Dracup, 2002). Usually, hydrological droughts are further divided into streamflow droughts and groundwater droughts depending on which type of water body is observed (Fleig, 2004). Due to the fact that regions are interconnected by hydrologic systems, the impact of hydrological drought may extend well beyond the borders of the precipitation-deficient area (NOAA, 2006). Whether drought leads to deficits in soil water, surface water and groundwater, depends not only on the lack of sufficient water input into the hydrological system of the area but also on the rate of water losses through evapotranspiration or discharge from the area, or any other anthropogenic activities (Fleig, 2004).

Agricultural drought relates characteristics of meteorological drought to agricultural impacts (Lourens, 1995; Nain *et al.*, 2005). It is usually linked to lack of soil water to support crop or grass production on farms and rangelands (Schulze, 1984; Nain *et al.*, 2005). Agricultural drought also relates soil water deficits for a particular crop at a certain growth stage as plant water needs are dependent on the crop variety, environment and stage of plant growth (Chowdhury & Gore, 1989; Łabędzki & Kanecka-

Geszke, 2009). For instance, 6-7 days without rainfall may characterize a severe drought period for shallow-rooted crops, whereas for crops with deep rooting systems this may not be considered drought (Brunini *et al*., 2000).

Socio-economic drought is associated with the failure of water resource systems to meet the societal water demands (Loukas & Vasiliades, 2004). It takes place when the supply of an economic good (water) cannot meet the demand for that product.

Even though drought is caused by lack of precipitation over long periods, its development is mostly slow (referred to as a creeping phenomenon) and difficult to detect because of its multifaceted nature (Unganai & Kogan, 1998; Sonmez *et al*., 2005; Morid *et al*., 2006; WMO, 2006). The socio-economic costs of this hazard require collaboration of all the stakeholders in government, non-governmental organizations, society and private sector to improve their monitoring mechanisms (Rhee & Carborne, 2008). According to Morid *et al.* (2006) the preparedness and mitigation of drought is dependent on reliable and timely information on the onset, progress, intensity and spatial extent of the phenomenon. Drought monitoring is an essential component of drought risk management and it is normally performed using various drought indices that are effectively continuous functions of rainfall and other hydrometeorological variables (Keyantash & Dracup, 2002; Morid *et al.,* 2005; Saeid *et al.,* 2006; Rhee & Carborne, 2008). The quantification and monitoring of drought is of critical importance politically, economically and environmentally in most countries. Policy makers at the national level, the provincial governments, researchers, farmers and water managers and national/international relief agencies are all interested in reliable and accurate drought information (Runtunuwu, 2005).

There are different indices which have been developed in the past to quantify environmental droughts (Morid *et al*., 2006). Most drought indices incorporate data on rainfall, temperature, evapotranspiration, streamflow, and other water supply indicators into a comprehensible big picture that is far more useful for decision making than raw data (NOAA, undated). The indices that are normally used include deciles index (DI), percent of normal (PN), Standard Precipitation Index (SPI), Palmer Drought Severity Index (PDSI), Standardized Water-level Index (SWI), Effective Drought Index (EDI), Normalized Difference Vegetation Index (NDVI), Crop Moisture Index (CMI), Vegetation Condition Index (VCI), Temperature Condition Index (TCI), Total water deficit (TWD), Cumulative Streamflow Anomaly (CSA), Palmer Hydrological Drought Severity Index (PHDI), Surface Water Supply Index (SWSI), Water Requirement Satisfaction Index (WRSI) and Vegetation Health Index (VHI) (Meyer*,* 1993; Keyantash & Dracup, 2002; Senay & Verdin, 2003; Bhuiyan, 2004; Morid *et al.*, 2006; Saeid *et al.,* 2006). The DI, PN and SPI have been used to monitor meteorological drought. The SWI, TWD, CSA, PHDI and SWSI have been developed for monitoring of hydrological drought. The indices normally used for agricultural drought include: NDVI, PDSI, TCI, CMI, WRSI, VCI and VHI (Senay & Verdin, 2003; Bhuiyan, 2004). Socio-economic drought uses other economic, vulnerability and harzard indicators which are not limited to drought and water supply and thus are not discussed here.

In semi-arid regions like the Free State Province of South Africa drought is the climate hazard that has the most detrimental effect on crop production (Lourens, 1995; de Jager et al*.,* 1998; du Pisani et al., 1998). In South Africa drought is a recurrent phenomenon occurring at different intensity (Unganai and Kogan, 1998; Backeberg and Viljoen, 2003). The most affected people are the resource-poor farmers whose productivity is highly threatened by frequent droughts (Reason et al., 2005; Zvomuya, 2007). These droughts are attributed to the high variability of inter-annual and intra-seasonal rainfall over most parts of southern Africa (Richard et al*.,* 2000; Tyson and Preston-Whyte, 2000). El Niño-Southern Oscillation (ENSO) phases play an important role in the climate variability of most southern African regions with the negative phase being attributed to drought conditions (Nicholson et al., 2001; Tyson and Preston-Whyte, 2000; Rouault and Richard, 2003; Tsubo and Walker, 2007). Water deficiency during the growing period of summer crops is the main limiting factor for optimum crop production in most semi-arid areas of South Africa (DOA, 2005; Moeletsi et al*.,* 2009a). Estimation of crop water requirements is one of the fundamental steps required during the planning, design and operation of water resource systems (Ali et al., 2009).

For the assessment of crop performance based on water available to the crop during the growing season the Water Requirement Satisfaction Index (WRSI) was developed by the Food and Agriculture Organization (FAO) of the United Nations as documented in the FAO Plant and Protection Papers 17 and 73 (Frere and Popov, 1979, 1986). Research shows that WRSI has a linear relationship with yield with high values of WRSI showing the potential of high yield and low values of WRSI translating to minimal yield (Martin et al., 2000; Verdin and Klaver, 2002; Diga, 2005; Verdin et al. 2005; Moeletsi et al., 2009a). WRSI has been used for drought monitoring and yield forecasting mostly in semi-arid regions in different parts of the world (Martin et al., 2000; Senay and Verdin, 2003; Rafi and Ahmad, 2005; Jayasree et al., 2008). According to Jayasree et al. (2008) WRSI is an index which shows the extent to which water demand of the crop has been met cumulatively during the growing period, hence one can have an indication of the water stress that the crop underwent.

In this study WRSI will be used to determine the agricultural drought related to maize production over the Free State using a 120-day length maize cultivar for different planting dates. Optimal planting dates which minimize crop failure due to water deficiency at different areas will also be determined.

5.2 Data and methodology

5.2.1 Data

The study was performed using data from 1950 to 2008 with majority of the data being from 1983 to 2004. Weather stations with more than 20 years of climatological data (rainfall and temperature) were chosen. Since many of the stations in the Free State only measure rainfall, among these stations those with more that 20 years of rainfall data from 1983 to 2008 were selected. At these stations, evapotranspiration will be estimated using the NASA satellite-derived temperature data as outlined in chapter 2 subsection 2.3. Figure 5.2 shows the distribution of all the 161 weather stations used in the study.

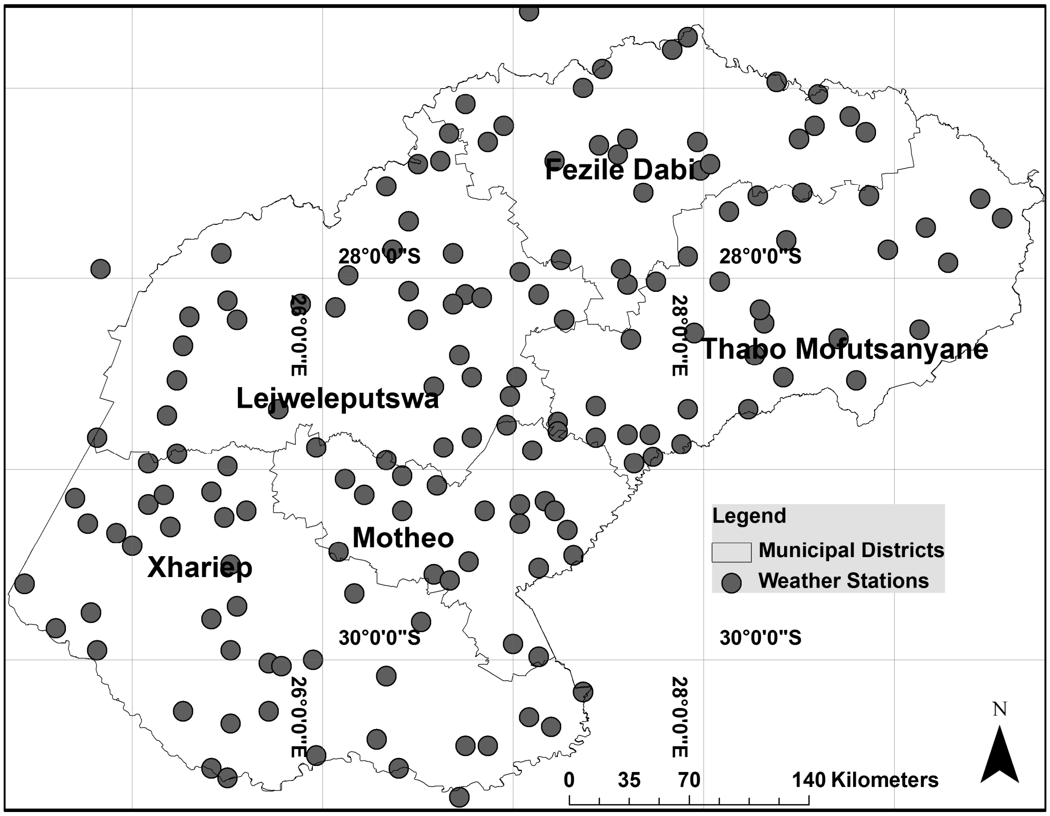


Fig. 5.2: Weather stations locations used in the study of agricultural drought over the Free State Province, South Africa.

WRSI estimation requires rainfall, evapotranspiration (ET_o), soil water holding capacity, cultivar length and crop coefficients (K_c) (Doorenbos & Pruitt, 1977; Jensen *et al.*, 1990; Senay & Verdin, 2003; Instat, 2007; Moeletsi *et al.*, 2009a). Daily rainfall data was obtained from the ARC-ISCW agroclimate databank and SAWS. The estimation of all missing rainfall and temperature data was done using methods explained in chapter 2 subsection 2.2. Soil water holding capacity was obtained from the ARC-ISCW geographic information system (GIS) database. Evapotranspiration for weather stations with temperature measurements was estimated using the Hargreaves equation as outlined in chapter 2 subsection 2.2.2 while for the stations with only rainfall measurements, the Hargreaves equation is also used, with NASA temperatue data but with different calibrations as outlined in section 2.3.

Crop coefficients (K_c) for the maize crop for the initial stage, mid-level stage and at the end of the crop cycle were obtained from FAO recommended values (Table 5.1 & Fig. 5.3) (Frere & Popov, 1979; Allen *et al.,* 1998). These standard crop coefficients (mid-season and late season) have to be modified for local conditions using equation 5.2 (Allen *et al.,* 1998).

Table 5.1: Maize crop coefficients for the initial, mid-season and late season phases and the approximate length of the stages for the 120-day maize crop.

Phases	**Crop Coefficient (K_c)**	**Duration of Phases(days)**
Initial	0.3	20
Development	Interpolation between 0.3 and 1.2	40
Middle	1.2	40
Late Season	Interpolation between 1.2 and 0.4 ($K_c$end)	20

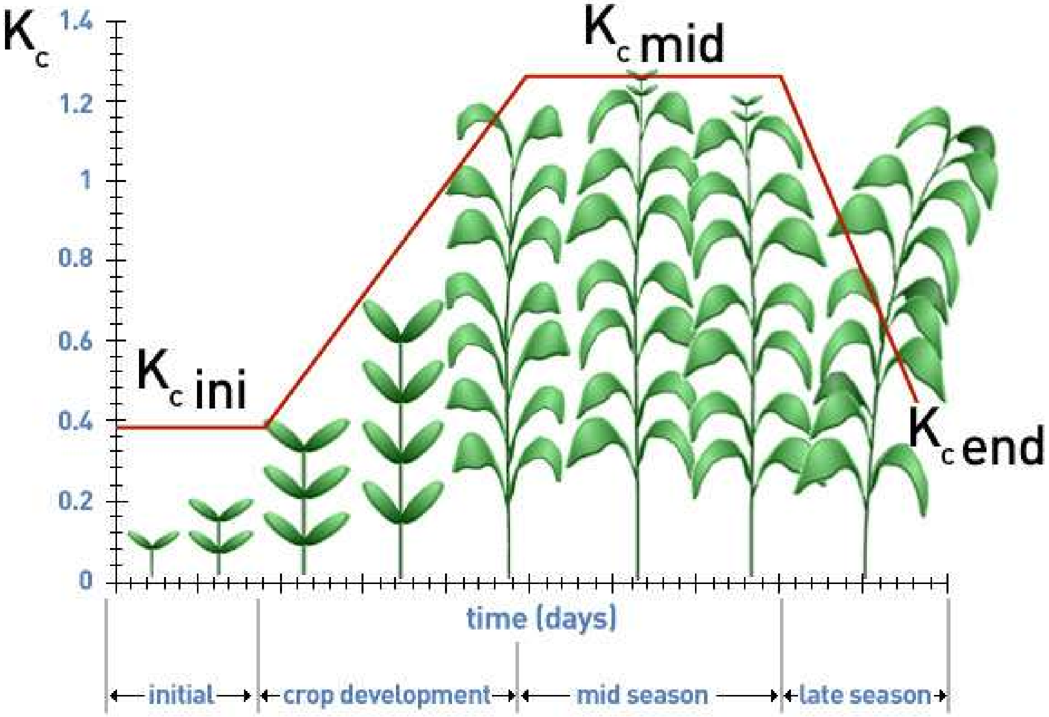


Fig. 5.3: Schematic diagram of the crop coefficient per crop phase (http://www.fao.org).

$$K_C = K_{C(tab)} + (0.04 * (U_2 - 2) - 0.004 * (RH_{\min} - 45)) * (\frac{h}{3})^{0.3} \qquad (5.2)$$

where:

K_c is the either mid-season or end of season crop coefficient, $K_{c(tab)}$ is the standard coefficient of maize, RH_{min} average minimum relative humidity, h is the height of the crop in meters and U_2 is wind speed in meters per second.

5.2.2 Calculation of WRSI

In this study the analysis was performed on a medium season maize cultivar with 120-day (12 dekads) growing period. For this investigation planting dekads were set at fixed dates starting at the 1st dekad of October to the last dekad of January. WRSI was determined for each of the planting dekads and for each year. The end of the season for each crop cycle is obtained by adding 11 dekads to the start of the season dekad. The WRSI model is dependent on the water requirements of maize and indicates as a percentage, the extent to which water requirements of the crop are met at any stage of the growing period. At the start of the season the WRSI value is 100. At any stage of the crop the water requirement is the product of dekadal evapotranspiration and crop coefficient for that particular stage given in equation 5.1 below:

$$WR_i = PET_i * K_{c_i} \tag{5.1}$$

where:

WR_i is the crop water requirement for that particular dekad, PET_i is the potential evapotranspiration in that particular dekad and K_c is the crop coefficient at ith time step.

Water stored in the profile is added to dekadal rainfall in the following dekad. Excess water is taken as runoff or deep drainage. The actual water available (WA) is calculated as follows:

$$WA_i = PPT_i + SW_{i-1} \tag{5.3}$$

where:

PPT_i is the dekadal effective rainfall, SW_{i-1} is the soil water stored in the previous dekad.

Soil water holding capacity (WHC) of the soil plays an important role because it limits the amount of water that can be stored at any point in time. Soil water content (SW) has the minimum of 0 and up to maximum of WHC and dekadal values are estimated using the simple mass balance equation as shown below:

$$SW_i = PPT_i + SW_{i-1} - WR_i \text{, bounded between 0 and WHC} \tag{5.4}$$

$$SW_i = WHC \quad \text{when } SW_i \geq WHC \tag{5.5}$$

$$SW_i = 0 \quad \text{when } SW_i \leq 0 \tag{5.6}$$

where:

SW_i is the soil water stored.

The index is reduced in two ways when there is excessive wetness and during drought conditions. WRSI also decreases by 3 points whenever there is a surplus water exceeding 100 mm. The WRSI values start from 100 and when there are any water deficit (WD) at a particular stage the WRSI decreases proportional to the total cumulative water requirements:

$$WD_i = WR_i - PPT_i - SW_{i-1} \quad \text{when } WR_i > PPT_i + SW_{i-1} \tag{5.7}$$

$$WD_i = 0 \quad \text{when } WR_i \leq PPT_i + SW_{i-1} \tag{5.8}$$

$$WRSI_i = WRSI_{i-1} - \frac{WD_i}{\sum_{i=1}^{end} WR} \tag{5.9}$$

where

$WRSI_i$ is the current WRSI, WD_i is the current water deficit and $WRSI_{i-1}$ is the WRSI in the previous dekad. The interpretation of the drought index (WRSI) is as per the following table (Frere & Popov, 1979; Martin *et al.*, 2000; Mukhala & Hoefsloot, 2004).

Table 5.2: Agricultural drought index values and their interpretation.

WRSI	Description
< 40	Total crop failure due to extreme drought conditions
41 – 60	Crops subjected to severe drought
61 – 80	Crops subjected to mild drought
81 – 95	Crop water requirements met
96 – 100	Crop water requirements highly met

5.2.3 Statistical analysis

The WRSI values for all the planting dekads were analyzed for each station using the Rainbow software to determine data distribution. The distribution fitting was done using the maximum likelihood procedure while the probabilities were estimated using the Weibull method (Raes et al., 2006). The Kolmogorov-Smirnov test and the closeness of linear relationship between the fitted line and data points were used to determine the distribution that best resembles the datasets from each station (Raes et al., 2006). Different non-exceeding probability levels (20%, 50% & 80%) were determined.

5.2.4 Mapping

All the interpolation of the WRSI at the three risk levels (20%, 50% and 80% non-exceeding pribability) was done using the ArcGIS 9.3. The inverse distance weighting model was used for interpolating all the indices.

5.3 Results and discussion

The 20% probability denotes one of the driest seasons (1 in 5 years return period of value of equivalent or less), the 50% probability denotes a normal season (1 in 2 years return period of WRSI value equivalent or less) while the 80% probability represents the wet seasons (4 in 5 years return period of value equivalent or less). It should be noted that WRSI values in the driest seasons (20% probability), normal seasons and wet seasons (80% probability) are locality dependent. In semi-arid places like the Free State where water in the most limiting factor to crop productivity (de Jager et al., 1998), even in wet seasons one place can have a WRSI value of less than 40 depending on the planting date which indicates extreme drought conditions affecting the maize crop. In other areas where water is not the limiting factor the WRSI obtained in the driest seasons can exceed 80 which indicates that water requirements of the crop has been met to a satisfactory level (Senay and Verdin, 2003).

5.3.1 WRSI for 120-day Maize planted in the 1st, 2nd and 3rd dekad of October

The WRSI maps for the 20%, 50% and 80% probability for planting 120-day maize in the 1st, 2nd and 3rd dekads of October planting are shown in Figures 5.4, 5.5 and 5.6 respectively. The 20% non-exceeding probability results show that most parts of the Free State Province record WRSI values of less than 40, during the one of the driest season when planting in all the October dekads (Figs. 5.4a, 5.5a & 5.6a). The areas with WRSI less than 40 include the whole of Lejweleputswa, Motheo and Xhariep districts. The WRSI values of less than 40 denote that there was severe drought affecting the maize crop during the season resulting in crop failure (Martin *et al.*, 2000). In contrast, most parts of the Fezile Dabi and Thabo Mofutsanyane districts experience relatively high (40 – 60) WRSI at 20% non-exceeding probability. Even though these places over the northern, northeastern and eastern Free State (Bethlehem, Reitz, Harrismith, Warden, Vrede, Frankfort, Heilbron, Parys, Sasolburg and Koppies and their surrounding areas) show WRSI values of up to 60 in dry years, they are still highly vulnerable to drought. A WRSI of 60 shows that water requirements of the maize crop have only been marginally met and the maize crop experienced mild drought conditions.

The median WRSI values for planting the 120-day maize cultivar in October are below 40 for most parts of the Lejweleputswa, Motheo and the whole of Xhariep district in all the planting dekads of October (Figs. 5.4b, 5.5b & 5.6b). In these areas water requirements of the maize crop are not met every 1 in 2 years and thus chances of crop failure are high when planting maize in October. The exceptions over the Lejweleputswa district are on the north or northeastern parts (surroundings Bothaville, Welkom and Virginia) where WRSI in normal rainy season ranges between 40 and 60. The exceptions over the Motheo district are evident on the eastern parts where the WRSI can also reach 60 indicating that the crop water requirements are marginally met. Marginal crop water satisfaction is an indication of low yields and thus in these areas maize varieties which are drought tolerant or varieties with high water use efficiency have to be planted. Almost the whole of the Fezile Dabi district and the western parts of the Thabo Mofutsanyane district record median WRSI values ranging from 40 to 60 (marginally met maize water requirements). Places where the rainy season matches the requirements of the crop better are over the central, eastern, northern and northeastern Thabo Mofutsanyane district where median WRSI values of up to 80 can be achieved. In these places the planting of maize in October is expected to yield better than in other parts of the Free State because WRSI values are proportional to yield in most parts of the world and southern Africa (Martin *et al*., 2000; Senay & Verdin, 2003; Diga, 2005; Rafi & Ahmad, 2005; Moeletsi *et al*., 2009a).

The 80th percentile WRSI maps for planting 120-day maize cultivar in all the three dekads of October show a great variation from the southwest to the northeast part of Free State (Figs. 5.4c, 5.5c & 5.6c). Over the southwestern parts of the Free State, the WRSI in wet seasons is still below 40 for these planting dekads. The areas extend from Boshof over the western Lejweleputswa district to Bethulie over southern Xhariep district. Maize is subjected to extreme drought conditions in these areas even in one of the wettest seasons during this growing period. The east of Xhariep, Lejweleputswa and Motheo districts shows WRSI values between 40 and 60 indicating severe drought conditions during the growing period. In the Fezile Dabi district, WRSI in wet seasons for the growing periods starting in the 1st, 2nd and 3rd dekads of October shows WRSI values of between 60 and 80. Over the Thabo Mofutsanyane district the WRSI at 80% non-exceeding probability ranges from below 60 over the southwestern parts to over 80 over the eastern parts (Bethelehem, Reitz, Harrismith and Warden).

Most places in the Thabo Mofutsanyane district record 60 to 80 WRSI values. Even though maize water satisfaction in very wet seasons exceeds 80 in some areas of the Thabo Mofutsanyane district, the values are still below 95 which is used as the value indicating total water requirement satisfaction (Martin et al., 2000).

In general planting of maize in October in the Free State will subject the maize plant to extensive drought over most parts of the province. Planting is not advised except in places over the central and eastern parts of the Thabo Mofutsanyane district where partial water requirement satisfaction is obtained from the October planting period.

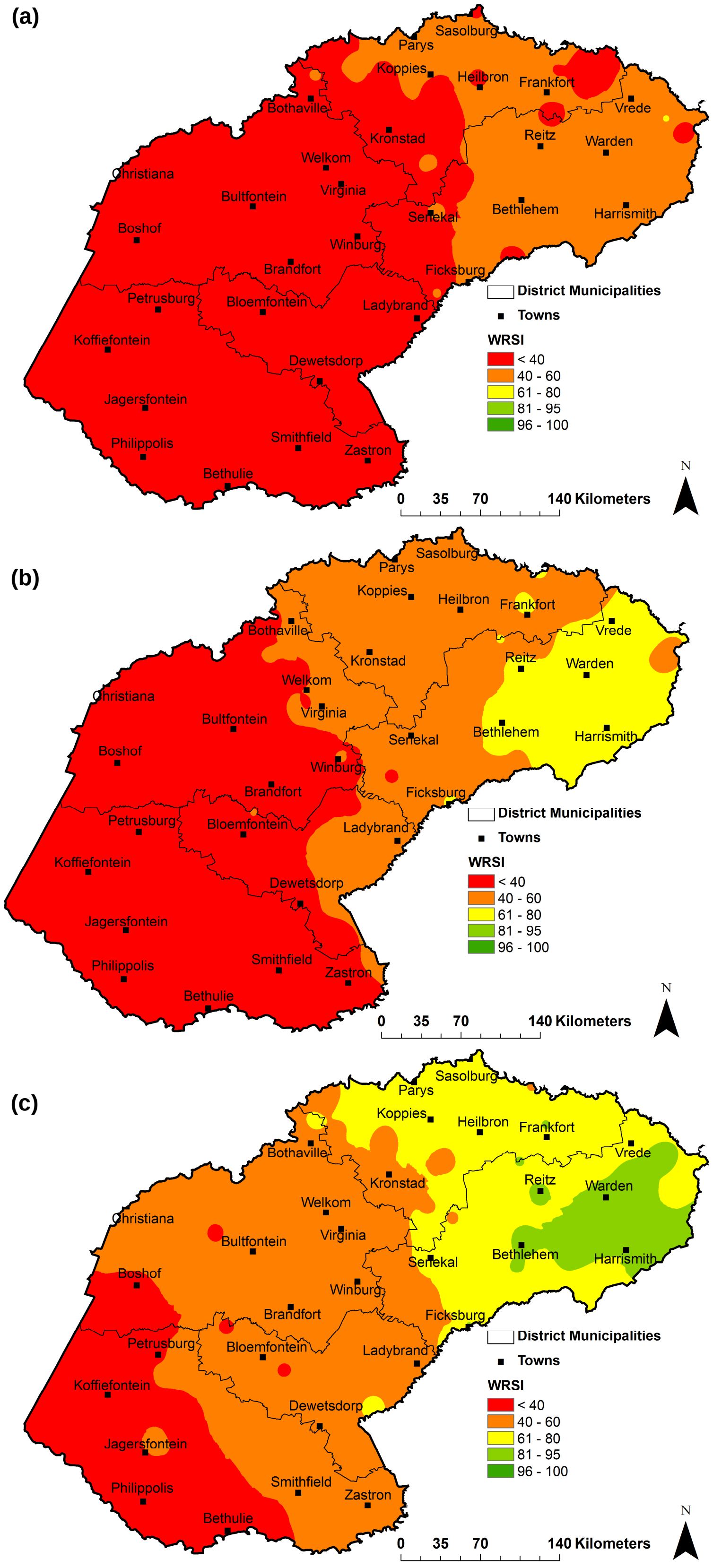


Fig. 5.4: WRSI values corresponding to planting a 120-day maize cultivar in October 1st dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

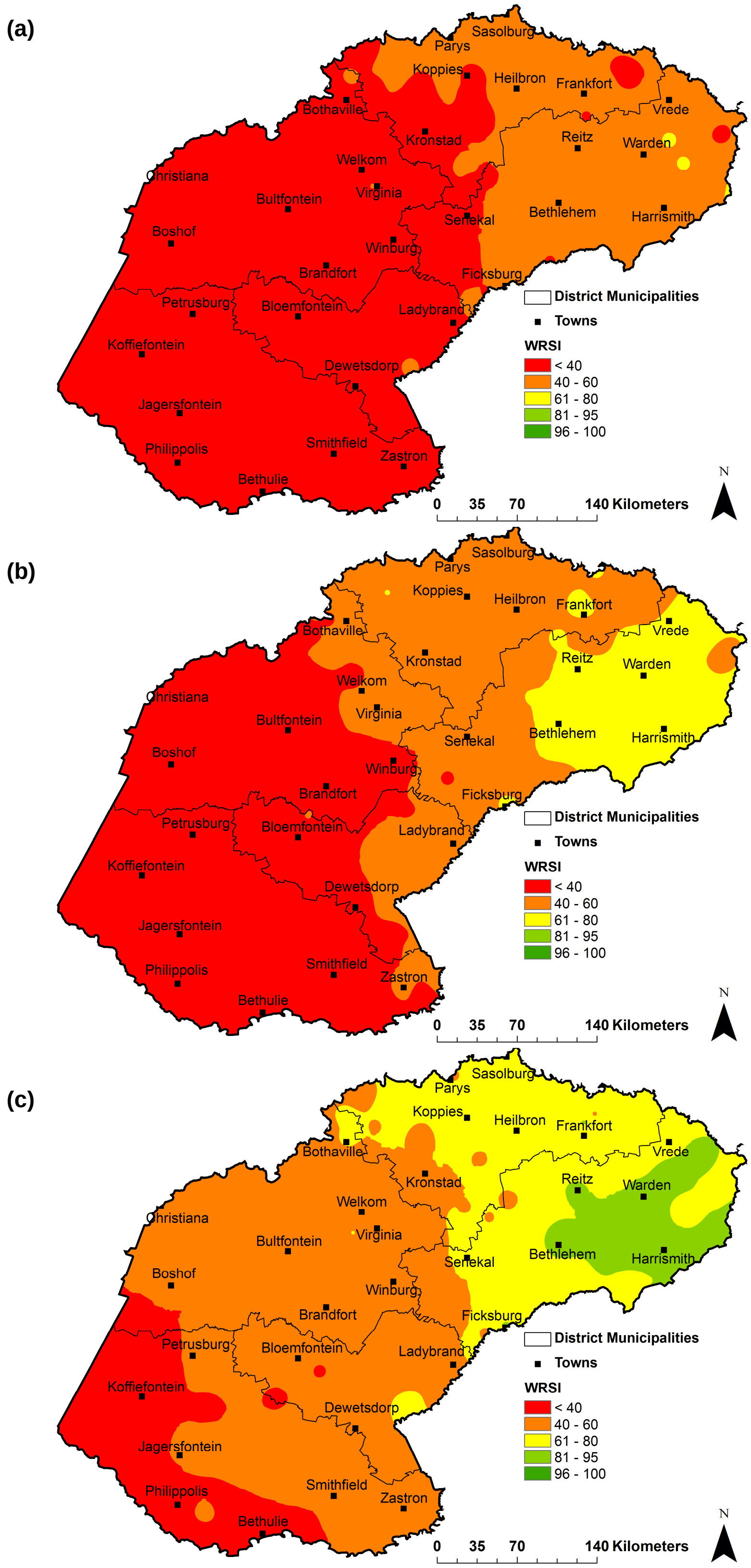


Fig. 5.5: WRSI values corresponding to planting a 120-day maize cultivar in October 2nd dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

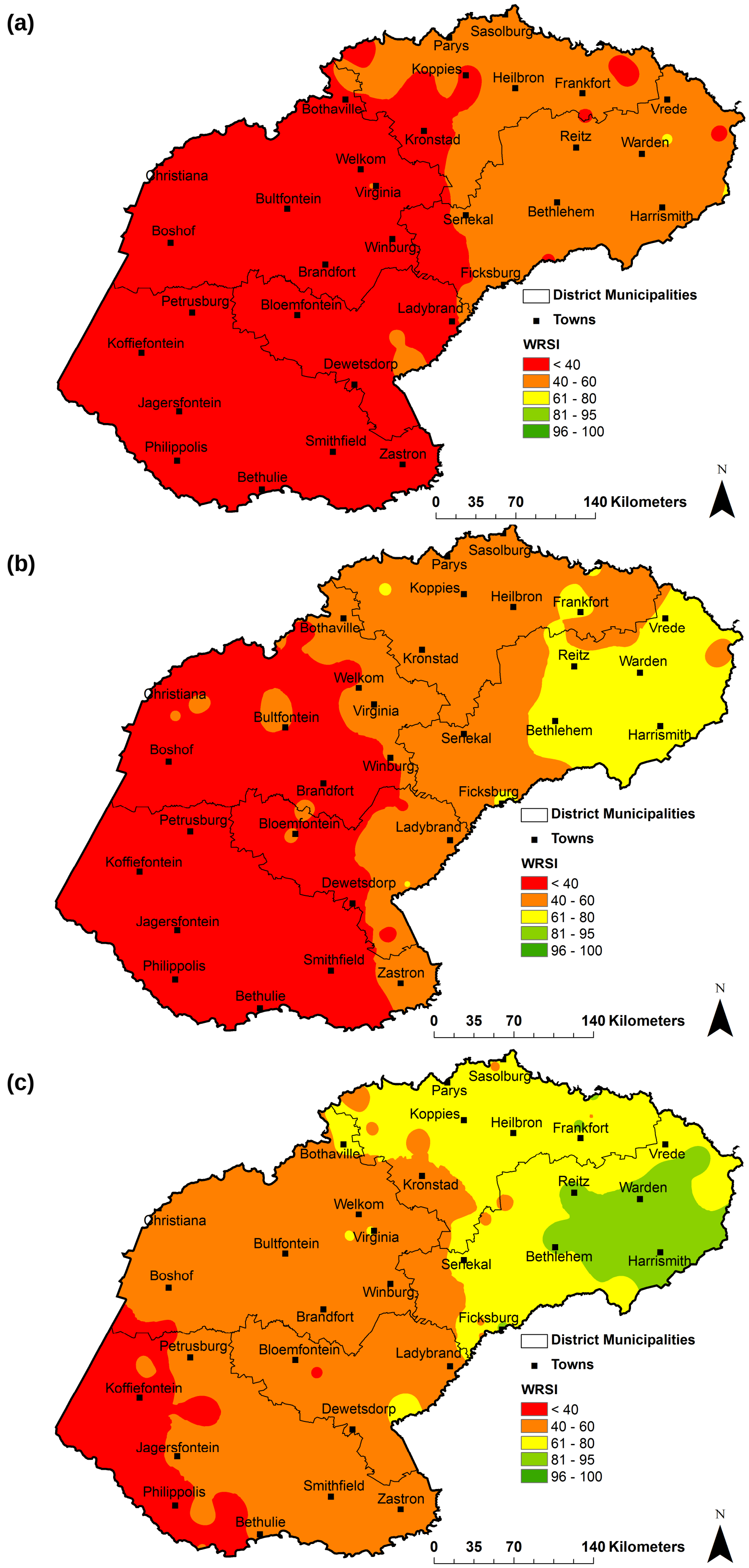


Fig. 5.6: WRSI values corresponding to planting a 120-day maize cultivar in October 3rd dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

5.3.2 WRSI for 120-day maize planted in the 1st , 2nd and 3rd dekad of November

WRSI maps for planting a 120-day maize crop at three different risk levels (20% probability, 50% probability & 80% probability) in the 1st, 2nd and 3rd dekads of November are shown in Figures 5.7, 5.8 and 5.9 respectively. Planting the 120-day maize during the 1st, 2nd and 3rd dekads of November implies projected maturity is on the 3rd dekad of February, 1st dekad of March and 2nd dekad of March respectively. From Figures 5.7a, 5.8a and 5.9a areas of very low WRSI values at 20th percentile level are evident over the Lejweleputswa, Motheo and whole of Xhariep districts. The values in these areas are below 40 clearly indicating the poor performance of the maize crop in dry seasons. As for the Fezile Dabi and Thabo Mofutsanyane districts, in dry seasons the WRSI values are mostly between 40 and 60. Maize planted in these areas can still produce in dry seasons even though it will be at a low potential due to water stress. In areas of high drought occurrences agronomic practices that can mininize its impact include the reduction of plant population and better weed management to reduce competition for water and also ensuring that soil fertility is high so as to increase plant health (Ofori and Kyei-Baffour, 2009). There are exceptions over the western parts of these districts (Lejweleputswa and Thabo Mofutsanyane) where below 40 WRSI values are obtained.

The WRSI values at the median level of risk are still very low over most parts of the Xhariep district (Figs. 5.7b, 5.8b & 5.9b) when planting the 120-day maize in any November dekad. The majority of this district still records 50% non-exceeding probability values of below 40 with exceptions over the far southeastern parts (Zastron area) where values of up to 60 can be obtained. Hence one should clearly discourage the planting of the 120-day maize in Xhariep. Since there is a lot of improvement being made to breed the maize varieties that are highly tolerant to drought, one would therefore recommend that the highly drought tolerant varieties be tested in these areas (DOA, 2001). The highly vulnerable areas are also the western Lejweleputswa and western Motheo districts. Improved WRSI values are evident over most parts of the Fezile Dabi, Lejweleputswa and eastern Motheo districts where the median WRSI values of between 40 and 60 are realized. These areas show that the water requirements are marginally met, hence they are still regarded are drought prone areas when planting maize in November. The Thabo Mofutsanyane district shows median WRSI values of up to 80 hence making the area more suitable than other places over the Free State for maize production when planting in November. This conclusion is solely based on soil water availability and thus other agroclimatic factors like frost and other factors like pests and diseases have not considered when these maps were constructed.

The WRSI values in one of the wettest seasons (80% non-exceeding probability) when planting in the 1st, 2nd and 3rd dekads of November still show the southwest to northeast gradient (Figs. 5.7c, 5.8c & 5.9c). Places over the southwestern tip of the province (Koffiefontein and to the west) still show WRSI values of below 40 even in the wet seasons. This area of excessive drought is reduced when shifting planting dates to the 2nd dekad of November and is at its lowest during the 3rd dekad of November planting. Most parts of the Lejweleputswa and Xhariep districts record WRSI values at 80% non-exceeding risk level of between 40 and 60. In these areas maize crop water requirements are marginally met in very wet growing periods and thus drought tolerant varieties which have high water use efficiency have to be planted to increase total maize productivity. Areas of higher WRSI are evident over the area surrounding Bothaville in northeastern Lejweleputswa particularly for the 3rd dekad of November. The WRSI values over the Motheo district are higher over the eastern parts (up to 80) and lower over the western parts (40 to 60). Most parts of the Fezile Dabi district can experience WRSI values of up to 80 in wet seasons indicating that in above-normal rainy seasons, 120-day maize planted in all the dekads of November is likely to have good productivity. Above-normal rains here refers to those years where rainfall obtained on a dekadal basis is above normal in most dekads hence implying that good rains were evenly distributed through growing periods. Above-normal rains which can result in better yields have to correspond to the most critical stages of the silking and grain-filling. WRSI values over the Thabo Mofutsanyane district are lower (40 to 60) over the southwestern parts (west of Senekal) except the 3rd dekad of November with most places having between 60 and 80. It also clear from the maps that over the Thabo Mofutsanyane district WRSI values of up to 95 can be obtained during the wet seasons. Maize production in this district has high potential to yield better when planted during November owing to high WRSI values as compared to other parts of the province.

