

Towards a heat-watch warning system for South Africa for the benefit of the health sector

By

Patience Tlangelani Mulovhedzi

Submitted in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

In Meteorology

In the

Faculty of Natural and Agricultural Sciences

University of Pretoria

2017

“... My soul doth magnify the Lord, and my spirit hath rejoiced in God my Saviour.” Luke 1:46-47

Declaration

I, Patience Tlangelani Mulovhedzi declare that the dissertation, which I hereby submit for the MSc degree in Meteorology at the University of Pretoria, is my own work and has not previously been submitted by me for a degree at this or any other tertiary institution.

SIGNATURE

DATE: / /2017

Towards a heat-watch warning system for South Africa for the benefit of the health sector

Patience Tlangelani Mulovhedzi

Supervisor: Prof. W.A. Landman

Department: Department of Geography, Geoinformatics and Meteorology

Degree: Master of Science

Faculty: Faculty of Natural and Agricultural Sciences

Institution: University of Pretoria

Co-supervisor: Dr. R. Garland

Council for Scientific and Industrial Research

Natural Resources and the Environment

SUMMARY

Heat waves are, amongst other weather hazards, projected to increase in frequency and intensity due to climate change. This increase has already been evident in parts of South Africa in the recent years. Their negative impacts are felt in many areas, including human health. This study aims to identify the most appropriate meteorological index for forecasting heat waves over South Africa and use it to develop an operational, numerical weather forecast based prediction system that will issue alerts whenever heat waves are expected. Data from temperature and relative humidity subsets from National Centers for Environmental Prediction (NCEP) Ensemble Forecast System (EFS), and observational temperature and dew-point temperature data from the South African Weather Service are used to evaluate and identify the most appropriate meteorological heat index, and to evaluate the model's skill in heat wave forecasting. A number of evaluation matrices, including bias, symmetric external dependence index and Clayton skill scores, are used for evaluation. Recent heat wave events are also used to identify the synoptic patterns that cause heat waves. This is achieved by plotting the mean sea-level pressure heights and 850hPa and 500hPa geopotential heights from NCEP reanalysis data for these cases. Since there is no evidence that the impacts of heat waves on human health have to date been conducted in South Africa, this study uses international literature to identify the best practices that can be used to prevent or mitigate the negative impacts of heat waves on human health. The Humidex index is identified as the most suitable index for forecasting heat waves over South Africa and has benefit

in the skill of up to five days ahead. This implies that heat wave warnings can be issued with confidence 1-5 days ahead of the phenomenon. Eight heat wave cases were identified between 2011 and 2015, and most of them occurred over the eastern interior of the country. These heat waves are caused by the presence of a broad surface trough over the interior that extends from the tropics, with no moisture influx from the Indian Ocean (IO), along with an upper-air high-pressure system over the central interior. Heat waves over the east coast are caused by the presence of a ridging high or continental high that are located in such a way that the east coast is on an off-shore flow. A ridging high that would normally cause berg winds and veld fires over the Western Cape is also the cause of heat waves. The heat-health watch-warning systems in other parts of the world are effective due to the involvement of different stakeholders. The same approach is recommended for adoption over South Africa. With the involvement of different sectors, and with the health sector taking the lead, the system is expected to accomplish the desired outcome.

Keywords: Heat index, Heat wave, Heat-health Watch-warning, Humidex, Weather systems.

Preface

Climate change has become an evident reality in the recent years. It has also been projected to cause an increase in the intensity and frequency of severe weather phenomena, including heat waves. Records of observed heat waves show that heat waves over South Africa have become more frequent since 2011. These heat waves were associated with hazards ranging from water scarcity to death of outdoor workers. Hence, it is of utmost importance to conduct research on heat waves and develop a heat action plan to help prevent and mitigate the negative impacts of heat waves.

The aim of this study is to develop a comprehensible heat watch-warning system for South Africa, which will consist of a model-based meteorological forecast and a guidance plan for heat waves. The specific objectives are to:

- Identify from a range of options the best index for defining heat waves over South Africa.
- Identify the synoptic weather systems that caused the recent heat waves during summer months.
- Verify the Ensemble Forecast System model's skill in predicting heat waves
- Construct the heat-health watch-warning system.
- Outline the implications and mitigation measures that can be employed whenever heat waves are predicted. The implications and mitigation measures are based on literature studies from other parts of the world and are developed as a guide to best practices from international literature.

Chapter 1 gives a background on the nature of heat waves, their negative impacts and a literature study on the impacts of heat waves on human health as well as heat action plans from other parts of the world. It further outlines the aim, objectives and benefits of this study. The data and methods used to achieve the goals of this study as well as the heat wave indices selected for this study are discussed in Chapter 2. Data from temperature and relative humidity subsets from National Centers for Environmental Prediction Ensemble Forecast System, and observational temperature and dew point temperature data from the South African Weather Service are used to derive and evaluate the heat indices. Mean sea-level pressure heights and 850hPa and 500hPa geopotential

heights from NCEP reanalysis data are used to identify the weather systems that caused heat waves over South Africa.

Five heat indices are selected for this study, and their skill in predicting extremely hot events is examined in Chapter 3. Single extremely hot events were examined because it is assumed that an index that can skilfully forecast single extremely hot events can also skilfully forecast prolonged extremely hot events, also referred to as heat waves. This evaluation also examines the skill of the EFS. A number of heat waves were reported in the recent years. The weather systems that caused these heat waves are discussed in Chapter 4.

Chapter 5 outlines the implications and mitigation measures that can be employed whenever heat waves are expected and give insight into the nature of heat waves. Chapter 6 contains the summary, conclusions and recommendations.

ACKNOWLEDGMENTS

This dissertation has been a success through the contribution of various parties. I would like to appreciate each one of them for their assistance.

I would first and foremost like to appreciate my God, who gave me life, strength and grace to carry out this study.

I also appreciate Prof. W.A. Landman and Dr. R. Garland for guidance and supervision. I'm grateful for your patience and faith in me.

To Dr. F. Engelbrecht thanks for the advice to conduct research on heat waves.

Thanks to the South African Weather Service for allowing me to use their resources to conduct this study. Thanks to my Research colleagues for assisting me in various ways, also for inspiring, advising and supporting me.

My gratitude goes to Applied Centre for Climate and Earth Systems Science for funding this study. Thanks to Dr. N. Sweid for your help and faith.

Thanks to my late mom for encouraging me to study further.

I appreciate my husband, M. Mulovhedzi for encouraging and assisting me through this study.

Finally, I would like to appreciate University of Pretoria for affording me the opportunity to conduct this study.

Table of Contents

Declaration.....	ii
SUMMARY	iii
Preface	v
ACKNOWLEDGMENTS.....	vii
LIST OF TABLES.....	x
LIST OF FIGURES	xi
LIST OF ABBREVIATIONS.....	xiii
CHAPTER 1: Introduction	1
1.1. Background	1
1.2. Impacts of heat waves	2
1.3. The heat watch-warning system	5
1.4. Research need	7
1.5. Aim and objectives	8
1.6. Benefits	9
1.7. Project outline.....	10
CHAPTER 2: Data and methodology	11
2.1. Introduction.....	11
2.2. The heat wave forecast index	11
2.2.1. The NCEP EFS	11
2.2.2. Observational data	12
2.2.3. Evaluation methods.....	12
2.3. The weather systems that caused heat waves over South Africa	16
2.3.1. NCEP reanalysis 2	16
2.4. The heat-health watch-warning system	17
2.5. Synopsis.....	18
CHAPTER 3: The performance of different heat indices in predicting extremely hot events over South Africa	19
3.1. Introduction.....	19
3.2. Evaluation results	19
3.3. Synopsis.....	31
CHAPTER 4: The weather circulation patterns that caused heat waves over South Africa	33
4.1. Introduction.....	33
4.2. The weather patterns responsible for observed heat waves	34
4.2.1. The average circulation patterns	34

4.2.2. Case studies	42
4.3. Synopsis.....	52
CHAPTER 5: The heat-health watch-warning system for South Africa.....	54
5.1. Background	54
5.2. Understanding heat waves	54
5.2.1. Defining heat waves.....	54
5.2.2. The heat-health watch-warning system.....	57
5.2.3. Potential heat-health risk factors	57
5.2.4. Preventative measures for heat waves.....	60
5.3. International heat wave notification and response plans	61
5.4. Heat-related illness and treatment (response measures).....	65
5.5. The heat-health watch-warning system for South Africa	67
5.5.1. Proposed considerations and structure for a heat-health watch-warning for South Africa	69
5.5.2. Implementation	70
5.5.3. Target population	71
5.5.4. System evaluation.....	72
5.5.5. Public awareness and education of heat waves	72
5.6. Discussion	73
CHAPTER 6: Discussions and conclusions.....	75
6.1. The performance of different heat indices in predicting extremely hot events over South Africa.....	75
6.2. The weather circulation patterns that caused heat waves over South Africa.....	75
6.3. The heat-health action plan for South Africa	76
6.4. Recommendations.....	76
CHAPTER 7: References.....	77

LIST OF TABLES

Table 1.1: The number of hours of sunlight during different seasons of the year (adapted from Southern AER, 2001)	1
Table 2.1: Summary of selected Bio-meteorological indices. T=surface temperature (°C), e=water vapour pressure, Td=dew-point temperature (°C) and RH=relative humidity (%) (Veneckova <i>et al.</i> , 2011; Bureau of Meteorology, 2014, Steadman, 1994; SAWS, 2014; Brotherhood, 2008; Yousif and Tahir, 2013).	14
Table 2.2: List of evaluation schemes that are used to evaluate the bio-meteorological indices under investigation, where a=number of hits, b=number of false alarms, c=number of misses and d=number of correct negatives (Ferro and Stephenson, 2011; Jolliffe and Stephenson, 2003; National Research Council, 2006).	17
Table 3.1: Summary of areal average skill scores per lead-time for each evaluation scheme	20
Table 4.1: Location/spatial distribution of heat waves that were recorded in the media and by SAWS between 2011 and November 2015 (eNCA, 2014; Health24, 2015; news24, 2015; The Citizen, 2015; SAWS, 2016; eNCA, 2015a; News24, 2011; News24, 2015a; IOL, 2015; News24, 2015b; SABC, 2011; de Jager, 2015; Sowetan, 2013; News24, 2013; SABC, 2014; News24, 2012).	35
Table 5.1: Summary of heat wave planning strategies used internationally (Department of Human Services, 2009; USEPA, 2006; WHO, 2009; Pascal <i>et al.</i> , 2005).	62
Table 5.2: The direct impacts of heat waves: symptoms of heat illnesses and the treatment thereof (City of Casey, 2015; Department of Human Services, 2009; Pascal <i>et al.</i> , 2005; US Department of Health and Human Services, 2016).	66