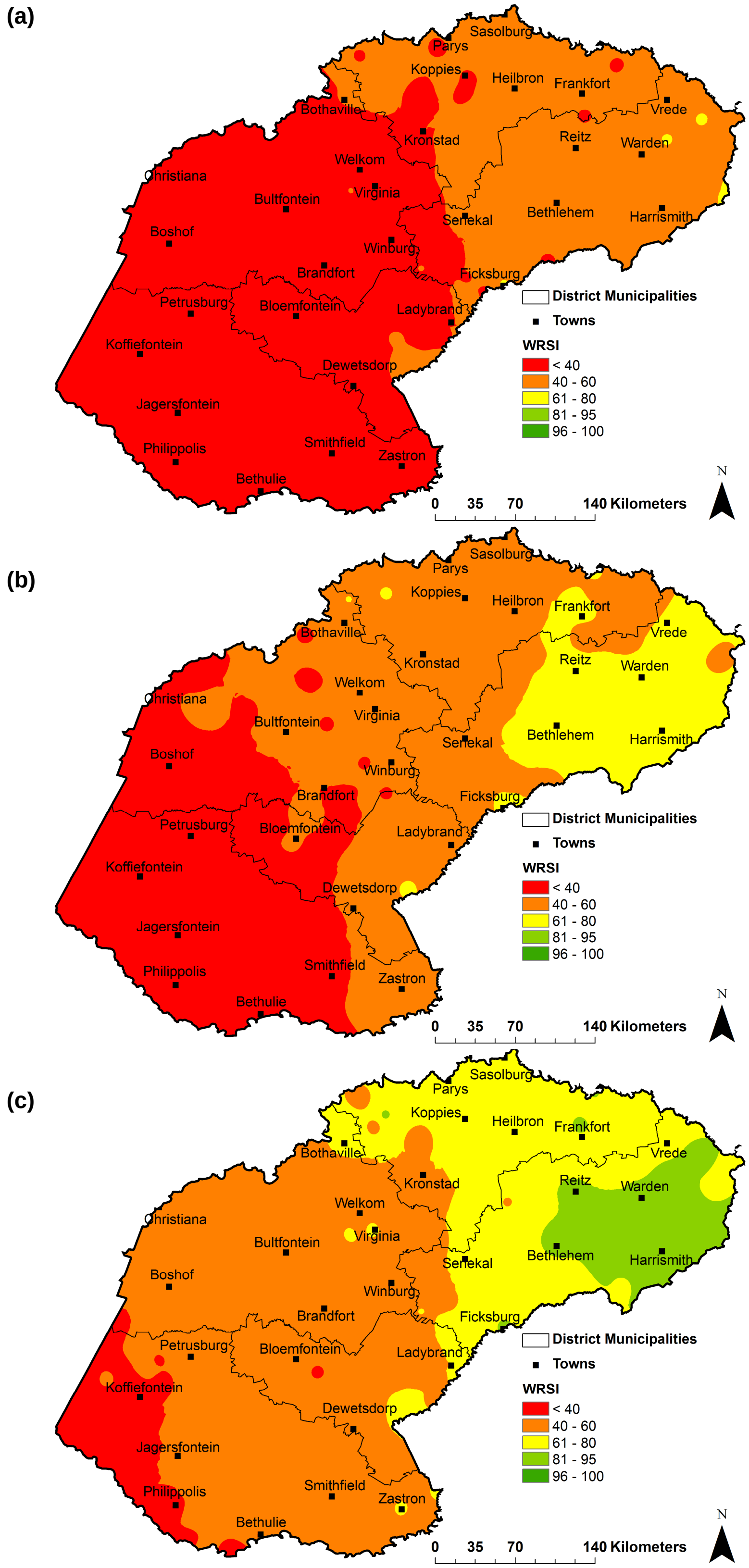


Fig. 5.7: WRSI values corresponding to planting a 120-day maize cultivar in November 1st dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

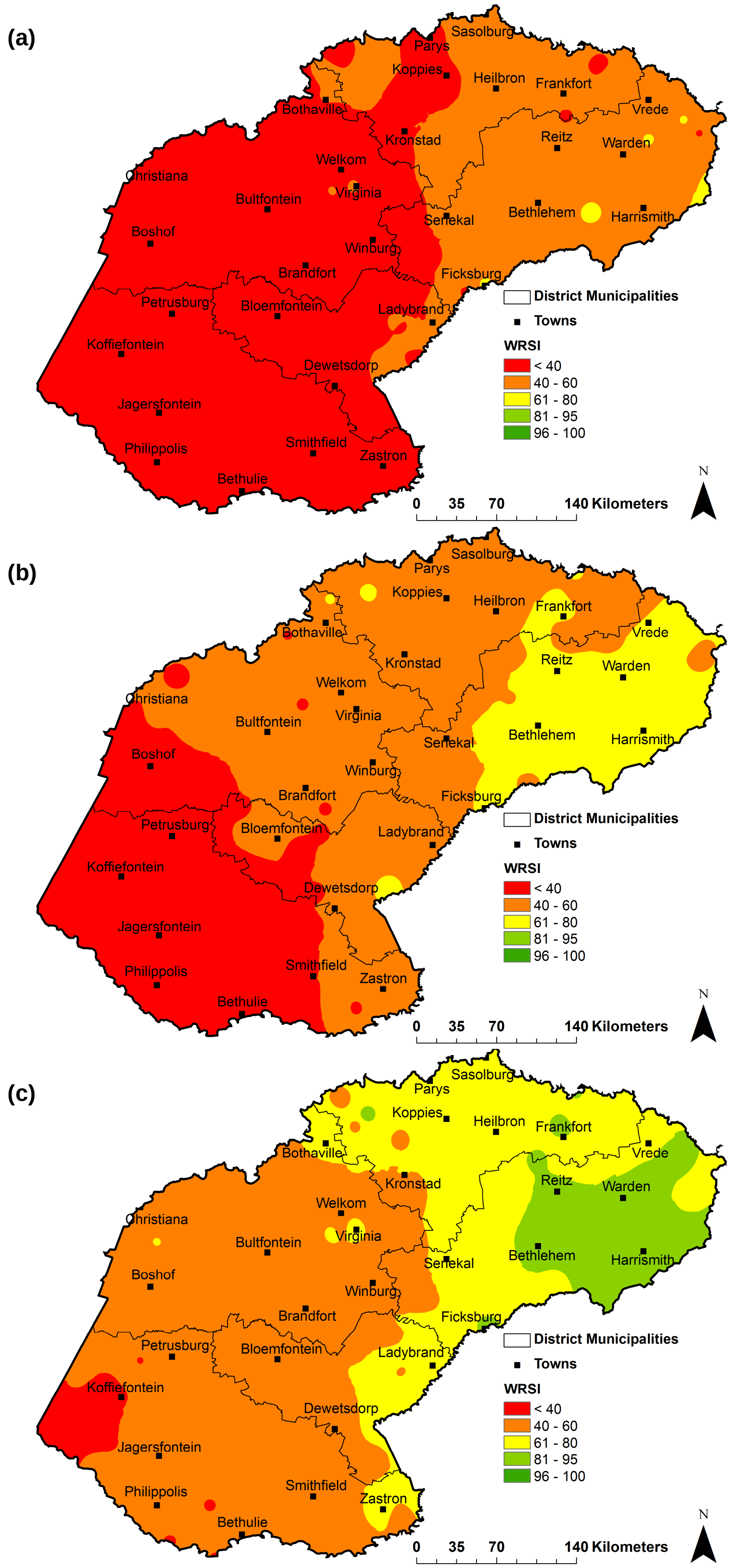


Fig. 5.8: WRSI values corresponding to planting a 120-day maize cultivar in November 2nd dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

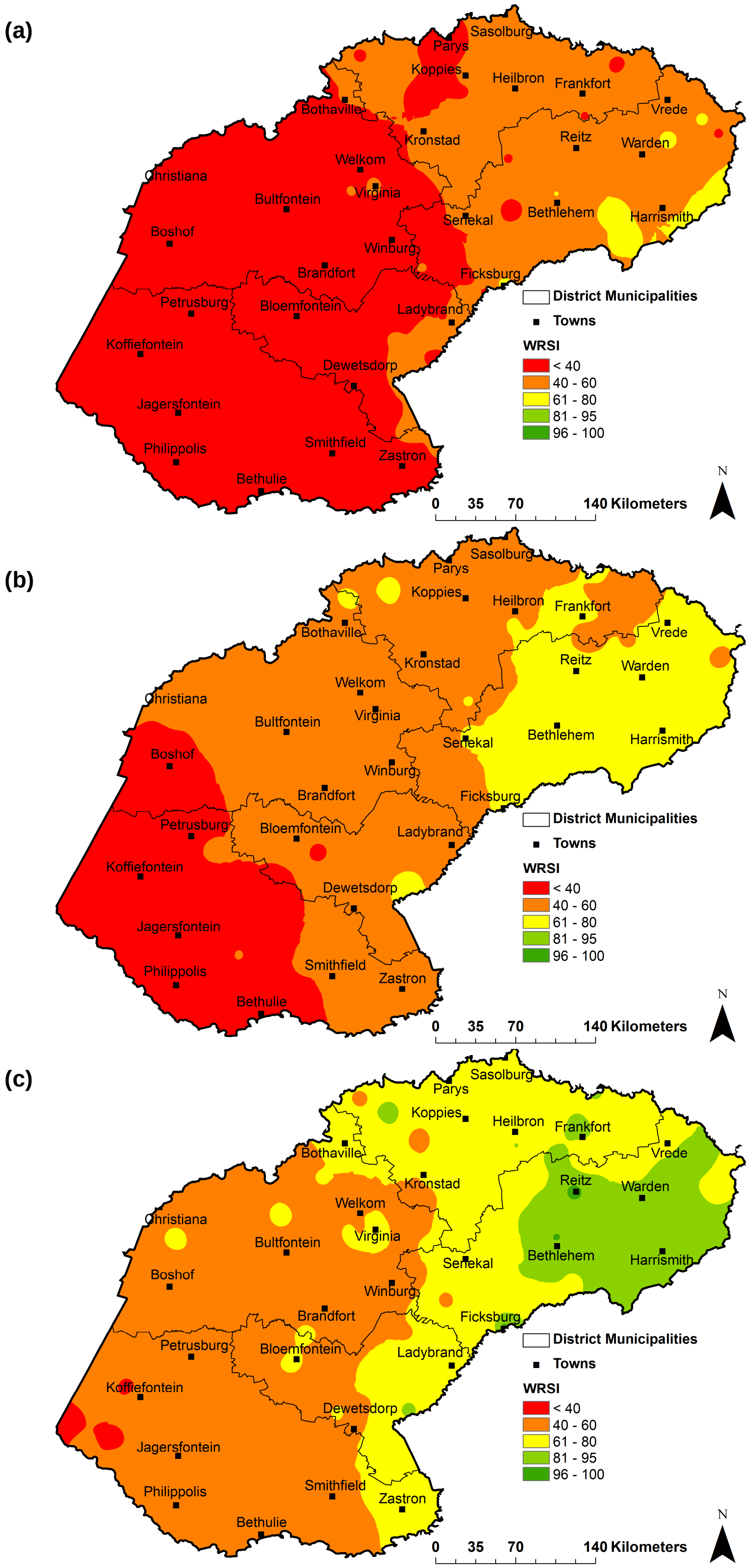


Fig. 5.9: WRSI values corresponding to planting a 120-day maize cultivar in November 3rd dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

5.3.3 WRSI for 120-day maize planted in the 1st, 2nd and 3rd dekad of December

When planting in the 1st, 2nd and 3rd dekads of December the expected maturity dates for the 120-day maize are in the 3rd dekad of March, 1st dekad of April and 2nd dekad of April respectively. The WRSI values for December planting are shown in Figures 5.10, 5.11 and 5.12. WRSI at 20th percentile level show very low WRSI values are over the Lejweleputswa, Motheo and Xhariep districts (Figs. 5.10a, 5.11a & 5.12a) with values of below 40 clearly indicating that water requirements of the maize crop in dry seasons are not met and will probably result in crop failure. The exceptions in these areas include the northern Lejweleputswa (Bothaville area), eastern and southern parts of the Motheo district as well as the southeastern tip of the Xhariep district. The WRSI values over most parts of the Fezile Dabi and Thabo Mofutsanyane districts in dry seasons mostly are between 40 and 60 indicating that the water requirements are met but not to a satisfactory level.

The WRSI values during the years in which the rainfall over the growing season was normal results in below 40 WRSI values for most parts of the southwestern part of Xhariep district (Figs. 5.10b, 5.11b & 5.12b) when planting the 120-day maize in December. The area of extremely low WRSI values extends into the southwestern parts of the Lejweleputswa district when planting in the 1st and 2nd dekads. The exception in this district is over the area along the border with Motheo district extending from Petrusburg to Zastron where WRSI index ranges from 40 to 60 denoting minimal water requirements. WRSI values over the Fezile Dabi, Lejweleputswa and Motheo districts are also mostly between 40 and 60. Most parts of the Thabo Mofutsanyane district and patches around the Bothaville area and eastern Motheo show median WRSI values of up to 80 for all the December planting dekads. In these areas planting maize in normal rainy seasons stands a better chance of reaching its potential productivity.

WRSI values during the wet seasons as depicted by Figures 5.10c, 5.11c and 5.12c show that maize crop can attain a minimum WRSI of 40 over the whole of the Free State. The Xhariep district still has relatively low values of up to 60 with exceptions over the southeastern parts where WRSI values of up to 80 can be achieved. Most parts of the southern and central Lejweleputswa district also show low WRSI values of between 40 and 60 in very wet rainy seasons when planting in the first dekad of December. By contrast, during the 2nd dekad and 3rd dekad planting, it is only the southwestern tip of the Lejweleputswa which shows values of less than 60 at 80% non-exceeding probability. These places are hence not suitable for planting maize due to high incidences of drought realized during the growing period. Most parts of the Fezile Dabi, Lejweleputswa and Motheo districts in wet seasons have high WRSI values of up to 80 during the 2nd and 3rd dekads of planting. The Thabo Mofutsanyane district (except west of Senekal) WRSI in wet rainy seasons during the December planting dates shows high values exceeding 95 in some isolated areas. These show that productivity can be maximized in these planting dekads provided other requirements are also met.

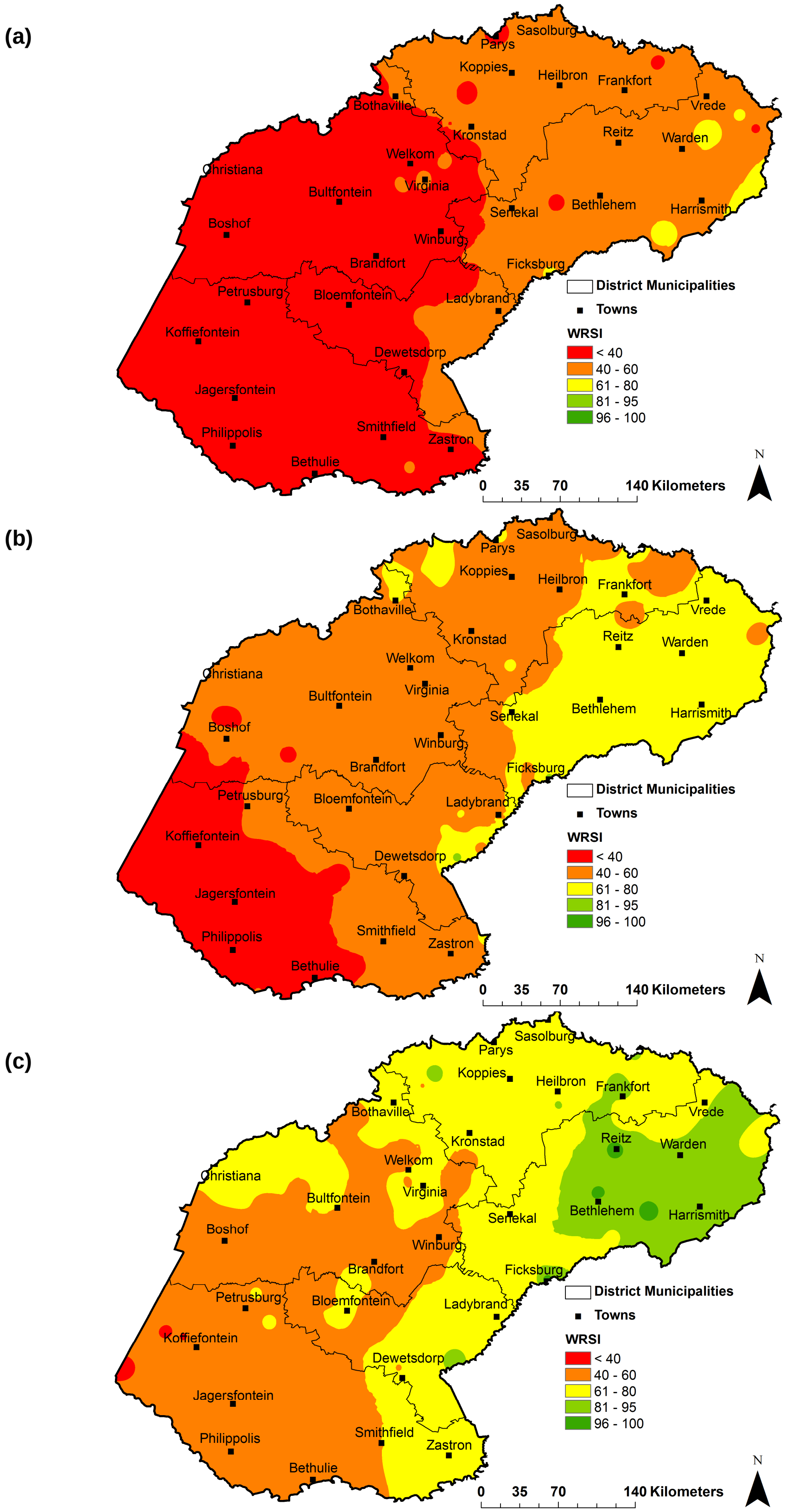


Fig. 5.10: WRSI values corresponding to planting a 120-day maize cultivar in December 1st dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

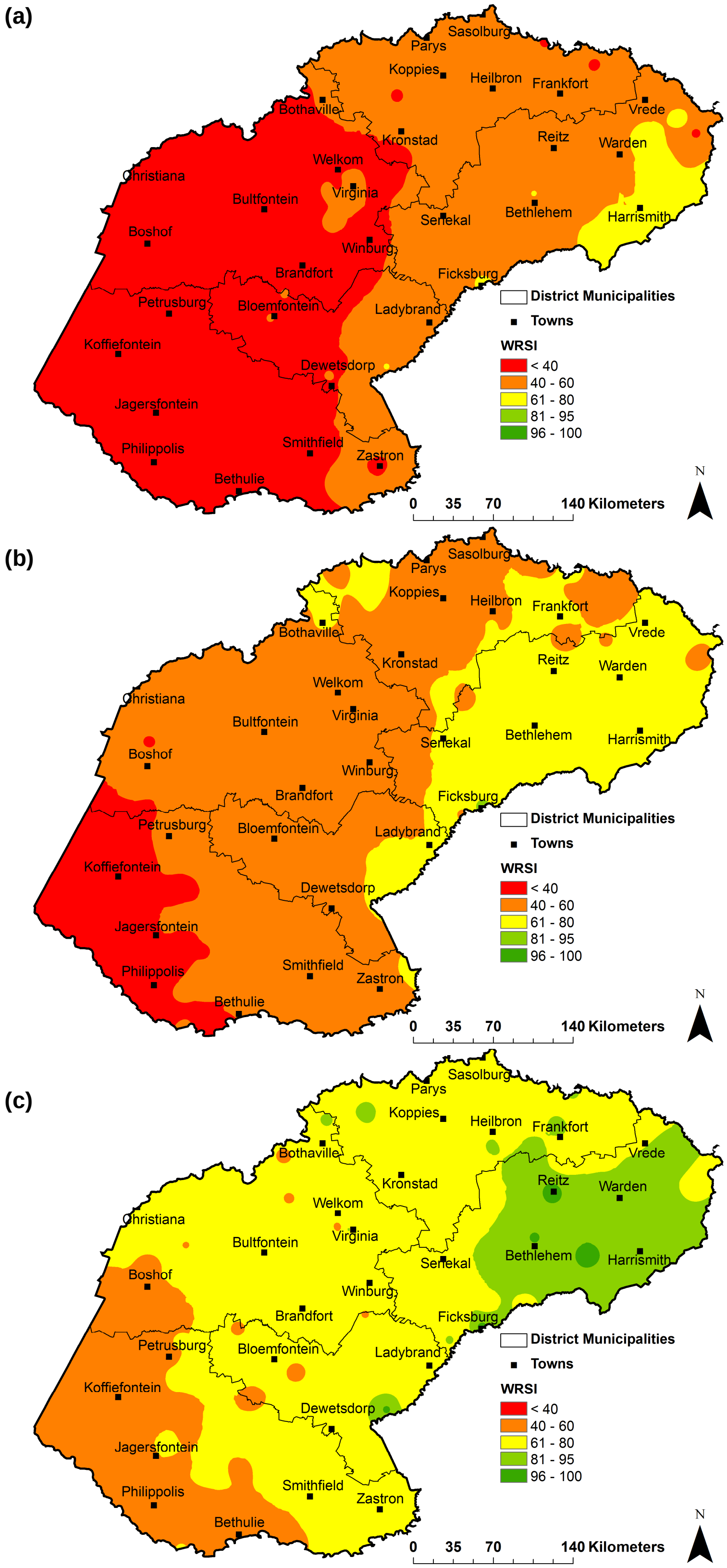


Fig. 5.11: WRSI values corresponding to planting a 120-day maize cultivar in December 2nd dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

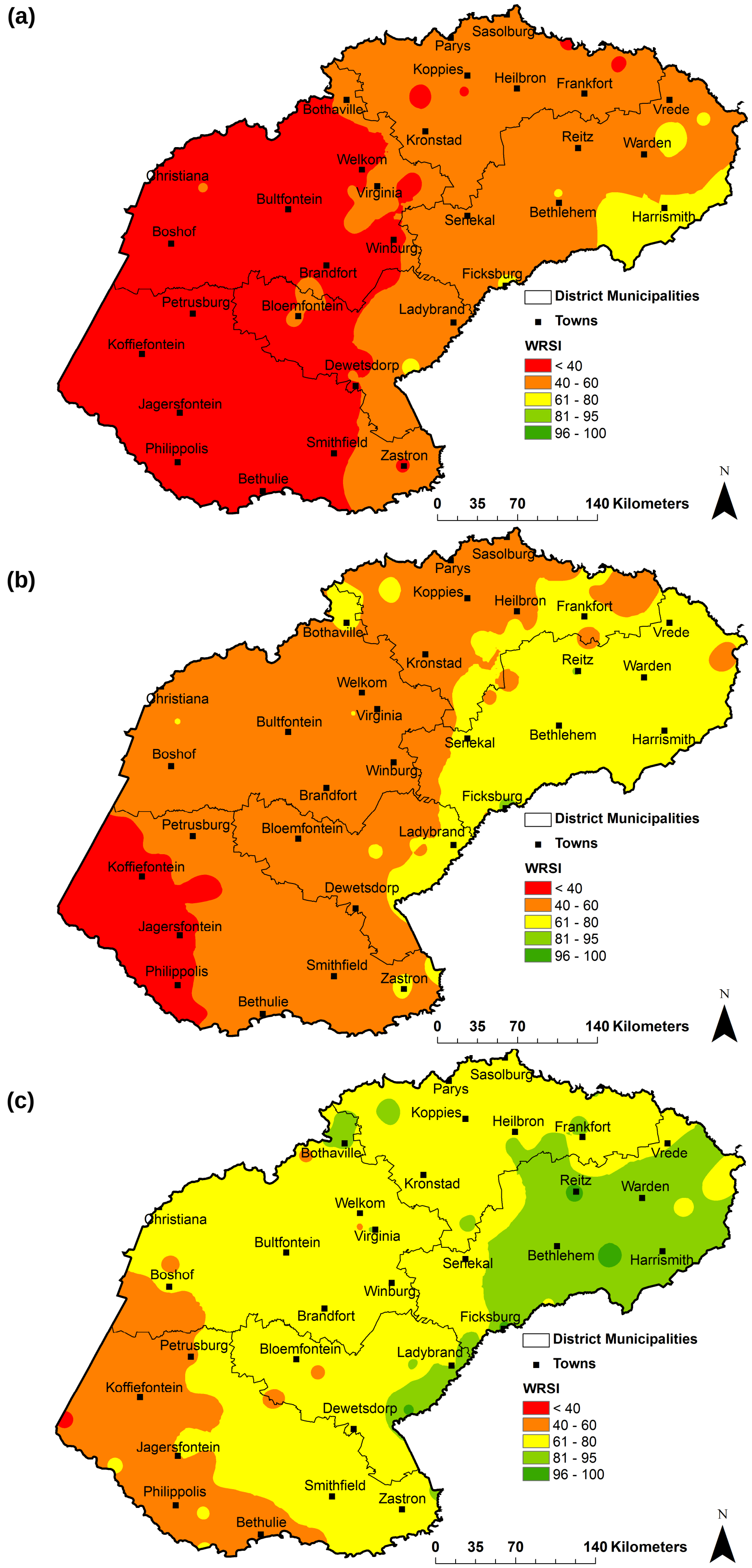


Fig. 5.12: WRSI values corresponding to planting a 120-day maize cultivar in December 3rd dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

5.3.4 WRSI for 120-day maize planted in the 1st, 2nd and 3rd dekad of January

The WRSI maps for the 20%, 50% and 80% probability for planting 120-day maize in the 1st, 2nd and 3rd dekads of January planting are shown in Figures 5.13, 5.14 and 5.15 respectively. The 20th percentile results show that most parts of the Lejweleputswa and Xhariep districts have WRSI of less than 40 when planting in the 1st dekad and 2nd dekad of January (Figs. 5.13a & Fig. 5.14a). Isolated patches of below 40 WRSI is evident over the Fezile Dabi district during the 1st and 2nd dekad planting, but the area increases tremendously to a band stretching northeastwards from Kroonstad through Koppies area to Sasolburg during the 3rd dekad of January planting (Fig. 5.15a). This observation is caused by the fact that cessation of rains occurs in April and May and thus late planting results in some growing periods extending outside the rainy season. Most parts of the Fezile Dabi and Thabo Mofutsanyane districts have their WRSI values in the range of 40 and 60 during the planting dekads of the 1st and 2nd dekads of January.

The median WRSI values for planting the 120-day maize cultivar in all the January planting dekads are below 40 for the area west of Koffiefontein and Jagersfontein in the southwestern parts of the province (Figs. 5.13b, Fig. 5.14b & Fig. 5.15b). Most parts of the Fezile Dabi, Lejweleputswa, Motheo and Xhariep districts have WRSI values ranging between 40 and 60. The exceptions are over eastern parts of Fezile Dabi and Motheo district and a few patches over the Bothaville area where relatively higher (60 to 80) WRSI is obtained. The greatest area of high median WRSI is over the Thabo Mofutsanyane district where also WRSI values of up to 80 can be achieved in 1 out of 2 years. Drought conditions associated with the January planting are minimal in areas where WRSI values of up to 80 are obtained.

The 80% probability WRSI values for planting 120-day maize cultivar in all the dekads of January are mostly between 60 and 80 for the Free State Province (Figs. 5.13c, Fig. 5.14c & Fig. 5.15c). Relatively low WRSI values are only obtained over the southwestern parts of the province (between 40 and 60). In these areas clearly planting of maize is subjected to unfavourable rainy season conditions and thus dryland planting will result in crop losses most of the time. The Thabo Mofutsanyane district mostly has between 80 and 100 WRSI indicating high chances of crop success, except around Senekal, as long as other factors like frost indices are also favourable. Isolated patches of over 80 WRSI are evident over the northern Lejweleputswa district. This area productivity is likely to be maximized during January planting because of less frost incidences experienced in those areas (Chapter 3).

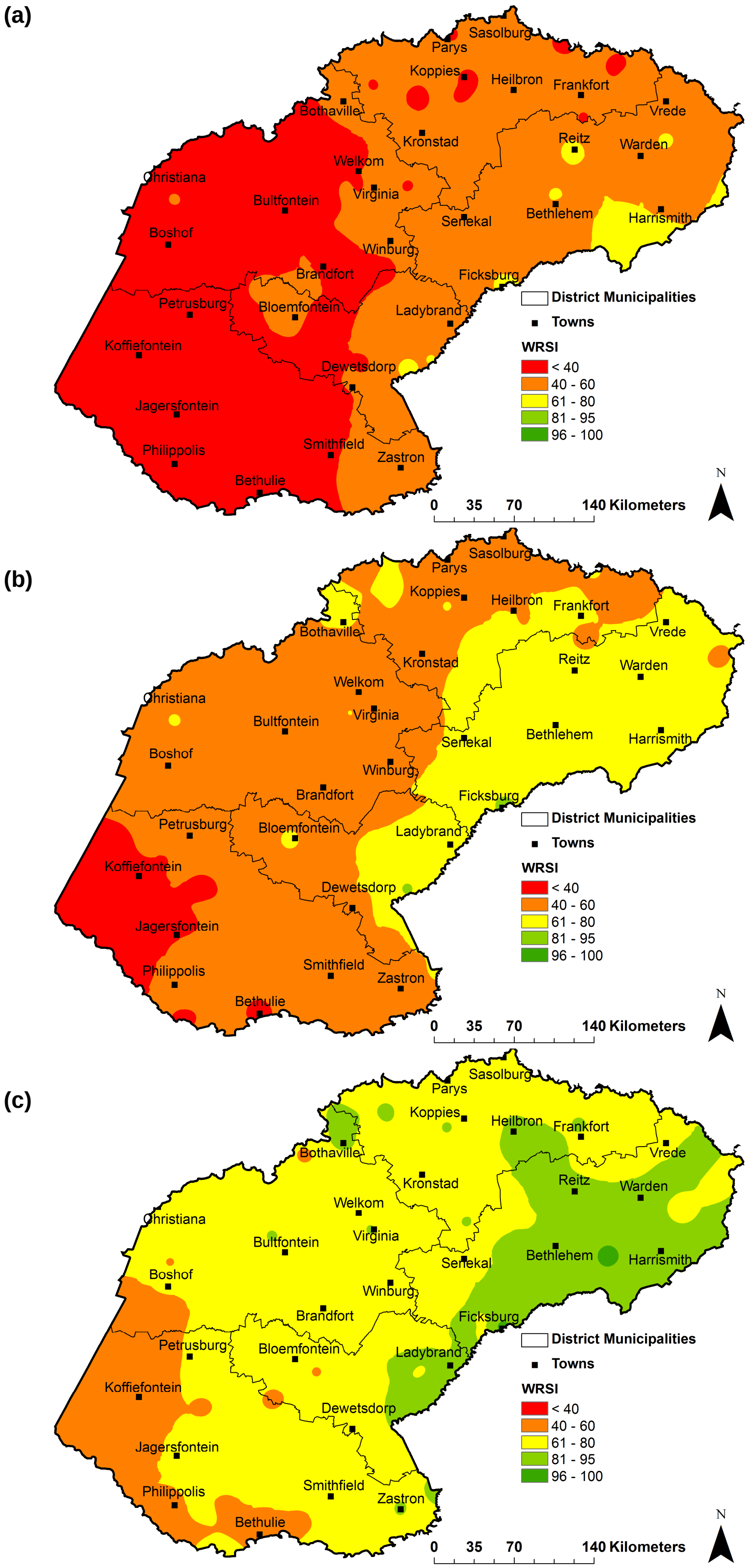


Fig. 5.13: WRSI values corresponding to planting a 120-day maize cultivar in January 1st dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

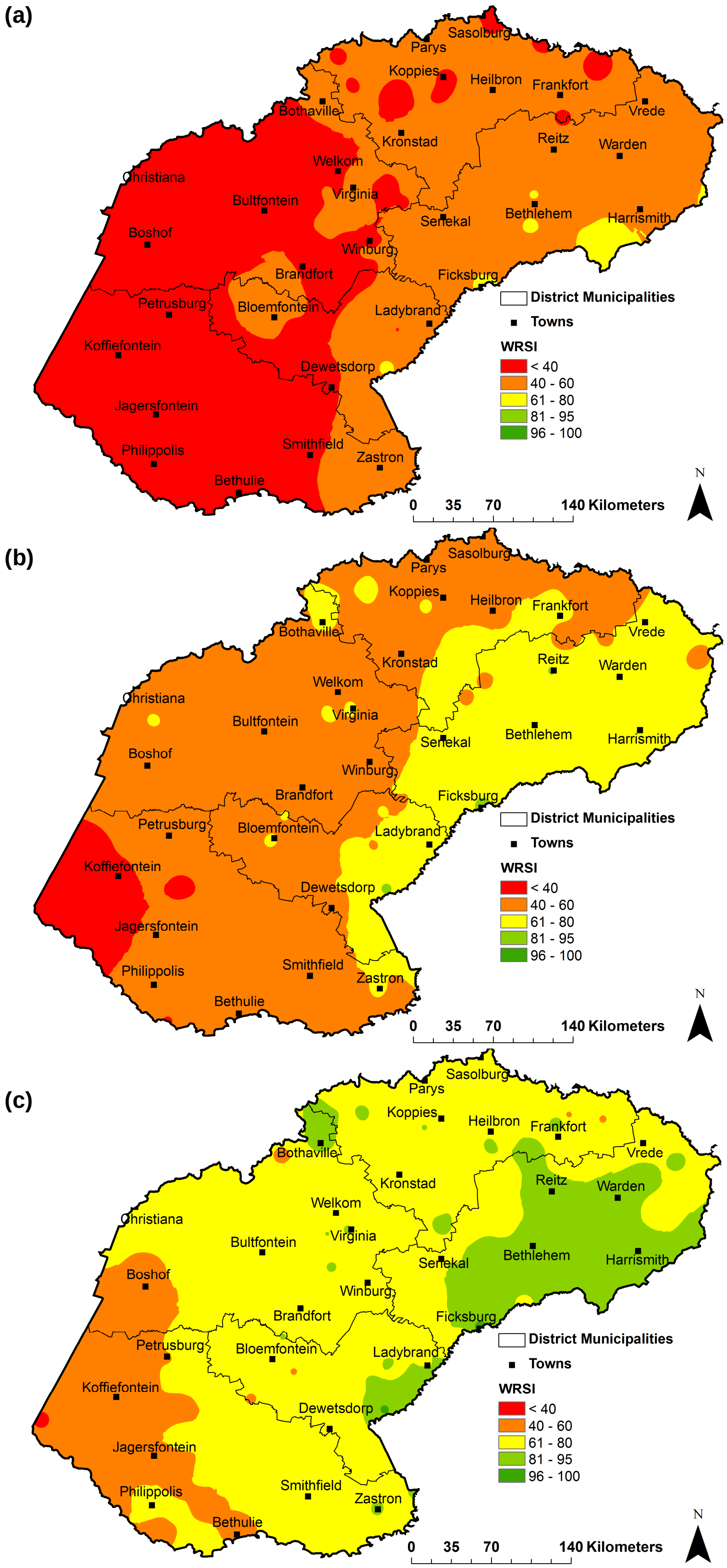


Fig. 5.14: WRSI values corresponding to planting a 120-day maize cultivar in January 2nd dekad at: (a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

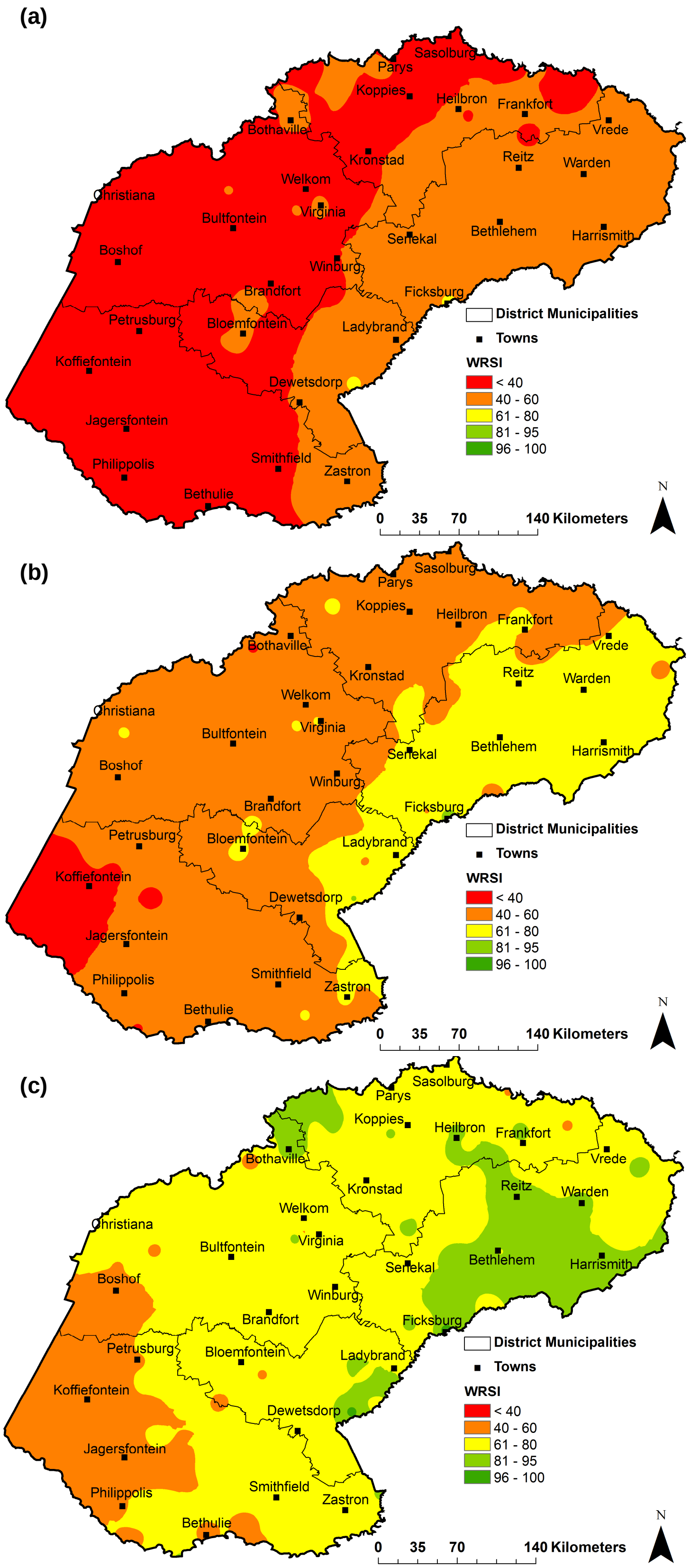


Fig. 5.15: WRSI values corresponding to planting a 120-day maize cultivar in January 3rd dekad at(a) 20%; (b) 50% and (c) 80% non-exceeding probabilities.

5.3.5 Best planting dates per region

The optimal planting dates that minimise crop losses caused by water deficiency extend from mid (11 to 20) November to end of January for the Fezile Dabi district. WRSI for the 120-day maize cultivar at 20% non-exceeding probability is mostly up to 60 while at 80% probability it ranges from 61 to 80 with a few patches in excess of 80 around Frankfort and west of Koppies. The southwestern parts of the district show relatively high incidences of drought with WRSI values at 80% non-exceeding probability reaching up to 60 especially for the early October to early November planting dates. Over the Thabo Mofutsanyane district, the southwestern parts show high vulnerability to agricultural drought with planting dates from early October to end of November having WRSI values of up to 60 even at the 80% probability level. In these areas, the WRSI values increased slightly (WRSI up to 80) during the planting period from the early December to end of January. The area in the vicinity of Bethlehem, Reitz, Warden, Vrede and Harrismith shows relatively low drought conditions during the growing period for an extended period of time. The best planting dates over these areas start from early October to end of January with WRSI at 50% non-exceeding probability being mostly between 61 and 80. At 80% non-exceeding probability WRSI values range from 81 to 95 with few occasions when values exceeding 95. As for the Lejweleputswa district, the far western part (around Boshof and to the west) shows a high chance of crop failure for all the planting periods (October to January) achieving the highest WRSI of 60 at 80% non-exceedence probability. Most parts of the Lejweleputswa district have their best planting periods from mid December to end of January. At 50% probability level, the maize crop is still subjected to severe drought conditions with WRSI values ranging from 41 to 60 during those planting periods. In these areas maize crop will not do well most of the time because water requirements are only marginally met. At 80% probability, WRSI values at those places go up to 80. Areas surrounding Virginia and Welkom in eastern Lejweleputswa are also affected by drought during the growing periods as depicted by WRSI at 50% probability of between 41 and 60 with a few patches exceeding 60 for January planting. The planting window that shows relatively low drought conditions starts in early December till end of January. The most suitable areas in the Lejweleputswa with low risk of drought are in the vicinity of Bothaville. The WRSI at 50% probability for these places from early December planting period to end of January is up to 80 while at 80% probability it can reach 95. Maize during this planting window is expected to flourish because water requirements of the 120-day maize crop are satisfied. Over the Motheo district, the central and western parts show relatively high drought risk especially for the planting period from early October to mid December. In this planting period the WRSI at 50% and 80% does not exceed 60. Planting maize at this window (1 October to 20 December) is not advisable due relatively high drought incidences. Drought during the growing periods subsides for the planting window from mid December to end of January where WRSI at 80% non-exceeding probability can reach 80. Other marginal areas but with extended planting window (mid November to end of January) are over the northern parts towards Winburg and southeast of Dewetsdorp. The most suitable areas in the Motheo district with WRSI at 50% and 80% non-exceeding probability of up to 80 and up to 95 respectively are evident over the eastern parts along the border with Lesotho. The best planting period for these areas extends from mid December to end of January. But care has to be taken when planting in January due to high risk of frost from

March onwards as per the findings in chapter 4. Xhariep district shows a large area of extreme drought conditions during all the growing periods. The highly unsuitable areas for dryland maize production extend from Petrusburg to Bethulie (including Jagersfontein, Koffiefontein and Philippolis). WRSI values at 50% probability level at these places are mostly below 40 for all the planting periods (October to January) investigated. Relatively high WRSI values are obtained over the far southeastern parts where WRSI values at 50% and 80% probability are up to 60 and 80 respectively. The best planting period starts at the end of November to end of January and the area of marginal suitability also increases westwards as time progresses.

5.3.6 Other cultivar lengths

The WRSI for the 100-day and 140-day maize cultivars are more or less similar to the WRSI values for the 120-day maize (Moeletsi *et al*., 2010). Figures 5.16, 5.17 & 5.18 show the drought index (WRSI) for selected stations over the northern, central and southern Free State respectively. It is evident that the drought index for the three cultivar lengths shows the same trend and the differences in the median values for planting dekads from October to 1st dekad of December are sometimes between mild and severe drought. At these three stations, from December 2nd dekad onwards the 140-day cultivar WRSI records relatively low WRSI. This is mainly caused by the decrease in rainfall amounts during the months of March to May. Thus the spatial differences obtained from the 100-day and 140-day cultivar maps would more or less be similar to that of the 120-day cultivar as shown.

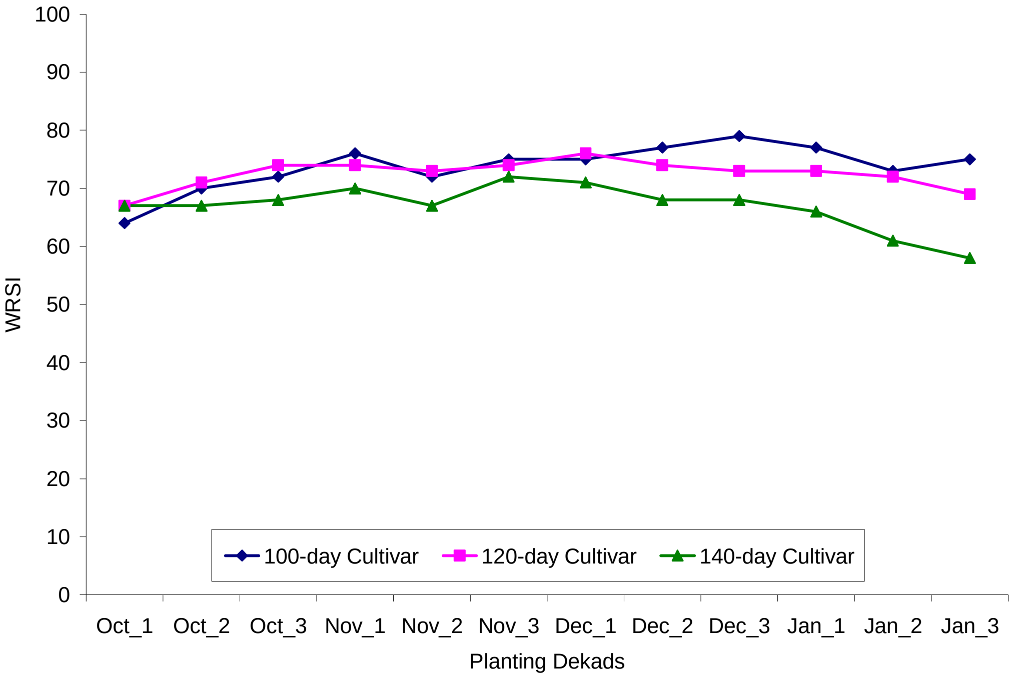


Fig. 5.16: Median WRSI for 100-day, 120-day and 140-day for different planting dates (October 1st dekad to January 3rd dekad) for Frankfort station in the northern Free State.

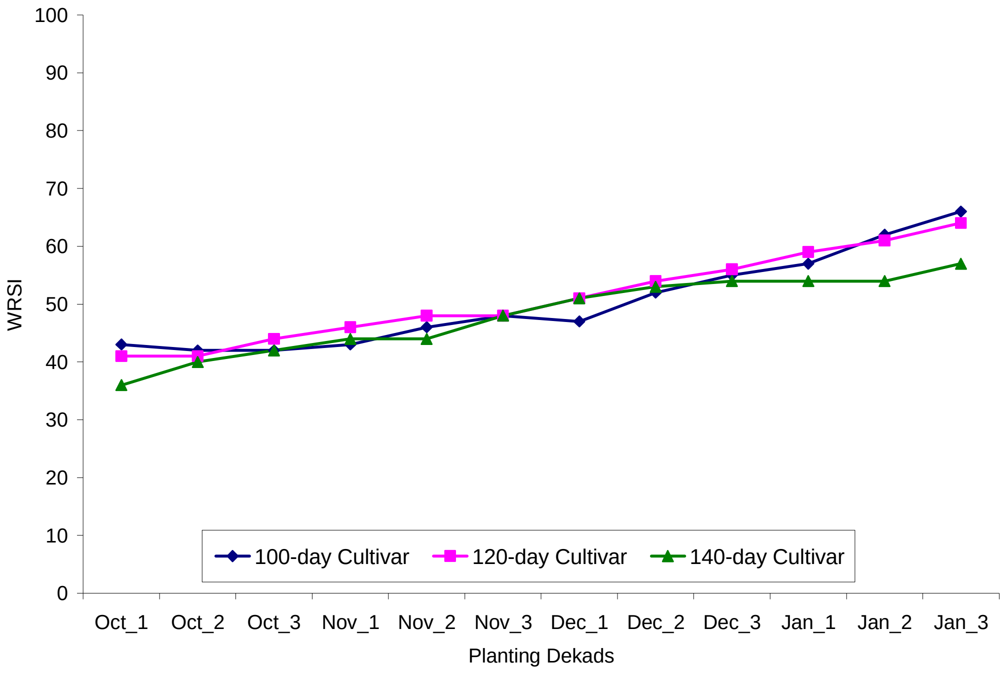


Fig. 5.17: Median WRSI for 100-day, 120-day and 140-day for different planting dates (October 1st dekad to January 3rd dekad) for Bloemfontein (Glen College) station in the central Free State.