LIST OF FIGURES

Figure 1.1: Number of heat waves (HW) and heat wave days recorded by the SAWS. The blue line is a trend line for the number of heat waves, which shows that heat wave occurrences are generally increasing with time.	7
Figure 2.1: Spatial distribution of stations (red circles) used for the study.	13
Figure 3.1: Areal average bias scores for selected heat indices through the entire domain.	21
Figure 3.2: Areal average HSS scores for selected heat indices through the entire domain.	22
Figure 3.3: Areal average hit rate scores for selected heat indices through the entire domain.	23
Figure 3.4: Areal average (A) EDI and (B) SEDI scores for selected heat indices through the entire domain.	25
Figure 3.5: Areal average ETS scores for selected heat indices through the entire domain.	26
Figure 3.6: The spatial distribution of 1- to 5-day lead-time Clayton skill scores (CSS) for HUM (A-E, respectively).	27
Figure 3.7: The spatial distribution of 1- to 5-day lead-time Critical success index (CSI) for HUM (A-E, respectively).	28
Figure 3.8: The spatial distribution of 1- to 5-day lead-time External dependence index (EDI) for HUM (A-E, respectively).	29
Figure 3.8: The spatial distribution of 1- to 5-day lead-time External dependence index (EDI) for HUM (A-E, respectively).	30
Figure 3.10: The spatial distribution of 1- to 5-day lead-time Probability of detection (POD) for HUM (a-e, respectively).	31
Figure 4.1: General circulation patterns at mean sea level pressure for heat wave events that were reported over the Western Cape from 2011 to November 2015. The averaging was done for each day of the heat wave events over the Western Cape as depicted in Table 4.1 above. The average is for 12:00 GMT of each case day for the NCEP reanalysis.	36
Figure 4.2: The average circulation patterns that caused heat wave events over the Western Cape from 2011 to November 2015, at 500h Pa (top) and 850 hPa (bottom).	38

Figure 4.3: The average surface temperature for heat wave events that were reported over the Western Cape from 2011 to November 2015.	39
Figure 4.4: General circulation patterns at mean sea level pressure for heat wave events that were reported over the eastern and north-eastern parts of the country	40
Figure 4.5: The average circulation patterns that caused heat wave events over the north-eastern parts of the country between 2011 and November 2015, at 500hPa (top) and 850hPa (bottom).	41
Figure 4.6: The average surface temperature for heat wave events that were reported over the eastern and north-eastern parts of the country between 2011 and November 2015.	42
Figure 4.7: The average circulation patterns at sea level that caused the heat wave over the Western Cape on (a) 15th, (b) 16th, (c) 17th and (d) 18th January 2012.	44
Figure 4.8: The circulation patterns at 850 hPa (blue) and 500 hPa (red) that caused the heat wave over the Western Cape on (a) 15th, (b) 16th, (c) 17th and (d) 18th January 2012.	45
Figure 4.9: The circulation patterns at sea level that caused the heat wave over large parts of the country on (a) 16th, (b) 17th and (c) 18th January 2014.	48
Figure 4.10: The circulation patterns at 850 hPa (blue) and 500 hPa (red) that influenced the heat wave over large parts of the country on (a) 16th, (b) 17th and (c) 18th January 2014.	49
Figure 4.11: The circulation patterns at sea level that caused the heat wave over the eastern interior on the 4th (a), 6th (b), 8th (c), 10th (d), 11th (e) and 12th (f) October 2015.	50
Figure 4.12: The circulation patterns at 850 hPa (blue) and 500 hPa (red) that caused the heat wave over the eastern interior on the 4th (a), 6th (b), 8th (c), 10th (d), 11th (e) and 12th (f) October 2015.	51
Figure 5.1: Effects of urban heat island (Taken from Department of Human Services, 2009).	55
Figure 5.2: Daily excess mortality and outside temperatures in France in August 2003 (Poumad'ere <i>et al.</i> , 2005). The x-axis is the days of the month.	56