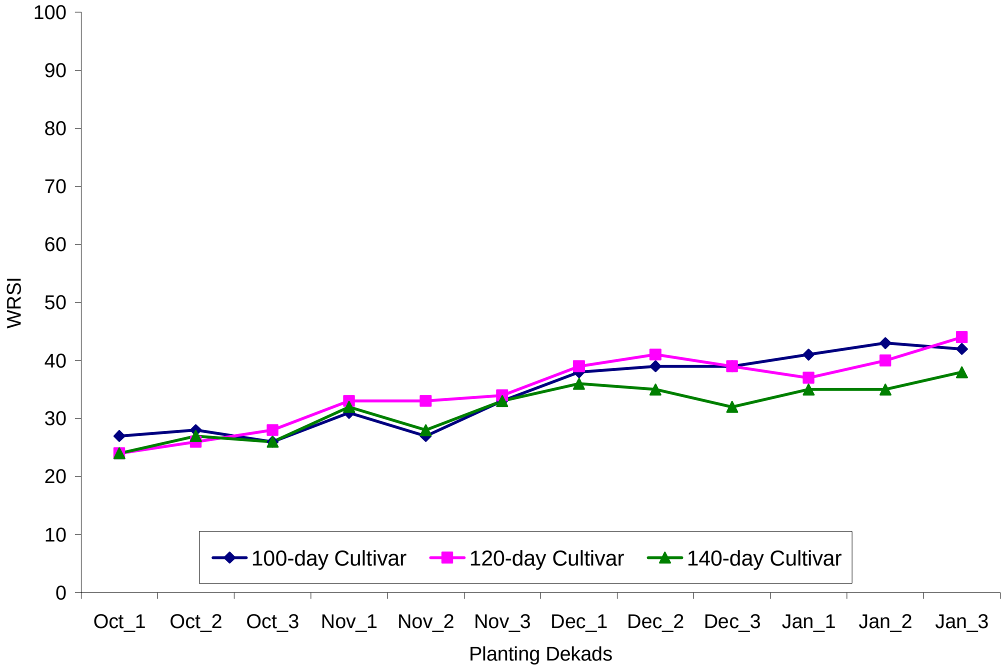


Fig. 5.18: Median WRSI for 100-day, 120-day and 140-day for different planting dates (October 1st dekad to January 3rd dekad) for Jagersfontein station in the southern Free State.

5.4 Conclusions

The analysis of WRSI (drought index) for a 120-day maize cultivar over the Free State Province was investigated for different planting dekads ranging from the 1st dekad of October to the last dekad of January. During the planting dekads of October, places with high chance of crop failure attributed to drought are over most parts of the Lejweleputswa, Motheo and Xhariep districts. In these areas WRSI values of less than 40 were obtained during the 50% and 80% non-exceeding probabilities. Places like Bethlehem, Reitz, Warden and Vrede show relatively high WRSI values of up to 80 for the median and 80% non-exceeding probability risk levels indicating that chances of crop water requirements of the 120-day maize being met are relatively higher. Other regions show marginal water requirements satisfaction and thus are also prone to drought. For November planting, areas of high WRSI increased slightly but with more or less similar spatial distribution of WRSI values as that of October. It is for December and January plantings where the whole of the Free State showed an increase in WRSI values implying that the water requirements of the maize crop are better matched to rainfall received during the growing periods starting at those months.

Overall, the area with WRSI below 40 at all the risk levels was only confined to the west of Koffiefontein, Bethulie, Philippolis and Jagersfontein over the southwestern parts of the Free State in most planting periods. In these areas planting maize at any time of the year would clearly result in crop failure in most years because of unfavourable rainfall characteristics. Most parts of the Free State Province record WRSI values between 40 and 60 at 50% probability level and between 61 and 80 at 80% probability level from December 2nd dekad to January 3rd dekad planting periods. These areas include most parts of the Lejweleputswa district, central and eastern Xhariep and western and central Motheo district. In these areas, maize water requirements are marginally met and planting maize under dryland conditions will subject the crop to severe drought but the use of drought tolerant varieties have the potential of increasing maize production. The other area of marginal maize water satisfaction is over the eastern Motheo, far southeastern Xhariep and southwestern parts of the Thabo Mofutsanyane districts but the best planting window in these areas extends from the 1st dekad of November to 3rd dekad of January. Most parts of the Fezile Dabi district also show marginal areas extent from the planting values are in most parts of the Lejweleputswa and Xhariep districts and western parts of the Motheo district. These areas are also categorized as drought-prone areas and thus planting of maize has to be done only if drought resistant maize varieties are used. As for most parts of the Fezile Dabi district and patches over the northern Lejweleputswa district (Bothaville area), these areas can achieve WRSI values of up to 80 especially during the planting dekads from the 2nd dekad of October to January. In these areas there are patches of WRSI exceeding 80 from the 2nd dekad of November to 3rd dekad of January planting periods for the Fezile Dabi district while for the Bothaville area these best planting periods are between the 2nd dekad of December to end of January. Hence one can conclude that maize planted in these places during that period stands a good chance of yielding better. High potential areas are evident over the Thabo Mofutsanyane district (areas surrounding Bethlehem, Reitz, Harrismith, Ficksburg and Warden) where WRSI values during dry years can reach up to 80 especially from planting during the 2nd dekad of November to 2nd dekad of January. During the wet seasons WRSI exceeding 95 can be realized in these places with plantings from 11 November to 20 January. It is fitting to conclude that these areas are the most suitable as far as the water requirements of the 120-day maize is concerned. However, maize planted in late December and the whole of January can be subjected to high frost incidences at maturity especially in high lying areas and thus careful consideration of first frost dates has to be included when planting (Moeletsi et al., 2009c).

The next chapter determines the suitability of maize crop using frost index from chapter 3, rainy season index in chapter 4 and drought index in chapter 5.

Chapter 6: Combined Climate Risk Assessment

6.1 Introduction

The main challenge the agricultural community is facing is to ways to use climate information for risk management strategies in order to increase preparedness and reduce vulnerability to climate variability (Meinke *et al.*, 2003). Climate risk management may include the prediction of the likely weather related hazards as well as determining the measures that can be used to minimize that risk to a level that can be managed (Ramesh, 2010). Diga (2005) acknowledged that there are different ways of assessing risk. Each method developed is appropriate for particular circumstances and thus, one should know the advantages and disadvantages of the method of choice. Assessment of risk associated with climate variability and extreme weather events on agricultural production is beneficial in determining the scheduling of agricultural activities for optimum production (Andre *et al.*, 2007).

Due to high climate variability in arid and semi-arid regions of developing countries farming is very risky (Ramesh, 2010). The main climate risks that affect maize production in the Free State are droughts, floods, hailstorms, frost risk, heat waves and low temperatures resulting to inadequate heat units. Among these climate risks, farmers mostly have a fear for drought because it can occur frequently and for an extended period depending on the locality (Lourens, 1995; de Jager *et al*., 1998; Guiroga & Iglesias, 2009). In order to reduce impacts of the climate risks and increase agricultural yield, farmers have to understand the climate of their locality and possible hazards that can be experienced. According to Das & Stigter (2010) it is important to develop the risk management strategies that will ensure prepardness in cases of climate disasters. According to Rockström (2003) climate hazards like droughts occurring in developing countries have a negative impact on food security and poverty because many of the people in these countries are dependent on small-scale farming which is mostly rainfed.

In agriculture the environmental factors which determine the suitability of specific crops mostly cannot be controlled or changed and thus plants should be cultivated in areas where the conditions suit their climatic requirements (Allemann, 1997). Climate conditions differ significantly from one place to another, in one place one element can be the most limiting factor to productivity while the same climate parameter can be at optimal level in another place but another weather element is a constraint in that place. Agroclimatological zoning is defined as the division of a certain area into several zones, according to the degree of favourability for growing a given crop considering climate factors (Todorov, 1981). Agroclimatological suitability is a useful tool for agricultural planning of new lands that need to be brought under cultivation and also for using old land resources more judiciously (Bishnoi, 1989). Agroclimatic classifications have proved to be of great utility for planning and management of various agricultural and forestry activities (Yazdanpanah *et al.*, 2001).

According to Oche (1998) different views regarding the climate factors to use when determining suitable areas for planting a certain crop have lead to different approaches or techniques for agroclimatic zoning. Zullo *et al.* (1999) used water supply at reproductive stage of the cotton crop to determine the climate risk zoning in Sao Paulo due to the fact that agricultural drought is the main climate risk affecting productivity of cotton in that area. Geerts *et al.* (2006) used reference evapotranspiration, length of rainy season, intra-seasonal dry spells and frost risk to perform the agroclimatic suitability mapping of quinoa crop in the Bolivian Altiplano. In their paper on “agroclimatic zoning of zoning of Azarbayjan-Sharghi province for rainfed almond using GIS” Yazdanpanah *et al.* (2001) used the following climate indices to delineate the most suitable area: 1) Probability of chilling occurrence on bud and flower of Almond; 2) Probablity of rainfall greater than 250mm; 3) Spring and summer precipitation to annual precipitation ratio; 4) Probablity of occurrence of growing degree days greater than 3500 G.D.D (base temperature 0^{o}Celsius) and 5) Amount of available moisture index. Ceballos-Silva & Lopez-Blanco (2003) used combination of climate and physical properties in their study of delineating suitable areas for planting maize and potato in central Mexico. The indices used were 1) minimum temperature; 2) precipitation; 3) soil depth; 4) soil texture; 5) pH of the soil; 6) slope of the terrain; 7) altitude and 8) maximum temperatures. White *et al.* (2001) used the ratio of rainfall to potential evapotranspiration, rainfall, minimum temperatures and maximum temperatures in “Agro-climatological Charecterization of Bread Wheat Production Areas in Ethiopia”. It is clear from all these examples that the number of different indices that were used to determine the climate suitability for a certain crop is not important but the use of significant indices which have adverse impact on productivity is key.

The aim of this part of the study is to first develop a simple agroclimatic risk index by combining three main climate risks namely rainy season onsets, frost and drought. The other objective is to use the index to perform an agroclimatological suitability mapping for maize in the Free State province.

6.2 Data and methodology

6.2.1 Data

The weather stations used in this study are distributed evenly across the Free State as shown in Figure 6.1. The data used is from 1950 to 2008. This investigation needs three kinds of dataset 1) frost probability during the growing period, 2) agricultural drought index (WRSI) and 3) non-exceeding probability of onsets of rains. The maize cultivar that was used in this study is the medium season that requires 1420 growing degree days to reach maturity. The suitability of maize over the Free State depends very much on the length of the growing period which is linked to heat unit requirements. Thus the findings and recommendations of this chapter will apply to this cultivar. Maize cultivars planted over the Free State vary a lot in their growing degree requirement and thus results obtained from this study are not universal but are specific to the above-mentioned cultivar. The probability of the onsets of rain is constant at each planting dekad and is obtained from the results of chapter 4. Frost–free probability at 0^{o}C (medium frost) is taken from results in chapter 3. The WRSI of medium season maize variety at three probability thresholds (20%, 50% and 80%) will be used.

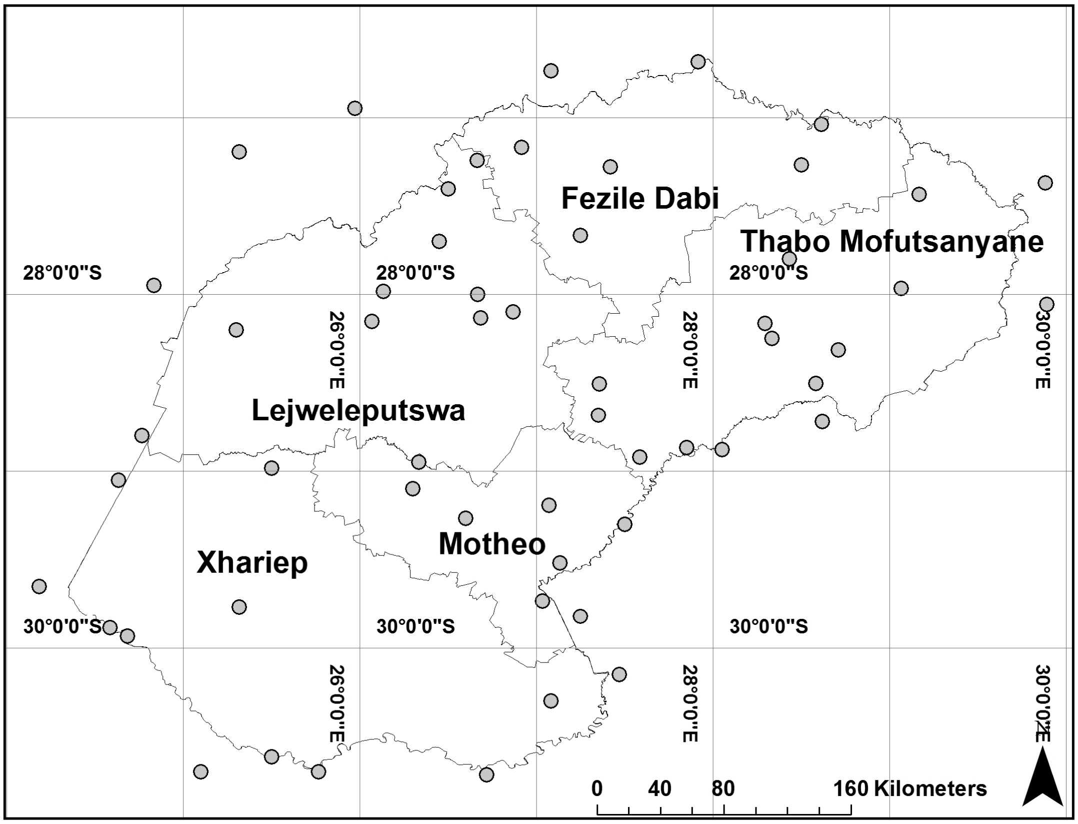


Fig. 6.1: Weather stations locations used in the study of climate risk zoning of rainfed maize production in the Free State Province, South Africa.

6.2.2 Development of a combined climate risk index

6.2.2.1 Rationale

In the previous chapters there has been an effort to investigate different climate risks over the Free State and their spatial distribution over the Province. Chapter 3 paid attention to frost risk assessment, chapter 4 looked at rainy season characteristics like onsets of rains while chapter 5 dealt with agricultural drought using WRSI. Combining all these three risk factors will enable one to have a complete picture of the effects of climate on rainfed maize production. It has been documented in the past that frost has adverse effects on crop production over the Free State mainly attributed to high altitude and undulating valleys present in the provinces' topography (van der Berg *et al.* 2002; Schulze *et al*. 2007). In chapter 3, it is concluded that, the effects of earlier than normal first frost and late cessation of frost on the maize crop at sensitive stages of grainfilling and early vegetative stage respectively have a negative impact on maize production in the Free State. The onset of rains plays a major role on the performance of the crop and failure to plant at the right time might lead to water stress at early stages of the crop or total crop failure, requiring re-planting which would have a major economic impact. In the Free State it is important to plant maize during or after significant rains (Tadross *et al*. 2003) and avoid the mistake of planting too early after receiving insufficient rains.

Agricultural drought is one of the main climate risks affecting maize production in the Free State (du Pisani, 1987; Lourens, 1995; de Jager *et al.*, 1998; Martin *et al.*, 2000; Rounalt & Richard, 2003). Martin *et al.* (2000) elaborated on the importance of aligning maize production to the growing periods that are associated with the least climate risk.

6.2.2.2 Poone AgroClimatic Suitability Index (PACSI)

Taking into consideration the factors outlined in subsection 6.2.2.1, a climate risk index for maize production was built on the onset of rains, frost risk and drought risk. These indices were chosen in consultation with experts in maize production and its relation to climate risks. The name given to the index is Poone Agroclimatic Suitability Index (PACSI) for Free State. The name "Poone" is borrowed from the Sesotho (indigenous language widely spoken in the Free State province) translation for "maize". Planting is desirable when the risk of false onset is low, frost risk during the growing period is low and likelihood of drought during the growing period is minimal. The relevent index for onset of rains used in this study is the non-exceedence probability of onset of rains at a particular planting date. In chapter 4, onset of rainy season is defined as the date in which the last ten days has accumulated 25mm and the following 20 days also records 20mm or more. This value is constant for that planting date regardless of the length of the cultivar planted (i.e not dependent on a crop). The probability of frost occurring during the maize growing period was used in this methodology. In chapter 3, three different frost thresholds were used representing light (2℃), medium frost (0℃) and heavy frost (-2℃). For this purpose the medium frost will be used because maize crop can be seriously be damaged by temperature at 0℃ or below (Carter & Hesterman, 1990; Trasmonte *et al.* 2008). The agricultural drought methodology as developed in chapter 6 will be adopted as it is. The Poone agroclimatic index has weights and since all the three indices chosen have a significant impact on productivity, almost equal weights will be assigned with drought having a slightly higher weighting. This conclusion was made after consulting the experts and other scientists are still being engaged to validate this decision. The onsets of rain and frost indices have been given 30% weights each with drought having 40% weight as shown in Table 6.1 below.

Table 6.1: Weights allocated to the climate risks used in the Free State Maize agroclimatic index.

Climate Risk	**Weights**
Onset of rains	0.3
Frost	0.3
Drought	0.4

The resulting index is given in equation 6.1.

$$PACSI = O*0.3 + FF*0.3 + D*0.4 \tag{6.1}$$

where:

O is the probability that planting conditions are met, FF is the probability of frost–free growing period and D is the drought index (WRSI).

Conditions for the PACSI

If O and/or FF and/or D is less than 40 then the Index is set to the lowest value obtained from individual indices if and only if it is lower than index value obtained from equation 6.1. This is due to the fact that, that particular climate risk has now been the most limiting factor. But if all the indices are over 40 then one uses the result of the equation 6.1.

All the indices have the scale of 0 to 100, with 100 being the most ideal situation for the maize crop to flourish and values below 50 indicating total failure of the crop due to climate constraints. The Poone index is interpreted as in Table 6.2.

Table 6.2: Poone agroclimatic suitability Index categories and interpretation

Index Categories	Interpretation
< 50	Total crop failure
51 – 60	Likely to fail
61 – 70	Slightly Suitable
71 – 80	Moderately suitable
81 – 90	Suitable
> 90	Highly suitable

6.2.2 Calculation of PACSI

The probability of frost for 100-day, 120-day and 140-day maize cultivars for Bethlehem is shown in Fig. 6.2. The graphs for all other places have the same trajectory with the probabilities during the first half of the agricultural window being the same for all the cultivar lengths owing to the fact that frost risk is high during the early stages of the crop at that time (Fig. 6.2). Planting in February onwards is not advisable due to high risk of frost even for short season variety. Figure 6.3 shows the variation of the drought index for all possible planting dates starting on the 1st dekad of October to 3rd dekad of January. The non-exceedence probability of onsets of rains for Bethlehem is shown in Fig. 6.4. During the second half of the season the probabilities start to differ depending on the cultivar length with longer cultivars being prone to frost at the end of the growing period. The drought index used is median WRSI for the 100-day, 120-day and 140-day maize cultivars. Note that these values are based on fixed cultivar lengths (100-day, 120-day & 140-day). However the maps generated in subsection 6.3 are based on the maize variety requiring 1420 GDD from planting to maturity implying that the length of the crop will change between growing seasons depending on temperatures. The results obtained for this illustration is given in Fig. 6.5 with distinct feature of significant drop in the suitability index after December caused by high frost incidence.

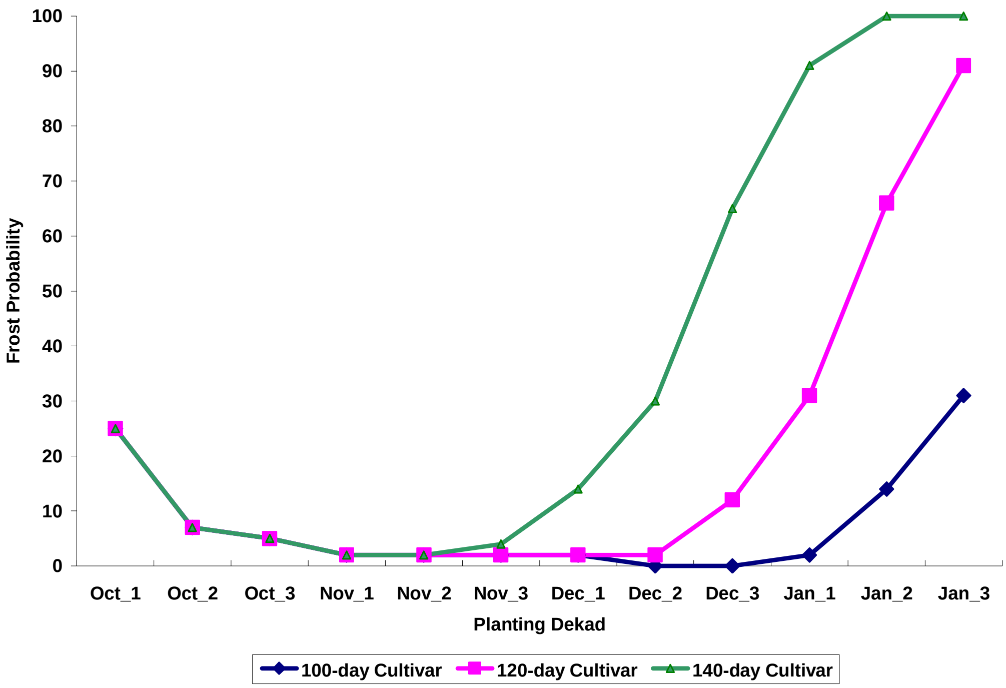


Fig. 6.2: Frost probability during the growing period of 100-day, 120-day and 140-day maize cultivars for the planting window from 1st dekad of October to 3rd dekad of January for Bethlehem station.

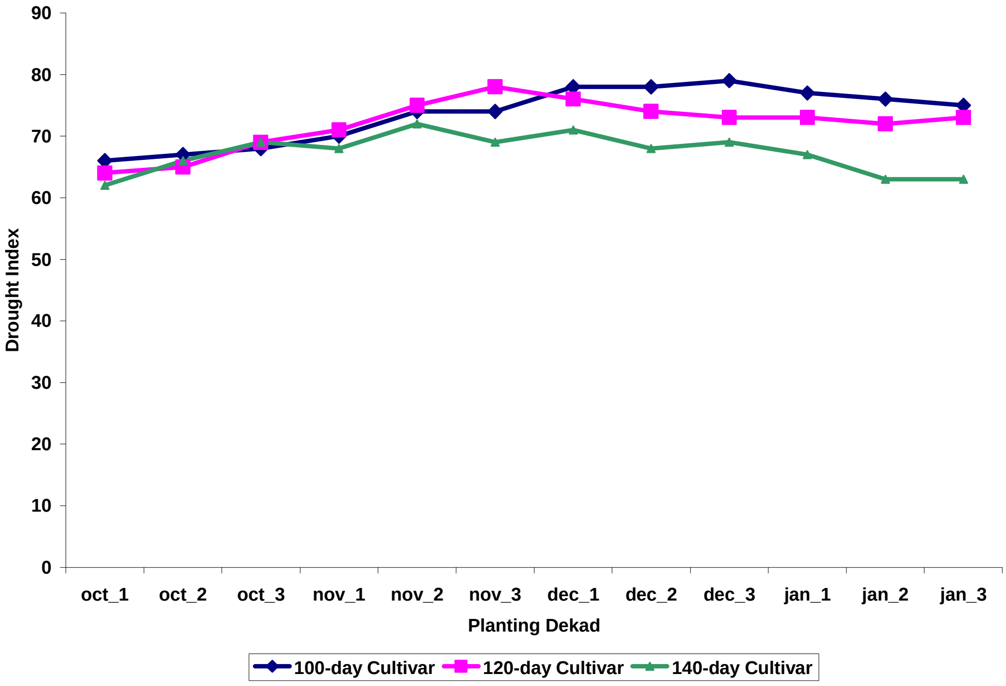


Fig. 6.3: Median drought index for 100-day, 120-day and 140-day maize cultivars for the planting window from 1st dekad of October to 3rd dekad of January for Bethlehem station.

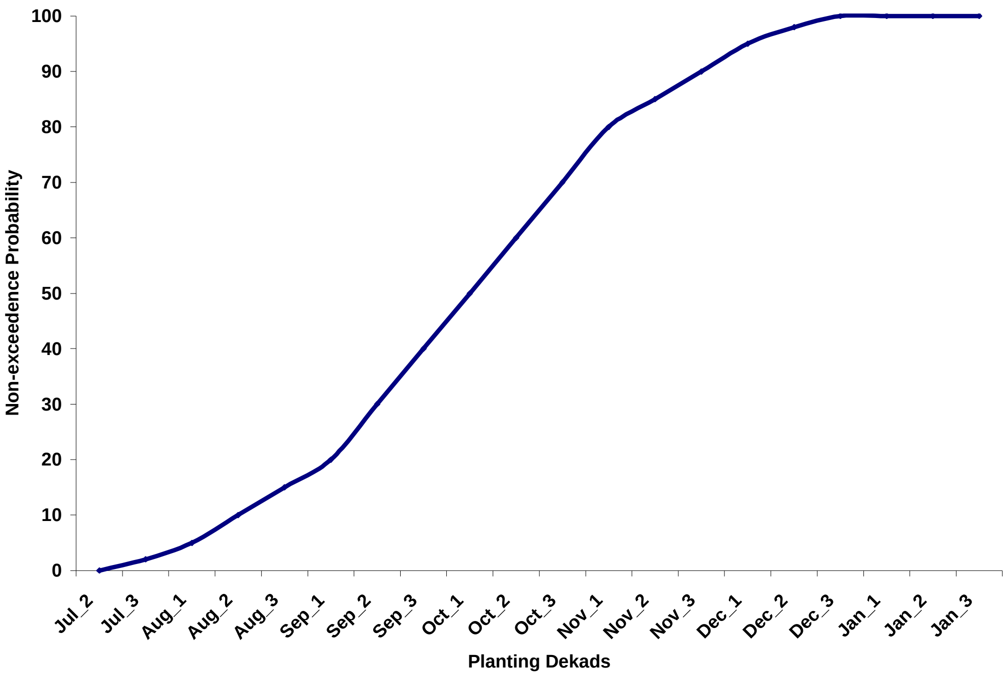


Fig. 6.4: Onset of rains probability of non-exceeding for the planting window from 1st dekad of October to 3rd dekad of January for Bethlehem station.

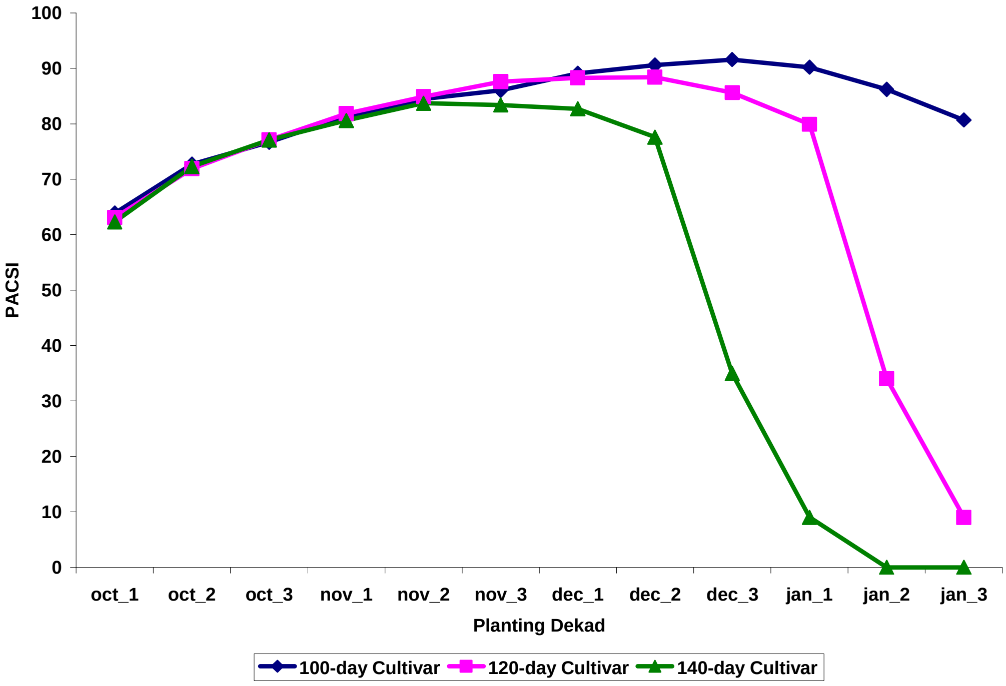


Fig. 6.5: PACSI for 100-day, 120-day and 140-day maize cultivars for the planting window from 1st dekad of October to 3rd dekad of January for Bethlehem station.

6.2.3 Mapping

All the interpolations of the index for the planting window from 1st dekad of October to 3rd dekad of January was done using the ArcGIS 9.3. The inverse distance weighting model was used for all the interpolation.

6.3 Results and discussion

The maps shown in this section are the results of the PACSI values calculated using the absolute frost probability during the growing period, non-exceedence probability and WRSI (drought index) at 20%, 50% and 80% probability level. Thus, three maps are generated at the three levels of drought index.

6.3.1 PACSI for Maize planted in the 1st, 2nd and 3rd dekad of October

The maize agroclimatic suitability map obtained from using the PACSI for the planting dates of October 1st dekad are shown in Fig. 6.6 (a), (b) and (c) for the suitability at 20%, 50% and 80% probability level respectively. During dry seasons medium season variety maize (with growing degree days requirement of 1420GDD) planted in the first dekad of October shows suitability index less than 50 in the most parts of the Province (whole of Fezile Dabi, Lejweleputswa, Motheo and Xhariep districts) (Fig.6.6a). In these areas maize planted in this planting date is expected to fail in drier than normal growing seasons. The main factor for crop failure in these places is later rainfall onsets and high drought risk at 20% level. The exception is over the Thabo Mofutsanyane district over eastern parts of Free State where the suitability index can reach up to 70. At these places especially around Vrede, Warden, north of Harrismith, early-planted maize is slightly suitable considering all the inputs to this combined index (onsets of rains, frost and drought index). Over these areas even in dry periods the drought index is still relatively high compared to other areas (Chapter 5). During the second dekad of October planting, the area of the province showing total crop failure (PACSI < 50) is reduced especially in Fezile Dabi district where PACSI values reaching 70 can be realized even at 20% drought level (Fig.6.7a). Over the Thabo Mofutsanyane district, there are patches over the far eastern parts with PACSI values exceeding 70. These areas show moderate sutability for planting maize crop under dryland conditions. It should be noted that successful planting is done when the onset criteria discussed in chapter 4 is met, implying that in the same dekad or previous dekad (still significant soil water available) significant rains were received. Dry seeding is thus not advised even though in dry years the Index is still high in these areas. As for the PACSI obtained at 20% drought probability level for 3rd dekad of October planting (Fig. 6.8a), values showing crop failure are still evident over the Lejweleputswa, Motheo and Xhariep districts. In contrast, almost the whole of the Fezile Dabi and Thabo Mofutsanyane districts (except the southwestern parts of these districts) show relatively high PACSI values. Thus, maize planted in 2nd and 3rd dekad of October is likely to yield better than maize planted in the 1st dekad according to the PACSI classification.

The PACSI for the median drought (Figs. 6.6b, 6.7b & 6.8b) clearly shows that the Fezile Dabi, Lejweleputswa and Motheo districts are less suitable for planting maize in October. The PACSI values obtained are mostly below 50. In the Fezile Dabi district, only maize planted in the first dekad of October shows low suitability values at 50% probability level. The 2nd dekad and 3rd dekad of October planting dates show a great improvement in this district with values of up to 70 being obtained. This is attributed to increased probability of adequate rains to start the agricultural season, reduced frost risk over the growing period and improved median WRSI (drought index). PACSI index over the Thabo Mofutsanyane district show values mostly of between 51 to 80 with low values towards the southwestern parts of the district and values exceeding 70 over the eastern parts of the district. Over the far southwestern parts (areas in the vicinity of Senekal and to the west), the index is below 50 indicating unfavourable conditions for maize planting in October. In the 2nd dekad and 3rd dekad, the suitability area increased over the district and extending wetwards across the province.

During the wet seasons (80% WRSI probability), the PACSI values obtained show the same spatial distribution as that obtained from the 20% and 50% probability levels. Still the values obtained from the Xhariep and Motheo districts show low values at same locations indicating unsuitability in all the October planting dekads. Lejweleputswa district also have great area unsuitable for maize production over the October planting especially the 1st and 2nd dekad plantings. In the third deakd planting areas around Bultfontein, Welkom and Virginia show an improved index showing marginal suitability (61-70) of planting maize according to the PACSI. The Thabo Mofutsanyane district had values exceeding 60 over the whole district for the 2nd dekad and 3rd dekad plantings while in the 1st dekad places over the southwestern parts (west of Senekal) are highly unsuitable mainly due to late onsets of rain and low drought index.

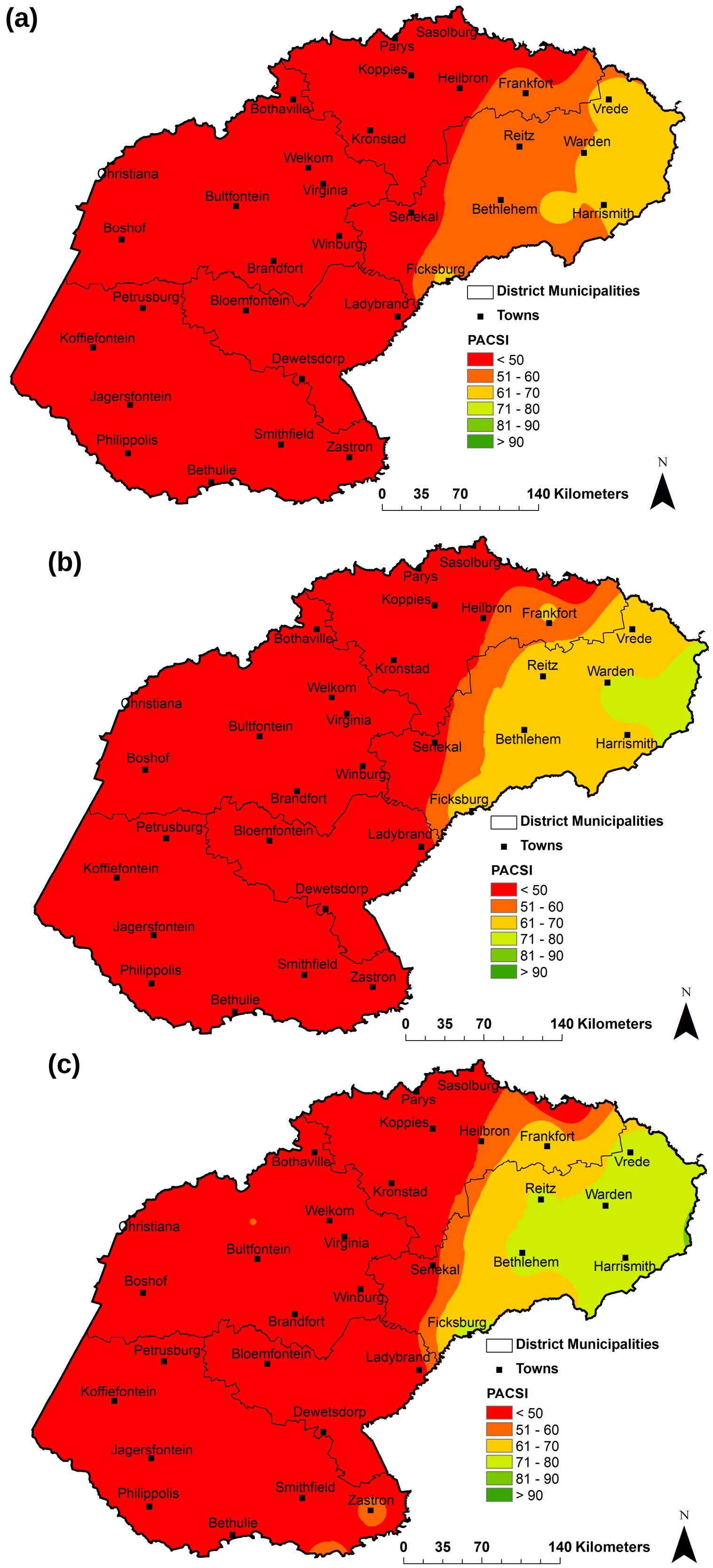


Fig.6.6: PACSI values corresponding to October 1st dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

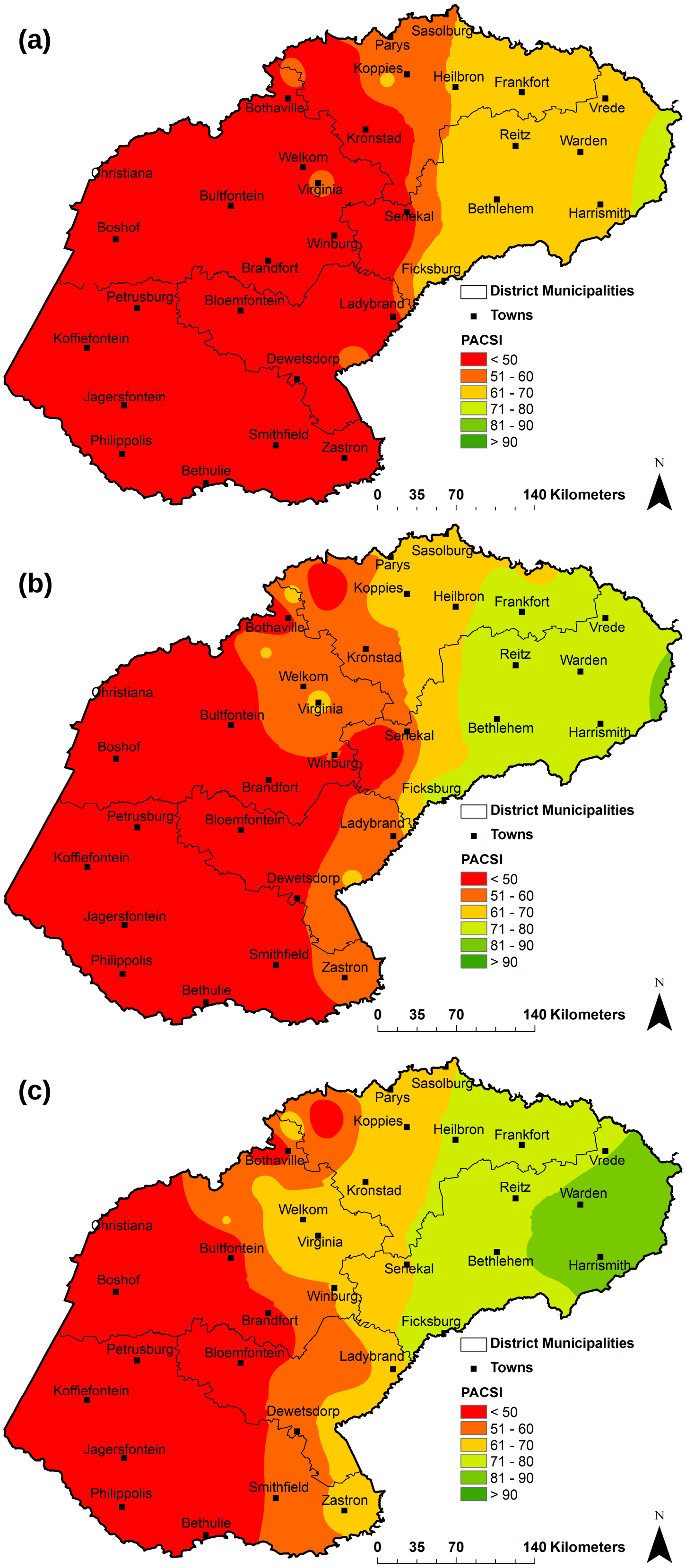


Fig. 6.7: PACSI values corresponding to October 2nd dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

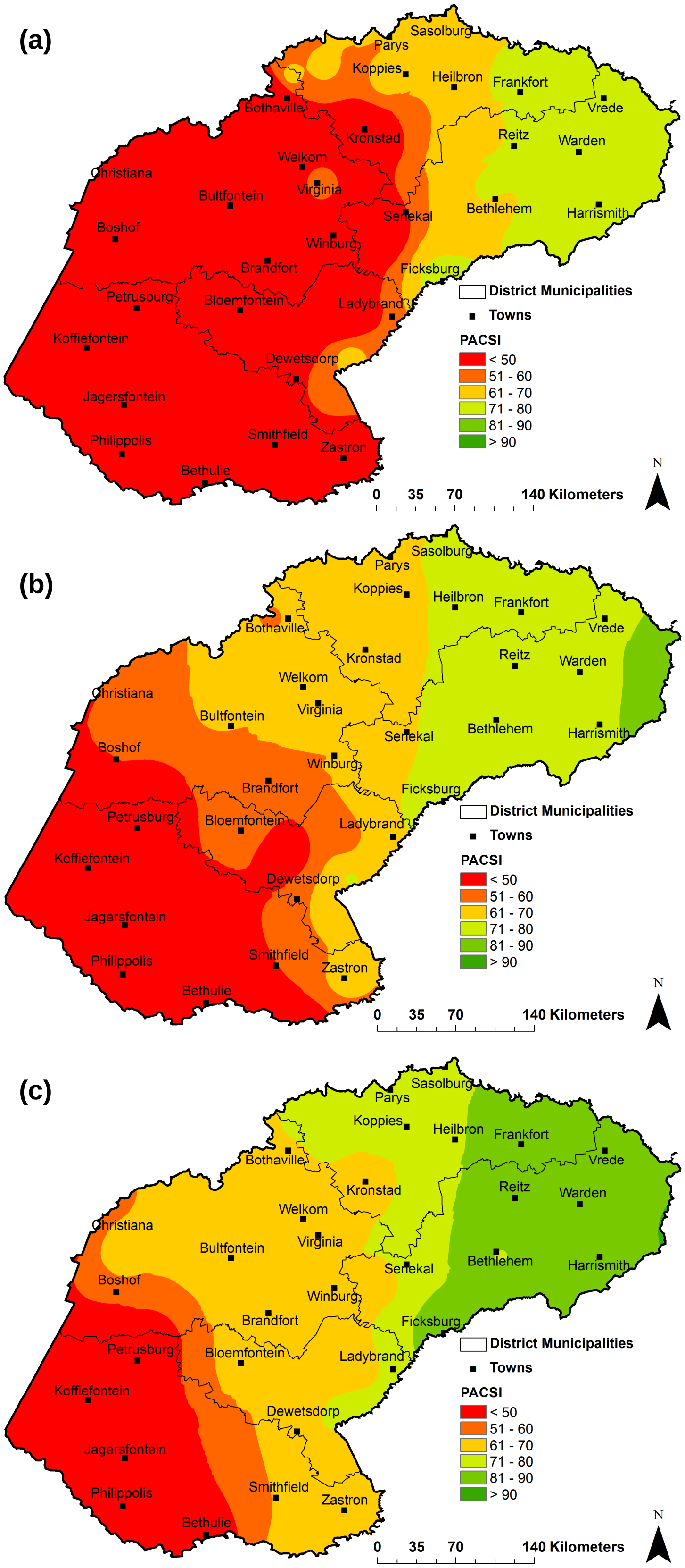


Fig. 6.8: PACSI values corresponding to October 3rd dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

6.3.2 PACSI for Maize planted in the 1st , 2nd and 3rd dekad of November

During the November plantings (Figs. 6.9, 6.10 & 6.11), the variation of the PACSI is great over the province. For the 20% probability level, in the 1st dekad of November, suitable areas are more or less similar to the scenario obtained in late October plantings whereby Thabo Mofutsanyane and Fezile Dabi districts show high values and to a certain extend in Lejweleputswa district. This is caused by high rainfall obtained (chapter 4) and reduced frost risk (chapter 3). The Motheo and Xhariep district still have not received adequate rains and high drought risk (low WRSI) according to climatological values, even though their frost risk is low compared to the former places. The 20% probability at the 2nd dekad of November planting show a greater area of high suitability values over the northern parts of the Thabo Mofutsnyane and most parts of the Fezile Dabi district. The eastern parts of the Thabo Mofutsanyane district now show a significant drop in PACSI values. The low values are solely caused by increased frost risk due to elongated growing period caused by low temperatures experienced in these places March and April. As an example Appendix 4.1 show that median growing period length for Warden station when planting this maize variety goes over 180 days. The area north of Bothaville emerged to be suitable and this area's suitability is attributed to low drought index and availability of adequate rains for the farmers to start planting. In the 3rd dekad planting, at 20% probability level, most parts of the province show unfavourable conditions for maize planting except over the western and eastern Fezile Dabi as well as eastern Lejweleputswa where optimum vales (> 70) are obtained. The areas of suitability are attributed to low frost risk and low drought risk in these northern parts. Unsuitable areas over the Xhariep and Motheo are caused by mostly high drought risk.

The median PACSI values during the 1st dekad of November planting show a great area where suitability index exceeds 70 over Free State Province. These areas are mostly over the Fezile Dabi and Thabo Mofutsanyane district while the Lejweleputswa and southeastern Xhariep mostly show marginal suitability of between 60 and 70 PACSI. Places over the Motheo and Xhariep still have lowest PACSI index. When planting maize during the 2nd dekad of November, median PACSI values exceeding 70 now cover new areas like the eastern Motheo (along the border with Lesotho), southeastern Xhariep (around Zastron). Over the western and eastern parts of Fezile Dabi, northern Thabo Mofutsanyane and some parts over the Lejweleputswa are shown to be highly suitable areas for planting maize. In the 3rd dekad of November planting, median PACSI values are high north of Bothaville towards the western Fezile Dabi district. There is also an improvement over the far eastern Motheo and southeastern Xhariep where patches of highly suitable areas are obtained. Most parts of the Thabo Mofutsanyane district show unsuitable areas mainly due to elongated growing periods subjecting the crop to high frost incidence.

At 80% WRSI probability (in relatively low drought periods in the growing periods), the PACSI corresponding to the 1st dekad of November planting show suitable areas over the Thabo Mofutsanyane and Fezile Dabi districts (values exceeding 80) while moderately suitable areas are evident over most parts of the Lejweleputswa district (Fig. 6.8c). Areas of moderate PACSI (61-70) are also evident over the eastern Motheo and south eastern Xhariep. In these areas the most limiting factor is the drought index which is relatively low compared to the suitable areas. The unsuitable areas even at 80% probability level are over the central and western parts of the Xhariep district where values below 60 are evident. At these places the limiting factor for maize productivity are high drought index (i.e low WRSI values) and unavailability of good rains to start the planting. During the 2nd dekad of November planting, the suitable areas for planting maize are over most parts of the Fezile Dabi and northern Thabo Mofutsanyane. Moderate areas of suitability are over most parts of the Lejweleputswa, Motheo and southwestern Thabo Mofutsanyane districts. The most unsuitable areas are still over the western Xhariep district where values lower than 50 are evident. During the 3rd dekad of November planting, suitable areas are evident over most parts of the Fezile Dabi district and northern parts of the Lejweleputswa (areas extending from Virginia to south of Sasolburg and patches around Frankfort) (Fig. 6.11c). Moderately suitable areas are over almost the entire Lejweleputswa district and western Motheo. Less suitable areas areas are over Xhariep district (area extending Petrusburg to Bethulie). Areas of unsuitable maize production at 80% probability are over the most parts of Thabo Mofutsanyane.

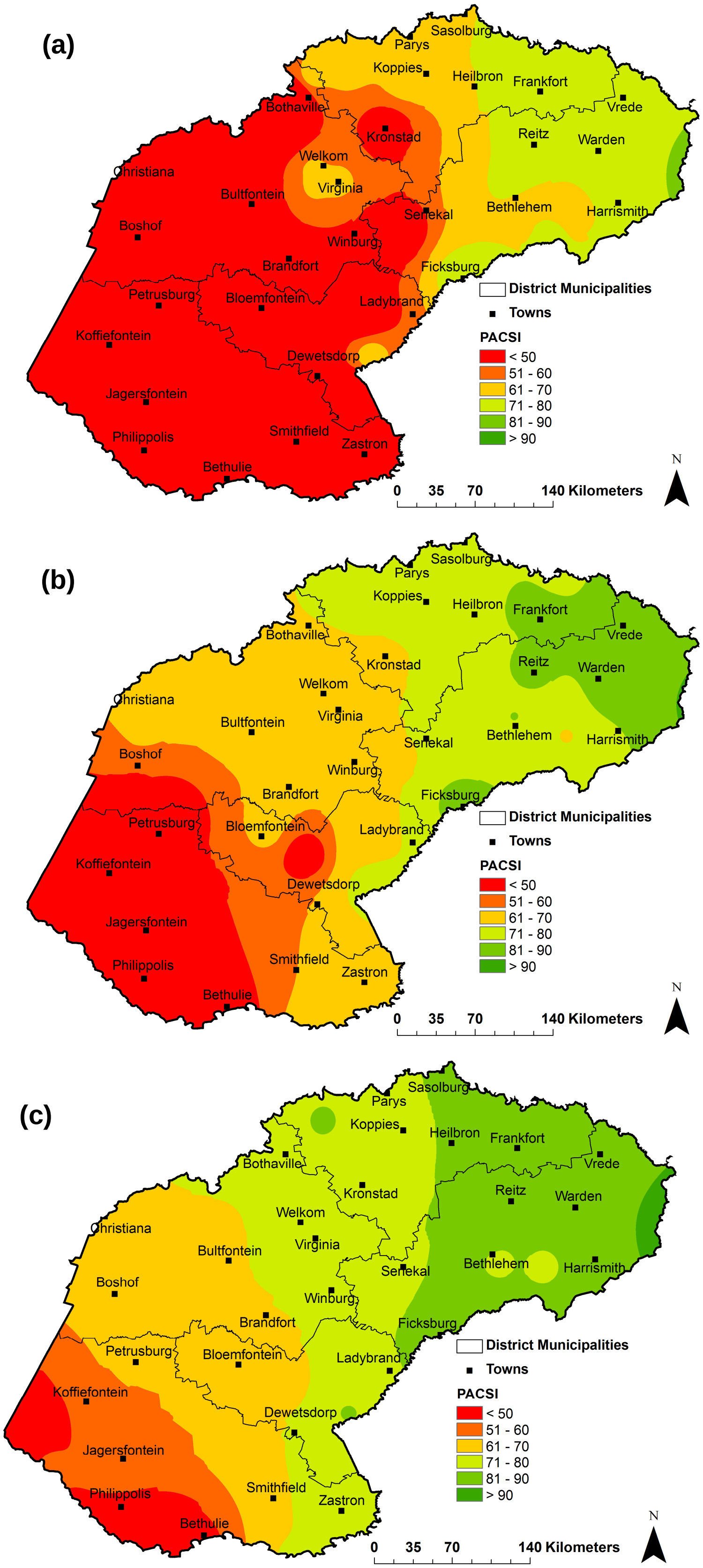


Fig. 6.9: PACSI values corresponding to November 1st dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

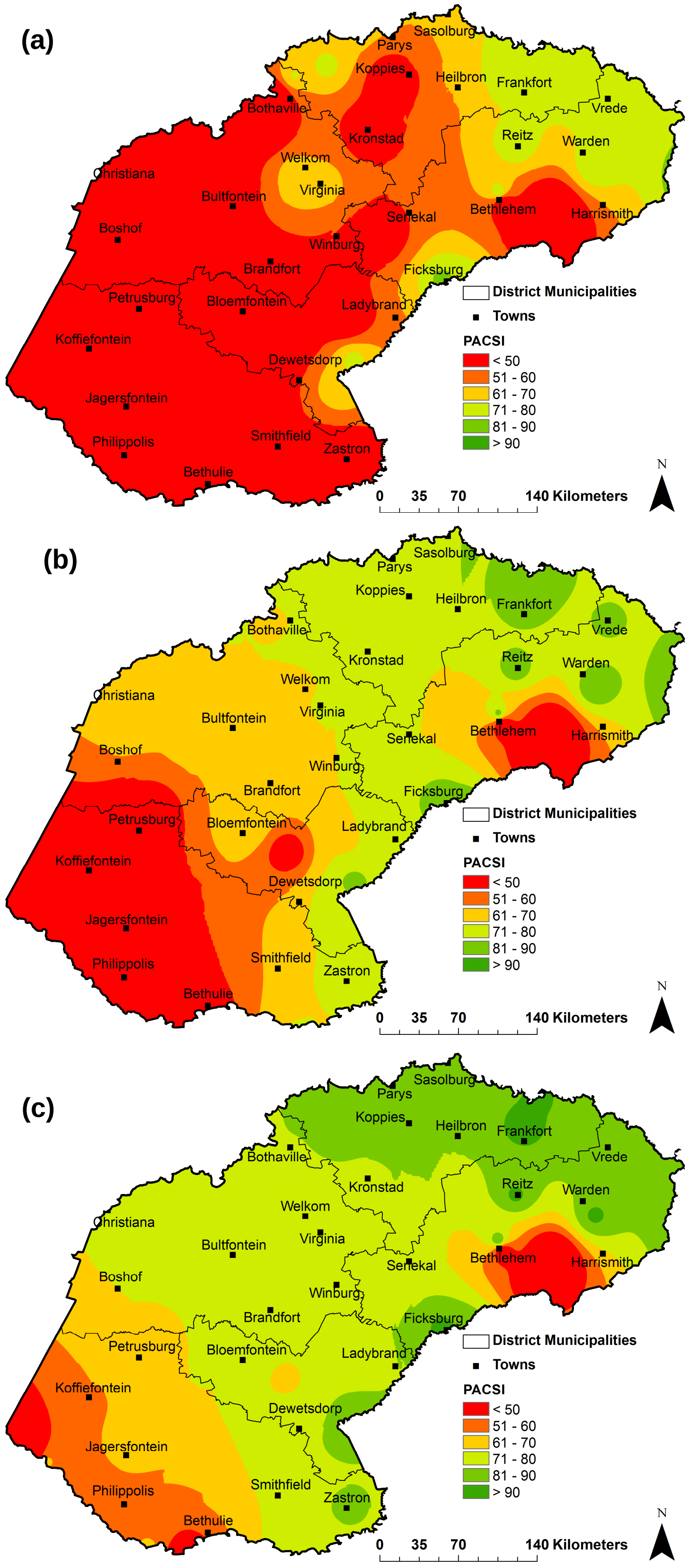


Fig. 6.10: PASCI values corresponding to November 2nd dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

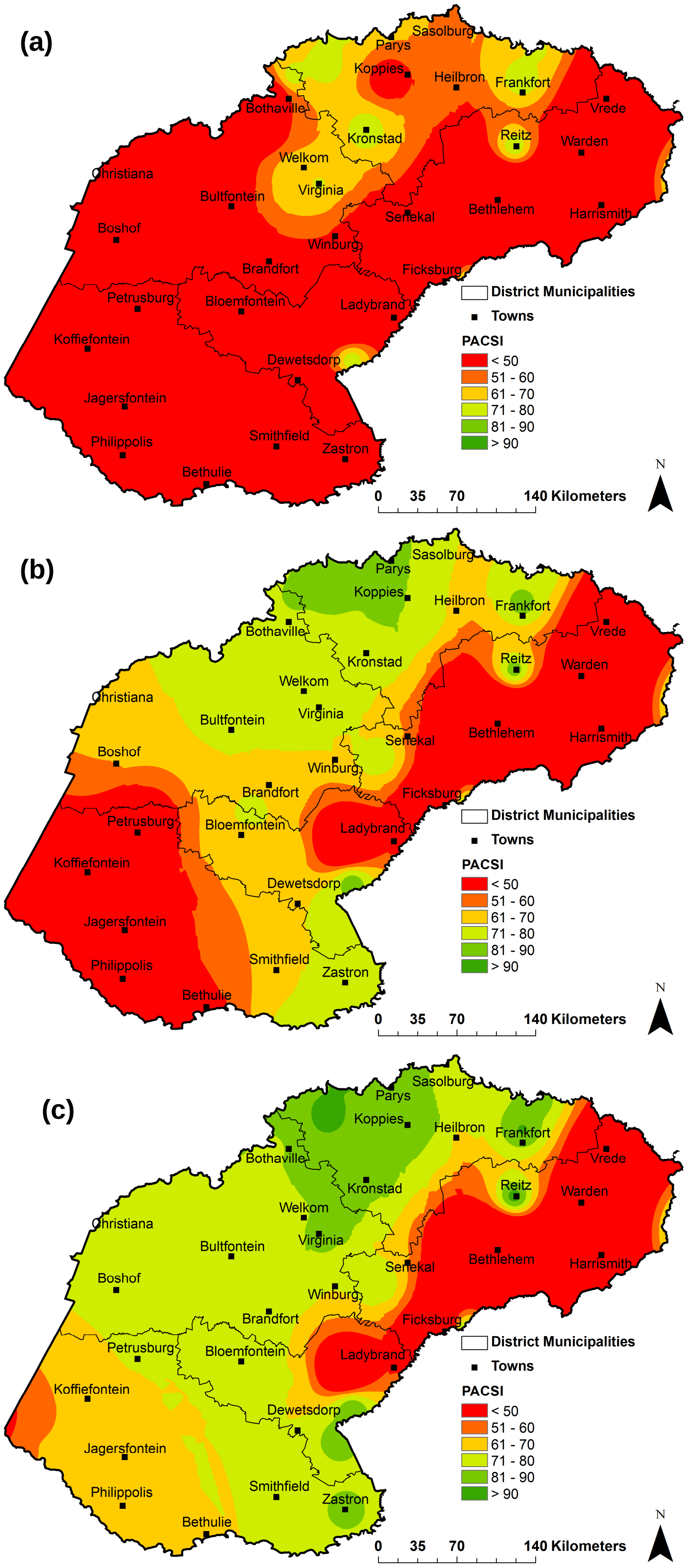


Fig. 6.11: PACSI values corresponding to November 3rd dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

6.3.3 PACSI for Maize planted in the 1st, 2nd and 3rd dekad of December

When planting maize (of 1420 GDD requirements) during the 1st dekad of December, PACSI values at 20% probability level show very low (<50) values over most parts of the province (Fig. 6.12a). The exceptions are over the western parts of Fezile Dabi district, eastern Lejweleputswa and patches over the southern parts of the province where suitable areas for rainfed maize production are obtained. Over the Thabo Mofutsanyane, eastern Fezile Dabi and central, western & eastern Motheo the most limiting factor is frost while over the Xhariep and Lejweleputswa drought is the most limiting factor for maize production (chapter 3 & 5). Over the Motheo it is mostly the combination of drought and frost. The December 2nd dekad PACSI maps show resemblance of that of the 1st dekad of December with notable difference being patches of suitability (in December 1st dekad) over the southern parts being unsuitable at this planting dekad (December 2nd dekad) (Fig. 6.13a). The December 3rd dekad planting at 20% suitability area is confined to areas around Welkom and Kroonstad for 120-day cultivar while all the other areas are unsuitable. The most limiting factor is frost in places over the Fezile Dabi and Thabo Mofutsanyane for the growing period of maize (1420 GDD requirements) planted on the third dekad of December (Fig. 6.14a).

Median PACSI values are below 50 denoting total crop failure over the eastern parts of Fezile Dabi, most parts of the Thabo Mofutsanyane, western Xhariep and eastern Motheo districts (Fig. 6.12b). Moderately suitable areas are mostly along the borders of Xhariep and Motheo districts while suitable areas are evident over western Fezile Dabi around Parys, Koppies and Bothaville. The December 2nd dekad planting shows unsuitable areas over the eastern part of Free State with exceptions of the Lejweleputswa and Fezile Dabi districts where median PACSI exceeding 70 are evident. Highly suitable areas in this planting dekad extend from Virginia to Kroonstad, Bothaville up to Koppies and west of Parys. During the 3rd dekad of December planting date, the suitable areas are mostly over the Lejweleputswa district while all the other areas show PACSI of less than 50.

The PACSI over the Free State province at 80% WRSI show unfavourable areas over the Thabo Mofutsanyane district and eastern Fezile Dabi district (Fig. 6.12c). Highly suitable areas are over the Lejweleputswa and Fezile Dabi districts. During the December 2nd dekad planting areas of unsuitability extends from the southern parts of the Province to the far northern parts encompassing the whole of Thabo Mofutsanyane, Motheo, southwestern Xhariep and eastern Fezile Dabi (Fig. 2.13c). Suitable maize producing areas are still over the western Fezile Dabi and Lejweleputswa. In Fig. 6.14c, the only suitable areas for maize (1420 GDD requirement) production are over the Lejweleputswa district with patches of highly suitable (>90) areas.

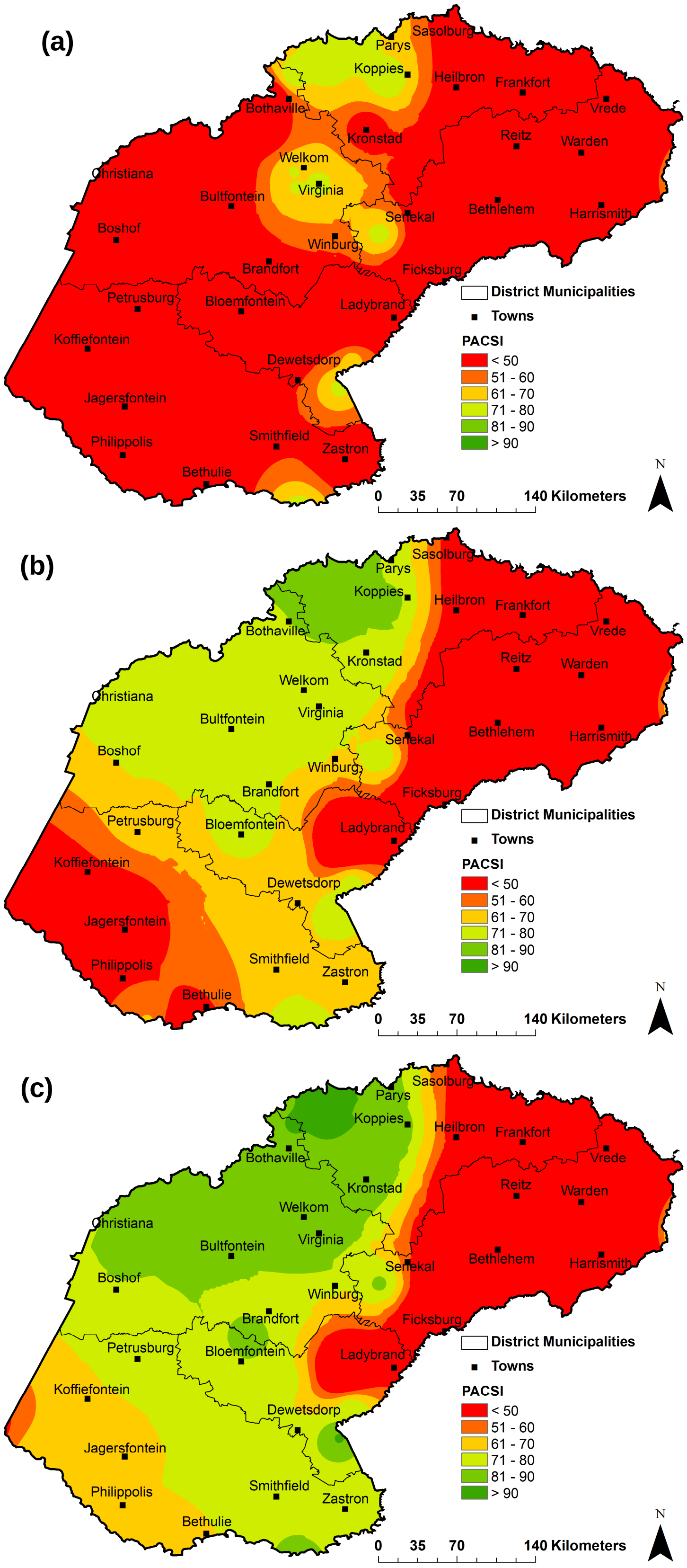


Fig. 6.12: PACSI values corresponding to December 1st dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

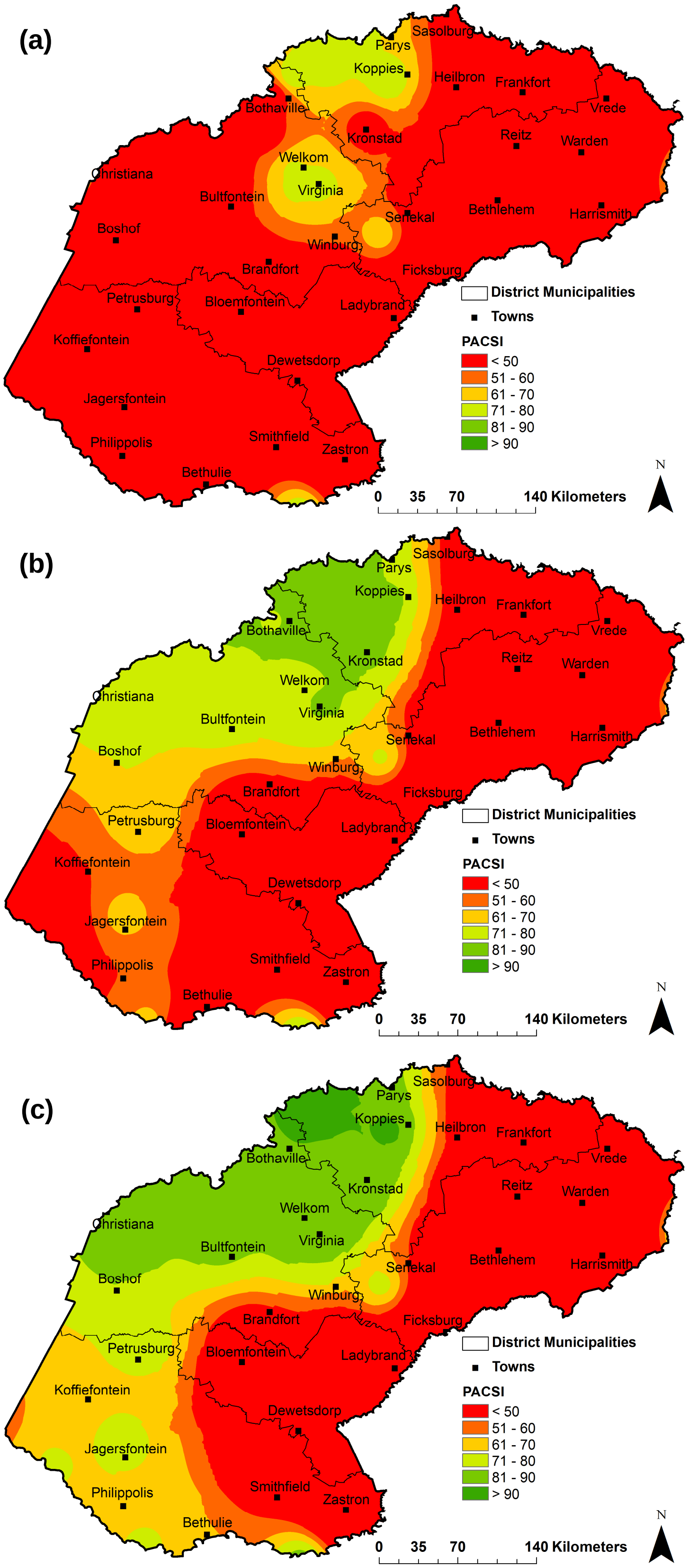


Fig. 6.13: PACSI values corresponding to December 2nd dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

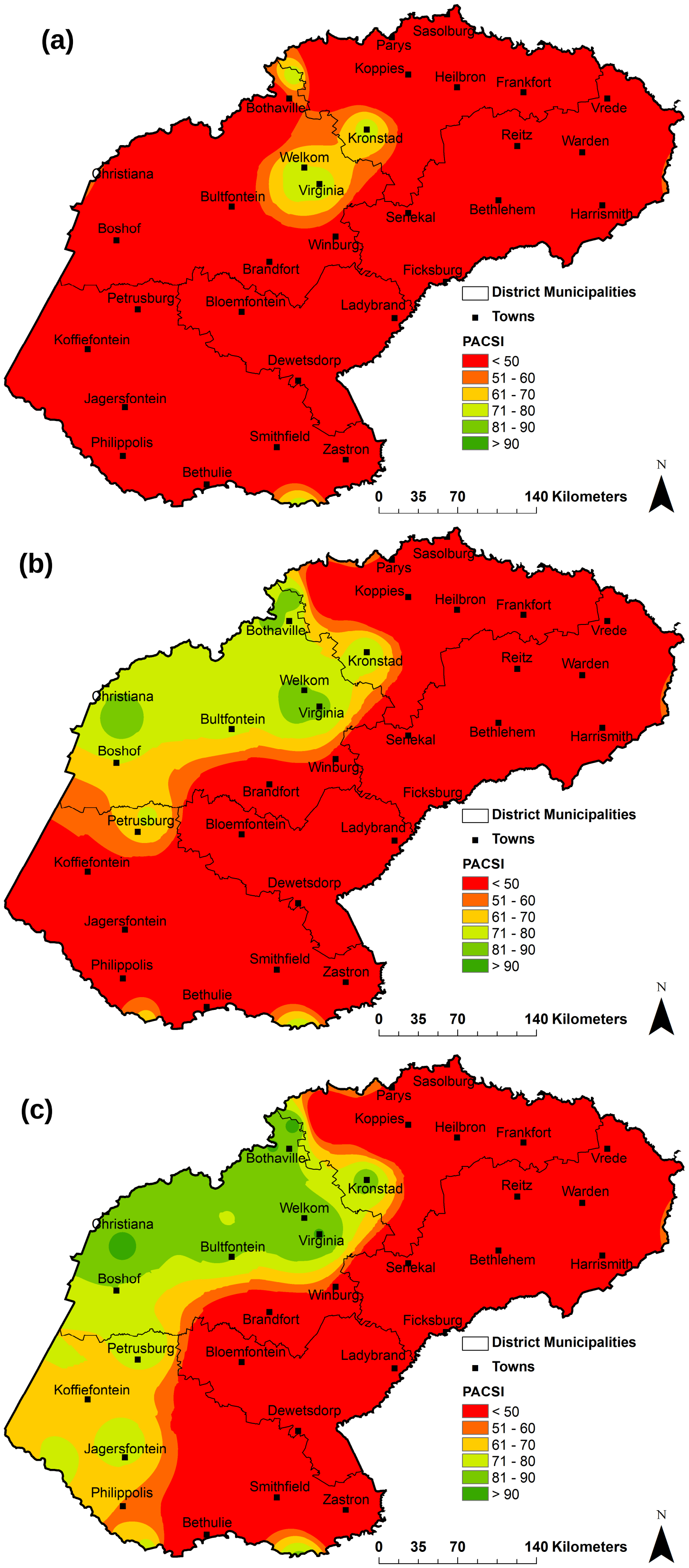


Fig. 6.14: PACSI values corresponding to December 3rd dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

6.3.4 PACSI for Maize planted in the 1st dekad of January

The planting of this maize (1420 GDD requirement) over the 1st dekad of January show unsuitable areas all over the Free State (Fig. 6.15). The main limiting climate factor in this planting dekad and the planting dekads later than 10th January is frost. Appendix 4.1 shows that most of the stations record a median growing period exceeding 200 days implying that maize planted in this planting dekad will definetly be damaged by severe frost occurring in May to July (Chapter 3). Planting of maize in this dekad can only be recommended for maize varieties that needs far less than 1420 heat units requirement. But, there is still a date limit after which maize cannot be planted as the growth and development is slow after April depending on the location. Generally the daily accumulated growing degree days of less than 2GDD are evident in most places after April. This will elongate the growing period of the crop to coincide with the frost period that could destroy the crop depending on the severity. There is also a constraint of water availability to the crops because the end of the rainy season also set in March and April for most parts of the Free State. Planting maize (1420GDD) after January is thus very risky especially if it's a medium or medium-late maize varieties and even the short season varieties are not advised to be planted after 10th of January.

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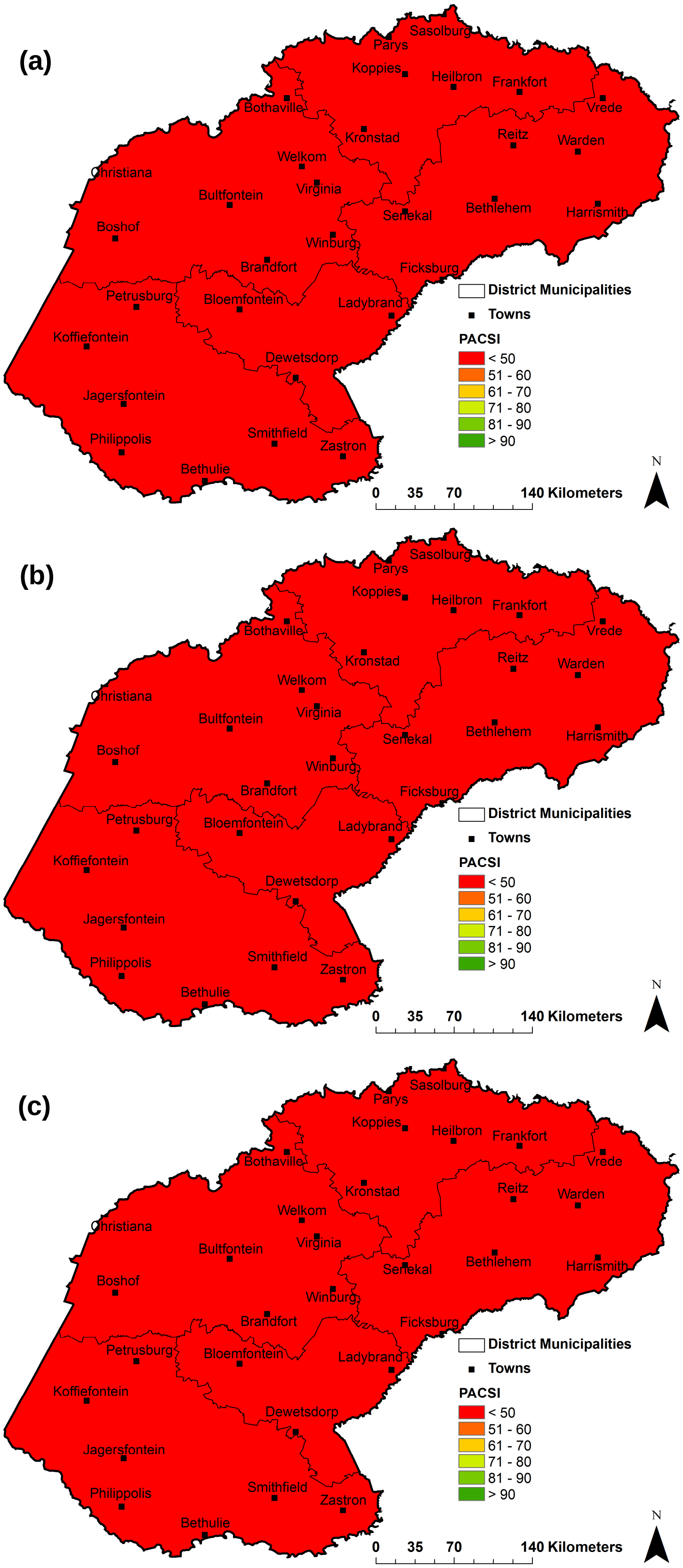


Fig. 6.15: PACSI values corresponding to January 1st dekad planting at: (a) 20% (b) 50% and (c) 80% non-exceeding probabilities for 120-day maize cultivar.

6.3.5 Overall planting recommendations

The mapping of the suitability index (PACSI) over the eastern Fezile dabi district (around Frankfort and to the east) showed the best planting dates from the 1st dekad of November to the 2nd dekad of November for maize with growing degree requirements of 1420 GDD. In this planting period the PACSI at 20% drought index (i.e dry years) exceeds 70, showing that even in dry seasons the chances of maize performing well in this region are high. The values in the relatively wet seasons (80% probability) can exceed 90 showing highly suitable in these areas. The risks of obtaining false onsets of rains, frost within the season and agricultural drought are low. The calendar dates corresponding to high suitability over the western and southern parts of the Fezile Dabi district starts from 10 November to 20 December. Schulze *et al.* (2008), in their delineation of maize growing areas using CERES-Maize model, also identified these areas as highly suitable. Other areas show poor to moderate suitability of maize at all times even at 80% non-exceeding probability of the drought index.

Over the northern and northeastern parts of Lejweleputswa district, highly suitable planting dates for maize (1420 GDD requirements) range from 3rd dekad of November to 3rd dekad of December. In this period the PASCI values can exceed 90 especially during the wet seasons (80% probability) while at the median level the values exceed 80. The highly suitable areas are mostly in the area extending from Bothaville down to Virginia which is a major maize growing area. These areas are also charecterized by deep soils with high water holding capacity. Other areas are shown to be moderately suitable during the same planting window. Areas where maize production is unsuitable are over the far western parts of the Lejweleputswa district. These areas are characterized by high risk of agricultural drought and poor onsets of rains.

Over the far eastern parts of the Motheo district, places of relatively high PACSI values are over the eastern parts and particularly southeastern parts along the border with Lesotho, where the best planting periods are from 1st dekad of November to 1st dekad of December. In other areas toward the Thabo Mofutsanayne district (including Ladybrand) show a shorter suitability period from 1st dekad of November to 2nd dekad of November. These areas are marked by high frost incidence during the maize growing period. The PACSI values are mostly over 70 showing moderate suitability. The central and western part of Motheo show areas of low suitability with a short planting window between 3rd dekad November and 1st dekad December. These places have high risk of drought in most years. Dryland farming in these areas is subject to high climate risks and other measures to make rainfed maize production viable, such as in-field water harvesting and inter-cropping techniques, are advised by other researchers (Mukhala, 1998; Tsubo, 2000; Walker & Ogindo, 2003; Walker *et al.*, 2010; Botha, 2006; Anderson, 2007).

Over the Thabo Mofutsanyane district great variation in suitable planting dates for maize (1420 GDD) are observed. The northeastern and central parts of the district show best planting dates from as early as 2nd dekad of October to 2nd dekad of November. Places included in this region are Bethlehem, Vrede, Warden and Harrismith. The most important climate factors contributing to high suitability index are low risk of drought and high probability of adequate rains to enable the planting and completion of season to produce grain. There is still risk of frost damage within the growing period because these areas are over the highlands. Areas around Senekal and to the west show moderate suitability from the 1st dekad of November to 1st dekad December. In these areas drought and late onset of rains lead to low PACSI values.

The Xhariep district shows a greater area that is unfavourable for dryland maize production. Its main constraints are agricultural drought and high probability of false rain onsets. Frost occurring during the season is not a concern (Low risk). These areas are mostly on the West, southern and southwestern parts of the province. PACSI values are constantly below 50 for the entire planting window at median drought risk level. The central parts and along the borders with the Motheo district shows slight suitability areas during the planting window from the 2nd dekad of November to 1st dekad December. Areas of moderate suitability are found over the southeastern parts (areas surrounding Zastron) from the planting window between 2nd dekad of November to 3rd dekad November. In these areas the risk of agricultural drought is relatively low and onset of rains probability relatively high in those planting dates.

6.3.6 Validation of PACSI

6.3.6.1 Validation against measured maize yield

Figure 6.16 represents the comparison of maize yields with PACSI at 10 different locations in the Free State province. The PACSI values used in the comparison are obtained from the mid-November planting (11-20 November) at all the sites. This planting period was chosen because it is the recommended planting period in most parts of the Free State (ARC, 2008). The assumption of planting period is made due to the fact that, the yield data obtained (http://www.grainSA.co.za) does not have corresponding planting dates mainly because it is an average yield calculated from production over a large area. The results show a relationship between the PACSI and measured yields with the minimum correlation of 0.436 for Ficksburg and maximum correlation of 0.804 for Bethlehem with an average correlation of 0.626 (Fig. 6.16). The PACSI trend mostly resembles that of the yield data with minimum values during the 1982/83, 1991/92 and 1994/95 agricultural seasons. The PACSI also shows peaks during the years of high yield like the 1980/81, 1988/89, 1993/94 and 1999/00 agricultural seasons. The results thus show that the PACSI can be used to perform agroclimatic zoning of dryland maize production in the Free State Province. The ability of this suitability index to resemble variations in actual maize yields at selected sites in the Free State Province makes it an important tool that should be investigated for its applicability in other semi-arid areas.

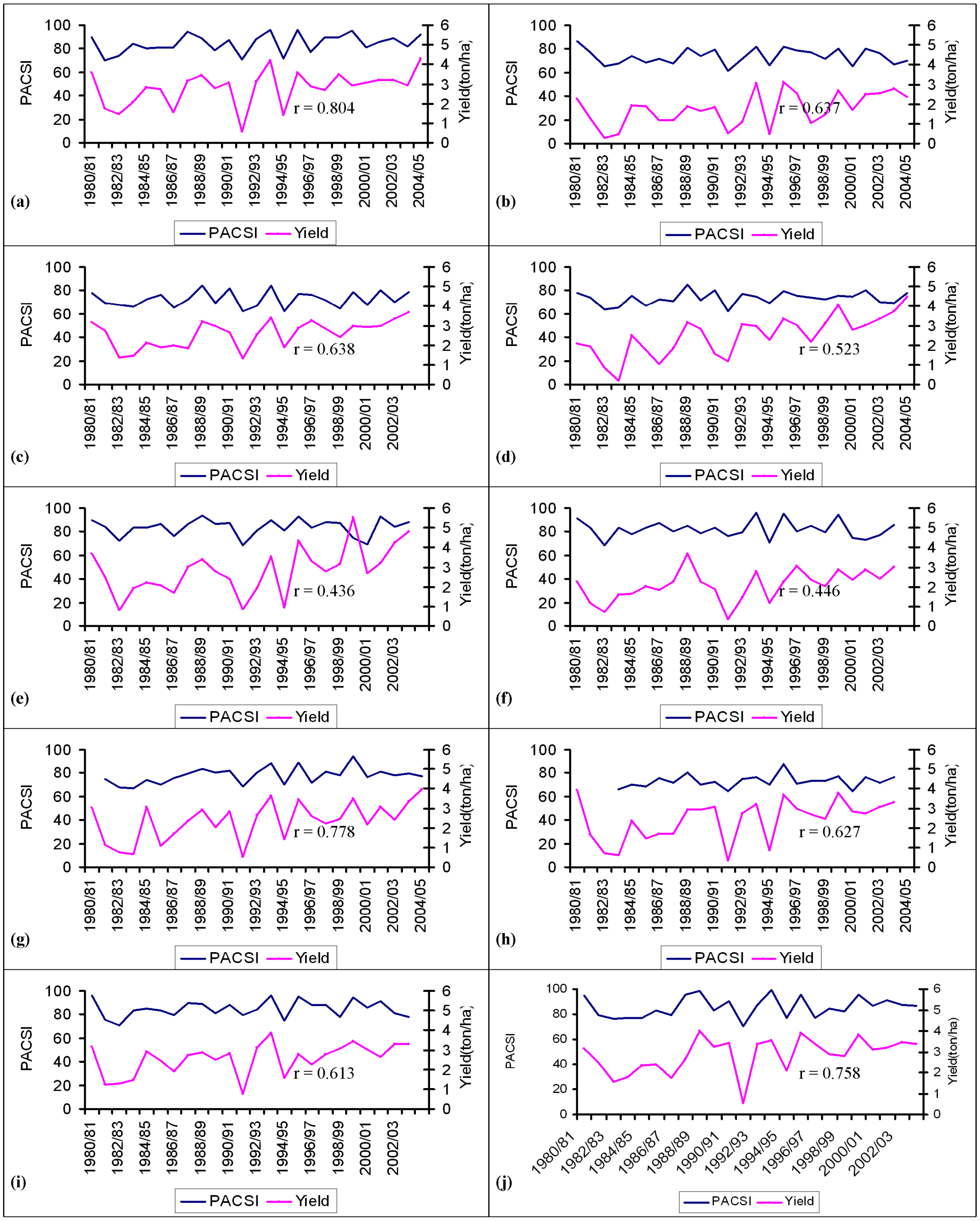


Fig. 6.16: Validation of PACSI against measured yield from 1981 to 2004 agricultural seasons for: a) Bethlehem, b) Bloemfontein, c) Bothaville, d) Bultfontein, e) Ficksburg, f) Frankfort, g) Koppies, h) Kroonstad, i) Reitz and j) Viljoenskroon.

6.3.6.2 Comparison with CERES-Maize yield estimates

In this section comparison of the suitability maps obtained from use of PACSI with the yield estimation maps obtained by using CERES-Maize model calibrated for South Africa (Schulze et al., 2007) will be made. CERES-model is highly recommended for predicting maize yields in South Africa (du Pisani, 1987; du Toit *et al*., 1997; Walker & Schulze, 2006). It has to be noted that, thermal time requirements of the maize variety used by Schulze *et al*. (2007) is not given in the report and thus the comparison is based on the fact that the Schulze *et al.* (2007) used a medium-duration hybrid. Figure 6.17 shows the yield estimates for planting medium maize on the 15th October over South Africa. The map shows high yields (3-6 t/ha) over the northeastern Free State (Thabo Mofutsanyane) and relatively low yields over the Fezile Dabi with around 2 to 4 t/ha. Most parts of the western and southern Free State record yields of less than 2 t/ha. The spatial distribution of these maize yield estimates are related to the PACSI values obtained for the 2nd dekad of October planting (Fig. 6.7). When looking at maize yields for planting in mid November (Fig. 6.18), the CERES-maize model still depicts an area along the border with Lesotho over the eastern parts of the Free State as the most suitable area. Figure 6.10, corresponding to 2nd dekad of November planting shows high suitability of maize (1420 GDD) over the northeastern Free State, patches along borders with Lesotho as well as over the Fezile Dabi district. There are substantial differences especially area in the vicinity of Bethlehem where unsuitable areas are obtained contrary to findings of the CERES-maize model. Over Fezile dabi district, the CERES-maize simulation does not consider the district as highly suitable for dryland maize production but the PACSI suitability index categorize most parts of this district are high yield potential areas. The disagreements might be caused by the differences in the maize varieties used because the heat units requirements used in the CERES-maize simulations are not known. Moderate suitability over most parts of the Lejweleputswa is evident in both maps. The southwestern and western parts of the Free State show low suitability in this planting date for both methodologies. Estimates of yield using CERES-maize model for the mid-December planting still show relatively high suitability along the border with Lesotho (Fig. 6.19), while PACSI shows possible crop failure during mid-December planting date at those areas. The areas around Bothaville and west of Koppies are highly suitable for maize according to PACSI but the CERES-maize model associated the area with low yields between 2 and 3 t/ha. The whole of Motheo district is classified as highly unsuitable by PACSI contrary to the results of the CERES-maize model. Though, there is still similarity over the far eastern parts where maize suitability is low in both maps and the unsuitability over the Xhariep district is still evident in both maps.