LIST OF ABBREVIATIONS

APT	Apparent temperature
AWS	Automatic Weather Station
CSI	Critical success index
CSS	Clayton skill scores
DJF	December-January-February
DSI	Thom discomfort index
EDI	External dependence index
EFS	Ensemble Forecast System
EHE	Extreme heat events
ETS	Equitable threat scores
FAR	False alarm ratio
GPH	Geopotential heights
HI	Heat Index
HSS	Heidke skill scores
HUM	Humiture
IO	Indian Ocean
ITCZ	Inter-Tropical Convergence Zone
MSLP	Mean sea level pressure
NCAR	National Centre for Atmospheric Research
NCEP	National Centers for Environmental Prediction
NWS	National Weather Service
POD	Probability of detection
RDA	Research Data Archive
SAW	Discomfort index from SAWS
SAWS	South African Weather Service
SEDI	Symmetric external dependence index
USA	The United States of America
WBG	Wet-bulb global temperature
WHO	World Health Organization

CHAPTER 1: Introduction

1.1. Background

Located between 22 °S and 35 °S, South Africa experiences a number of days with extremely high temperatures (temperatures that may have an effect on human health and other sectors)

Table 1.1: The number of hours of sunlight during different seasons of the year (adapted from Southern AER, 2001)

Length of Time from Sunrise to Sunset for Various Latitudes on Different Dates				
Northern Hemisphere (read down)				
Latitude	March 20	June 21	Sept 22	Dec 21
0°	12 hr	12 hr	12 hr	12 hr
10°	12 hr	12.6 hr	12 hr	11.4 hr
20°	12 hr	13.2 hr	12 hr	10.8 hr
30°	12 hr	13.9 hr	12 hr	10.1 hr
40°	12 hr	14.9 hr	12 hr	9.1 hr
50°	12 hr	16.3 hr	12 hr	7.7 hr
60°	12 hr	18.4 hr	12 hr	5.6 hr
70°	12 hr	2 months	12 hr	0 hr
80°	12 hr	4 months	12 hr	0 hr
90°	12 hr	6 months	12 hr	0 hr
Southern Hemisphere (Read up)				
Latitude	Sept 22	Dec 21	March 20	June 21

every year, especially during summer when the Southern Hemisphere is tilted towards the sun and the sun's rays are shining directly at the Tropic of Capricorn (23,5 °S) (Southern AER, 2001). Extreme temperatures during summer over South Africa are also as a result of long hours of exposure to the sun's radiance at a high intensity since solar radiation travels through a smaller width of the atmosphere (Burgess, 2009). Table 1.1 depicts that the number of hours of sunlight over South Africa are highest during the summer (over 13 hours) and lowest during winter. Long hours of sunlight during summer months are a further source of extreme heat events and heat waves. Another cause of extreme temperatures is the synoptic weather systems that influence South Africa during summer months. There can be days when temperatures in parts of the country are expected to be extremely high. If this is expected to persist for more than two consecutive days, then heat wave warnings need to be issued.

Most nations consider heat waves as a persistence of high temperatures, usually with high humidity, for three or more days (Peng *et al.*, 2011). For example, in a study of heat waves over Africa, a heat wave was defined as a period of three or more consecutive days when the daily maximum temperature exceeds the 90th percentile for DJF season (Lyon, 2009). In Australia, heat waves are defined whenever the combined effects of high temperatures and excess heat are higher than usual for at least three days within the local climate (Steffen *et al.*, 2014). Frich *et al.* (2002) define heat waves as a period of at least five consecutive days with maximum temperatures exceeding the 1961-1990 daily maximum temperature anomaly by 5 °C. The National Weather Service from the United States of America (USA) defines a heat wave as a period of two or more days with abnormally and uncomfortably hot and unusually humid weather conditions (NOAA's National Weather Service, 2016).

Prediction and issuing of early warnings for heat waves are essential since they may have severe negative impacts on human health, economy, air quality, agricultural production, etc. (Sheridan and Kalkstein, 2004). Also, anthropogenic climate change is projected to bring with it an increase in the frequency of heat waves/extreme temperatures, which can intensify droughts, increase the risk of fires and mortality rates (Risbey & Tryhorn, 2006; Peng *et al.*, 2011).

1.2. Impacts of heat waves

Heat waves are considered as significant weather hazards and have a wide range of negative impacts on human health, economy and the environment (Sheridan and Kalkstein, 2004). They may also result in loss of agricultural production and livestock, resulting in food shortage and

bankruptcy of farmers, forest fires, inadequate supply of clean drinking water, power failures and power cuts as a result of water shortage (Jendritzky, 2000).

Heat waves may also cause life-threatening diseases and sicknesses in humans, such as heat stroke, heart disease and heat cramps. The young, elderly, sickly and overweight are most vulnerable to such heat-related diseases (Nicholls *et al.*, 2009). The physiological reaction to excessive heat generates an increase in circulation in order to boost heat loss through radiation and evaporative cooling by sweat (Kalkstein and Sheridan, 2004). The increase in circulation leads to an increase in cardiac output until the body can no longer maintain a healthy temperature balance hence death may occur.