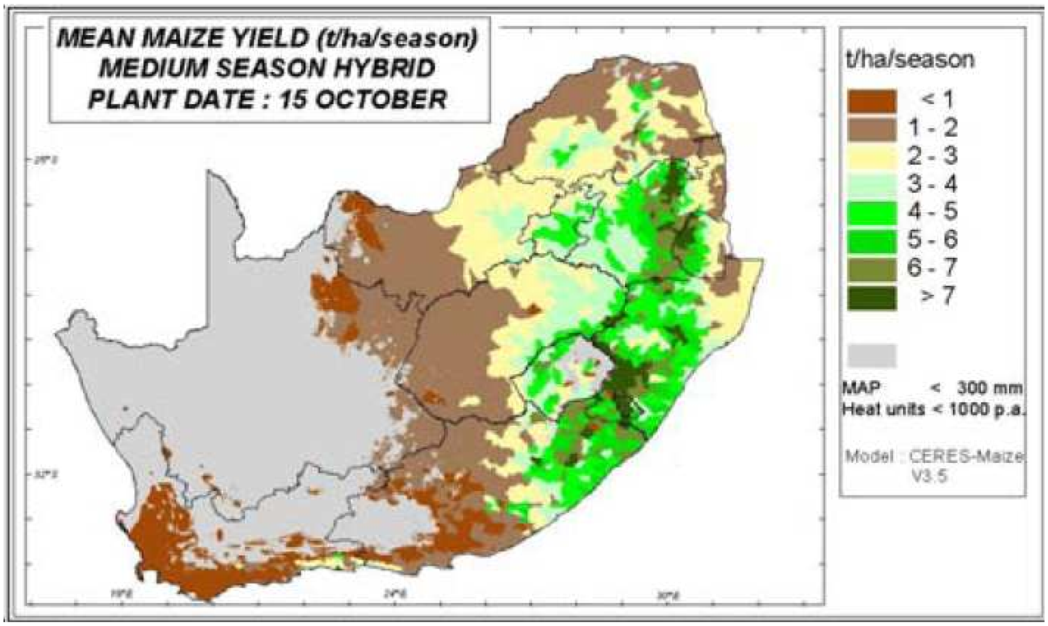


Fig. 6.17: Mean maize yield estimation using CERES-maize model for medium season hydrid planted 15th October (Schulze *et al*., 2007).

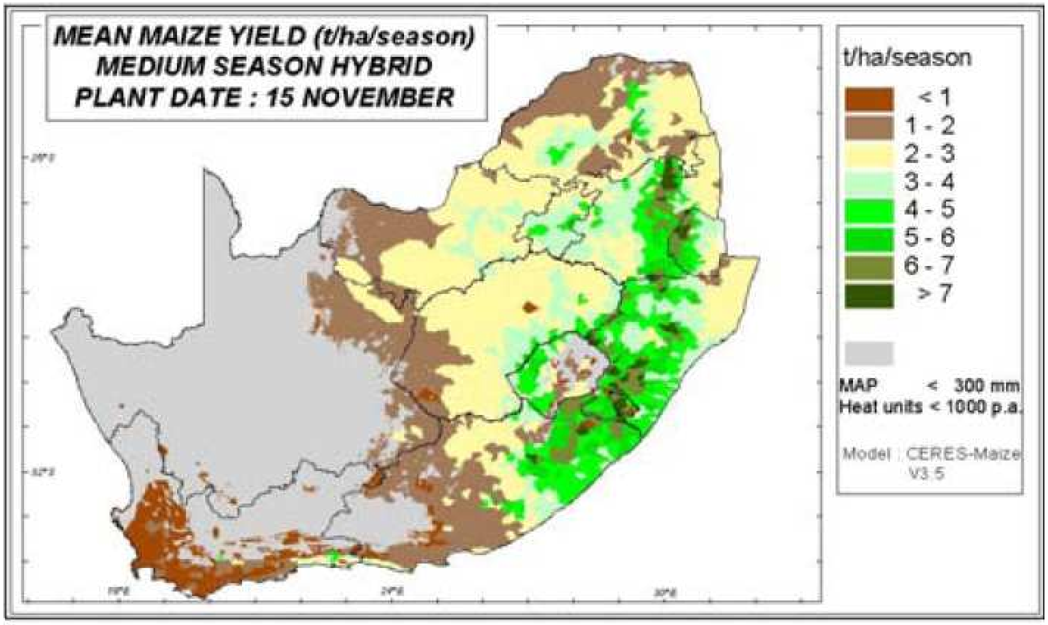


Fig. 6.18: Mean maize yield estimation using CERES-maize model for medium season hydrid planted 15th November (Schulze *et al*., 2007).

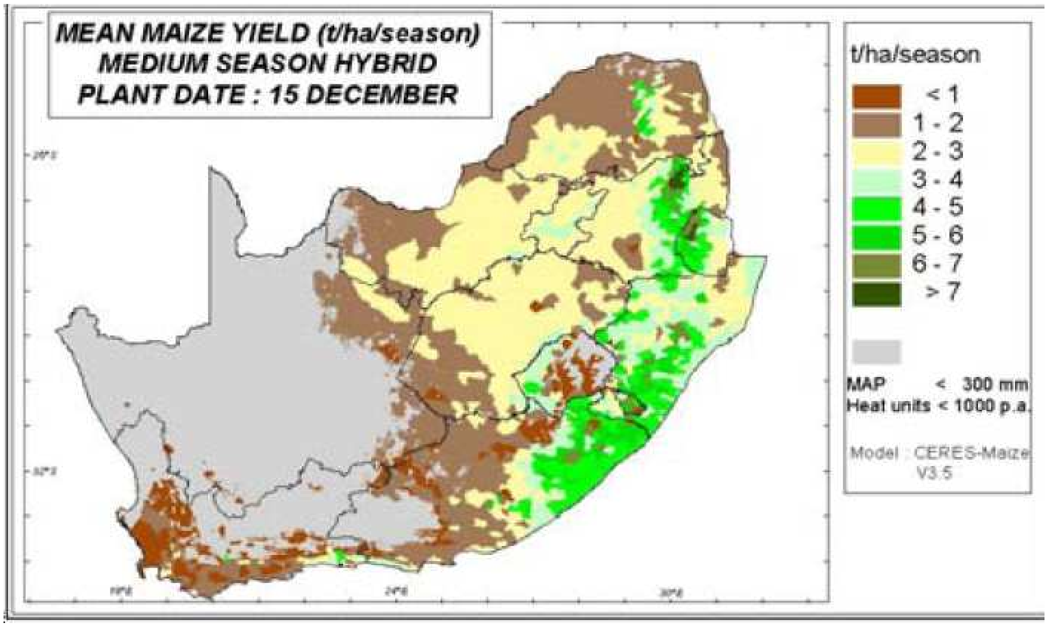


Fig. 6.19: Mean maize yield estimation using CERES-maize model for medium season hydrid planted 15th December (Schulze *et al*., 2007).

6.4 Conclusions

This chapter presented a methodology for determining suitable areas by combining frost risk, risk of onsets and drought risk at three probability levels (20%, 50% and 80%). The analysis was based on the mid-season maize variety (120-day cultivars) that requires 1420 growing degree days to mature. The combined climate risk index PACSI (Poone Agroclimatic Suitability Index) was used to map suitable areas for planting maize over the Free State.

It was found that early planting occurring from mid October to early November is the best planting period for the northeastern parts of the Free State province. Significant rains required to start the planting and low agricultural drought risk in at least 80% of the years were both favourable. The area of high suitability shifted to northern parts of the Province from early November to mid-December. Some pockets of suitable maize production were also found over the northern and eastern Lejweleputswa district especially from mid-November to December. Other areas over the central part, eastern, southeastern and western parts of the Province showed moderate suitability of planting maize. The most limiting factor for the central parts is agricultural drought. In the eastern and southeastern parts of the province, a combination of agricultural drought and frost seriously impact dryland maize production. In the western parts of the province, late onset of rains and drought drastically reduce the planting window for maize production. Places over the Xhariep district, especially the central, western and southern parts are not suitable at all for planting maize. In these areas drought over the growing period is the most limiting factor. The unavailability of adequate rains for planting is another major limiting factor across the Xhariep district.

Comparison of the PACSI with the actual maize yields at ten sites in the Free State Province showed good correlation of up to 0.80. Comparison of the PACSI maps for the mid-October, mid-November and mid-December planting with the CERES-maize model mean yield estimates during the same planting period were also made. The results show similarity in spatial distribution especially for the October and November planting dates. Planting in December showed disagreement between the two methods over large areas. It is thus concluded that PACSI can be used to delineate suitable areas of maize but further evaluation of the index is still in progress.

In the next chapter, the development of a simple agroclimatological risk tool is discussed. The tool puts together all the analysis done in the whole study of the agroclimatological risk assessment for dryland maize production in the Free State Province of South Africa.

Chapter 7: Developing a Simple Maize Agroclimatological Risk Tool

7.1 Introduction

Agricultural production is more vulnerable today than ever before due to increasing population, high inputs costs and changing climate across the world including South Africa. These have lead to development of decision support tools or systems in recent times to help maximize agricultural production by integrating various datasets and to provide intelligent knowledge transformed into useful information (Druzdzel & Flynn, 2002). Decision support systems/tools are basically interactive computer based systems that assist users in making decisions or solving problems in an environment of complex considerations (Cox, 1995; Lynch, 2002; Karmakar *et al.*, 2007; Tyran, 2010). In the agricultural sector, decision support tools (DST) are supposed to help farmers and their advisers in making better decisions helping them to alter their production systems accordingly for optimum production as well as reducing production costs (Newman *et al*., 1999; Lynch, 2002). During the worst times, the system should be able to assist the farmer by minimizing losses. DST or tools developed for agricultural production are mostly built on raw input data like rainfall, soil water content and temperature. These data are normally transformed to information tailored for specific users or producers and it should be in the language or terminology they are used to in order for it to be comprehended. Anyway, intensive training of users will be necessary to gain a good uptake rate of the tool. There are different platforms of developing DST due to recent advances in technologies including spreadsheet based DST, GIS and web-based DST's (Engel *et al.*, 2003; Tyran, 2010).

In the Free State, maize production varies a lot from one year to another owing mainly to climate risks that affect the area. Years of poor harvests impact negatively on the economy of South Africa which is reliant on agricultural production. The fact that maize forms the staple food of most South Africans, food insecurity issues arises during years of poor maize production. For sustainable maize production, it is imperative to equip the producers and advicers with tools that will enhance their decision making (Dewandel *et al*., 2007). Thus the development of the agroclimatic risk tool equipped with simple forecasting techniques will be helpful to the agricultural community in the Free State. According to Badini & Dioni (2004), rainfall is the most important factor that the farmers use to gauge/predict how the production for this season will be compared to other years. Thus, making rainfall one of the main inputs to this decision tool aligns it with the decision making of the farmers. This will enhance the chances of better adoption of the tool (Fernandez & Trolinger, 2007; Nanja, 2010; Zuma-Netshiukhwi, 2010). Better understanding of other climate parameters influencing productivity, and predictability of onsets of rains and frosts provide a foundation for designing tools that will be helpful to the farmers (Badini & Dioni, 2004).

The Free State Maize Agroclimatological Risk Tool (FS-Macrt) is aimed at helping farmers, agricultural extension officers and agricultrural risk officers in the Free State province to make informed decisions related to rainfed maize production (Table 7.1). The tool is built from climatology and will be used with weather forecasts. Its main outputs are the agroclimatological risk associated with rainfall, frost and drought (expressed as crop water requirement satisfaction) at different planting dates for varying cultivar lengths.

7.2 Aim of the development of the agroclimate tool

The main aim of the tool is to be a reference for agricultural producers, risk managers, agricultural cooperative consultants and policy-makers for determining climate risks that are associated with dryland maize production in the Free State (Table 7.1).

7.3 Tool description

The name of the tool is “FS-Macrt” derivered from the **F**ree **S**tate **M**aize **A**gro**C**limatological **R**isk **T**ool. The tool was developed as a windows application using the Visual Studio 2008 with C# programming language. The tool is point-based, implying that it only determines agroclimatological risk at specific locations over the Free State province of South Africa.

7.3.1 Model categories

FS-Macrt tool has three kinds of model categories depending on the need or requirement (Fig. 7.1). The first category contains the agroclimatology models, second is the suitability model and the third category is the Risk forecasting model. The agroclimatology models contain the long-term agroclimatological risk assessment results obtained from chapter 3, 4 & 5. The suitability model contains the results of PACSI introduced in chapter 6. These models or equations are based on long-term climatological data. However, the risk forecasting models are designed to be used for forecasting of onset of rains and agricultural drought for specific year. Farmers need to know in advance whether the climate for the up-coming agricultural season will be favourable for crop production. The most important phenomenon to forecast is agricultural drought. In order to decide on possible planting days, farmers should also be informed about the onsets of rains.

7.3.2 Models

There are three climate risk model options namely: 1) Drought, 2) Frost and 3) Rainy season onset. The suitability model (PACSI) is the synthesis of drought risk, frost risk and risk associated with onset of rains. There are two risk forecasting models namely: 1) Drought forecasting 2) Forecasting of onset of rains.

Table 7.1: Target groups and the possible use of the Free State Maize AgroClimatological Tool.

Group	**Purpose**
Farmers	To determine drought risk associated with planting maize near their location on different planting dates.
	To determine frost risk associated with planting maize at their locations for different cultivar lengths and severity.
	To determine the frost-free period at their locations at different frost thresholds for planning of agricultural activities for different crops depending on their frost hardiness.
	To determine the rainy season characteristics (onset, cessation and duration of rainy season) of their locations based on climatology data to help in planning of major agricultural activities like planting dates.
	To help in planning the activities for the forth-coming season using forecast start of rains and agricultural drought risk depending on the planting dates.
Extension officers	As an educational tool for the climate risk affecting crops in their designated area to equip them with climate information that will contribute in their decision-making towards ensuring natural resource protection and productivity of farms
	To help in their formulation of advisories to farmers before the start of the agricultural season on the cultivar choice using risk forecasting of drought and onsets of rain.
Agricultural risk officers - Government	To help in issuing advisories related to climate risks associated with dryland maize production across the Free State
Agricultural Disaster Managers	To help in formulating policies that aim at adaptation to the climate risks affecting maize production in the Province as well as in the policies that aim at mitigating the effects of climate risks in agriculture
Agricultural insurance officers	To assist in kinds of insurance that are applicable for different localities depending on the degree of the climate hazards normally encountered in the past.

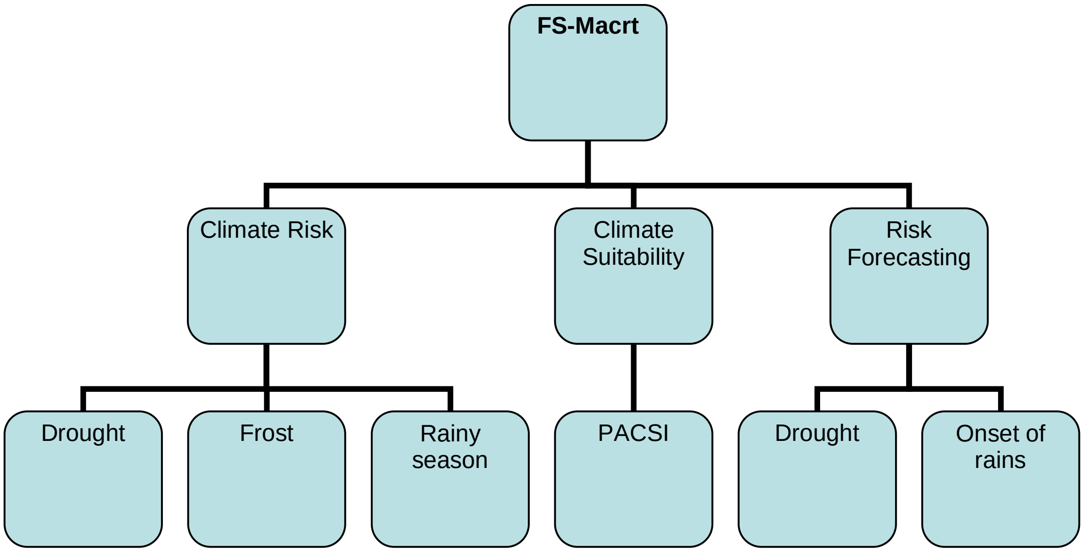


Fig. 7.1: Flowchart for the model options of the FS-Macrt tool for dryland Maize production in the Free State Province.

7.3.2.1 Climate risk models

The drought models are based on regression equations generated from the non-exceedence probabilities/percentiles of agricultural drought indices. Percentiles (10%, …, 90%) were regressed against their corresponding drought index values to enable for easy computation of drought risk using one equation for each of the stations. The predictor in all the regression equations in this section is the percentiles/probabilities while the predictand is the climate risks (e.g drought index). Using a regression equation as a base model will help in reducing computation time and storage capacity as compared with the case where each an every value for each percentile is stored. At all 161 stations used in the analysis of the agricultural drought, the correlation determination (r^2) exceeded 0.90 implying a very good estimation. Each planting dekad has its own linear regression equation. The regression equations for the drought index are in the format outlined in Equation 7.1:

$$y_i = m_i x + c_i \tag{7.1}$$

where:

y_i is the drought index (WRSI) for the i^{th} planting dekad, mi is the regression slope for the i^{th} planting dekad, x is the risk level (ranging from 10% to 90% non-exceedence probability) and c_i is the regression constant for the ith planting dekad.

Table 7.2 shows an example of the Bethlehem constants and r^2 obtained from the regression equations. Each climatological station has its own regression models corresponding to each planting dekad (October to January) to estimate drought risk at different risk level (percentiles). These drought models estimate risk associated with the availability of water to meet the growing maize crop planted at different planting dates and with different cultivar growing lengths (chapter 5).

Table 7.2: Regression constants for estimating drought index for different planting dekads and different maize cultivar length and their corresponding coefficient of determination (r^2) for Bethlehem.

Planting Dekads	**Regression slope (m)**			**Regression constant (c)**			**Coefficient of determination (r^2)**		
	100d	**120d**	**140d**	**100d**	**120d**	**140d**	**100d**	**120d**	**140d**
Oct_1	0.580	0.551	0.546	36.30	36.5	36.0	0.989	0.982	0.959
Oct_2	0.564	0.500	0.504	39.6	43.4	41.1	0.975	0.979	0.978
Oct_3	0.587	0.517	0.528	40.0	45.2	42.1	0.989	0.974	0.981
Nov_1	0.552	0.503	0.546	43.8	46.1	43.2	0.985	0.988	0.988
Nov_2	0.542	0.541	0.586	46.2	46.7	42.6	0.982	0.982	0.988
Nov_3	0.585	0.596	0.608	46.8	46.1	42.2	0.990	0.992	0.977
Dec_1	0.640	0.613	0.624	46.7	46.4	41.3	0.987	0.992	0.970
Dec_2	0.614	0.567	0.543	48.1	48.3	44.0	0.993	0.980	0.964
Dec_3	0.610	0.541	0.541	48.1	48.4	42.8	0.980	0.982	0.969
Jan_1	0.573	0.489	0.520	49.8	50.2	42.4	0.978	0.948	0.960
Jan_2	0.532	0.497	0.533	50.0	46.8	38.5	0.942	0.931	0.980
Jan_3	0.561	0.544	0.546	46.1	45.1	36.0	0.970	0.982	0.989

The frost risk model estimates the risk of onset of frost, cessation of frost and duration frost-free period at different frost severity levels (2℃, 0℃ & -2℃). Regressions models for each station for all the frost indices (onset, cessation & frost-free duration) at varying severity levels were generated. Equation 7.2 shows the generic equation for determining frost index while Table 7.3 shows the example of Bethlehem regression constants. The estimation of the onset and cessation are done in Julian days to simplify the interpolation process outlined in sub-section 7.3.1.5 and the final answer is converted back to the calendar days. At all the 55 stations used in the investigation of frost risk assessment, the coefficient of determination (r^2) exceeds 0.97 implying a very good correlation hence usable for prediction. Climatological frost determination is important in planning of agricultural activities of crops that are not resistant to frost damage. The tool presents a platform to obtain frost incidence information over the Free State for the light, medium and heavy frost levels. Probabilities for frost of varying severity occurring during the planting window from first dekad of October to last dekad of January for the 100-day, 120-day and 140-day cultivars are determined (chapter 3). With this information one can easily determine the best growing period with minimal frost occurrences depending on the hardiness of the crop.

$$y_j = m_j x + c_j \tag{7.2}$$

where:

y_j is the frost index (onset, cessation date and duration of frost at x probability level) for the j^{th} severity level where j levels are light, medium and heavy frost, m_j is the regression slope for the j^{th} severity, x is the risk level (ranging from 10% to 90% non-exceedence probability for onset and frost free duration; exceeding probability for cessation) and c_j is the regression constant for the j^{th} severity level.

Table 7.3: Regression constants for estimating frost indices for different frost severity levels and their corresponding coefficient of determination (r^2) for Bethlehem.

Frost Index type	Frost severity	Regression slope (m)	Regression constant (c)	Coefficient of determination (r^2)
Onset	Light (2℃)	0.291	101.054	0.986
	Medium (0℃)	0.325	110.137	0.949
	Heavy (-2℃)	0.352	120.108	0.974
Cessation	Light (2℃)	-0.546	306.103	0.988
	Medium (0℃)	-0.470	284.211	0.973
	Heavy (-2℃)	-0.499	274.279	0.957
Frost-Free Duration	Light (2℃)	0.758	162.377	0.997
	Medium (0℃)	0.561	204.642	0.979
	Heavy (-2℃)	0.628	224.485	0.982

Rainy season characteristics, like onset of rains, cessation of rain and rainy season duration regression equations were determined for each of the stations (chapter 4). The regression equations for the rainy season characteristics (onset, cessation & duration of rains) resulted in r^2 of above 0.98 for all the 310 stations. The regression equations for all the rainy season indices are in the format shown in equation 7.3. This shows that indices obtained from these models have a good resemblance to the actual risk values. Table 7.4 shows an example of the regression constants obtained for the Bethlehem station located over the northeastern part of the Province. It is imperative to know the probabilities of onsets of rain for the farmer to align the planting with significant rains. Proper determination of the onsets lowers probabilities of obtaining false onsets which will result in total loss of inputs for the farmers. The cessation of rains is also an important parameter for the agricultural advisors and farmers to know as it signals the end of the growing period. Aligning the crop growing period to fall within the rainy season will reduce risk of low soil water availability that has a detrimental effect on the crop production. When one looks at both the onset and cessation of rains, the resultant parameter is the duration of the rainy season. The rainy season duration risk levels will enable the users of the tool to choose appropriate cultivar length to use in different areas of the Free State.

$$y_k = m_k x + c_k \tag{7.3}$$

where:

y_k is either the onset or cessation date or rainy season duration , m_k is the regression slope for either the onset or cessation date or rainy season, x is the probability level (ranging from 10% to 90% non-exceedence probability for onset and rainy-season duration; exceeding probability for cessation of rains) and c is the regression constant.

Table 7.4: Regression constants for estimating rainy season indices and their corresponding coefficient of determination (r^2) for Bethlehem.

Rainy season index	**Regression slope (m)**	**Regression constant (c)**	**Coefficient of correlation (r^2)**
Onset	1.061	42.784	0.993
Cessation	-0.881	348.598	0.994
Rainy season duration	1.054	156.245	0.993

The risk at the pre-defined place is obtained using the regression equations as outlined above. But if the user is interested in the finding risk at a place where there were no climate analysis that were performed (i.e through entering coordinates of the location), the tool uses the Inverse distance weighting (IDW) method of interpolation which is derived from the Tobler's first law of Geography which states "Everything is related to everything else, but near things are more related than distant things" (Longley *et al.*, 2001). In this tool the estimation of the risk at that particular coordinate is obtained by using three nearest stations risk at the level that the user has chosen. The equation for the IDW used is as follows:

$$y_t = \frac{\sum_{i=1}^{3} x_t^i / D_i^2}{\sum_{i=1}^{3} 1 / D_i^2} \qquad (7.4)$$

Where y_t is the estimated value of the required point, x_t^i is the risk value of the ith nearest location, and D_i is the distance between the station of missing dataset and the ith nearest location (Longley *et al.*, 2001).

7.3.2.2 Suitability model

The suitability model is comprised of the Poone AgroCliamtic Suitability Index (PACSI). The index is the combination of onset of rains, frost probability and drought risk during the growing period. The details are in chapter 6. The tool can be used to find whether a location is suited for dryland maize production for different growing periods and growing lengths. If the result of the index is smaller than 50 then in that location and that particular growing period, the growth and development of the maize crop will be hampered by either or two or all of the three climate risks that constitutes the PACSI. In contrast values exceeding 80 denote suitability of the location for dryland maize production. The calculations in this section use the same functionalities deployed in the previous sub-section (7.3.3). The main difference is in the determination of frost probabilities. These values are obtained for each of the weather stations at each planting date and growing period and for different frost severity levels as explained in chapter 6.

7.3.2.3 Risk forecasting models

The tool (FS-Macrt) contains simple forecasting models that will act as an early warning system for determining onsets of rains and agricultural drought for the upcoming season. Lourens (1995) described two early warning methodologies which are forecasting and monitoring of risks. In forecasting, the risk is determined long before the start of the agricultural season. By contrast, monitotring of climate risks involves using measured values during the season to assess the risk. Monitoring and forecasting can also be coupled during the season whereby observations up to the current date can be extended using weather forecasts to estimate risk.

The drought risk model uses the methodology employed in chapter 6 to determine the drought risk namely WRSI. The only difference is the use of weather forecasts information while in chapter 6 the past climatological recorded data was used. The deterministic forecasts of up to 6 months period can be obtained from forecasting centres like CSIR atmospheric group (personal communication with W.A. Landman). It is ideal for this forecast to be obtained before the start of the agricultural season in September or October. The model will determine drought index at the end of the growing period for the 100-day, 120-day and 140-day maize cultivars. The drought index will be calculated for each of the future growing seasons provided the forecast weather data is long enough for the cultivars chosen. Prior knowledge of the planting dates and their corresponding drought index will help in the planning of the farm activities. This will enable farmers to plant maize crop in planting periods that minimise crop losses caused by water deficiency. It has to be noted that, the reliability of the drought index is solely dependent on the forecast ability to resemble the actual forthcoming rainfall and temperature during season.

The tool determines onset of rains as per the methodology used in chapter 4 and categorize the onsets as the 1st onset, 2nd onset and so on. The computation of multiple planting opportunities will help the farmer in planning for agricultural activities like soil preparation and planting which is normally being done using tractors. The availability of this mechanization equipment can be a challenge especially in the resource-poor farmer regions and thus knowledge of multiple planting opportunities will enable the farmer to have alternative plan if the first onset has passed and operations have not begun due to tractor un-availability. Multiple onsets can also help if the farmers plan to stagger their planting as an adaptation methodology. This method of planting can minimise agricultural losses which might be caused by one of the disasters (climate included) because planted crops would be subjected to different growing periods. The other advantage of having multiple planting dates is that, one can compare the planting dates obtained with the climatological risk of frost or any other climate hazard discussed in previous chapters to determine which onset date has minimum climate risks depending on the length of the growing period (cultivar length).

7.3.3 Tool inputs

The main inputs to the models used in the tool are the planting dekads, cultivar length, risk level, frost severity level, forecasting data (rainfall, minimum and maximum temperatures), crop coefficients, soil water holding capacity and choice of selected area or input your own coordinates (Tables 7.5, 7.6, 7.7 & 7.8). Planting dekads start from 1st dekad of October and ends in the last dekad of January (planting window for Free State). This makes the total of 12 different planting dekads from which to choose. There are three cultivar lengths that were investigated in this study, 1) 100-day maize cultivar, 2) 120-day maize cultivar and 3) 140-day cultivar representing the short, medium and long-season maize cultivars respectively. The user has an option of choosing from 12 risk (probability) levels representing different return periods (Table 7.6). The frost severity level consists of 3 choices: light frost, medium frost and heavy frost representing the 2°C, 0°C and -2°C minimum temperature thresholds respectively. Forecast data is obtained from the CSIR or SAWS. The elements forecasted are daily rainfall, minimum temperatures and maximum temperatures. Minimum and maximum temperatures are used to estimate evapotranspiration using calibrated Hargreaves equations (Chapter 2) (Eq.7.5):

$$ET_{CH} = 0.408 * C_H * (Tmean + 17.8) * (T\max - T\min)^{0.5} * Ra \qquad (7.5)$$

where:

Tmean is the daily average temperature, Tmax and Tmin are the minimum, maximum temperatures, Ra is the extraterrestrial radiation (MJ $m^{-}2$ per day) and C_H is the monthly calibrations for the Free State province (Median values used to adjust Hargreaves values for temperature values measured at weather stations are shown in Table 7.7).

The raw forecast data is entered into the Excel file for forecasting drought. This file converts daily rainfall data into dekadal data and further estimate evapotranspiration using equation 7.5 and the daily values are summed into dekadal values which form an input for the forecasting model. The crop coefficients are required for the 100-day, 120-day and 140-day maize cultivars for forecasting agricultural drought. In cases where the crop coefficients and soil water holding capacity (WHC) are not input by the user, Table 7.8 shows the default values that are used (Allen *et al.*, 1998). If WHC is unavailable, a default of 60mm is used, based on the average value for Free State. Cultivar length is linked to the rainy season length at different planting dates and recommended planting dates with minimal risk are determined.

Table 7.5: Models and their corresponding inputs in the Free State Maize Agroclimatological Risk Tool (FS-Macrt).

Models	**Choice of area/enter coordinates**	**Select Cultivar length**	**Select planting dates**	**Frost severity level**	**Select probability (risk) level**	**Forecasting data**			**Crop coefficients**	**Water Holding capacity**
						Rain	**Tmin**	**Tmax**		
Climatology models										
Drought	x	x	x		x				x	x
Frost	x	x		x	x					
Rainy Season	x				x					
Suitability	x	x	x	x	x					
Risk Forecasting models										
Drought		x				x	x	x	x	x
Onset of rains						x				

Table 7.6: Probability levels and their return periods for non-exceeding and exceeding probabilities.

Probability levels (%)	Return period in years (non-exceeding probability)	Return period in years (exceeding probability)
10	1.11	10
20	1.25	5
25	1.33	4
30	1.43	3.33
33	1.49	3.03
40	1.67	2.5
50	2	2
60	2.5	1.67
67	3.03	1.49
70	3.33	1.43
75	4	1.33
80	5	1.25
90	10	1.11

Table 7.7: Median Hargreaves evapotranspiration coefficient adjustment and resultant Hargreaves coefficient for the Free State Province according to month of the year.

Months	**Coefficient adjustment**	**Resultant Hargreaves Coefficient (C_H)**
January	0.99	0.00228
February	1.00	0.00230
March	0.97	0.00223
April	0.98	0.00225
May	1.00	0.00230
June	1.09	0.00251
July	1.10	0.00253
August	1.21	0.00278
September	1.19	0.00274
October	1.10	0.00253
November	1.08	0.00248
December	1.08	0.00248

Table 7.8: Default crop coefficients for the 100-day, 120-day and 140-day maize varieties.

Dekads	**Crop Coefficients (Kc)**		
	100-day	**120-day**	**140-day**
1	0.3	0.30	0.30
2	0.3	0.30	0.30
3	0.6	0.50	0.40
4	0.9	0.70	0.60
5	1.2	1.00	0.80
6	1.2	1.20	1.00
7	1.2	1.20	1.20
8	1.2	1.20	1.20
9	0.8	1.20	1.20
10	0.35	1.20	1.20
11		0.80	1.20
12		0.35	0.90
13			0.70
14			0.35

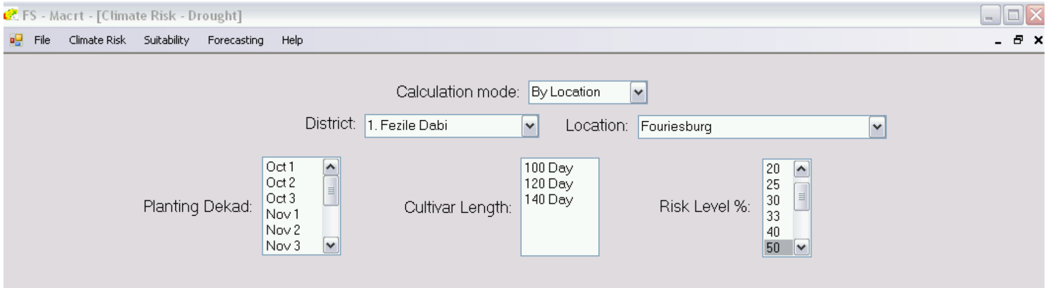
7.3.4 User-Interface

The user-interface is the interaction of the DST with the user and its one of the most important components (Santos & Holsapple, 1989; Druzdzel & Flynn; 2002). The user-interface should not be filled with complex information that is abstract to users. Udo & Davis (1992) outlined the user friendliness and easy to understand dialogue between the users and the tool as the one of the characteristics of the successful DST. Previous studies have shown that, one of the many reasons for poor adoption rate of DSTs is producing a tool that is too advanced to a user (Fernandez & Trolinger, 2007). In this tool, the user has to specify the location of the farm of interest or choose from the pre-defined places in order to assess climate risks associated to the vicinity of the farm.

The front page for the FS-Macrt is shown in Figure 7.2 with three main options (Climate risk, suitability and risk forecasting) as outlined in previous sections. The User-interfaces for the determining agricultural drought at a particular location and by coordinates are shown Figures 7.3 and 7.4 respectively. The user-interface for the frost risk and rainy season characteristics are shown in Figures 7.5 and 7.6 respectively.

Free State Maize Agroclimatological Risk Tool

Fig. 7.2: Front page for the Free State agroclimatological risk tool.



Calculation mode: By Location

District: 1. Fezile Dabi

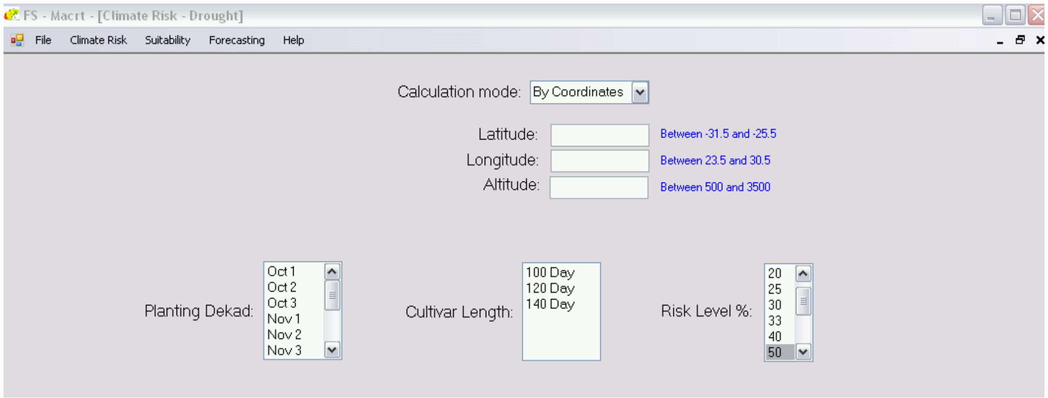
Location: Fouriesburg

Planting Dekad: Oct 1, Oct 2, Oct 3, Nov 1, Nov 2, Nov 3

Cultivar Length: 100 Day, 120 Day, 140 Day

Risk Level %: 20, 25, 30, 33, 40, 50

Fig. 7.3: User-interface for determining agricultural drought by using pre-determined locations



Calculation mode: By Coordinates

Latitude: Between -31.5 and -25.5

Longitude: Between 23.5 and 30.5

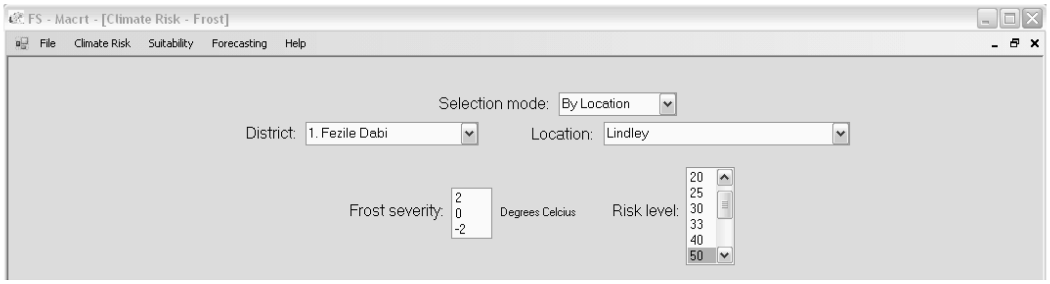
Altitude: Between 500 and 3500

Planting Dekad: Oct 1, Oct 2, Oct 3, Nov 1, Nov 2, Nov 3

Cultivar Length: 100 Day, 120 Day, 140 Day

Risk Level %: 20, 25, 30, 33, 40, 50

Fig. 7.4: User-interface for determining agricultural drought by inserting own coordinates within the Free State Province.



Selection mode: By Location

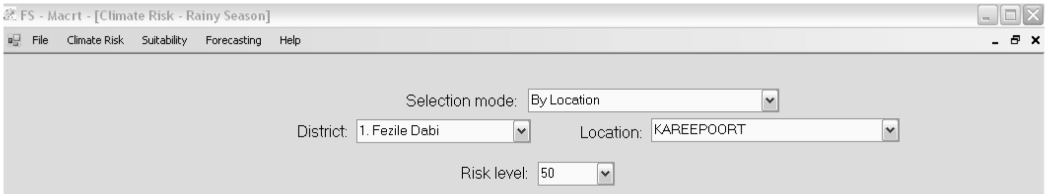
District: 1. Fezile Dabi

Location: Lindley

Frost severity: 2 0 -2 Degrees Celcius

Risk level: 20 25 30 33 40 50

Fig. 7.5: User-interface for determining frost risk by location.



Selection mode: By Location

District: 1. Fezile Dabi

Location: KAREEPOORT

Risk level: 50

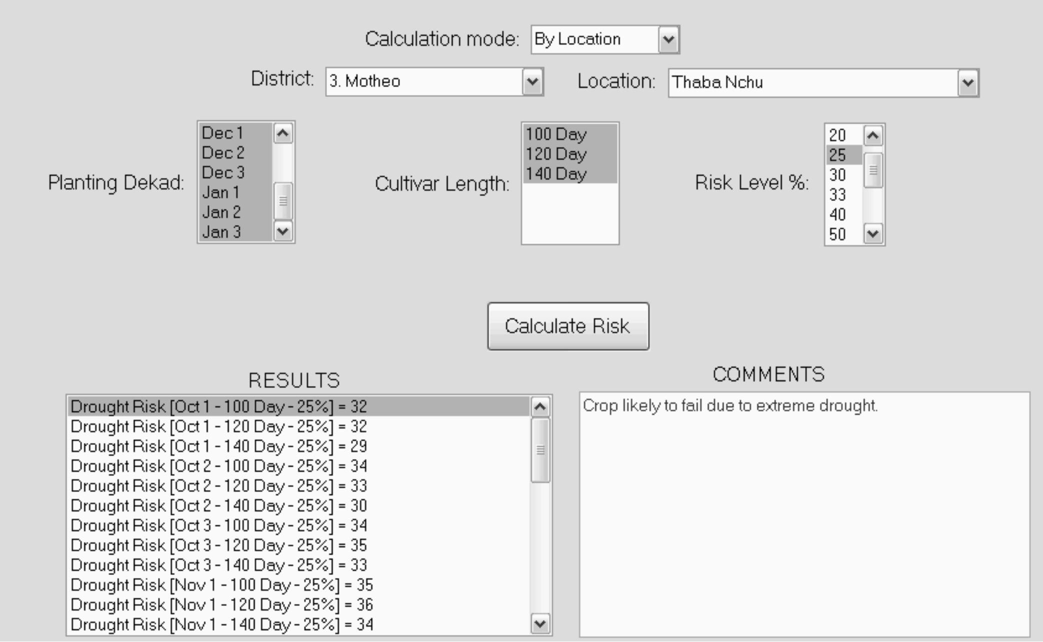
Fig. 7.6: User-interface for determining rainy season characteristics by location.

7.3.5 Outputs

The user of the tool should be able to assess the risk of making a good harvest or crop failure while keeping other factors that contribute towards enhancement of production optimal. The outcomes of the interaction with the program will be discussed for the functionality of the tool. An example of the results for the drought risk, rainy season characteristics and frost risk would be discussed for the Thaba Nchu location in the central part of Free State.

7.3.5.1 Drought risk

Fig. 7.7 shows the results of multiple selection of planting dekads for two choices of cultivars namely 100-day, 120-day and 140-day maize cultivar at 25% risk level for determining drought index. The results show drought indices for all the selected planting dekads and cultivar length. All the WRSI values obtained are below 40 for the 100-day, 120-day and 140-day cultivars showing extreme drought conditions during the season at 25% risk level (Fig. 7.7). At 50% level (Normal) the drought index values are mostly less than 50 while at 75% (relatively wet seasons) the values are below 60 (Figs. 7.8 & 7.9). It is evident that, drought is a climate risk that can hamper maize productivity during the planting dates from October 1st dekad to November 1st dekad. The comment for the planting dekads is “Plants are likely to fail due to extreme drought conditions” at the 25% risk level. From the farmer’s perspective, planting maize in this condition would result in economic losses unless high drought resistant cultivars are planted. From the Insurance advisor perspective, this area is a high drought risk area and insurance on drought would be the right choice for the farmer. But the insurance company is likely to loose money because the area is a high risk one hence alternative crops would be suggested. The other scenario would be high insurance premiums for these planting dates due to high likeihood of crop failure. Agricultural extension service and government officers would use this information to help in introducing programmes like supplementary irrigation, inter-cropping and water harversting techniques to address the soil water shortages (Mukhala, 1998).


Calculation mode: By Location

District: 3. Motheo

Location: Thaba Nchu

Planting Dekad: Dec 1, Dec 2, Dec 3, Jan 1, Jan 2, Jan 3

Cultivar Length: 100 Day, 120 Day, 140 Day

Risk Level %: 20, 25, 30, 33, 40, 50

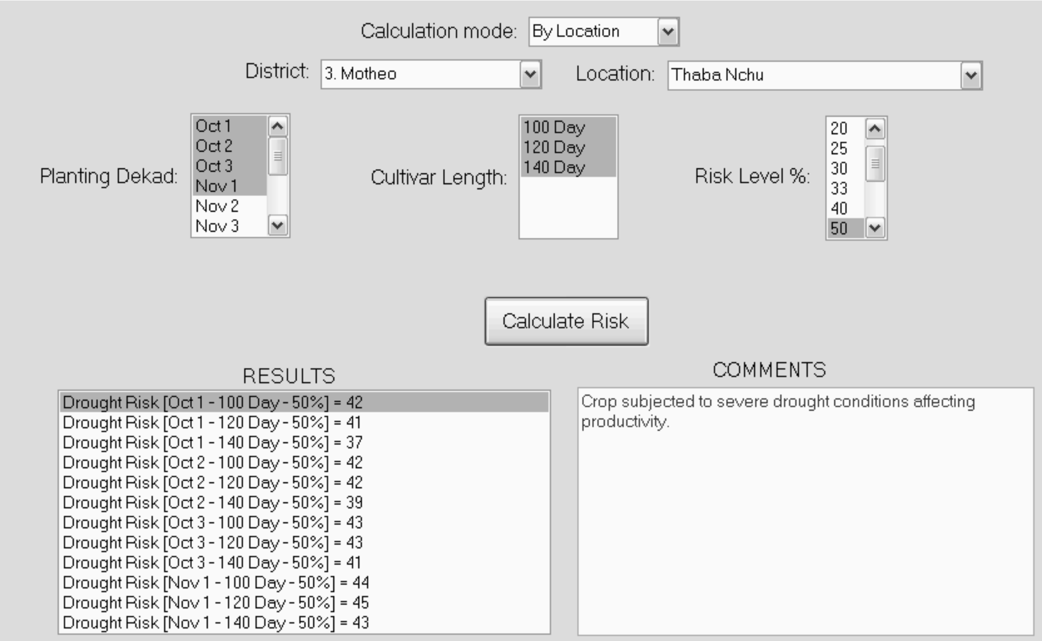
RESULTS

```
Drought Risk [Oct 1 - 100 Day - 25%] = 32
Drought Risk [Oct 1 - 120 Day - 25%] = 32
Drought Risk [Oct 1 - 140 Day - 25%] = 29
Drought Risk [Oct 2 - 100 Day - 25%] = 34
Drought Risk [Oct 2 - 120 Day - 25%] = 33
Drought Risk [Oct 2 - 140 Day - 25%] = 30
Drought Risk [Oct 3 - 100 Day - 25%] = 34
Drought Risk [Oct 3 - 120 Day - 25%] = 35
Drought Risk [Oct 3 - 140 Day - 25%] = 33
Drought Risk [Nov 1 - 100 Day - 25%] = 35
Drought Risk [Nov 1 - 120 Day - 25%] = 36
Drought Risk [Nov 1 - 140 Day - 25%] = 34
```

COMMENTS

Crop likely to fail due to extreme drought.

Fig 7.7: Drought index at 25% probability for multiple selection of planting dekads and cultivar lengths.


Calculation mode: By Location

District: 3. Motheo

Location: Thaba Nchu

Planting Dekad: Oct 1, Oct 2, Oct 3, Nov 1, Nov 2, Nov 3

Cultivar Length: 100 Day, 120 Day, 140 Day

Risk Level %: 20, 25, 30, 33, 40, 50

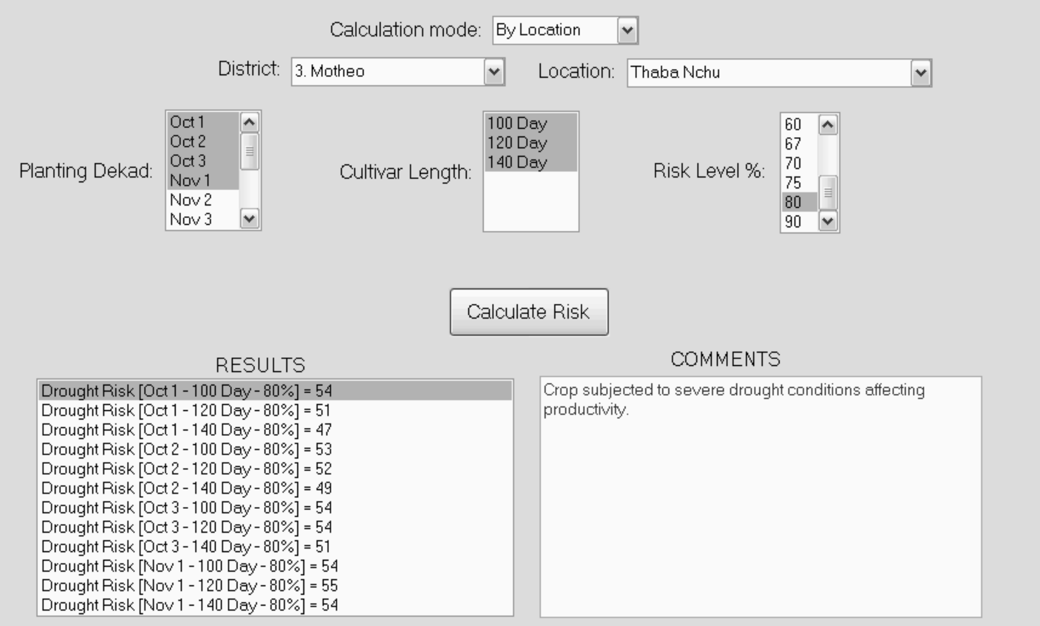
RESULTS

```
Drought Risk [Oct 1 - 100 Day - 50%] = 42
Drought Risk [Oct 1 - 120 Day - 50%] = 41
Drought Risk [Oct 1 - 140 Day - 50%] = 37
Drought Risk [Oct 2 - 100 Day - 50%] = 42
Drought Risk [Oct 2 - 120 Day - 50%] = 42
Drought Risk [Oct 2 - 140 Day - 50%] = 39
Drought Risk [Oct 3 - 100 Day - 50%] = 43
Drought Risk [Oct 3 - 120 Day - 50%] = 43
Drought Risk [Oct 3 - 140 Day - 50%] = 41
Drought Risk [Nov 1 - 100 Day - 50%] = 44
Drought Risk [Nov 1 - 120 Day - 50%] = 45
Drought Risk [Nov 1 - 140 Day - 50%] = 43
```

COMMENTS

Crop subjected to severe drought conditions affecting productivity.

Fig. 7.8: Drought index at 50% probability for multiple selection planting dekads and cultivar lengths.



Calculation mode: By Location

District: 3. Motheo

Location: Thaba Nchu

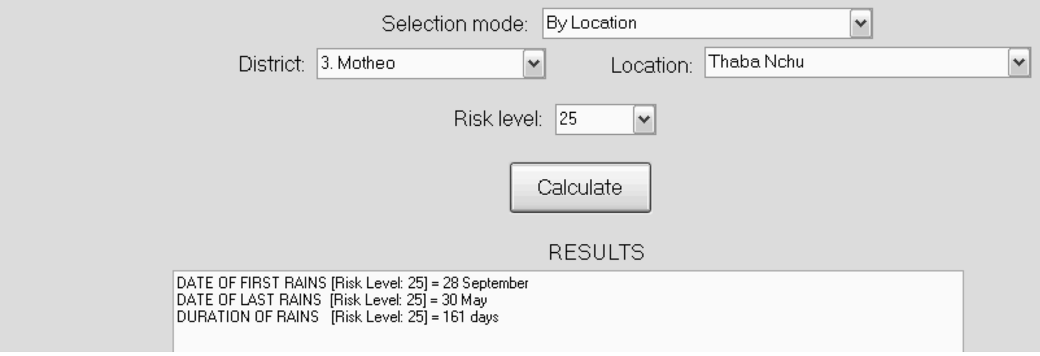
Drought Risk [Oct 1 - 100 Day - 80%] = 54
Drought Risk [Oct 1 - 120 Day - 80%] = 51
Drought Risk [Oct 1 - 140 Day - 80%] = 47
Drought Risk [Oct 2 - 100 Day - 80%] = 53
Drought Risk [Oct 2 - 120 Day - 80%] = 52
Drought Risk [Oct 2 - 140 Day - 80%] = 49
Drought Risk [Oct 3 - 100 Day - 80%] = 54
Drought Risk [Oct 3 - 120 Day - 80%] = 54
Drought Risk [Oct 3 - 140 Day - 80%] = 51
Drought Risk [Nov 1 - 100 Day - 80%] = 54
Drought Risk [Nov 1 - 120 Day - 80%] = 55
Drought Risk [Nov 1 - 140 Day - 80%] = 54

Crop subjected to severe drought conditions affecting productivity.

Fig. 7.9: Drought index at 80% probability for multiple selection planting dekads and cultivar lengths.

7.3.5.2 Rainy season characteristics

Examples of the results for determining the onset, cessation and duration of rains at 25%, 50% and 80% probability level are shown in Figures 7.10, 7.11 & 7.12. At 25% probability, the duration of rainy season is 161 days making the place ideal for any cultivar length even during one of the shortest rainy seasons. The values at 50% and 75% are 194 and 228 days respectively. The rainy season characteristics are not limiting to the maize production in this area. Even in one of the shortest rainy seasons (25% probability), the rainy season duration is long enough to enable planting of medium-late to late season varieties which have high yield potential.



Selection mode: By Location

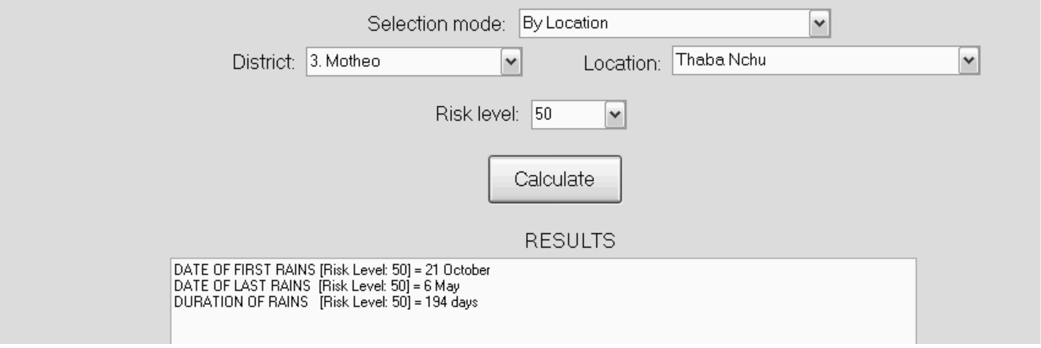
District: 3. Motheo

Location: Thaba Nchu

Risk level: 25

DATE OF FIRST RAINS [Risk Level: 25] = 28 September
DATE OF LAST RAINS [Risk Level: 25] = 30 May
DURATION OF RAINS [Risk Level: 25] = 161 days

Fig. 7.10: Results for onset, cessation and duration of rains for Thaba Nchu at 25% probability level.



Selection mode: By Location

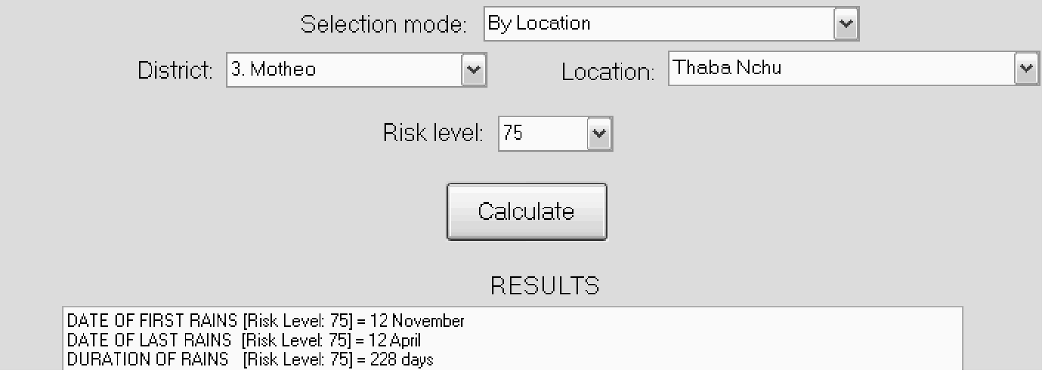
District: 3. Motheo

Location: Thaba Nchu

Risk level: 50

```
DATE OF FIRST RAINS [Risk Level: 50] = 21 October
DATE OF LAST RAINS  [Risk Level: 50] = 6 May
DURATION OF RAINS   [Risk Level: 50] = 194 days
```

Fig. 7.11: Results for onset, cessation and duration of rains for Thaba Nchu at 50% probability level.



Selection mode: By Location

District: 3. Motheo

Location: Thaba Nchu

Risk level: 75

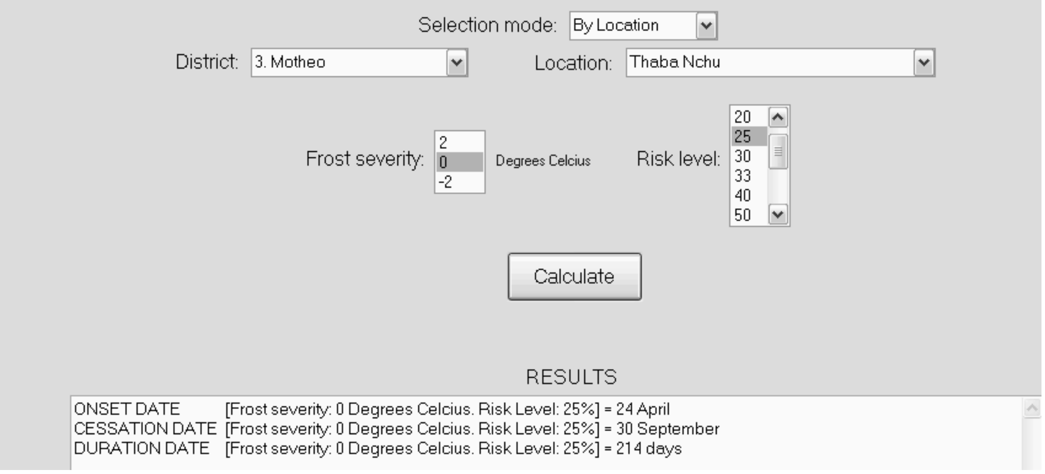
```
DATE OF FIRST RAINS [Risk Level: 75] = 12 November
DATE OF LAST RAINS  [Risk Level: 75] = 12 April
DURATION OF RAINS   [Risk Level: 75] = 228 days
```

Fig. 7.12: Results for onset, cessation and duration of rains for Thaba Nchu at 75% probability level.

7.3.5.3 Frost risk

The results of onset & cessation of frost and duration of frost-free season are shown in Fig. 7.12 for Thaba Nchu weather station. The frost severity chosen is medium frost and 214 days of frost-free duration is obtained at this location at 25% probability (Fig. 12). The 50% and 80% probability levels records the growing period of 219 and 244 respectively (Fig. 13 & 14). The chances of frost damage are scarce at Thaba Nchu area if the maize crop is planted outside the frost period due to long frost-free seasons. The farmer at this area would have little concern about frost damage and thus insurance premiums for covering this climate hazard would have to be small.

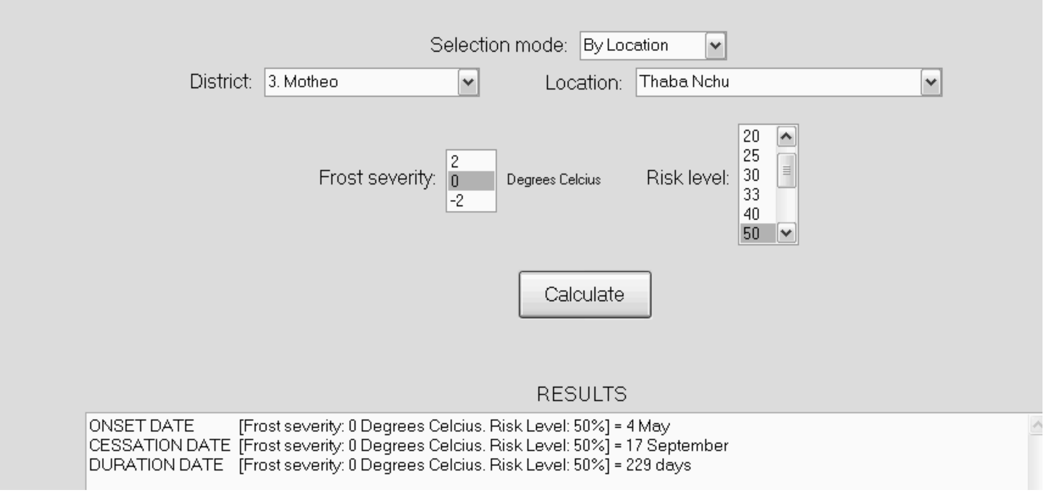
These three climate risks (drought in 7.3.8.1; rainy season charecteristics in 7.3.8.2 and frost risk in 7.3.8.3) determined for Thaba Nchu in the central parts of the Free State Province show that drought is the most limiting factor to productivity in Thaba Nchu.



Selection mode: By Location
District: 3. Motheo
Location: Thaba Nchu
Frost severity: 0 Degrees Celcius
Risk level: 25

```
ONSET DATE        [Frost severity: 0 Degrees Celcius. Risk Level: 25%] = 24 April
CESSATION DATE [Frost severity: 0 Degrees Celcius. Risk Level: 25%] = 30 September
DURATION DATE   [Frost severity: 0 Degrees Celcius. Risk Level: 25%] = 214 days
```

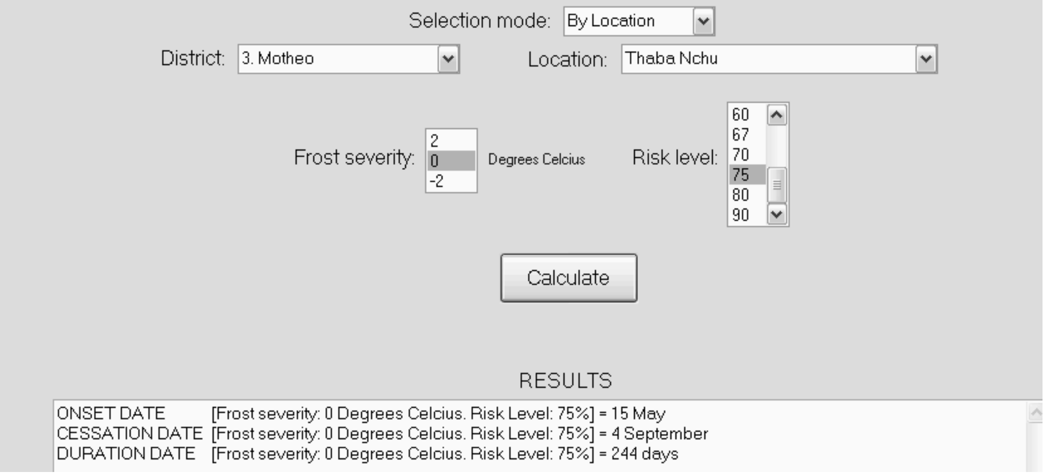
Fig. 7.13: Results of onset & cessation of frost and duration of frost-free period for Thaba Nchu at 25% probability level.



Selection mode: By Location
District: 3. Motheo
Location: Thaba Nchu
Frost severity: 0 Degrees Celcius
Risk level: 50

```
ONSET DATE        [Frost severity: 0 Degrees Celcius. Risk Level: 50%] = 4 May
CESSATION DATE [Frost severity: 0 Degrees Celcius. Risk Level: 50%] = 17 September
DURATION DATE   [Frost severity: 0 Degrees Celcius. Risk Level: 50%] = 229 days
```

Fig. 7.14: Results of onset & cessation of frost and duration of frost-free period for Thaba Nchu at 50% probability level.



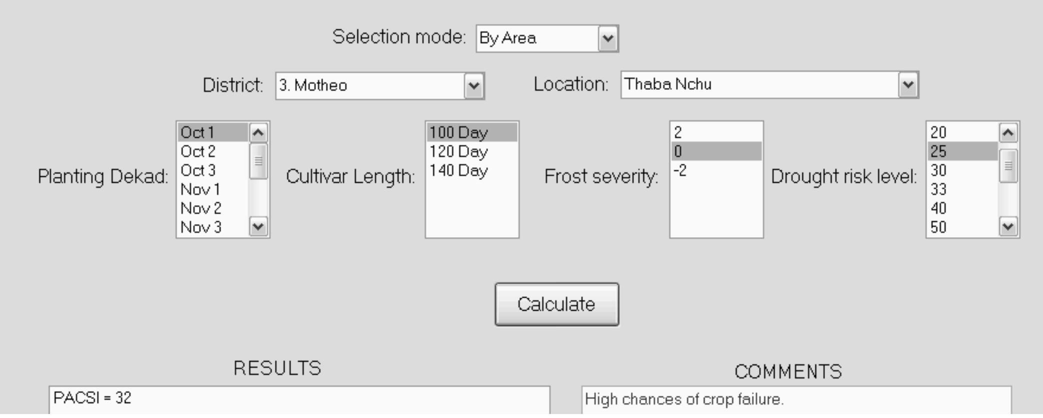
Selection mode: By Location
District: 3. Motheo
Location: Thaba Nchu
Frost severity: 0 Degrees Celcius
Risk level: 75

```
ONSET DATE        [Frost severity: 0 Degrees Celcius. Risk Level: 75%] = 15 May
CESSATION DATE [Frost severity: 0 Degrees Celcius. Risk Level: 75%] = 4 September
DURATION DATE   [Frost severity: 0 Degrees Celcius. Risk Level: 75%] = 244 days
```

Fig. 7.15: Results of onset & cessation of frost and duration of frost-free period for Thaba Nchu at 75% probability level.

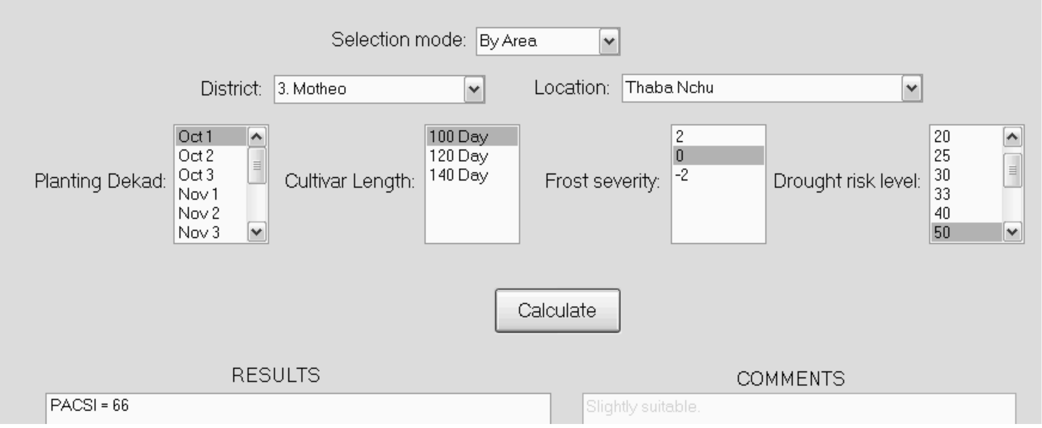
7.3.5.4 PACSI

Figures 7.15, 7.16 and 7.17 show suitability index for planting a 100-day maize cultivar in October 1st dekad at the medium frost severity level and 25%, 50% and 75% drought risk levels respectively. At 25%, 50% & 75% risk levels (relatively dry seasons), the PACSI are 32, 66 and 77 respectively. It is still evident that drought has a great influence in maize production in these areas because of great differences in PACSI values corresponding to different drought risk levels.



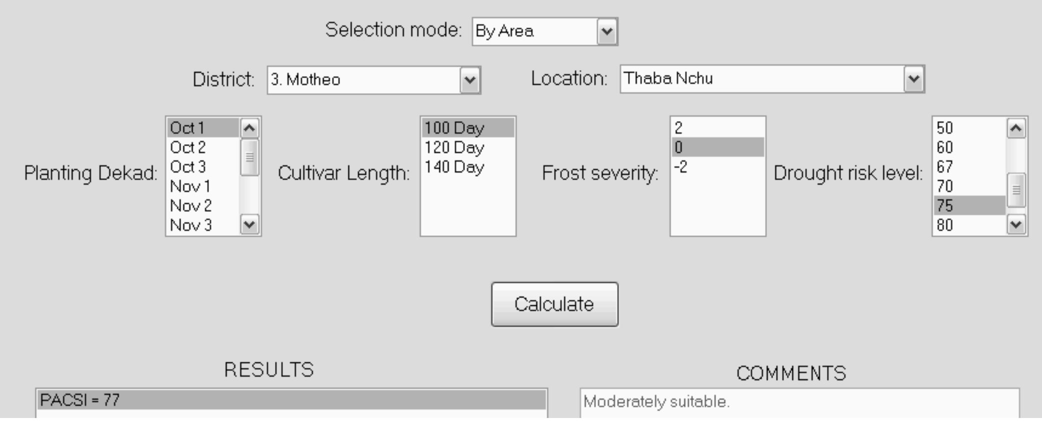
Selection mode: By Area
District: 3. Motheo
Location: Thaba Nchu
Planting Dekad: Oct 1
Cultivar Length: 100 Day
Frost severity: 0
Drought risk level: 25
RESULTS: PACSI = 32
COMMENTS: High chances of crop failure.

Fig. 7.16: Results of PACSI for Thaba Nchu at 25% probability level.



Selection mode: By Area
District: 3. Motheo
Location: Thaba Nchu
Planting Dekad: Oct 1
Cultivar Length: 100 Day
Frost severity: 0
Drought risk level: 50
RESULTS: PACSI = 66
COMMENTS: Slightly suitable.

Fig. 7.17: Results of PACSI for Thaba Nchu at 50% probability level.



Selection mode: By Area
District: 3. Motheo
Location: Thaba Nchu
Planting Dekad: Oct 1
Cultivar Length: 100 Day
Frost severity: 0
Drought risk level: 75
RESULTS: PACSI = 77
COMMENTS: Moderately suitable.

Fig. 7.18: Results of PACSI for Thaba Nchu at 75% probability level.

7.4 Conclusions

The development of the agroclimatic risk tool to help farmers, agricultural extensionists and other stakeholders is useful in a number of ways over the Free State Province. The farmers acknowledged the fact that climate variability and its impact on production needed to be addressed. By developing this risk tool (FS-Macrt), farmers would be able to make informed decisions based on climatological knowledge of the distribution of climate hazards during the agricultural season. The importance of categorizing these hazards according to their severity and at different risk levels (probability) makes it possible for the producer to strategize on the best practices at that given period. The climate risks of concern to the Free State are frost risk, drought risk and risks associated with the rainy season. The tool (FS-Macrt) enables the computation of each of these climate risks for different planting dates at different risk levels. The suitability index incorporated in the tool would make it possible for the user to determine whether the location is suited for planting dryland maize.

FS-Macrt also has the capabilities of using weather forecasts for agricultural puporses. It is a concern from agricultural community that weather forecasts disseminated over the national media are not addressing the needs of the farmers and thus FS-Macrt incorporated forecasting of drought in its functionality as well as onset of rains. The drought forecasting would enable farmers to plan ahead of time by choosing the cultivars that are drought tolerant is cases where drought (low WRSI) is forecasted. By contrast, in cases where high WRSI is forecasted farmers would choose the high yielding cultivars that would maximize on near normal to above normal rains. The other early warning facility of the tool is the ability to forecast onset of rains when being fed with rainfall forecasts. Depending on the length of the forecast, multiple onsets dates can be obtained to help risk averse farmers to stagger their plants to spread the production risk. Combining the two forecasting capabilities in decision making before the start of the season would enhance productivity especially in cases of wet seasons. But in cases of below normal rains, making choices like decreasing plant density that would minimize economic losses are also important.

Agricultural production over the Free State is vulnerable to climate risks and the knowledge of the timing and severity of these hazards would help decion makers in reducing their impacts. The Free State Agroclimatological Tool (FS-Macrt) aims at equipping the agricultural community with knowledge of the likelihood of the first rains and cessation of frost at all the places over the Free State for planning of ploughing and planting dates. Knowledge of drought climatology is essential for producers and decision-makers in determining best planting dates associated with low drought risk. The suitability of the places for planting maize can be helpful in re-zoning marginal lands to increase their productivity. With all these reasons, the potential use of FS-Macrt is expected to form a climatological basis for determining risk affecting maize production and its early warning capabilities be used to alleviate the impacts of climate variability and change over different parts of the Free State Province.

Chapter 8: Summary, Conclusions and Recommendations

Climate variability affects agricultural production in the semi-arid climates and therefore it is important for the stakeholders to be equipped with agrometeorological information to decrease vulnerability. This thesis is focused on the agroclimatological risks affecting maize production over the Free State. The conclusions of this study will be categorized according to the main objectives outlined in chapter 1.

8.1 Objective 1

To identify data needs required for proper agroclimatological risk assessment and devise ways of bridging the data gaps

Continuous measurement of any time series dataset that is measured and archived for long-term purposes always has missing values or corrupt data resulting in an incomplete dataset and/or misleading data. However, the use of missing data in research or modelling usually results in wrong simulations and incomplete findings and thus it is important to find ways of filling the gaps in the dataset using scientifically correct and acceptable methods. Similarly, the use of corrupt data even if it is for a short period of time, can also lead to wrong conclusions and recommendations. Thus the system that one uses to store or process that data should be able to have some basic quality control measures incorporated in it to filter out erroneous data, and there must also be standard methods to patch the missing data.

Rainfall data used (Chapter 2) was quality controlled and missing or corrupt data was estimated using the Inverse Distance Weighting (IDW) methodology, which used data from 2-5 nearby stations to estimate missing data giving more weight to patching stations that are closest to the target station. This method was evaluated on dekadal basis because it is the time-scale that is being used for all the analysis in this study. Overall, the IDW method gave good results for dekadal estimated rainfall, with r^2 ranging from 0.78 to 0.91 for all stations. The K-S tests also showed that estimated values were statistically similar to the measured values. Therefore IDW method is a recommended patching method for rainfall in the Free State Province.

The UK traditional method was used to estimate minimum and maximum temperatures. This method calculated monthly differences (for both T_{min} and T_{max}) between the closest stations and the target station; which were used adjust the value of the closeby station to estimate the values for the target station. The evaluation results using six weather stations spread over the Free State showed a good correlation between estimated dekadal minimum and maximum temperatures. The overall r^2 for the minimum temperatures ranged from 0.96 to 0.99 while that for the maximum temperatures were between 0.96 and 0.98, which is considered excellent. The MAE for both the maximum and minimum temperatures is below 1℃. The K-S tests also clearly depicted the similarity of the estimated dekadal values with the measured values with few exceptions. Thus, one can clearly conclude that, the UK traditional method of estimating temperature data results in statistically accepted estimations in the

Free State Province. Therefore the UK traditional method was used for patching minimum and maximum temperatures in the Free State Province for climate stations from 1950 to 2008.

Evapotranspiration (ET) data is one of the elements needed for simulating crop water performance. The best way of estimating ET is by using the Penman-Monteith equation, but the methodology has high data demands (Relative humidity, wind, vapour pressure etc) that were not available for most stations over the Free State in the period 1950 to 2000. Thus other empirical methods, with less data requirements have to be used. In this study the Hargreaves method of estimating ET was investigated using six stations situated across the different climates zones of the Free State. The results show that the Hargreaves estimates correlated well with the Penman-Monteith values with the r^2 ranging from 0.85 to 0.95. Monthly values r^2 showed a lot of variation from month to month with the lowest correlations of less than 0.4 being evident in the winter months (May and June). These low values had little impact on the results obtained from this study because the analysis was performed during the summer agricultural season which excluded winter months. However, care should be taken if they are used for a study with winter crops. The Hargreaves estimate was mostly underestimating ET mostly from July to November. The Hargreaves equation was therefore calibrated using the slope of the regression line between the Penman-Monteith and Hargreaves estimates with the data from 1999 to 2004 for the six stations that were selected. The results of the calibrated Hargreaves yielded better estimates of the Penman-Monteith ET during the validation period (2005-2008). Overall the RMSE, RE and MBE were greatly reduced when using the calibrated equation as compared to the original equation. Therefore it was concluded that calibrated Hargreaves equation can be used to estimate evapotranspiration in the Free State Province of South Africa.

Over the Free State Province, the majority of the stations only measure rainfall. These stations cover the maize growing area and excluding them from the network would have resulted in sparsely distribution of stations. As agricultural drought index used in this study depends on rainfall, evapotranspiration, plant characteristics and soil properties of the fields it was important to include as many stations as possible. The possibility of using NASA-derived satellite temperature data to estimate temperature at these rainfall stations was investigated. Before using this data, it was ground truthed or evaluated against measured values from a standard weather station. Both minimum and maximum temperatures showed good relationships with the measured values. The r^2 for minimum temperatures ranged from 0.81 to 0.87, while maximum temperatures values ranged from 0.69 to 0.79. NASA satellite-derived data overestimated minimum temperatures in all the months while maximum temperatures underestimated measured maximum temperature values. To use NASA satellite-derived and modelled data to estimate temperature values in the Free State, one has to make bias corrections to the dataset in order to resemble measured data. The Hargreaves equation (using NASA temperature data as inputs) was then calibrated with the Penman-Monteith equation for 36 stations over the Free State. The main reason of obtaining the median value for the Free State was to apply it in places where calibration is not possible due to lack of data. The calibrated Hargreaves was then used to estimate agricultural drought index which was compared with the drought index obtained when using Penman-Monteith equation keeping all other variables constant. The resultant r^2 ranges from 0.78 to 0.95 clearly indicating that NASA satellite derived temperature data can be used to estimate the drought index in places where temperature data is missing or not measured. Therefore the regionally calibrated Hargreaves equation ET estimates was used to estimate agricultural drought in the stations lacking temperature data using NASA satellite-derived and modelled data as inputs.

8.2 Objective 2

To identify and quantify the agroclimatological risk associated with dryland maize production in the Free State province of South Africa

The Free State agricultural production is affected by a number of agroclimatological risks mainly frost, rainfall variability and drought which have a significant effect on maize productivity. In chapter 3 frost risk assessment was investigated, chapter 4 addressed the rainy season characteristics, in chapter 5 the risk associated with agricultural drought was studied while in chapter 6 combined climate risk index to delineate suitable maize growing areas was presented.

Extremely low temperatures affect plant growth in many ways depending on the hardiness of the crop. A maize crop is very sensitive to low temperatures as its leaf growth stops at temperatures below 10℃ (du Plessis, 2003). Freezing temperatures causes damage to the crop depending on the severity and persistence. In chapter 3, frost was categorised into three frost categories light frost with a threshold of 2℃, medium frost with a threshold of 0℃ and heavy frost with a threshold of -2℃. Daily minimum temperatures were analysed using data from 1950 to 2008 for 55 stations in the Free State and surrounding Provinces (including Lesotho). The results showed early last frost date over the western and southwestern parts. For light frost the median last frost date in these areas was on or after 20th September, while for the medium frost it occurs by 10th September and for heavy frost in mid-August with some isolated patches where heavy frost is usually not experienced. The first frost dates in these areas are late occurring only in early May, end of May and in June for light frost, medium and heavy frost respectively. There is a long frost-free duration period in these places with median period exceeding 220 days for light frost, 240 days for medium frost and 280 days for heavy frost. Therefore, the western parts of Free State have low frost risk and thus favour the growth and development of the maize crop. Over the Thabo Mofutsanyane district, late cessation of frost was evident with the light frost being in mid-October at 50% probability level. Medium and heavy frost occurs until the end of September while heavy frost ends by mid-September. The onset of frost is relatively early over the Thabo Mofutsanyane, especially along the border with Lesotho. In these areas, median onset is on or before 20th April, on or before end of April to early May and on or before 20th May for light, medium and heavy frost respectively. The duration of the frost-free period for these areas is less than 200 for light frost, less than 220 for medium frost and 240 days for heavy frost. Even though the frost-free period is shorter than at other places over the Free State, the season is still long enough to accommodate long-season maize varieties, as long as caution is exercised with the planting dates. It should be noted that in eastern parts of Free State, there is high risk for early planted crops during October and November while the earliest frosts can affect the late maturing maize crops during their latter stages of development. In most places over the Free State median frost-free period is over 200 days for light frost, between 220 and 240 days for medium frost while for heavy frost on average is between 250 and 260 days.

Rainfall is an important variable for agriculture over the Free State because the majority of the land cultivated is under rain-fed agriculture. It is important to know, to a certain degree of confidence, when the rains will be starting and when they will end. Also of importance, is the actual amount of rain that can be expected during the growing season period. The rainy season characteristics considered in this were onsets of rains, cessation of rains and duration of the rainy season as well as cumulative seasonal amount of rainfall (chapter 4). The other important rainy season characteristics that were presented include the probability of onset failure, and probabilities of rainy season duration of less than 50, 100, 120 and 140 days as this would limit the cultivars that can be grown.

The results showed earliest rain onset occurring over the Thabo Mofutsanyane district with 50% chance of onset before 10 October and 80% chance of onset happening on or before 10 November. The central and eastern parts of the Fezile Dabi district also experienced relatively early onset of rains with the median onset on or before 20th October. Most parts of the Lejweleputswa district have their onsets in early November. The far western parts of the Province showed the latest onsets of rains with dates as late as 31st December as median rainfall onset. Generally onset of rains is early over East and moves gradually later to West across FS with the latest onstes over the western and soutwestern parts of the Province. The probability that onset criteria were not realized during the agricultural seasons are high over the western parts of the Free State with up to 10% chance of not obtaining significant rains to start the season. Comparison of onsets dates across the years according to the dates of occurrence of El Niño and La Niña events yielded inconsistent findings indicating that there is no clear indication of any later or earlier than normal onsets associated with ENSO episodes.
Date of cessation of rains was estimated as the last day in which 25mm was accumulated over 10 days. These dates varied significantly across the province of Free State. Places with late cessation of rains occur in southern and southwestern Thabo Mofutsanyane, Eastern Xhariep and Motheo districts as well as patches over the Fezile Dabi district. In these places, median cessation was on or after 10th May, while 80% probability was on or after 10th April. Most places over the Free State recorded median cessation of rains on or after 20th April and 80% dates on or after 20th March. The earliest cessations of rains are evident over the western parts of the Province where the 50% and 80% probability levels were on or after 10th April and 10th March respectively. There was a slight bias showing early cessation of rains in El Niño years and late cessation in La Niña years hence indicating some effects of ENSO on the cessation of rains.

Duration of the rainy season also showed a large amount of variance from one place to another with the shortest rainy season observed over the western parts of the Province. In these places the 20%, 50% and 80% probabilities were below 100 days, 140 days and 180 days respectively, thus they are subjected to high risk of rainy seasons which are shorter than the maize growing periods. In contrast, the longest rainy seasons are evident over the Thabo Mofutsanyane, eastern Motheo and far eastern Xhariep districts where 20%, 50% and 80% probability seasons are longer than 160 days, 200 days and 240 days. Therefore, in these areas, long rainy season duration is associated with low risk of crop failure. A long season can allow multiple planting dates to spread the risk. Most parts of the Lejweleputswa and Fezile Dabi districts recorded rainy season length between 121 and 160,161 and 200 days and 201 and 240 days at 20%, 50% and 80% non-exceeding probability so all varieties of maize can be grown. The probability of rainy season of less than 100 days, 120 days and 140 days was found to be high over the western parts and low over the Fezile Dabi and Thabo Mofutsanyane district. There is up to 60% probability of rainy season being less than 140 days, indicating that in the western parts of the country medium to long-season maize cultivars are subject to crop failure.

The spatial distribution of seasonal rainfall amounts (accumulated between November and March) was similar to the other rainy season characteristics (onset, cessation and duration). The western parts of the country have low seasonal rainfall of below 200mm, below 250mm and below 350mm for the 20%, 50% and 80% probability levels respectively. In these places chances of water requirements of the maize crop being met are minimal. Seasonal rainfall over the Fezile Dabi and most parts of the Lejweleputswa district was between 300 & 400mm, 350 & 450mm and 450 & 550mm at 20%, 50% and 80% probabilities respectively. Highest seasonal rainfall was obtained over the far eastern parts of the Thabo Mofutsanyane district where 20%, 50% and 80% non-exceeding probabilities exceed 400mm, 500mm and 600mm. These areas showed low risk of maize crop failure due to water scarcity, when considering the total seasonal amounts. Accumulated seasonal rainfall was found to be influenced by ENSO phases, with below normal rainfall observed during El Niño years in most places and above normal rainfall recorded in La Niña years.

Agricultural drought is perceived by the farmers and agricultural community as the most serious climate risk affecting agricultural production in South Africa. During agricultural droughts, crops are deprived of soil water necessary for growth and development. Drought impact on crop growth is dependent on the stage of the crop and the severity of drought. In this study, agricultural drought (chapter 5) represented by FAO Water Requirement Satisfaction Index (WRSI) showed that for the 120-day maize variety there was great variation from one planting dekad to another but overall the drought index improved as planting dates are delayed (mid November onwards). The October planting dates showed very low WRSI values with most parts of the Lejweleputswa, Motheo and the whole of Xhariep experiencing total crop failure (Drought Index<40). Fezile Dabi, far eastern Motheo and western Thabo Mofutsanyane district recorded drought Index (WRSI) of less than 60 denoting marginal satisfaction of water requirements. The eastern parts of the Thabo Mofutsanyane district show higher WRSI values between 61 and 80 showing satisfactory maize water requirements. For

November palnting dates, the area of total crop failure is reduced and was mostly confined over the western tip of Lejweleputswa and Xhariep districts. In December and January planting the area of WRSI exceeding 80 is more pronounced over the Thabo Mofutsanyane district especially at the 80% non-exceeding probability. Few patches over the Fezile Dabi and northern Lejweleputswa showed WRSI between 81 and 95 at the 80% probability. These areas are more suitable for maize production and productivity is expected to be higher than in other parts of the Province.

Determining crop suitability using multiple indices that are important for the growth and development of the crop is of paramount importance. In chapter 6, the Poone AgroClimatic Suitability Index (PACSI) was introduced. This index combined the three climate hazards which were found to be critical to rainfed maize production over the Free State namely:

- Probability of frost occurring during the season
- Non-exceedence probability of onset of rains
- Agricultural drought during the growing period

The PACSI index was further used for agroclimatic zoning of maize production in the Free State. The analysis was done for the maize crop requiring 1420 growing degree days (GDD) from earmegence to maturity. This index showed suitability of maize production from the 2nd dekad of October onwards to the 3rd dekad of December. The relatively low suitability at most parts of the Free State during the 1st dekad of October was caused by high frost risk. During the January 1st dekad planting, the whole of the Free State showed unsuitability also attributed to high frost risk. From the 2nd dekad of October to the 1st dekad of November, high values of PACSI (>70 at 50% probability level) are mostly over the Thabo Mofutsanyane, along borders with Lesotho and eastern Fezile Dabi. This showed that maize planted at these places during those planting dates is subjected to lower climate risks favouring high productivity. The area of highest suitability shifted from November 2nd dekad to 3rd dekad of November to the northern Thabo Mofutsanyane and the whole of Fezile Dabi district. High PACSI values between the 1st dekad of December to 2nd dekad of December was confined to the western Fezile Dabi and eastern parts of the Lejweleputswa district. Planting this maize variety (1420 GDD requirement) during the 3rd dekad of December showed relatively high suitability (up to 90) over some parts of the Lejweleputswa district. The areas where maize is not advised to be planted under dryland conditions is at the western and southern parts of the Xhariep district. At these places, PACSI is less than 50 in most planting dates at 50% probability level.

8.3 Objective 3

To develop a simple agroclimatological risk assessment decision making tool for dryland maize production over the Free State province.

Decision support tools can be helpful aids for sustainable natural resource management and the deployment of these tools depends on the usability and simplicity. In chapter 7, a simple agroclimatic risk tool (FS-Macrt) was developed for quantifying climate risks that affects maize production in the

Free State. This chapter is the intergration of all the chapters from 2 to 6. The agroclimatic tool consists of three main categories: “climate risk” which uses climatological information generated in the preceeding chapters, “suitability” which uses the PACSI index to determine the suitability of producing maize for a particular location and the “risk forecasting” category which uses actual weather forecasts as input to estimate selected future climate risk. The climate risk is made up of the drought risk, frost risk and rainy season. Suitability comprises only of the PACSI calculation. Risk forecasting is maded up of agricultural drought forecasting and onset of rains forecasting. In most of these models the user has to select the planting dekad, the risk probability level and the cultivar length of concern. Risk values can be chosen from the following pre-determined values: 20%, 30%, 33%, 40%, 50%, 60%, 67%, 70%, 75%, 80% and 90%. The user has the choice of selecting the location from the pre-determined areas where the analysis has been made using historical climate data or the user inputs the coordinates for the location which is not on the list. By selecting the latter, an IDW interpolation method is triggered which uses three nearest weather stations with analysed risk values to generate an ouput for that place.

Drought risk was determined for 3 Maize cultivars, the 100-day, 120-day and 140-day denoted as short, medium and long-season maize cultivars or early, mid and late season varieties respectively. The choice of multiple planting dekads gives the user an opportunity to compare drought risk depending on the cultivar. With this information one would be able make decisions and plan their activities based on the climatology of the location. Drought indices can also be determined for different risk levels. Frost risk is determined for three frost severity levels namely, light frost (2^{o}C), medium frost (0^{o}C) and heavy frost (-2^{o}C). The onset, cessation and duration of frost-free period is determined for these thresholds. These frost indices can be determined for different risk levels. The rainy season includes onset or rains, cessation of rains and duration of rainy season. The main controls for the suitability index (PACSI) are the choice of severity levels, drought risk level and cultivar length. The PACSI uses the frost probability during growing period to determine frost and non-exceedence probability of onsets while the drought index is calculated similarly to the climate risk methodology.