Low income and poor population groups are more prone to the effects of heat since they do not have sufficient resources to aid in mitigation. Residents in towns and cities are also susceptible to the effects of excessive heating due to the effect of heat islands (Nicholls *et al.*, 2009; Voogt, 2004). In towns and cities heat is stored in bricks, walls and concrete (Bureau of Meteorology, 2012). Also, the building materials and structure, and human and industrial activities in cities contribute to the climate thereof. As a result, nights become warmer during heat waves, the city's warmer nights result in excessive thermal stress on humans, which then leads to increased mortality in urban areas. Citizens in cities are also exposed to higher levels of air pollution, making them more vulnerable to illness and mortality during heat waves. Humans living in areas located in temperate regions may also be exposed to conditions suitable for the spread of vector-borne diseases, such as malaria, during heat waves (Voogt, 2004).

During periods of heat waves in towns/cities, energy demand for air conditioning may increase (Voogt, 2004). According to the Eskom Demand Side Management Fact Sheet, in the summer heat, air conditioners are many people's appliance of choice to keep cool and usually with thermostats set at 18 °C or even lower (Eskom, 2010a). Use of air conditioners may release more heat as well as greenhouse gases into the atmosphere (Eskom, 2010b). Degrading air quality may also cause or contribute to an increase in mortality or an increase in irrevocable or unbearable reversible illnesses (Peach, 1997). According to the World Health Organization (WHO) report, clean air is one of the basic requirements of human health (WHO, 2005). Furthermore, this WHO report states that more than 2 million untimely deaths every year can be ascribed to urban outdoor air pollution and its effects. Amongst other illnesses, poor air quality may cause respiratory illnesses, asthma, bronchitis, non-fatal heart attack and hypertension (Resosudarmo *et al.*, 2002). Humans with these conditions or illnesses are most likely to

experience difficulties or even mortality during heat waves (Palecki *et al.*, 2001; Ebi and Meehl, 2007) These health problems in turn negatively impact the economy.

During heat waves, water supply and quality may be affected, especially among the low-income and poor populations. Poor water quality may affect human health drastically, by causing diseases such as cholera, Mycobacterium Avium Complex (one of the most common infections causing death in HIV-infected individuals), and other infections caused by bacteria, protozoa, protozoan parasites, parasitic worms and fungi (CSIR, 2010). According to CSIR (2010), populations in areas of low-water supply may suffer severe dehydration during periods of sustained heating, resulting in many hospital admissions or even deaths. Decreased water quality and supply may also have a negative impact on irrigation, commercial forestry plantations, mining, industry, power generation as well as domestic sectors (CSIR, 2010).

The impacts of heat waves have been studied in other parts of the world. Excessive heat claims more lives each year than many other causes of fatalities in the USA (NOAA, 2012). NOAA (2012) also reports that the disastrous heat wave of 1980 in the USA claimed over 1 250 lives and 700 deaths were attributed to heat during the heat wave of 1995 over Chicago. NOAA (2012) further reports that approximately 50 000 lives were claimed as a result of the heat wave in August 2003 in Europe.

Over 300 deaths were attributed to excessive heat during the period of June-July 1954 in the USA (Westcott, 2011). Most of the deaths in this study were in the 50-90 year age group and also, retail, agriculture and water-supply services were greatly impacted during the period. From 1979 to 1999, about 8 015 deaths in America were associated with excessive heat exposure and nearly 15 000 lives may have been claimed during the hot summer of 2003 in France, Europe (Kalkstein and Sheridan, 2004).

Chinganon *et al.* (1996) studied the impacts and responses to the mid-July 1995 heat wave over the USA. The heat wave caused 830 deaths nationally, of which 525 were in Chicago. The research showed that most of the fatalities were elderly. Further investigation on the cause of these deaths revealed that many factors played a part, including inadequate heat wave warning systems, power failures, questionable death assessments, inadequate ambulance and hospital facilities, heat island, and lack of resources for fans and air conditioning.

The Department of Human Services of the State Government of Victoria, Australia assessed the health impacts of the heat wave over Victoria in January 2009 (State of Victoria, 2009). The report shows that this heat wave has had a massive impact on humans, especially on the elderly (over 65 years old). It was found that during the event there was a 46% increase in total emergency cases, increase in cases of conditions that were directly related to heat and cardiac arrests, and the number of patients that died on arrival in hospitals. A State of Victoria (2009) report further shows a 62% increase in total all-cause mortality of which most occurred in those 75 years or older.

Guirguis *et al.* (2014) investigated the impacts of heat waves on human health in six sub-regions of California: the north and south coasts, central valley, Mojave Desert, southern deserts, and northern forests. The study was focused on the recent cases of heat waves (1999 - 2009). The study was done through the application of canonical correlation analysis on daily maximum temperature and morbidity data. Morbidity data was in the form of unscheduled hospitalizations throughout the entire study period, from which 19 cases of heat waves spanning a period of 3-15 days were identified. The results showed an average of 7% increase in hospital admissions on peak heat wave days. A significant impact was seen in people suffering from conditions such as respiratory diseases, vascular diseases, dehydration, acute renal failure, renal failure and mental health. The results further showed that the health impacts differed with region and seasons.

In an analysis of the French episode of a heat wave in August 2003, Poumadère *et al.* (2005) discussed the relationship between heat waves and natural and social factors. They reported almost 15 000 deaths, an excess of 60% over expected mortality for the period. Poumadère *et al.* (2005) further stated that factors such as urban living conditions, poverty, isolation, ill-health, dehydration, age and gender, as well as heat stroke also had an impact on drastically increased mortality rate.

1.3. The heat watch-warning system

In order to mitigate these health impacts, heat watch-warning systems (also referred to as heat-health watch-warning systems or heat watch/warning systems) have been developed in many countries (e.g. Nicholls *et al.*, 2009 and Greene *et al.*, 1996). These are weather-forecast systems that are used to issue public alerts whenever heat wave phenomena are expected, with the aim to prevent or mitigate heat-related impacts on human health (Kovats and Kristie, 2006).

The systems consist of a meteorological-based heat wave forecast and a public health action plan.

Sheridan and Kalkstein (2004) developed a synoptic-based heat watch-warning system over the USA. They used both health data (mortality) and weather data (i.e. air temperature, dew-point temperature, pressure, wind and cloud cover) to develop the algorithm. Threshold levels above which some alert or emergency response would be recommended were then developed. Heat watch-warning systems, when applied along with mitigation activities such as media announcements, are effective in alleviating the effects of heat waves (Greene *et al.*, 1996). Currently, South Africa does not have such a system; however, a similar system developed for South Africa may have comparable positive impacts.

After considering the deadly impacts of heat waves over the USA, the National Weather Service (NWS) improved on its efforts to send early warnings for heat waves to the public and relevant stakeholders (NOAA, 2012). The NWS devised the Heat Index (HI), also referred to as apparent temperature, to issue these heat wave warnings, provided the HI value exceeds 105 °F for at least two consecutive days. The warning system was mainly developed for the public, state/health officials and the media, and gives details on the extent of the heat wave, the persons at risk and the safety rules for reducing the risk (NOAA, 2012).

A project called EuroHeat was developed by WHO in collaboration with the European Commission for the European region (Menne and Matthies, 2009). The goal of this project was to help improve public health responses to heat waves in the European region by developing a heat-health plan. This development was conducted as a result of climate change being projected to lead to an increase in frequency and intensity of heat waves, which may have major impacts on human health. Menne and Matthies (2009) consider this system to be effective in reducing health problems and mortality caused by heat waves.

A heat wave of July 1999 over the Mid-western USA (which consists of Illinois, Indiana, Iowa, Kentucky, Michigan, Minnesota, Missouri, Ohio, and Wisconsin) had similar conditions to those of the heat wave of 1995, but resulted in fewer mortalities compared to 1995 (Palecki *et al.*, 2001). The damage due to this heat wave extended to road infrastructure and electricity supply amongst others. According to this study, the heat wave watch system has helped save hundreds of lives that could have been lost during this period. It is further indicated that the response from

the community was effective and could be improved further by utilizing more communication mediums.

1.4. Research need

South Africa is located in an area where the sun's rays are perpendicular to the northern parts of the country during summer months, resulting in intense, frequent heating thereof. The synoptic systems that influence summer weather may also result in the occurrence of heat waves. The circulation patterns include subtropical anticyclones, easterly lows, and subtropical lows, westerly waves, ridging anticyclones, west-coast troughs, thunderstorms and tropical cyclones (Tyson and Preston-Whyte, 2000).

Also, based on the projection of climate change extreme weather events, heat waves are expected to increase in frequency and intensity (Risbey & Tryhorn, 2006; Peng *et al.*, 2011). According to the South African Weather Service (SAWS), over the past years, South Africa has already experienced an increase in extreme weather events that have resulted in the loss of lives, damage to infrastructure and property (SAWS, 2012). Figure 1.1 depicts the number of heat wave events and heat wave days, as defined by SAWS, that have been observed over South Africa from 1993 to 2015 (Fig. 1.1). SAWS definition of a heat wave is at least three