The risk forecasting model includes the forecasting of agricultural drought and onset of rains. The drought forecasting requires daily rainfall, minimum temperatures and maximum temperatures as inputs from the forecasting office. Forecasting of drought before the season starts enables the farmer to determine the best planting date and cultivar length combination. Estimating onset of rains only requires daily or dekadal rainfall. Onset dates are very important to farmers as they symbolize the beginning of the agricultural year. Multiple onsets dates can be obtained depending on the length of the forecast data and these dates can help in spreading risk by staggering planting dates. Also of importance is to know the possibility of obtaining another onset in cases where the previous one was missed. This tool can be used by agricultural extension officers, farmers, agricultural risk officers and agricultural insurance personnel in determining climate risks affecting the province as well as future trends of these hazards.

8.4 Recommendations and future studies

Better maintenance of weather stations and more technical staff to man the weather stations are required. The quality of the weather data stored has to be improved significantly, the percentage of missing data in most stations is high resulting in those stations been discarded from the investigation and thus affecting the spatial distribution of the station. Increased number of stations in the future with appropriate data for estimating Penman-Monteith evapotranspiration will also improve the accuracy of the models used in this study.

The findings of this thesis can be further be improved by incorporating the actual data on areas affected by the climate risks. This data is not readily available from the crop insurance companies. Linking the hypothetical findings of this thesis with the farmers' experiences (yield losses) will greatly form important research work.

Future work will include developing the methodologies of this study further and creating a spatial decision support system which can utilize also remote sensing data to supplement the weather station recordings. The digital terrain mapping modules could also be included.

To incorporate more functionalities into the FS-Macrt (Free State Agroclimatic risk Tool) to cater for climate change studies, by making it compatible to use outputs of different climate change models as an input dataset. Determining the spatial and temporal changes of suitable areas in the Free State province using PACSI would help build adaptation activities for climate change related to rainfed maize production in the Free State.

References

Agrawal, K.K. and Upadhyay, A.P., 2009. Thermal indices for suitable sowing time of chickpea in Jabalpur region of Madhya Pradesh. *Journal of Agrometeorology* 11(1): 89 – 91.

Akpalu, W., Hassan, R.M. & Ringler, C., 2009. Climate Variability and Maize Yield in South Africa: Results from GME and MELE Methods, IFPRI Discussion Paper No. 843 (Washington, DC).

Alberta Atlas, 2003. Agroclimatic Atlas of Alberta: Agricultural Climate Elements Available at http://www1.agric.gov.ab.ca/$department/deptdocs.nsf/all/sag6301 Viewed 10/06/2007.

Alexandris, S., Kerkides, P. & Liakatas, A., 2006. Daily reference evapotranspiration estimates by the Coipas approach. *Agricultural Water Management* 82: 371 – 386.

Allemann, J., 1997. Crop studies for the Frankfort, Reitz and Vrede Magisterial districts. Report no. GW/A/97/71. Agricultural Research Council, Vegetable and Ornamental Plant Institute, Pretoria, South Africa.

Allen, R.G., Pereira, L.S., Raes, D. & Smith, M., 1998. Crop evapotranspiration: Guidelines for computing crop water requirements. FAO Irrigation and Drainage Paper 56. Rome, Italy.

Almorox, J., Benito, M. & Honotoria, C., 2005. Estimation of monthly Angström–Prescott equation coefficients from measured daily data in Toledo, Spain. *Renewable Energy* 30: 931 – 936.

Ali, M.H., Adham, A.K.M., Rahman, M.M. & Islam, A.K.M.R., 2009. Sensityivity of Penman-Monteith estimates of reference evapotranspiration to errors in input climatic data. *Journal of Agrometeorology* 11(1): 1 – 8.

Anderson, J.J., 2007. Rainfall-runoff relationships and yield response of maize and dry beans on the Glen-Bonheim ecotope using convectional tillage and in-field rainwater harvesting. Ph.D thesis, Department of Soil, Crop and Climate Sciences, University of Free State, Bloemfontein, South Africa.

Andre, R., Garcia, A., Abreu, J.P., Nieto, R., Prasad, P.V.V. & White, D., 2007. Climate and weather risk assessment for agricultural planning. Guide to Agricultural Meteorological Practices (GAMP) Draft 3rd Edition (WMO-No.134) Chapter 7. Available at *http://www.wmo.ch/pages/prog/wcp/agm/gamp/documents/chap***7***-draft.pdf Viewed 20/10/2007.*

ARC-ISCW, 2010. GIS database. Institute for Soil, Climate and Water, Agricultural Research Council, 600 Belvedere, Arcadia, Pretoria, South Africa.

ARC-ISCW Agroclimatological Databank, 2010. GIS database. Institute for Soil, Climate and Water, Agricultural Research Council, 600 Belvedere, Arcadia, Pretoria, South Africa.

Ati, O.F., Stigter, C.J. & Oladipo, E.O., 2002. A comparison of methods to determine the onset of the growing season in northern Nigeria. *International Journal of Climatology* 23: 731 – 742.

AuditNet, undated. Risk Assessment Survey and Risk Mapping Tool. Available at http://www.auditnet.org/docs/risk1.doc viewed 23/07/2010.

Auer, I., Matulla, C., Bohm, R., Ungersbock, M., Mauguri, M., Nanni, T. & Pastorelli, R., 2005. Sensitivity of frost occurrence to temperature variability in the European Alps. *International Journal of Climatology* 25: 1749 - 1766.

Aviad, Y., Kutiel, H. & Lavee, H., 2004. Analysis of beginning, end, and length of the rainy season along a Mediterranean-arid climate transect for geomorphic purposes, *Journal of Arid Environments* 59(1): 189 – 204.

Backenberg, G.R. & Viljoen, M.F., 2003. Drought management in South Africa. Paper presented at a workshop of the ICID working Group on Irrigation under Drought and Water Scarcity, Tehran, Iran, 13-14 July 2003, 17pp.

Badini, O. & Dioni, L., 2004. Application of rainfall analysis*,* biophysical modeling and GIS to *a*groclimatic decision support in Madiama Commune, Mali (West Africa). Available at http://www.sipeaa.it/tools/CropSyst/RainAn.pdf date viewed 20 February 2010.

Bai, J., Chen, X., Dobermman, A., Yang, H., Cassman, K.G. & Zhang, F., 2010. Evaluation of NASA satellite- and model –derived weather data for simulation of maize yield potential in China. *Agronomy Journal* 102(1): 9 – 16.

Balaghi, R., Badjeck, M.C., Bakari, D., De Pauw, E., De Wit, A., Defourny, P., Donato, S., Gommes, R., Jlibene, M., Ravelo, A.C., Sivakumar, M.V.K., Telehigue, N. & Tychon, B., 2010. Managing Climatic Risks for Enhanced Food Security: Key Information Capabilities. *Procedia Environmental Sciences* 1:313-323.

Barron, J., Rockström, J., Gichuki, F. & Hatibu, N., 2003. Dry spell analysis and maize yields for two semi-arid locations in east Africa. *Agricultural and Forest Meteorology* 117: 23 – 37.

Basco, D.T., undated. Farm weather services. PAGASA/DOST. Available at http://www.agrometeorology.org/index.php?id=35 Viewed 5/08/2008.

Bautista, F., Bautista, D. & Delgado-Carranza, C., 2009. Calibration of the equations of Hargreaves and Thornthwaite to estimate the potential evapotranspiration in semi-arid and subhumid tropical climates for regional applications. *Atmósfera* 22(4): 331-348.

Bello, N.J., 1996. An investigation of the charecteristics of the onset and cessation of rains in Nigeria. *Theoretical and Applied Climatology* 54: 161 – 173.

Beniot, P., 1977. The start of the growing season in the Northern Nigeria. *Agricultural and Forest Meteorology* 18: 91 – 99.

Bennett, N.D., Newham, L.T.H., Croke, B.F.W., & Jakeman, A.J., 2007. Patching and Disaccumulation of Rainfall Data for Hydrological Modelling. Proceedings of the International Congress on Modelling and Simulation MODSIM2007 Modelling and Simulation Society of Australia and New Zealand Inc. (MSSANZ), Oxley, L. & Kulasiri, D. (Eds), Christchurch, NZ., pp 1526 - 1532.

Berengena, J. & Gavilán, P., 2005. Reference evapotranspiration estimation in a highly advective semiarid environment. *Journal of Irrigation and Drainage Engineering* 131: 147 - 163.

Bharwani, S., Bithell, M., Downing, T.E., New, M., Washington, R. & Ziervogel, G., 2005. Multi-agent modelling of climate outlooks and food security on a community garden scheme in Limpopo, South Africa. *Philisophical Transactions of the Royal Society B* 360: 2183 – 2194.

Bhuiyan, C., 2004. Various Drought Indices For Monitoring Drought Condition In Aravalli Terrain Of India. XXth ISPRS Congress, 12–23 July 2004, Istanbul, Turkey.

Bishnoi, O. P., 1989. Agroclimatic Zoning. World Meteorological Publications CAgM Report No. 30. 147pp.

BOM (Australian Bureau of Meteorology), 2008. About frost. Available at http://www.bom.gov.au/climate/map/frost/what-is-frost.shtml viewed 12/08/2009.

Bootsma, A. & Brown, D. M., 1985. Freeze protection methods for crops. FACTSHEET –ISNN 1198-712X. Ontario.

Bootsma, A. & Suzuki, M., 1985. Critical autumn harvest period for Alfalfa in the Atlantic region based on growing degree-days. *Canadian Journal of Plant Sciences* 65: 573-580.

Botha, J.J., 2006. Evaluation of maize and sunflower in a semi-arid area using in-field rainwater harvesting, Department of Soil, Crop and Climate Sciences, University of Free State, Bloemfontein, South Africa.

Brown, D.M. & Bootsma, A., 1993. Crop Heat Units for Corn and Other Warm Season Crops in Ontario. Available at http://www.omafra.gov.on.ca/english/crops/facts/93-119.htm viewed 06/07/2010.

Brunini, O., Pinto, H. S., Zullo, JR, J., Camargo, M. B. P. & Alfonsi, R. R., 2000. Drought quantification and preparedness in Brazil . The example of São Paulo State. World Meteorological Organization, Suiça 1:89-130, Available at http://www.drought.unl.edu/monitor/EWS/ch8_Brunini.pdf viewed 23/09/2009.

Camberlin, P. & Diop, M., 2003. Application of daily rainfall principal component analysis to the assessment of the rainy season characteristics in Senegal. *Climate Research* 23: 159 – 169.

Carter, P.R. & Hesterman, O.B., 1990. Handling corn damaged by Autumn frost. National Corn Handbook, Climate & Weather NCH-57. Cooperative Extension Service, Michigan State University. 3pp.

Ceballos-Silva, A. and López-Blanco, J., 2003. Delineation of suitable areas for crops using a Multi-Criteria Evaluation approach and land use/cover mapping: a case study in Central Mexico. *Agricultural Systems* 77(2), 117-136.

Chadler, W.S., Hoell, J.M., Westberg, D., Whitlock, C.H., Zhang, T. & Stackhouse, P.W., 2010. Near real-time global radiation and meteorology web services available from NASA. Available at www.ases.org/papers/120.pdf viewed on 02/08/2010.

Chiew, F.H.S., Kamaladasa, N.N., Malano, H.M. & McMahon, T.A., 1995. Penman-Monteith, FAO-24 reference crop evapotranspiration and class A pan data for Australia. *Agricultural Water Management* 28: 9 – 21.

Chowdhury, A. & Gore, P. G., 1989. An Index to Assess Agricultural Drought in Indian. *Theoretical and Applied Climatology* 40:103- 109.

Cittadini, E.D., de Ridder, N., Peri, P.L. & van Keulen, H., 2006. A method for assessing frost damage risk in sweet cherry orchards of South Patagonia. *Agricultural and Forest Meteorology* 141: 235 – 243.

Cox, P.G., 1995. Some issues in the design of agricultural decision support systems. *Agricultural Systems* 52 (2/3): 355 – 381.

DAFF (Department of Agriculture, Forestry and Fisheries), 2010. Abstract of Agricultural statistics, 2010. National Department of Agriculture, Forestry and Fisheries, Pretoria, South Africa. 145pp.

Das, H.P. & Stigter, C.J., 2010. Problems and solutions in using of and coping with weather phenomena in need of tactical decision making and challenges remaining for the use of science to contribute to problem analyses and designing viable solutions in this context: Monocropping. In Stigter, C.J. (Ed) Applied Agrometeorology. Springer-Verlag Berlin Heidelberg, p 379 – 383.

Davis, J., Tavasci, D. & Marais, L., 2006. Fostering Rural and Local Economic Development in the Free State of South Africa. Natural Resources Institute, University of Greenwich, UK.

de Jager, J.M., Potgieter, A.B. & van den Berg W.J., 1998. Framework for forecasting the extent and severity of drought in maize in the Free State Province of South Africa. *Agricultural Systems* 57(3): 351-366.

de Jager, J.M., van Zyl, W.H., 1989. Atmospheric evaporative demand and evaporation coefficient concepts. *Water SA* 15(2): 49-53.

de la Casa, A., 2009. Onset of the rainy season in the province of Córdoba (Argentina) determined by rainfall records and evaluation of its agricultural risk condition. *Chilean Journal of Agricultural Research* 69(4): 567 – 576.

DehghaniSanij H., Yamamoto, T. & Rasiah, V., 2004. Assessment of evapotranspiration estimation models for use in semiarid environments. *Agricultural Water Management* 64: 91–106.

Dewandel B., Gandolfi, J.M., Zaidi, F.K., Ahmed, S., & Subrahmanyam, K., 2006. A decision support tool with variable agro-climatic scenarios for sustainable groundwater management in semi-arid hard-rock areas. *Current Science* 92(8): 1094 – 1102.

Diga, G.M., 2005. Using seasonal climate outlook to advise on sorghum production in the central rift valley of Ethiopia. Ph.D thesis, Agrometeorology, Department of Soil, Crop and Climate Sciences, University of the Free State, Bloemfontein, South Africa, 171pp.

(DOA) Department of Agriculture, 2001. News Release: South Africa – CGIAR Partnership Results in New Maize Varieties With 30 to 50 Percent Higher Yields.

(DOA) Department of Agriculture, 2005. Drought Monitoring Plan: A discussion document for public comment. Seventh edition. Department of Agriculture, Forestry and Fisheries South Africa, 14pp.

DRR, 2007. Climate risk assessment at community level in the agriculture sector. Ministry of Food and Disaster Management, Bangladesh.

Druzdzel, M.J., Roger, R. & Flynn, R.R., 2002. Decision Support Systems. Available at http://www.pitt.edu/~**druzdzel**/psfiles/dss.pdf viewed 21 February 2010*.*

Doorenbos, J. & Kassam, A.H., 1979. Yield response to water. FAO Irrigation and Drainage Paper 33. Rome, Italy.

Doorenbos, J. & Pruitt, W.M., 1977. Guidelines for predicting crop water requirements. FAO Irrigation and Drainage Paper 24. Rome, Italy.

Dos Santos, B.L. & Holsapple, C.W., 1989. A Framework for Designing Adaptive Decision DSS Interfaces. *Decision Support Systems* 5: 1-11.

du Pisani, A.L., 1987. The CERES-MAIZE model as a potential tool for drought assessment in South Africa. *Water SA* 13(3):159 – 164.

du Pisani, A.L., Erasmaus, J.F. & Koch, F.G.L., 1982. The determination of suitable planting dates for maize using climatic data. *Crop Production* 11: 36 – 39.

du Pisani, A.L., Fouche, H.J. & Venter, J.C., 1998. Assessing rangeland drought in South Africa. *Agricultural Systems* 57(3): 367 – 380.

du Plessis, J., 2003. Maize production. Directorate Agricultural Information Services, Department of Agriculture South Africa, 90pp.

du Toit, A.S., Booysen, J. & Human, J.J., 1997. Use of linear regression and correlation in the evaluation of CERES3 (Maize). *South African Journal of Plant and Soil* 14: 177–182.

Dube, L.T. &Jury M.R., 2003. Structure and precursors of the 1992/93 drought in KwaZulu-Natal, South Africa from NCEP reanalysis data. *Water SA* 29 (2) 201 – 207.

Eccel, E., Rea, R., Caffarra, A. & Crisci, A., 2009. Risk of spring frost to apple production under future climate scenarios: the role of phonological acclimation. *International Journal of Biometeorology* 53(3): 273 - 286.

Elshorbagy,A.A., Panu, U.S. & Simonovic, S.P., 2000. Group-based estimation of missing hydrological data: I. Approach and general methodology. *Hydrological Sciences Journal* 45(6): 849-866.

Engel, B. A., Choi, J., Harbor, J. & Pandey, S., 2003. Web-based DST for hydrologic impact evaluation of small watershed land use changes. *Computers and Electronics in Agriculture* 39: 241-249.

Fauchereau, N., Trzaska, S., Rouault, M. & Richard, Y., 2003. Rainfall variability and changes in Southern Africa during the 20th century in the global warming context. *Natural Hazards* 29: 139 – 154.

Feldhake, **C.M., 2002**. Forage frost protection potential of conifer silvopastures. *Agricultural and Forestry Meteorology* 112: 123 - 130.

Fernandez, C.J. & Trolinger, T.N., 2007. Development of a web-based decision support system for crop managers: structural considerations and implementation case. *Agronomy Journal* 99: 730 – 733..

FEWSNET (Farmine Early Warning System Network), 2009. Southern Africa Food Security Update-Novemner 2009. 11pp. Available at http://www.reliefweb.int/rw/RWFiles2009.nsf/FilesByRWDocUnidFilename/SODA-7YDSVB-full_report.pdf/$File/full_report.pdf viewed on 10 January 2010.

Finan, T.J. & Nelson, D.R., 2001. Making rain, making roads, making do: public and private adaptations to drought in Ceará, Northeast Brazil. *Climate Research* 19: 97 – 108.

Fleig, A., 2004. Hydrological drought – A comparative study using daily discharge series from around the world. M.Sc. Thesis, Institut für Hydrologie der Albert-Ludwigs-Universität Freiburg i. Br.

Fooladmand, H.R. & Haghighat, M., 2007. Spatial and temporal calibration of Hargreaves equation for calculating monthly ET0 based on Penman-Monteith method. *Irrigation and Drainage* 56: 439 – 449.

Fooladmand, H.R., Zandilak, H. & Ravanan, M.H., 2008. Comparison of different types of Hargreaves equation for estimating monthly evapotranspiration in the south of Iran. *Archives of agronomy and soil science* 54 (3): 321-330.

Francois, C., Bosseno, R. & Seguin, B., 1999. Frost risk mapping derived from satellite and surface data over the Bolivian Altiplano. *Agricultural and Forest Meteorology* 95: 113 – 137.

Frere, M. & Popov, G. 1979. Agrometeorological crop monitoring and forecasting. FAO Plant Production and Protection paper 17, 64pp.

Frere, M. & Popov, G. 1986. Early agrometeorological crop yield assessment. FAO Plant Production and Protection paper 73, 144pp.

Friesland, H. & Lopmeier, F.J., 2006. The activities of the German Weather Service (DWD) in the field of agroclimatology. *Meteorological Applications (Supplement)* 13: 61–67.

(FSP) Free State Province Government, 2005. Free State Province Provincial Growth and Development Strategy (PGDS) 2005 - 2014. Free State Provincial Government, Bloemfontein, South Africa, 18pp.

Garcia, M., Raes, D., Allen, R. & Herbas, C., 2004. Dynamics of reference evapotranspiration in the Bolivian highlands (Altiplano). *Agricultural and Forest Meteorology* 125: 67 – 82.

Gavilán, P., Lorite, I.J., Tornero, S. & Berengena, J., 2006. Regional calibration of Hargreaves equation for estimating reference ET in a semiarid environment. *Agricultural Water Management* 81: 257 – 281.

Geerts, S., Raes, D., Garcia, M., Del Castillo, C. & Buytaert, W., 2006. Agro-climatic suitability mapping for crop production in the Bolivian Altiplano: A case study for quinoa**.** *Agricultural and Forest Meteorology* 139: 399 – 412.

Gordon, R. & Bootsma, A. 1993. Analyses of growing degree-days for agriculture in Canada. *Climate Research* 3: 169 – 176.

GrainSA, 2005. Yield estimates for selected locations in South Africa. http://www.grainsa.co.za

Guiroga, S. & Iglesias, A., 2009. A comparison of the climate risks of cereal, citrus, grapevine and olive production in Spain. Agricultural Systems 101(1-2): 91-100.

Gyau-Boakye, P. & Schultz, G.A., 1994. Filling gaps in runoff time series in West Africa. *Hydrological Sciences Journal* 39 (6): 621 – 636.

Hachigonta, S., Reason, C.J.C., Tadross, M., 2008. An analysis of onset date and rainy season duration over Zambia. *Theoretical and Applied Climatology* 91, 229–243.

Hammer, Ǿ, Harper, D.A.T. & Ryan, P.D., 2001. PAST: Paleontological statictics software package for education and data analysis. *Palaeontologia Electronica* 4 (1): 9pp.

Hansen J.W., 2002. Realizing the potential benefits of climate prediction to agriculture: issues, approaches, challenges. *Agricultural Systems* 74: 309-330.

Hansen, **J**. **W**. **& Jones**, **J**. **W**. **2000**. Scaling-up crop models for climatic variability applications. *Agricultural Systems* 65: 43 – 72.

Hargreaves, G.H. & Allen, R.G., 2003. History and evaluation of Hargreaves evapotranspiration equation. *Journal of Irrigation and Drainage Engineering* 129: 53 – 63.

Hejazizadeh, Z. & Naserzadeh, M.H., 2007. Calculation and analysis of frost duration times by using Delphi programming: A case study in Lorestan, Iran. *Journal of Applied Sciences* 7(23): 3831 - 3835.

Hu, Q. & Buyanovsky, G., 2003. Climate Effects on Corn Yield in Missouri. J*ournal of Applied Meteorology* 42: 1626 - 1635.

Instat, 2007. Instat software. Available at http://www.ssc.rdg.ac.uk/software/download.html downloaded on the 23/07/2008.

Jabloun, M. & Sahli, A., 2008. Evaluation of FAO-56 methodology for estimating reference evapotranspiration using limited climatic data_Application to Tunisia. *Agricultural Water Management* 95: 707 – 715.

Jacovides, C.P. & Kontoyiannis, H., 1995. Statistical procedures for evaluation of evapotranspiration computing models. *Agricultural Water Management* 27: 365 – 371.

Jagtap, S.S. & Chan, A.K., 2000. Agrometeorological aspects of agriculture in the sub-humid and humid zones of Africa and Asia. *Agricultural and Forest Meteorology* 103: 59 – 72.

Jayasree, G., Lingaiah, D., Reddy, D.R. & Rao, S.B.S.N., 2008. Assessment of moisture stress using water requirement satisfaction index in *Kharif* Maize. *Journal of Agrometeorology* 10(2): 118 - 122.

Jeffrey, S.J., Carter, J.O., Moodie, K.B. & Beswick, A.R., 2001. Using spatial interpolation to construct a comprehensive archive of Australia climate data. *Enviromental Modelling & Software* 16: 309- 330.

Jensen, M.E., Burman, R.D. & Allen, R.G., 1990. Evapotranspiration and Irrigation Water Requirements. ASCE-Manuals and Reports on Engineering Practice – No. 70. American Society of Civil Engineers.

Kalma, J.D., Byrne, G.F., Johnson, M.E., & Laughlin, G.P., 1983. Frost mapping in southern Victoria :An assessment of HCMM thermal imagery. *Journal of Climatology* 3: 1 – 19.

Karmakar, S., Laguë, C., Agnew, J., & Landry, H., 2006. Integrated decision support system (DST) for manure management: A review and perspective. *Computers and Electronics in Agriculture* 57: 190 – 201.

Kasei, C.N. & Afuakwa, J.J., 1991. Determination of optimum planting date and growing season of maize in the northern savanna zone of Ghana.Proccedings of the Niemey Workshop, February 1991. IAHS publication no. 199.

Kassomenos, P., Flocas, A. H., Lykoudis, S. & Petrakis, M., 1997. A study of frost events in areas characterised by the absence of observations. *Meteorology and Atmospheric Physics* 62: 249 – 256.

Kelleher, F.M., Rollings, N.M., Poulton, D.M. & Cornish, P.S., 2001. Temperature variation and frost risk in undulating cropland. In: Proceedings of the 10th Australian Agronomy Conference, 2001, Hobart, Australia.

Keyantash, **J**. **& Dracup**, **J.A**., **2002**. The quantification of drought: An analysis of drought indices. *Bulletin of the American Meteorological Society* 83(8): 1167 - 1180.

Khushu, M.K., Rahman, N.U., Singh, M., Prakash, A., Tiku, A.K. & Bali, A.S., 2008. Thermal time indices for some mustard genotypes in the Jammu region. *Journal of agrometeorology* 10(2): 224-227.

Kim, T. & Ahn, H., 2009. Spatial rainfall model using a pattern classifier for estimating missing daily rainfall data. *Stochastic Environmental Research and Risk Assessment* 23: 367-376.

Kumar, K.K., Kumar, K.R., Ashrit, R.G., Deshpande, N.R. & Hansen, J.W., 2004. Climate impacts on Indian agriculture. *International Journal of Climatology* 24: 1375-1393.

Kumari, P., Wadood, A., Singh, R.S. & Kumar, R., 2009. Response of wheat crop to different thermal regimes under the agroclimatic conditions of Jharkhand. *Journal of Agrometeorology* 11 (1): 85 – 88.

Łabędzki, L. & Kanecka-Geszke, E., 2009. Standardized evapotranspiration as an agricultural index. *Irrigation and Drainage* 58: 607 – 616.

Landman, W.A. & Mason, S.J., 1999. Change in the seasonal association between Indian ocean sea-surface temperatures and summer rainfall over South Africa and Namibia. *International Journal of Climatology* 19, 1477 – 1492.

Landman, W.A., Mason, S.J., Tyson, P.D. & Tennant, W.J., 2001. Statistical downscaling of GCM simulations to streamflow. *Journal of Hydrology* 52: 221 – 236.

Laughlin, G. P. & Kalma, J. D., 1990. Frost hazard assessment from local weather and terrain data. *Agricultural and Forest Meteorology* 40: 1-16.

Liang, L., Li, L. & Liu, Q., 2010. Temporal variation of reference evapotranspiration during 1961 – 2005 in the Taoer River basin of Northeast China. *Agricultural and Forest Meteorology* 150: 298 – 306.

Lindkvist, L., Gustavsson, T. & Bogren, J., 2000. A frost assessment method for mountainous areas. *Agricultural and Forest Meteorology* 102: 51-67.

Lobell, D.B. & Field, C.B., 2007. Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters* 2: 1 – 7.

Lloyd-Hughes, B. & Saunders, M.A. 2002. A Drought Climatology for Europe. *International Journal of Climatology* 22: 1571–1592.

Longley, P.A., Goodchild M.F., Maguire, D.J. & Rhind, D.W, 2001. Geographic Information Systems and Science, New York: Wiley.

Loukas, **A. & Vasiliades**, **L. 2004.** Probabilistic analysis of drought spatiotemporal characteristics in Thessaly region, Greece. *Natural Hazards and Earth System Sciences* 4: 719–731.

Lourens, U.W., 1995. A system for drought monitoring and severity assessment. Ph.D. Department of Agrometeorology, University of Free State, Bloemfontein, South Africa.

Lynch, T.A., 2002. Intelligent support systems in Agriculture: A study of their adoption and use. Ph.D. dissertation, Central Queensland University, Australia.

McMaster, G.S. & Wilhem, W.W., 1997. Growing degree-days: one equation, two interpretations. *Agriculture and Forest Meteorology* 87(4): 291-300.

Maphalla, L.T. & Salmon, M.V., 2002. Provincial report on education and training for agriculture and rural development: Free State Province. 85pp.

Martin, R.V., Washington, R. & Downing, T.E., 2000. Seasonal Maize forecasting for South Africa and Zimbabwe derived from an Agrometeorological model. *Journal of Applied Meteorology* 39: 1473-1479.

Mason, S. J., 2001. El Niño, climate change, and southern African climate. *Environmetrics* 12: 327-345.

Maths/Science Nucleaus, 2000. Earth Sciences-Types of maps Teacher's guide. Available at (viewed on 12/03/2010) http://www.msnucleus.org/membership/html/jh/earth/mapstype/jhmapstypes.pdf

Mavi, H.S. & Tupper, G.J., 2004. Agrometeorology: Principles and applications of climate studies in Agriculture.Food Products Press , New York,London, Oxford. 364pp.

Meinke, H., Abawi, Y., Stone, R.C., Hammer, G.L., Potgieter, A.B., Nelson, R.A., Howden, S.M., Baethgen, W. & Selvaraju, R., 2003. Climate Risk Management and Agriculture in Australia and beyond: Linking Research to Practical Outcomes. The International Conference on Total Disaster Risk Management 2-4 December 2003. Kobe, Japan.

Meyer, S.J., 1993. A crop specific Drought index for corn I. Model development and validation. *Agronomy Journal* 85(2): 388-395.

Moeletsi, M.E., 2004. Agroclimatic characterization of Lesotho for dryland maize production. M.Sc. thesis, University of Free State, Bloemfontein. 176pp.

Moeletsi, M.E., Mellaart, E.A.R. & Mpandeli, N.S., 2009a. Crop water requirements analysis for maize trial sites in Makhado during 2007/08 season. 4pp. International conference on "Challenges and Opportunities in Agrometeorology". 23-25 February 2009. New Delhi, India.

Moeletsi, M.E., Mellart, E.A.R. & Mpandeli, N.S., 2009b. Response farming scientific report. FIRCORP project 08. SADC, Gaborone, Botswana.

Moeletsi, M.E., Walker, S., & Landman, W.A., 2009c. Frost risk assessment in the Free State. Paper presented at the 2009 SASAS conference, Cape Town, South Africa. 2pp

Moeletsi, M.E., Walker, S., Hamandawana, H. & Landman, W.A., 2010. Water satisfaction analysis for dryland maize production in Frankfort. Paper presented at the 2010 SASAS conference, Gariep Dam, South Africa. 2pp

Morid, S., Smakhtin, V. & Moghaddasi, M., 2005. Comparison of seven meteorological indices for drought monitoring in Iran. *International Journal of Climatology* 26: 971 – 985.

Msangi, J.P., 2004. Drought hazard and desertification management in the drylands of Southern Africa. *Environmental Monitoring and Assessment* 99: 75 – 87.

Mugulavai, E.D., Kipkorir, E.C., Raes, D. & Rao, M.S., 2008. Analysis of rainfall onset, cessation and length of growing season for western Kenya. *Agricultural and Forest Meteorology* 148: 1123 – 1135.

Mukhala, E., 1998. Radiation and water utilization efficiency by mono-culture and inter-crop to suit small-scale irrigation farming. Ph.D thesis. Agrometeorology, University of the Free State. 239 pp.

Mukhala, E.,Hoefsloot, P., 2004. AgrometShell Manual. Available at (viewed 24/09/2009) http://www.fao.org/nr/climpag/pub/AMS%20manual%20Part1.pdf

Mwale, D., Gan, T.Y. & Shen, S.S.P., 2004. A new analysis of and predictability of seasonal rainfall of Central Southern Africa for 1950-94. *International Journal of Climatology* 24: 1509 – 1530.

Nadler, A.J., 2007. An agroclimatic risk assessment of crop production on the Canadian Prairies. M.Sc. thesis, Department of Soil Science, University of Manitoba, Winnipeg, Manitoba.

Nain, A.S., Kersebaum, K. & Mirschel W., 2005. Are Meteorological Parameters Based Drought Indices Enough for Agricultural Drought Monitoring: A Comparative Study of Drought Monitoring with SPI and Crop Simulation Model. ICID 21st European Regional Conference 2005 - 15-19 May 2005 - Frankfurt (Oder) and Slubice - Germany and Poland.

Nanja, D.H., 2010. Dissemination of climatic information to smallholder farmers: A case study of Mujika area, Zambia. Ph.D thesis, Agrometeorology, Department of Soil, Crop and Climate Sciences, University of Free State, Bloemfontein. pp 283.

NASA, 2006. NASA Surface meteorology *and* Solar Energy*:* Methodology available at (viewed 09/07/2009)
http://www.ceoe.udel.edu/windpower/ResourceMap/SSE_Methodology.pdf

NASA, 2010. NASA Climatology Resource for Agroclimatology
Daily Averaged Data (Evaluation Version) available at (viewed 23/08/2009) http://earth-www.larc.nasa.gov/cgi-bin/cgiwrap/solar/agro.cgi?email=agroclim@larc.nasa.gov

Nash, D.J. & Endfield, G.H., 2008. 'Splendid rains have fallen': Links between El Niño and rainfall variability in the Kalahari, 1840 – 1900. *Climate Change* 86: 257 – 290.

National Drought Monitoring Centre, 2006. What is drought? Understanding and defining drought. Available at http://www.drought.unl.edu/whatis/concept.htm viewed on 20/08/2009

Neog, P., Bhuyan, J. & Baruah, N., 2008. Thermal indices in relation to crop phenology and seed yield of soybean (Glycine max L. Merrill). Journal of Agrometeorology (special issue – part 2): 300-392.

Newman, S., Lynch, T. & Plummer, A.A., 1999. Success and failure of decision support systems: Learning as we go. *Proceedings of the American Society of Animal Science*, 1999.

Nicholson, S.E., Leposo, D. & Grist, J., 2001. The relationship between El Nino and drought over Botswana. *Journal of Climate* 14: 323 – 335.

Nicholson, S.E. & Selato, J.C., 2000. The influence of La Niña on African rainfall. *International Journal of Climatology* 20: 1761 – 1776.

NOAA, 2006. Drought Public Fact Sheet August 2005. Available at http://www.nws.noaa.gov/om/brochures/climate/Drought.pdf viewed on 22/09/2009

NOAA, 2010. Multivariate ENSO Index. Available at http://www.esrl.noaa.gov/psd/people/klaus.wolter/MEI/ viewed on 10/05/2010.

NOAA, undated. Drought: The Creeping Disaster. Information sheet. National Weather Service, U.S. Department of Commerce. Available at http://www.crh.noaa.gov/dvn/ahps/dvn_drought_info.pdf viewed on 10/05/2010.

Nonhebel, S.I., 1993. The importance of weather data in crop growth simulation models and assessment of climatic change effects. Ph.D. thesis, Wageningen University, Wageningen, Netherlands.

Nova, N.A.V., Pereira, A.B. & Shock, C.C., 2007. Estimation of reference evapotranspiration by an energy balance approach, *Biosystems Engineering* 96 (4): 605-615.

Null, J., 2010. El Niño and La Niña Years and Intensities. Available at http://ggweather.com/enso/oni.htm viewed on the 10/05/2010.

Oche, C.Y., 1998. Agroclimatic Zonation for Wheat Production in the Savanna Region of Nigeria. *Singapore Journal of Tropical Geography* 19(1): 39-50.

Odekunle, 2006. Determining rainy season onset and retreat over Nigeria from precipitation amount and number of rainy days. *Theoretical and Applied Climatology* 83: 193 – 201.

Ofori, E & Kyei-Baffour, N., 2009. Agrometeorology and maize production: Chapter 12 of Guide on Agricultural Meteorological Practices (GAMP). 3rd Edition of WMO No. 134 by the World Meteorological Organisation/Technical Committee for Agro-Meteorology (WMO/CAgM), pp 1-22 accessed on 20 March 2009 from *http://www.wmo.int*

Ojonigu, F.A., Sedu, Q.M. & Maeyam, H.A., 2008. Variations and trends in annual rainfall amounts and the onset of the rainy season for Kano for 87 years (1916 – 2002). *Journal of Applied Sciences Research* 4(12): 1959 – 1962.

Oladipo, E.O. & Kyari, J.D., 1993. Fluctuations in the onset, termination and length of the growing season in Northern Nigeria. *Theoretical and Applied Climatology* 47: 241 – 250.

Oztekin, T., 2008. Analysis of frost damage risks in peach orchards around Tokat, Turkey. *International Journal of Natural and Engineering Sciences* 2(2): 45 – 51.

Pannar, 2010. 2010 product Catalogue. PANNAR SEED, PO Box 19, Greytown 3250, South Africa. 27 pp.

Pannar, undated. Know your maize plant. Available at http://www.pannar.com/admin/tech_article/Know%20the%20Maize%20Plant.pdf
Viewed on the 12/03/2010.

Peng, S., Huang, J., Sheehy, J.E., Laza, R.C., Visperas, R.M., Zhong, X., Centeno, G.S., Kush, S.K. & Cassman, K.G., 2004. Rice yields decline with higher night temperature from global warming. Proceedings of the National Academy of Sciences of the United States of America.

Peralta Hernández, A.R. & Barba-Martìnez, L.R.,2009. The risk of early and late frost behavior in central México. *Atmósfera* 22(1): 111-123.

Pereira, A.R. & Pruitt, W.O., 2004. Adaptation of the Thornthwaite scheme for estimating daily reference evapotranspiration. *Agricultural Water Management* 66: 251 – 257.

Phillips, J.G., Cane, M.A. & Rosenzweig, C., 1998. ENSO, seasonal rainfall patterns and simulated maize yield variability in Zimbabwe. *Agricultural and Forest Meteorology* 90: 39–50.

Popova, Z., Kercheva, M. & Pereira, L.S., 2006. Validation of the FAO methodology for computing ETo with limited data, application to south Bulgaria. *Irrigation and Drainage* 55: 201 – 215.

Porter, J.R. & Semenov, M.A., 2005. Crop responses to climate variation. *Philosophical Transactions of the Royal Society B* 360: 2021- 2035.

Potgieter, C.J., 2008. A comparison of regression-based and weighted-average approaches for the reconstruction of daily maximum temperatures. Paper presented at the 2008 Combined Congress, 21 – 24 January 2008, Grahamstown.

Plett, S., 1992. Comparison of seasonal thermal indices for measurement of corn maturrty in a prairie environment. *Cananadian Journal of Plant Sciences* 72: 1157-1162.

Rafi, Z. & Ahmad, R., 2005. Wheat crop model based on water balance for Agrometeorological crop monitoring. *Pakistan Journal of Meteorology* 2(3): 23-33.

Raes, D., Mallants, D. & Song, Z., 1996. RAINBOW, a software package for analyzing hydrologic data. Reference manual.

Raes, D., Sithole, A., Makarau, A. & Millford, J., 2004. Evaluation of first planting dates recommended by criteria currently used in Zimbabwe. *Agricultural and Forest Meteorology* 125: 177 – 185.

Raes, D., Williams, G. & Gbaguidi, F., 2006. RAINBOW: a software package for analysing climatological/hydrologic data frequency analysis-Test of homogeneity. Department of Land Management, Faculty of Agricultural and Applied Biological Sciences, K.U., Leuven, Belgium available at http://www.iupware.be date downloaded 21 February 2007.

Rahimi, M., Hajjam, S., Khalili, A., Kamali, G.A. & Stigter, C.J., 2007. Risk analysis of first and last frost occurrences in the Central Alborz Region, Iran. *International Journal of Climatology* 27: 349-356.

Ramadoss, M., Birch, C.J., Carberry, P.S. & Robertson, M., 2004. Water and high temperature stress effects on maize production. Poster presented at the *4th International Crop Science Congress* Brisbane, Australia, 26 Sep - 1 Oct 2004.

Ramesh, K., 2010. More efficient use of agricultural inputs as part of adoption of prepardness startergies: Multiple cropping. In. Stigter, C.J., 2010 (eds) Applied Agrometeorology. Springer-Verlag Berlin Heidelberg, pp 435 – 439.

Ransom, J., Franzen, D., Glogoza, P., Hellevang, K., Hofman, V., MacMullen, M. & Zollinger, R., 2004. Basics of corn production in North Dakota. North Dakota State University available at http://www.ag.ndsu.edu/pubs/plantsci/rowcrops/a834w.htm accessed on the 23/06/2009.

Reason, C.J.C., Hachigonta, S. & Phaladi, R.F., 2005. Interannual variability in rainy season characteristics over the Limpopo region of Southern Africa. *International Journal of Climatology* 25: 1835 – 1853.

Reason, C.J.C. & Mulenga, H., 1999. The relationship between South Africa rainfall and SST anomalies in the Southwest Indian ocean. *International Journal of Climatology* 19: 1651 – 1653.

Rebbeck, M. & Hayman, P., 2009. Frost risk Fact sheet. Grains Research & Development Corporation. Available at http://www.grdc.com.au viewed on the 23/07/2008.

Reddy, S.J., 1983a. Agroclimatic classification of the semi-arid tropics. I. A method for the computation of classifactory variables. *Agricultural Meteorology* 30: 158 – 200.

Reddy, S.J., 1983b. Agroclimatic classification of the semi-arid tropics. II. A method for the computation of classifactory variables. *Agricultural Meteorology* 30: 201 – 219.

Reid, J., Pearson, A. & Stone, P., 2006. Land Management for Grain Maize: recommended best management practices for New Zealand. Crop & Food Research Report No. 31, Christchurch, New Zealand Institute for Crop & Food Research Limited. 38 pp.

Reid, S., Smit, B., Cadwell, W. & Belliveau, S. 2007. Vulnerability and adaptation to climate risks in Ontario agriculture. *Mitigation and Adaptation Strategies of Global Change* 12: 609–637.

Rhee, J. & Carbone, G.J., 2008. Drought index mapping at different spatial units. *Journal of Hydrometeorology* 9(6): 1523 – 1534.

Richard, Y., Trzaska, S., Roucou, P. & Rouault, M., 2000. Modification of the Southern African rainfall variability/ENSO relationship since the late 1960s. *Climate Dynamics* 16: 883 -895.

Richard, Y., Faucherau, N., Poccard, I., Rouault, M. & Trzaska, S., 2001. 20th century droughts in southern Africa: spatial and temporal variability, teleconnections with oceanic and atmospheric conditions. *International Journal of Climatology* 21: 837-885.

Richards, K. & Baumgarten, M., 2003. Towards topoclimate maps of frost and frost risk for Southland, New Zealand. In: 15th Annual Colloquium of the Spatial Information Research Centre (SIRC 2003: Land, Place and Space), 1-2 December 2003, Dunedin, New Zealand, p. 1-10.

Rijks, D. & Baradas, M.W., 2000. The clients for agrometeorological information. *Agricultural and Forest Meteorology* 103: 27–42.

Rockström, J., 2003. Resilience building and water demand management for drought mitigation. *Physics and Chemistry of the Earth* 28: 869 - 877.

Ropeleskwi, C., 1999. The great El Niño of 1997 and 1998: Impacts on precipitation and temperature. Consequences 5(2): 17-25.

Rouault, M. & Richard, Y., 2003. Intensity and spatial extension of drought in South Africa at different time scales. *Water SA* 29(4): 489 – 500.

Ruml, M., Vuković, A. & Milatović , D., 2009. Evaluation of different methods for determining growing degree-day thresholds in apricot cultivars. *International Journal of Biometeorology* 54: 411 – 422.

Runtunuwu, E., 2005. Utilization of Satellite Imagery for Vegetation Drought Monitoring in Indonesia. The 11th CEReS International Symposium on Remote Sensing, 11 – 16 December 2005, Chiba, Japan.