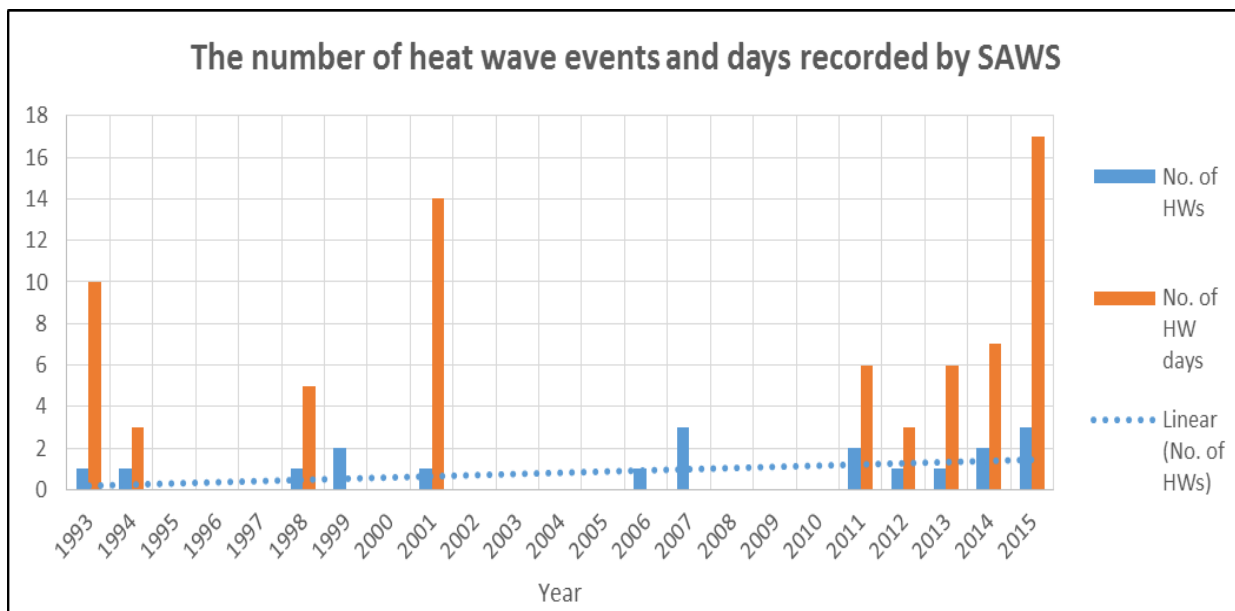


Figure 1.1: Number of heat waves (HW) and heat wave days recorded by the SAWS. The blue line is a trend line for the number of heat waves, which shows that heat wave occurrences are generally increasing with time.

consecutive days when the average temperature for the warmest month at a station was exceeded by 5 °C. The blue line shows the trend for heat wave events over the years, which is on an increase. This corresponds with the projections for climate change that show an expected increase in extreme events such as heat waves (Risbey & Tryhorn, 2006; Peng *et al.*, 2011). The figure further depicts that heat waves over South Africa have become more frequent.

Projections from climate change and its impacts have raised an interest among scientists to investigate the impacts of climate change (particularly, heat waves) on human health over South Africa. Currently, there is extensive research being undertaken by a number of scientists on the subject. A recent paper by Wichmann (2017) used relative humidity, temperature and “City-level all-cause non-accidental mortality data” to study the association between apparent temperature and mortality in three major Cities of South Africa, namely, Cape Town, Durban and Johannesburg. The study was carried out using apparent temperature thresholds of 18,6 °C; 24,8 °C and 18,7 °C for Cape Town, Durban and Johannesburg, respectively. Results showed that the elderly (≥ 65 years old) were more at risk, especially in Cape Town and Johannesburg. Furthermore, Cape Town elderly women were more at risk than elderly men. This gives anecdotal evidence that heat impacts human health and may even cause fatalities. News24 has also reported a death case of a construction worker in southern Paarl, Western Cape (News24, 2012). Three of his co-workers were admitted to hospital and treated for dehydration. It was suspected that the cause of his death was heat-related. It was reported that temperatures on that day were hovering between 36 °C and 43 °C in the Paarl and the rest of Cape Town. For these reasons, this research will study the different aspects of heat waves and also develop an early warning system for heat waves that will help minimize their negative impacts.

This study will create a warning system for heat waves over South Africa based on the forecasts produced by numerical weather prediction models and best practice guides/action plans informed by heat-health action plans from other parts of the world. The purpose of the guide will be to provide recommendations for the types of health warnings and intervention methods that could be applied in South Africa, as well as information on the methodologies used to draft heat-health plans.

1.5. Aim and objectives

The project’s aim is to develop a comprehensible heat watch-warning system for South Africa. The system will be derived from temperature and humidity forecast data produced by the National Centers for Environmental Prediction (NCEP) Ensemble Forecasting System (EFS).

This system shall comprise guidance products for heat waves and give insight into the nature of heat waves and their health impacts in South Africa. The specific objectives are:

- Identify from a range of options the best index for defining heat waves over South Africa.
- Identify the synoptic weather systems that caused the heat waves during summer months.
- Verify the EFS model's skill in predicting heat waves
- Construct the heat-health watch-warning system
- Outline the implications and mitigation measures that can be employed whenever heat waves are predicted. The implications and mitigation measures will be based on literature studies from other parts of the world and will be developed as a guide for best practices from international literature.

1.6. Benefits

Though the impacts of heat waves on human health have not been studied and no heat watch-warning system for societal benefit has been developed for South Africa, there is evidence from studies done in other parts of the world that such a system may be very helpful in reducing the impacts, or even death due to heat waves. A study by Confalonieri *et al.* (2007) used actual mortality data from 1995-1998 for the city of Philadelphia to evaluate the effectiveness of heat watch-warning system. They showed that within 4-5 warning days during the study period approximately 117 lives were saved by the implementation of the system. Michelozzi *et al.* (2005) evaluated their heat watch-warning system for the summer of 2003 over Rome. The research indicated that the model forecasted most days when there were excess deaths in the city. Issuing early warnings is essential for mitigating, or even preventing disaster as a result of severe weather.