SA (South Africa) Info, 2010. Free State Province. Available at (viewed 12/07/2010) http://www.southafrica.info/about/geography/free-state.htm

SADC-RRSU (Southern African Development Community- Regional Remote Sensing Unit), 2004. Special Agromet- Update: Followup analysis of drought situation in Southern Africa 2003/2004 crop growing season, 4pp

Saeid, M., Vladimir, S. & Mahnosh, M., 2006. Comparison of seven meteorological indices for drought monitoring in Iran*. International Journal of Climatology* 26(7): 971-985.

Samani, Z., 2000. Estimating solar radiation and evapotranspiration using minimum climatological data. *Journal of Irrigation and Drainage Engineering* 126: 265 – 267.

Sameshima, R., Hirota,T. & Hamasaki, T., 2007. Mapping of first-frost days and risk of frost damage to soybeans. *Journal of Agricultural Meteorology* 63 (1): 25 - 32.

Schulze, R.E., 1984. Hydrological simulation as a tool for agricultural drought assessment. *Water SA* 10 (1): 55 – 62.

Schulze, R.E., Maharaj, M., Warburton, M.L., Gers, C.J., Horan, M.J.C., Kunz, R.P. & Clark, D.J., 2007. South African Atlas of Climatology and Agrohydrology, Water Research Commission, Pretoria, Report TT 82/96.

Senay, G.B. & Verdin, J., 2003. Characteristization of yield reduction in Ethiopia using a GIS-based crop water balance model. *Canadian Journal of Remote Sensing* 29 (6): 687 - 692.

Shaozhong, K., Huanjie, C & Zhang, J., 2000. Estimation of Maize evapotranspiration under water deficits in a semiarid region. *Agricultural Water Management* 43: 1 – 14.

Sharma, B. R., 2006. Crop water requirements and water productivity: Concepts and practices. Available at (viewed on 27/05/08) http://www.waterandfood.org/gga/Lecture%20Material/BRSharma_CWR&WP.pdf

Sivakumar, M.V.K, 1990. Exploiting rainy season potential from the onset of rain in the Sahelian zone of West Africa, *Agricultural and Forest Meteorology* 51(3-4): 321 – 332.

Smithers, J.C. & Schluze, R.E., 2000. Long duration design rainfall estimates for South Africa. Water Research Commission Report No: 811/1/00, Pretoria, South Africa.

Sonmez, F.K., Komuscu, A.U., Erkan, A. & Turgu, E., 2005. An analysis of spatial and temporal dimension of drought vulnerability in Turkey using the standardized precipitation index. *Natural Harzards* 35: 243 – 264.

Sreenivas, G., Devender, R. & Reddy, D.R., 2008. Prediction of phenology in aerobic rice using agromeeorological indices. *Journal of Agrometeorology* (special issue – Part I): 111 – 114.

Stern, R.D., Dennett, M.D. & Dale, I.C., 1982. Analysing daily rainfall measurements to give agronomically useful results I: Direct methods. *Experimental Agriculture* 18: 223 – 236.

Stigter, C.J., 2010. Agrometerological services. In Stigter, C.J. (ed) Applied Agrometeorology. Springer Heidelberg. p 19 - 30.

Suleiman, A., A., & Hoogenboom, G., 2009. A comparison of ASCE and FAO-56 reference evapotranspiration for a 15-min time step in humid climate conditions. *Journal of Hydrology* 375: 326 – 333.

Sun, L., Li, H. & Ward, M.N., 2006. Climate variability and corn yields in semiarid Ceará, Brazil. *Journal of Applied Meteorology and Climatology* 46: 226 – 240.

Tadross, M.A., Hewitson, B. C. & Usman, M.T., 2003. The interannual variability of the onset of the maize growing season over South Africa and Zimbabwe. *Journal of Climate* 18: 3356 – 3372.

Tadesse, T., Wilhite, D.A., Harms, S.K., Hayes, M.J. & Goddard, S., 2004. Drought Monitoring Using Data Mining Techniques: A Case Study for Nebraska, U.S.A. *Natural Hazards* 33(1):137-159.

Tait, A. & Zheng, X., 2003. Mapping frost occurrence using satellite data. *Journal of Applied Meteorology* 42: 193-203.

Tang, W.Y., Kassim, A.H.M. & Abubakar, S.H., 1996. Comparative studies of various missing data treatment methods - Malaysian experience**.** *Atmospheric Research* 42(1-4), 247-262.

Teitel, M., Peiper, U.M. & Zvieli, Y., 1996. Shading screens for frost protection. *Agricultural and Forest Meteorology* 81: 273–286.

Temesgen, B. Eching, S., Davidoff, B. & Frame, K., 2005. Comparison of Some Reference Evapotranspiration Equations for California. *Journal of Irrigation Drainage Engineering* 131 (1): 73-84.

ThinkQuest, undated. El Niño and La Niña. Available at http://library.thinkquest.org/5818/elnino.html viewed on 10/05/2010.

Thornthwaite, C.W.,1948. An approach toward a rational classification of climate. Geographical Review 38 (1): 55-94.

Tilahun, K. 2006. Analysis of rainfall climate and evapo-transpiration in arid and semi-arid regions of Ethiopia using data over the last half a century. *Journal of Arid Environments* 64: 474-487.

Tsheko, R., 2003. Rainfall reliability, drought and flood vulnerability in Botswana. *Water SA* 29(4): 389 – 392.

Todorov, A.V., 1981. Agroclimatic Zoning of Agricultural Crops - 15th Conference Report of the Agrometeorological Division of the American Meteorological Society. LA. p135 – 138.

Trajkovic, S., 2007. Hargreaves versus Penman-Monteith under Humid conditions. *Journal of Irrigation and Drainage Engineering* 33: 38 – 42.

Trapasso, L.M, 1986. Meteorological data acquisitions in Ecuador, South America: Problems and solutions. *GeoJournal* 12(1): 89 – 94.

Trasmonte, G., Chavez, R., Sergura, B. & Rosales, J.L., 2008. Frost risks in the Mantaro river basin. *Advances in Geosciences* 14: 265-270.

Tsubo, M. & Walker, S., 2007. An assessment of productivity of maize grown under water harvesting system in a semi-arid region with special reference to ENSO*. Journal of Arid Environments* 71: 299 - 311.

Tumbare, M.J., 2000. Mitigating floods in Southern Africa. 1st WARSFA/WATERNET Symposium: Sustainable Use of Water Resources, Maputo, Mozambique.

Tveito, O.E., Bjørdal, I., Skjelvåg, A.O. & Aune, B., 2005. A GIS-based agro-ecological decision system based on gridded climatology. *Meteorological Applications* 12: 57–68.

Tyran, C.K., 2010. Designing the spreadsheet-based decision support systems course: An application of Bloom's taxonomy. *Journal of Business Research* 63: 207–216.

Tyson, P.D. & Preston-Whyte, R.A., 2000. The Weather and Climate of Southern Africa. Second edition, Oxford University Press Southern Africa, Cape Town, South Africa, p 228 – 236.

Udo, G. J. & Davis, J. S., 1992. A comparative analysis of DSS user-friendliness and effectiveness *International Journal of Information Management* 12(3): 209 – 223.

Unganai, L.S., 1994. Drought and Southern Africa: A note from the Harare Regional Drought Monitoring Centre. Available at http://www.drought.unl.edu/pubs/dnn/arch18.pdf Viewed on the 7/05/2010.

Unganai, L.S. & Kogan, F.N., 1998. Drought Monitoring and Corn Yield Estimation in Southern Africa from AVHRR Data. *Remote Sensing of Environment*. 63: 219-232.

USDA (United States Department of Agriculture), 2007. World Agricultural production. Foreign Agricultural service, Circular Series WAP 04-07. available at (viewed 10/09/2010) http://www.fas.usda.gov/wap/circular/2010/10-05/productionfull05-10.pdf

Usman, M.T. & Reason, C.J.C., 2004. Dry spell frequencies and their variability over Southern Africa. *Climate Research* 26: 199 – 201.

Van Bockstaele, F., Janssens, A., Piette, A., Callewaert, F., Pede, V., Offner, F., Verhasselt, B. & Philippe, J., 2006. Kolmogorov-Smirnov statistical test for analysis of ZAP-70 expression in B-CLL, compared with quantitative PCR and IgV_H mutation status. *Cytometry Part B (Clinical Cytometery)* 70B: 302 – 308.

van den Berg, J., Manley, C. & Strauss, H., 2002. Climatic suitability and production risk for selected agricultural commodities in the Free State. Report prepared by ENVIRO VISION, Free State Department of Agriculture, Bloemfontein, South Africa.

Verdin, J., Funk, C., Senay, G. & Choularton, R. 2005. Climate science and famine early warning. *Philosophical Transactions of the Royal Society B: Biological Sciences* 360: 2155-2168.

Verdin, J. & Klaver, R. 2002. Grid-cell-based crop water accounting for the famine early warning system. *Hydrological Processes* 16: 1617-1630.

Vilazón, M.F. & Willems, P., 2010. Filling gaps and daily disaccumulation of precipitation data for rainfall-runoff model. BALWOIS 2010, Ohrid, Republic of Macedonia, 25-29 May 2010.

Vogel, C.H. & Drummond, J.H., 1993. Dimensions of drought: South African case studies. *GeoJournal* 30(1): 93 – 98.

Walker, N.J. & Schulze, R.E., 2006. An assessment of sustainable maize production under different management and climate scenarios for smallholder agro-ecosystem in KwaZulu-Natal, South Africa. *Physics and Chemistry of the Earth* 31:995-1002.

Walker, S., Mukhala, E., van den Berg, W.J. & Manley, C.R., 2001. Assessment of communication and use of climate outlooks and development of scenarios to promote food security in the Free State Province of South Africa. Final report submitted to the Drought Monitoring Centre (Harare, Zimbabwe) on the pilot project DMCH/WB/AAA 6.02/13/1, 163pp.

Walker, S. & Tsubo, M., 2003. PutuRun: A simulator for rainfall-runoff-yield processes with in-field water harvesting. WRC Report No. KV 142/03, 21pp.

Wang, E., Yu, Q., Wu, D. & Xia, J., 2008. Climate, agricultural production and hydrological balance in the North China Plain. *International Journal of Climatology* 28 (14): 1959 – 1970.

Wang, Y., Yam, R.C.M. & Zuo, M.J., 2004. A multi-criterion evaluation approach to selection of the best statistical distribution. *Computers & Industrial Engineering* 47 (2-3): 165 – 180.

Wentz, F. J., Gentemann, C., Smith, D., & Cheiton, D., 2000. Satellite measurements of sea surface temperature through clouds. *Science* 288 (5467): 847 – 850.

Westberg, D., Soja, A. & Stackhouse, P.W., 2010. Linking satellite-derived fire counts to satellite-derived weather data. *Geophysical Research Abstracts* 12.

Whaley, J. M., Kirby, E. J. M., Spink, J. H., Foulkes, M. J. & Sparkes, D. L., 2004. Frost damage to winter wheat in the UK: The effect of plant population density. *European Journal of Agronomy* 21 (1): 105-115.

White, J.F., Hoogenboom, G., Stackhouse Jr., P.W. & Hoell, J.M., 2008. Evaluation of NASA satellite- and assimilation model-derived long-term daily temperature data over the continental US. *Agricultural and Forest Meteorology* 148: 1574 – 1584.

White, J.W., Tanner, D.G. & Corbett, J.D., 2001. An agroclimatological characterization of bread wheat production areas in Ethiopia. NRG-GIS Series 01-01.Mexico, CIMMYT.

Wiebold, B., undated. Growing Degree Days and Corn Maturity. Available at http://www.psu.missouri.edu/cornx viewed on the 21/06/2008

Wikipedia, 2010. A picture is worth a thousand words. Available at (viewed 12/10/2010) http://en.wikipedia.org/wiki/A_picture_is_worth_a_thousand_words

Wilhelmi, O. V., Hubbard, K. G. & Wilhite, D. A., 2002. Spacial representation of Agroclimatology in the study of agricultural drought. *International Journal of Climatology* 22: 1399 – 1414.

Wilhelmi, O.V. & Wilhite, D.A., 2002. Assessing vulnerability to agricultural drought: A Nebraska case study. *Natural Hazards* 25: 37–58.

WMO (World Meteorological Organization), 2006. Drought monitoring and early warning: concepts, progress and future challenges. Weather and climate information for sustainable agricultural development, WMO-No.1006.

Xia, Y., Fabian, P., Winterhalter, M., & Stohl, A., 1999. Forest climatology: estimation of missing values for Bavaria, Germany. *Agricultural and Forest Meteorology* 96: 131-144.

Xu, C.Y. & Singh, V.P.1998. Dependence of evaporation on meteorological variables at different time-scales and intercomparison of estimation methods. *Hydrological Processes* 12: 429-442.

Xu, C.Y. & Singh, V.P., 2002. Cross comparison of empirical equations for calculating potential evapotranspiration with data from Switzerland. *Water Resources Management* 16: 197 – 219.

Yazdanpanah, H., Hajam, S., Khalili, A. & Kamali, G., 2001. Agroclimatic zoning of Azarbayjan-Sharghi province for rainfed almond using GIS. 4pp Available online at http://www.gisdevelopment.net/application/agriculture/overview/agrio0006c.htm Viewed 09/11/2003.
Zebiak, S., 1999. El Niño and the science of climate prediction. *Consequences* 5 (2): 3-15.

Zenoni, F., Antolini, G., Campisi, T., Marletto, V. & Rossi, F., 2002. Characteristics of Emilia-Romagna region in relation with late frost risk. *Physics and Chemistry of the Earth* 27: 1091 – 1101.

Zhang, J., 2004. Risk assessment of drought disaster in the maize-growing region of Songliao Plain, China. *Agriculture Ecosystems & Environment* 102: 133 – 153.

Zullo, J., Pinto, H.S., Brunini, O., Assad, E.D. & Pellegrino, G. Q., 1999. Climatic risk zoning in the state of Sao Paulo. Proceedings of the third International Symposium on Systems Approaches for Agricultural Development. Lima, Peru, 8–10 November 1999.

Zuma-Netshiukhwi, G.N.C., 2010. Integrating weather / climate forecasts into farmer decision making in the South-Western Free State. Ph.D. Agrometeorology, University of the Free State, Bloemfontein.

Zvomuya, F., 2007. Limpopo looks to the sky. NAFU Farmer empowerment newsletter, June Issue, pp 25-27.

Appendices

Appendix 1: The differences between target stations and neighboring's stations monthly mean temperatures

Appendix 1.1: Bethlehem's neighbouring station differences per month

Stations	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Bethlehem (14725)	Tmin	0	0.1	0	0.2	0.3	0.4	0.3	0.3	0	0.5	0.1	0.1
	Tmax	-0.1	0	0	0.7	0.4	0.3	0.1	0.3	-0.3	-0.1	0	-0.4
Loch Lomond	Tmin	0.3	0.4	0.5	0.3	-0.4	-1.8	-1.6	-0.8	-0.1	0.1	0.5	0.5
	Tmax	-0.1	0	0.2	-0.4	-0.3	0.4	0	0	0.3	0.6	0.4	0.7
Bethlehem-WK	Tmin	0.6	1.2	0.9	0.9	0.8	0.8	0.7	1.3	0.9	1	0.7	0.7
	Tmax	0.1	0.3	-0.2	0.9	0.6	0.6	0.1	0.2	-0.5	-0.1	0.5	-0.2
Rietkuil	Tmin	-0.3	-0.4	-0.3	-0.7	-0.9	-0.9	-0.9	-1.5	-1.4	-1	-0.6	-0.5
	Tmax	-2.9	-2.7	-2.1	-2.2	-1.6	-1.5	-1.3	-1.3	-1.8	-2	-2.1	-2.5
Reitz	Tmin	0.2	0.3	0.4	0.3	-1	-2	-1.8	-1.7	-0.7	-0.3	0	0.2
	Tmax	0.5	0.3	0.4	0.1	-0.5	-0.7	-0.1	0.4	0.6	0.6	0.5	0.6

Appendix 1.2: Bloemfontein's neighbour station differences per month

Stations	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Glen(19839)	Tmin	-0.7	-0.4	-0.2	-0.5	-0.6	-0.3	-0.7	-1.3	-1.1	-0.4	-0.4	-0.1
	Tmax	-0.3	0.0	0.0	-0.5	-0.7	0.0	0.2	-0.3	-0.2	0.2	0.0	-0.7
Bloemfontein-Hertzog	Tmin	-0.7	-0.4	-0.2	-0.5	-0.6	-0.3	-0.7	-1.3	-1.1	-0.4	-0.4	-0.1
	Tmax	0.1	0.6	0.5	0.5	0.3	0.9	0.5	0.5	0.8	0.7	0.3	0.1
Bansvlei	Tmin	1.6	1.4	0.9	0.0	-0.6	-0.9	-1.2	-1.4	-1.2	0.0	0.8	1.5
	Tmax	0.0	-0.1	-0.3	-0.7	-0.5	-0.1	-0.2	-0.1	0.0	-0.9	0.3	-0.7
Rustfontein dam	Tmin	0.1	0.1	0.2	-0.2	0.2	0.0	-0.3	0.6	-0.3	0.2	-0.1	0.3
	Tmax	0.3	0.4	0.5	0.8	0.9	0.7	0.4	0.4	0.7	0.7	0.5	0.3
Ficksburg	Tmin	1.6	1.4	0.9	0.0	-0.6	-0.9	-1.2	-1.4	-1.2	0.0	0.8	1.5
	Tmax	4.2	3.6	3.2	2.5	2.2	1.8	2.0	2.0	2.6	3.1	3.6	4.1

Appendix 1.3: Frankfort's neighbour station differences per month

Stations	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Villiers	Tmin	0.2	-0.7	-0.5	-1.0	-0.7	-0.5	-0.7	-1.2	-0.8	-0.6	-0.5	-0.3
	Tmax	0.1	-1.1	-0.1	-1.8	-1.3	-1.3	-0.2	-0.3	-0.1	-0.5	-0.7	0.0
Reitz	Tmin	0.7	-0.3	-0.1	-1.0	-1.5	-1.4	-1.6	-1.5	-0.5	0.1	0.5	0.3
	Tmax	0.6	-0.2	1.0	-0.4	0.0	-0.1	1.1	1.1	1.5	1.1	0.7	0.8
Bethlehem	Tmin	1.0	0.1	0.2	-0.3	-0.6	-0.5	-0.7	0.0	0.9	1.1	1.1	0.9
	Tmax	1.3	0.5	1.8	0.8	1.2	1.0	1.8	2.0	2.1	1.6	1.2	1.2
Bethlehem-WK	Tmin	1.3	0.5	0.7	0.1	-0.9	-2.4	-2.3	-0.8	0.8	1.2	1.6	1.4
	Tmax	1.2	0.6	2.0	0.4	0.9	1.4	1.8	1.9	2.4	2.2	1.5	1.9
Villiers	Tmin	0.2	-0.7	-0.5	-1.0	-0.7	-0.5	-0.7	-1.2	-0.8	-0.6	-0.5	-0.3
	Tmax	0.1	-1.1	-0.1	-1.8	-1.3	-1.3	-0.2	-0.3	-0.1	-0.5	-0.7	0.0

Appendix 1.4: Hertzogville's neighbour station differences per month

Stations	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Vaalharts	Tmin	-0.9	-0.8	-1.2	-0.8	-0.3	-0.7	-0.7	-0.8	-0.8	-0.8	-0.9	-1.0
	Tmax	-1.1	-1.0	-1.4	-0.9	-0.5	-1.2	-1.4	-1.2	-1.7	-1.4	-1.5	-1.0
Jan Kempdorp	Tmin	-0.6	-0.3	-0.5	-1.1	0.8	0.7	0.4	0.2	0.0	-1.2	-0.9	-1.0
	Tmax	-1.0	-0.1	-1.1	-2.0	-1.4	0.5	-1.9	-1.6	-1.0	-0.6	-0.9	-0.6
Bultfontein	Tmin	1.0	0.7	0.3	0.7	1.7	1.7	1.8	1.8	1.7	1.1	1.0	0.7
	Tmax	0.3	0.1	-0.3	-0.4	-0.1	-0.6	-0.6	-0.6	-0.6	-0.6	0.1	0.3
Kimberly	Tmin	-1.4	-1.2	-1.5	-1.3	-1.0	-1.7	-1.9	-1.7	-1.5	-1.1	-1.4	-1.5
	Tmax	-1.1	-0.9	-0.8	0.0	0.4	-0.1	-0.6	-0.2	-0.6	-0.5	-0.9	-0.9
Vaalharts	Tmin	-0.9	-0.8	-1.2	-0.8	-0.3	-0.7	-0.7	-0.8	-0.8	-0.8	-0.9	-1.0
	Tmax	-1.1	-1.0	-1.4	-0.9	-0.5	-1.2	-1.4	-1.2	-1.7	-1.4	-1.5	-1.0

Appendix 1.5: Oukraal's neighbour station differences per month

Stations	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
LE Roux Dam	Tmin	-0.4	0.0	-0.9	-1.9	-2.6	-3.0	-2.8	-2.0	-2.3	-1.5	-0.2	1.4
	Tmax	-1.3	0.1	-0.1	0.3	1.2	1.0	0.3	0.2	-0.5	-0.6	-1.2	-1.0
Bleskop.	Tmin	1.0	1.1	1.4	0.9	0.3	0.7	0.9	0.6	0.5	1.4	1.2	1.0
	Tmax	-0.3	0.6	0.2	0.1	-0.4	0.1	0.1	0.3	0.4	0.6	0.0	0.0
Fauresmith	Tmin	2.5	2.4	2.3	2.1	1.6	1.7	2.3	2.1	1.5	1.9	2.0	2.6
	Tmax	1.3	1.5	1.5	1.9	1.7	1.2	0.9	1.2	0.3	0.8	0.5	1.0
Colesburg	Tmin	3.2	2.9	2.5	2.1	1.6	1.7	2.1	2.1	1.8	2.2	2.6	3.1
	Tmax	1.4	1.4	1.6	1.9	2.0	1.9	2.2	1.7	1.5	1.8	1.8	1.8
De Aar	Tmin	2.4	2.3	2.0	1.9	1.2	0.6	1.2	1.8	1.6	2.4	2.2	2.4
	Tmax	0.5	0.9	1.1	2.0	2.0	1.8	1.4	1.7	1.0	1.2	0.5	0.4

Appendix 1.6: Welkom's neighbour station differences per month

Stations	Type	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Welkom- Sandvet	Tmin	0.8	0.5	0.9	1.5	1.5	1.9	1.7	1.8	1.4	1.0	0.8	0.4
	Tmax	-0.5	-1.3	-0.8	-1.3	-1.1	-1.1	-0.5	-0.3	-0.5	-0.7	-0.8	-0.8
Virginia	Tmin	0.4	0.2	0.7	4.2	2.0	1.7	1.9	1.8	1.2	0.7	0.4	0.0
	Tmax	-0.1	-0.6	0.0	-0.4	0.4	-0.5	-0.1	0.1	-0.1	-0.3	-0.1	-0.1
Wesselsbron	Tmin	1.1	1.0	1.2	1.7	2.1	2.5	2.5	2.4	1.9	1.0	0.8	0.5
	Tmax	-0.9	-1.4	-1.1	-1.4	-1.2	-1.4	-0.8	-0.7	-1.0	-1.1	-0.8	-0.9
Plessisdrai	Tmin	1.2	0.7	1.5	2.3	3.2	3.5	3.7	3.4	2.6	1.8	1.3	1.0
	Tmax	-1.2	-1.7	-1.2	-2.2	-1.7	-1.4	-1.2	-0.9	-0.6	-1.1	-1.3	-1.3
Bultfontein	Tmin	1.4	0.7	1.2	1.7	2.2	2.5	2.8	2.9	2.8	1.9	1.4	0.9
	Tmax	-1.4	-1.7	-1.4	-1.9	-1.4	-1.4	-0.7	-0.6	-0.7	-1.6	-1.2	-1.4

Appendix 2: NASA Hargreaves coefficient adjustment for Free State Province and surrounding places

StationName	Lat	Lon	Alt	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Aliwal Noord	-30.68	26.65	1321	1.39	1.29	1.31	1.26	1.3	1.32	1.4	1.59	1.39	1.4	1.4	1.47
Bergville	-28.82	29.4	1238	1.07	1.02	1.04	1.12	1.3	1.36	1.45	1.59	1.29	1.1	1.15	1.13
Bethlehem	-28.16	28.3	1850	1.35	1.32	1.39	1.48	1.7	1.96	1.93	1.91	1.61	1.46	1.44	1.44
Bloemfontein	-29.11	26.19	1417	1.39	1.27	1.29	1.28	1.3	1.45	1.34	1.45	1.33	1.39	1.38	1.45
Bloemhof	-27.71	25.47	1228	1.33	1.18	1.17	1.1	1.1	1.09	1.15	1.26	1.26	1.23	1.28	1.31
Boshof	-28.59	25.51	1277	1.53	1.36	1.44	1.52	1.6	1.67	1.76	1.8	1.58	1.57	1.6	1.59
Boskop	-27.17	25.45	1360	1.22	1.13	1.18	1.27	1.4	1.54	1.61	1.81	1.55	1.47	1.53	1.43
Bultfontein	-28.15	26.06	1298	1.3	1.13	1.21	1.3	1.4	1.47	1.49	1.64	1.42	1.47	1.51	1.46
Clarens	-28.5	28.58	1849	1.26	1.25	1.28	1.34	1.6	1.82	1.91	1.73	1.49	1.32	1.34	1.34
Clocolan	-29.02	27.66	1582	1.16	1.06	1.17	1.22	1.3	1.35	1.32	1.48	1.27	1.2	1.24	1.28
De Brug	-29.19	25.98	1342	1.41	1.31	1.32	1.29	1.3	1.46	1.42	1.58	1.41	1.35	1.41	1.46
Doornhoutrivier	-27.15	26.58	1300	1.27	1.12	1.16	1.24	1.4	1.5	1.59	1.75	1.52	1.55	1.6	1.56
Excelsior	-28.89	26.94	1400	1.37	1.2	1.22	1.22	1.2	1.26	1.3	1.38	1.26	1.26	1.34	1.41
Grootrivier	-30.67	27	1437	1.18	1.06	1.18	1.19	1.1	1.21	1.21	1.35	1.3	1.27	1.23	1.26
Harrismith	-28.31	29.12	1714	1.34	1.26	1.37	1.54	1.8	2.05	2.02	2.07	1.71	1.47	1.47	1.41
Hobhouse	-29.48	27.13	1512	1.22	1.04	1.11	1.1	1.1	1.15	1.15	1.34	1.18	1.22	1.25	1.36
Hoopstad	-27.94	25.71	1314	1.32	1.16	1.18	1.29	1.4	1.48	1.55	1.69	1.45	1.39	1.5	1.49
Hope Town	-29.64	24.19	1133	1.38	1.39	1.28	1.18	1.1	1.14	1.21	1.31	1.23	1.27	1.33	1.42
Jankempdorp	-27.96	24.84	1181	1.25	1.14	1.19	1.13	1.1	1.17	1.23	1.28	1.2	1.2	1.29	1.37
Koffifontein	-29.33	25.05	1220	1.51	1.39	1.51	1.6	1.7	1.82	1.79	1.94	1.58	1.58	1.61	1.63
Lonetree	-28.51	28.11	1726	1.39	1.35	1.23	1.43	1.8	1.98	2.05	1.92	1.52	1.49	1.52	1.48
Marquard	-28.5	27.36	1446	1.29	1.13	1.22	1.27	1.4	1.47	1.41	1.51	1.28	1.3	1.41	1.41
Oukraal	-29.94	24.67	1222	1.48	1.28	1.33	1.29	1.3	1.44	1.45	1.64	1.34	1.29	1.34	1.57
Pardys	-29.23	26.2	1406	1.31	1.23	1.24	1.33	1.2	1.45	1.63	1.8	1.45	1.43	1.5	1.63
Petrusburg	-29.12	25.51	1281	1.55	1.41	1.43	1.42	1.5	1.51	1.5	1.57	1.62	1.48	1.53	1.53
Qwaqwa	-28.48	28.83	1696	1.29	1.25	1.32	1.41	1.7	1.75	1.88	1.87	1.59	1.41	1.38	1.35
Reitz	-27.8	28.44	1623	1.17	1.15	1.16	1.24	1.3	1.4	1.39	1.5	1.43	1.31	1.3	1.3
Rietpan	-27.18	26.91	1330	1.11	1	1.08	1.12	1.2	1.25	1.3	1.47	1.36	1.33	1.37	1.37
Rietrivier	-29.1	24.58	1131	1.26	1.28	1.23	1.22	1.2	1.21	1.25	1.34	1.26	1.25	1.26	1.34
Sediba	-29.02	26.95	1486	1.11	1.06	1.19	1.3	1.4	1.54	1.48	1.62	1.33	1.24	1.27	1.34
Senekal	-28.39	27.59	1487	1.38	1.33	1.31	1.37	1.5	1.54	1.54	1.58	1.43	1.4	1.41	1.38
Verkykerskop	-27.95	29.43	1780	1.32	1.31	1.42	1.62	2.0	2.15	2.13	2.02	1.78	1.55	1.56	1.46
Villiers	-27.04	28.62	1523	1.14	1.12	1.09	1.14	1.2	1.27	1.31	1.47	1.37	1.26	1.24	1.25
Waterfall	-27.79	30.25	1206	1.06	1.1	1.1	1.14	1.2	1.28	1.42	1.46	1.31	1.15	1.23	1.18
Wegsluit	-29.45	26.04	1357	1.27	1.23	1.32	1.38	1.2	1.36	1.37	1.56	1.32	1.3	1.31	1.43
Wesselsbron	-27.69	26.44	1285	1.44	1.23	1.27	1.32	1.4	1.39	1.44	1.60	1.47	1.43	1.48	1.50
Minimum				1.06	1.00	1.04	1.10	1.1	1.09	1.15	1.26	1.18	1.10	1.15	1.13
Median				1.30	1.20	1.20	1.30	1.3	1.5	1.40	1.6	1.40	1.3	1.40	1.40
Maximum				1.55	1.41	1.51	1.62	2.00	2.15	2.13	2.07	1.78	1.58	1.61	1.63
Stddev				0.13	0.11	0.11	0.14	0.23	0.27	0.26	0.21	0.15	0.12	0.12	0.12

Appendix 3.1(a): The 20%, 50% and 80% probability as well as standard deviation for the cessation, onset and frost-free period for light frost (2°C) for weather stations in the Free State

Weather stations	Light Cessation of frost				Light onset of frost				Light frost-free period			
	20	50	80	Stddev	20	50	80	Stddev	20	50	80	Stddev
Bethlehem-ARC	296	281	262	19	108	116	125	12	177	201	223	24
Bethlehem	292	279	260	21	99	111	124	13	179	194	217	21
Bleskop	280	271	254	15	106	117	129	29	197	210	234	33
Bloemfontein_Hertzog	300	284	272	17	104	114	127	14	181	195	207	20
Bothaville -Balkfontein	280	255	241	20	110	126	137	16	208	233	255	27
Bothaville_Nampo	284	271	259	18	108	117	127	16	193	215	232	29
Bultfontein	292	277	268	18	108	118	128	14	190	206	218	19
Clocolan	320	300	281	22	92	107	117	16	153	172	193	26
Faurismith	295	276	255	21	105	116	127	17	183	206	236	28
Ficksburg	295	276	254	22	105	120	128	14	185	208	230	24
Frankfort	289	275	260	18	104	114	121	12	180	206	220	22
Gariep Dam	278	255	240	24	119	133	157	27	213	244	278	41
Glen College	299	282	270	17	101	113	123	20	171	192	211	28
Golden Gate	292	274	255	21	102	116	127	16	179	202	221	29
Hertzogville	271	258	245	13	109	127	140	19	213	232	245	22
Hobhouse	301	285	277	17	98	109	118	24	172	183	204	26
Kestell	288	273	258	20	105	113	122	11	180	204	220	23
Koppies	278	268	251	14	108	119	133	16	206	221	235	23
Kroonstad	280	266	250	20	114	126	134	13	206	223	240	24
Marquard	305	282	271	17	99	116	127	17	171	190	206	18
Oukraal	270	256	241	16	116	128	143	14	216	238	255	23
Petrusburg	288	273	258	20	105	113	122	11	180	204	220	23
Plessis Draai	283	271	254	19	106	119	127	20	191	214	232	28
Reitz	292	274	255	21	102	116	127	16	179	202	221	29
Rietpan	286	273	262	14	106	112	128	18	181	206	223	24
Rusfontein Dam	294	276	265	17	107	118	128	12	185	203	222	21
Tweespruit	318	301	281	20	99	108	116	15	147	173	201	25
Villiers	284	271	252	21	103	112	123	24	190	213	230	22
Virginia	277	261	245	17	114	126	134	12	213	233	242	20
Vrede	278	260	252	15	108	119	128	12	202	218	236	22
Warden	278	268	239	21	105	130	146	22	200	227	267	36
Welkom	278	266	252	20	110	123	132	21	203	222	241	36
Welkom-AER	273	252	241	17	120	136	144	22	230	247	273	31
Wepener	299	286	274	16	101	109	118	12	171	189	202	20
Wesselsbron	279	271	261	13	109	120	128	18	194	215	231	28
Zastron	299	286	276	14	100	109	117	12	171	187	201	17

Appendix 3.1(b): The 20%, 50% and 80% probability as well as standard deviation for the cessation, onset and frost-free period for medium frost (0°C) for weather stations in the Free State

Weather stations	Medium Cessation of frost				Medium onset of frost				Medium frost-free period			
	20	50	80	Stddev	20	50	80	Stddev	20	50	80	Stddev
Bethlehem-ARC	276	257	249	16	115	127	135	11	218	234	249	19
Bethlehem	278	260	247	19	116	128	136	12	217	232	249	23
Bleskop	256	245	235	16	117	139	153	33	228	253	277	38
Bloemfontein_Hertzog	280	261	248	24	116	128	139	15	202	237	247	29
Bothaville -Balkfontein	257	245	235	18	126	138	150	18	241	256	278	24
Bothaville_Nampo	277	267	244	21	119	129	144	14	215	234	255	26
Bultfontein	272	255	242	16	121	131	147	15	221	241	262	22
Clocolan	295	276	260	21	105	116	130	17	182	207	227	27
Faurismith	274	251	235	21	115	131	147	19	217	245	271	30
Ficksburg	273	254	240	20	120	133	144	14	223	241	263	26
Frankfort	275	253	244	17	113	122	129	10	213	233	244	19
Gariep Dam	249	235	212	24	135	159	181	29	264	291	344	37
Glen College	282	268	252	21	111	121	131	21	195	218	240	34
Golden Gate	268	253	239	17	119	128	141	18	224	240	262	23
Hertzogville	256	239	227	17	136	148	158	13	249	274	287	22
Hobhouse	285	272	254	17	111	123	132	14	203	215	237	22
Kestell	269	255	237	16	109	122	136	16	216	235	249	24
Koppies	271	251	238	15	120	137	148	13	233	245	269	18
Kroonstad	267	251	241	19	128	137	145	13	233	244	270	20
Marquard	279	265	251	19	118	127	133	12	208	227	242	21
Oukraal	248	241	221	15	130	145	155	17	246	278	292	27
Petrusburg	269	255	237	16	109	122	136	16	216	235	249	24
Plessis Draai	279	255	242	22	120	130	138	21	214	238	260	33
Reitz	268	253	239	17	119	128	141	18	224	240	262	23
Rietpan	277	264	245	16	110	121	132	14	211	223	247	25
Rusfontein Dam	275	254	246	21	113	129	137	16	213	237	244	24
Tweespruit	295	281	273	15	105	114	125	13	182	202	211	19
Villiers	264	253	241	13	110	127	134	12	221	237	250	16
Virginia	253	245	234	24	130	144	153	14	245	261	281	29
Vrede	264	251	238	15	122	134	142	14	230	247	262	18
Warden	255	239	221	17	134	148	161	21	258	277	291	30
Welkom	269	251	240	16	130	139	147	12	237	250	273	20
Welkom-AER	248	237	226	16	132	151	160	23	258	282	290	22
Wepener	290	272	254	20	110	121	131	13	194	218	236	27
Wesselsbron	278	257	242	17	121	134	143	11	222	243	261	22
Zastron	290	272	255	19	109	121	131	13	195	220	237	26

Appendix 3.1(c): The 20%, 50% and 80% probability as well as standard deviation for the cessation, onset and frost-free period for heavy frost (-2°C) for weather stations in the Free State

Weather stations	Heavy Cessation of frost				Heavy onset of frost				Heavy frost-free period			
	20	50	80	Stddev	20	50	80	Stddev	20	50	80	Stddev
Bethlehem-ARC	264	250	236	18	128	136	149	13	239	256	276	24
Bethlehem	264	242	232	18	130	142	158	21	245	267	286	21
Bleskop	244	224	216	18	144	150	163	33	271	288	305	38
Bloemfontein_Hertzog	255	244	230	23	128	139	155	19	241	260	283	26
Bothaville -Balkfontein	241	232	204	24	144	155	168	19	269	293	320	31
Bothaville_Nampo	267	242	234	23	135	145	152	13	242	264	280	30
Bultfontein	248	238	228	15	134	146	154	15	252	273	285	19
Clocolan	273	264	244	17	119	133	146	15	221	238	257	23
Faurismith	248	239	217	19	138	154	168	21	263	286	308	32
Ficksburg	256	238	222	19	141	154	163	18	252	280	302	26
Frankfort	255	248	232	13	124	135	144	13	240	251	264	17
Gariep Dam	218	N/A	N/A	22	164	183	N/A	23	317	366	366	29
Glen College	264	250	238	20	124	143	152	19	236	254	271	34
Golden Gate	252	242	226	18	128	144	154	20	240	269	287	26
Hertzogville	242	235	205	20	149	162	178	18	282	298	337	28
Hobhouse	262	251	236	13	125	135	150	16	237	247	271	20
Kestell	253	245	221	21	120	136	158	20	233	258	290	32
Koppies	251	238	232	14	142	149	158	12	258	271	282	20
Kroonstad	247	235	221	16	141	152	163	15	260	283	300	25
Marquard	256	242	235	14	131	137	150	13	243	257	277	18
Oukraal	239	218	197	21	149	158	166	14	275	306	335	29
Petrusburg	253	245	221	21	120	136	158	20	233	258	290	32
Plessis Draai	249	239	232	12	133	147	155	12	254	274	283	16
Reitz	252	242	226	18	128	144	154	19	240	269	287	26
Rietpan	265	246	235	27	121	136	151	16	231	249	269	28
Rusfontein Dam	250	242	231	13	130	139	156	14	246	269	282	20
Tweespruit	281	270	250	16	118	127	137	12	208	228	246	22
Villiers	254	242	234	13	129	139	148	12	244	265	275	17
Virginia	239	228	217	19	145	155	168	18	281	295	315	23
Vrede	252	236	226	16	135	147	152	14	259	273	284	17
Warden	238	218	N/A	25	158	166	N/A	23	287	316	366	36
Welkom	245	235	222	13	139	150	160	14	272	282	297	18
Welkom-AER	232	222	205	21	154	165	185	23	293	315	343	30
Wepener	269	253	243	20	125	135	148	15	234	248	259	24
Wesselsbron	257	242	235	14	137	148	161	14	257	270	281	21
Zastron	267	253	245	19	125	135	148	15	230	249	259	24

Appendix 4.1: 50% growing length for the maize cultivar requiring 1420 GDD to mature.

StationName	**Lat**	**Lon**	**Alt**	Oct_1	**Oct_2**	**Oct_3**	Nov_1	**Nov_2**	**Nov_3**	Dec_1	**Dec_2**	**Dec_3**	Jan_1	**Jan_2**	**Jan_3**
Bethelehem	-28.16	28.29	1631	166	163	159	159	158	187	N/A	N/A	N/A	N/A	N/A	N/A
Bethelehem-WK	-28.25	28.33	1680	170	169	171	167	176	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Bleskop	-29.88	24.58	1145	115	111	106	104	102	102	100	103	108	125	201	N/A
Bloemfontein- Hertzog	-29.1	26.3	1351	131	126	123	122	120	120	124	141	N/A	N/A	N/A	N/A
Bloemfontein-Glen College	-28.95	26.33	1304	127	122	119	119	118	119	122	131	218	N/A	N/A	N/A
Bothaville - Balkfontein	-27.4	26.5	1280	117	114	111	112	111	110	110	114	125	160	N/A	N/A
Bothaville-Nampo	-27.24	26.66	1300	120	118	117	115	114	114	117	123	137	N/A	N/A	N/A
Bultfontein	-28.15	26.07	1306	122	118	116	114	114	114	115	119	129	N/A	N/A	N/A
Clocolan	-28.92	27.58	1602	134	131	129	127	127	126	136	198	N/A	N/A	N/A	N/A
Faurismith	-29.77	25.32	1522	125	119	117	115	115	112	114	119	138	N/A	N/A	N/A
Ficksburg	-28.87	27.85	1829	163	162	159	163	163	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Frankfort	-27.27	28.5	1502	146	143	141	142	144	153	N/A	N/A	N/A	N/A	N/A	N/A
Gariep dam	-30.61	25.5	1324	120	117	113	112	112	109	110	114	122	202	N/A	N/A
Golden Gate	-28.5	28.58	1846	174	172	170	168	183	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Hertzogville	-28.2	25.3	1326	117	115	111	110	110	110	110	114	124	155	N/A	N/A
Hobhouse	-29.57	27.13	1448	140	136	135	135	135	137	154	N/A	N/A	N/A	N/A	N/A
Kestell	-28.31	28.71	1692	174	171	172	179	203	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Koppies	-27.28	27.42	1401	129	123	120	119	120	121	126	134	160	N/A	N/A	N/A
Kroonstad	-27.67	27.25	1348	126	122	120	121	121	120	125	135	190	N/A	N/A	N/A
Marquard	-28.5	27.36	1447	136	131	129	129	130	132	135	142	N/A	N/A	N/A	N/A
Oukraal	-29.93	24.68	1143	111	106	103	101	99	97	98	101	104	119	158	N/A
Petrusburg	-28.98	25.5	1219	119	115	110	109	109	107	109	111	119	156	N/A	N/A
Plessisdraai	-27.98	26.13	1249	120	117	113	113	113	111	113	118	133	N/A	N/A	N/A
Reitz	-27.8	28.43	1615	153	151	147	149	160	154	N/A	N/A	N/A	N/A	N/A	N/A
Rietpan	-27.17	26.92	1321	127	124	121	121	121	121	124	132	181	N/A	N/A	N/A
Rustfontein Dam	-29.26	26.6	1382	128	124	121	119	119	121	127	138	N/A	N/A	N/A	N/A
Tweespruit	-29.19	27.07	1567	159	155	156	152	160	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Villiers	-27.04	28.61	1493	143	140	139	138	139	146	167	N/A	N/A	N/A	N/A	N/A
Virginia	-28.1	26.87	1335	123	119	116	116	116	114	116	123	141	N/A	N/A	N/A
Vrede	-27.43	29.17	1670	159	156	155	157	163	185	N/A	N/A	N/A	N/A	N/A	N/A
Warden	-27.97	29.07	1770	173	172	173	179	189	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Welkom	-28	26.67	1338	121	117	114	114	114	113	114	119	128	194	N/A	N/A
Welkom	-28.13	26.68	1295	121	117	115	114	114	113	114	119	130	203	N/A	N/A
Wepener	-29.73	27.03	1438	132	127	125	124	124	124	131	148	N/A	N/A	N/A	N/A
Wesselsbron	-27.7	26.45	1325	121	116	114	113	115	115	117	121	130	180	N/A	N/A
Zastron	-30.3	27.08	1661	148	143	139	138	139	143	N/A	N/A	N/A	N/A	N/A	N/A