The heat-health watch-warning system developed in this study will give warnings for heat waves a day to 14 days before the event. When effectively communicated through mitigation activities such as the media, the system will help prevent/alleviate damage and even prevent loss of lives (Greene *et al.*, 1996). The Department of Health, as well as other relevant stakeholders can also take the appropriate mitigation actions to protect those most vulnerable. This collaboration should also aid in reducing economic strain on the country during periods of heat waves.

1.7. Project outline

Chapter 2 describes the data (both model and observational) used to conduct this study, the evaluation methods and indices used. In Chapter 3 the skill scores for each index are discussed and the index with the highest skill is identified.

In Chapter 4, the dominant weather systems on the heat wave days that were recorded by SAWS and other media are discussed and summarized. Chapter 5 outlines the implications and mitigation measures that can be employed whenever heat waves are expected and give insight into the nature of heat waves. The mitigation measures are based on literature studies from other parts of the world and are developed as a guide to best practices from international literature. Chapter 6 contains the summary, conclusions and recommendations.

CHAPTER 2: Data and methodology

2.1. Introduction

The aim of this study is to construct a comprehensible heat-health watch-warning system over South Africa. This development is done using model forecast data (temperature and relative humidity) from the NCEP EFS (Toth *et al.*, 1996). Prior to the development of the heat watch-warning system, the NCEP model has to be evaluated to assess the quality of its forecasts. This evaluation helps the users to know how much they can rely on the heat wave forecast system and model forecast in general. Forecast verification involves the comparison of model forecasts against observations to which they pertain (National Research Council, 2006). Surface temperatures and relative humidity from the NCEP model forecasts are used for evaluation of the model against observational data from SAWS Automatic Weather Stations (AWS's). The observational data are obtained from the archive database of the SAWS.

2.2. The heat wave forecast index

2.2.1. The NCEP EFS

The chaotic nature of the atmosphere, as well as uncertainties from the initial conditions, make it hard to predict the future state of the atmosphere at a certain lead time (Wilks, 2006). Ensemble forecasting is a way to address this problem and so reduces uncertainty in the forecast outcome.

Ensemble forecasting has been operational at NCEP since December 1992 (Toth *et al.*, 1996). More ensemble members were added in March 1994 and 17 forecasts are run daily with the NCEP global model, for a 16-day lead time. The model uses three control forecasts: T126 and T62 resolution at 00:00 UTC and T126 resolution at 12:00 UTC, and makes 14 other perturbed forecasts at T62 resolution.

SAWS has started using subsets of NCEP EFS for short and medium range forecasting (up to 16 days ahead) since March 2000 (Tennant *et al.*, 2006) In 2004, the products downloads were done at 2.5x2.5° resolution, for 23 ensemble members. In September 2005, downloading 1x1° resolution ensemble subsets for 45 members at 6-day lead time began. Ensemble members for 1x1° products were increased to 60 for a 14-day lead time in June 2006. The subsets have been kept in the archive system of SAWS since 2007.

Toth *et al.* (2001) have studied the benefits of using ensemble forecasts instead of an equivalent or higher resolution control forecast. In Toth *et al.* (2001), the 14-member set of the T62 horizontal resolution NCEP ensemble was evaluated against the Medium Range Forecast model (T62 resolution) and T126 for the period of April – June 1999. The outcome of the study shows that it is more beneficial to use ensemble forecasts because they provide more detailed forecast probability distribution and they are able to discriminate high predictability from low predictability cases. A study on the application of the NCEP EPS to medium range forecasting in South Africa has shown similar results (Tennant *et al.*, 2006). According to Tennant *et al.* (2006), using NCEP ensemble forecasts reduces the instance of missed events in forecasts and is useful in estimating confidence in forecasts.

It is, however, important to note that skillful models need to be used in order to capture the predictability of the atmosphere. For this reason, the NCEP model will be evaluated for its ability to predict extremely hot events. Ensemble forecast data for $1 \times 1^\circ$ resolution are used to conduct this study. The data is first bias corrected. Bias correction is a process to suppress large-scale errors that are often found within the regional domain in the dynamical downscaling procedure (Kanamaru and Kanamitsu, 2007). In this study, average bias for each station for the entire period is calculated and added to the ensemble average temperature.

2.2.2. Observational data

SAWS archives observational (synop) data from about 200 AWS in its database on a daily basis. The location of these AWS's is shown in Figure 2.1. The observations include temperature and dew point temperature. In cases where relative humidity is required to calculate a heat index, it is derived from temperature T ($^\circ\text{C}$) and dew point temperature T_d ($^\circ\text{C}$): $R=100-5(T-T_d)$, where R is the relative humidity.

2.2.3. Evaluation methods

Forecast verification is the assessment of forecast quality, the association between forecasts and observation to which they pertain (Wilks, 2006). Forecast verification is critical for ensuring that forecast products are accurate, skillful and reliable, and also efficiently and effectively meet the public's needs (Gordon and Morimoto, 2000). The purpose of verification is to give information to the model users about the uncertainty and the performance of the forecasts (National Research Council, 2006).

In order to evaluate the NCEP’s ability to predict recent heat waves, daily data for September – March for the years 2010 – 2013 is used. Five heat indices from different parts of the world are selected for this study. The indices are calculated for single-day phenomena (extreme events),

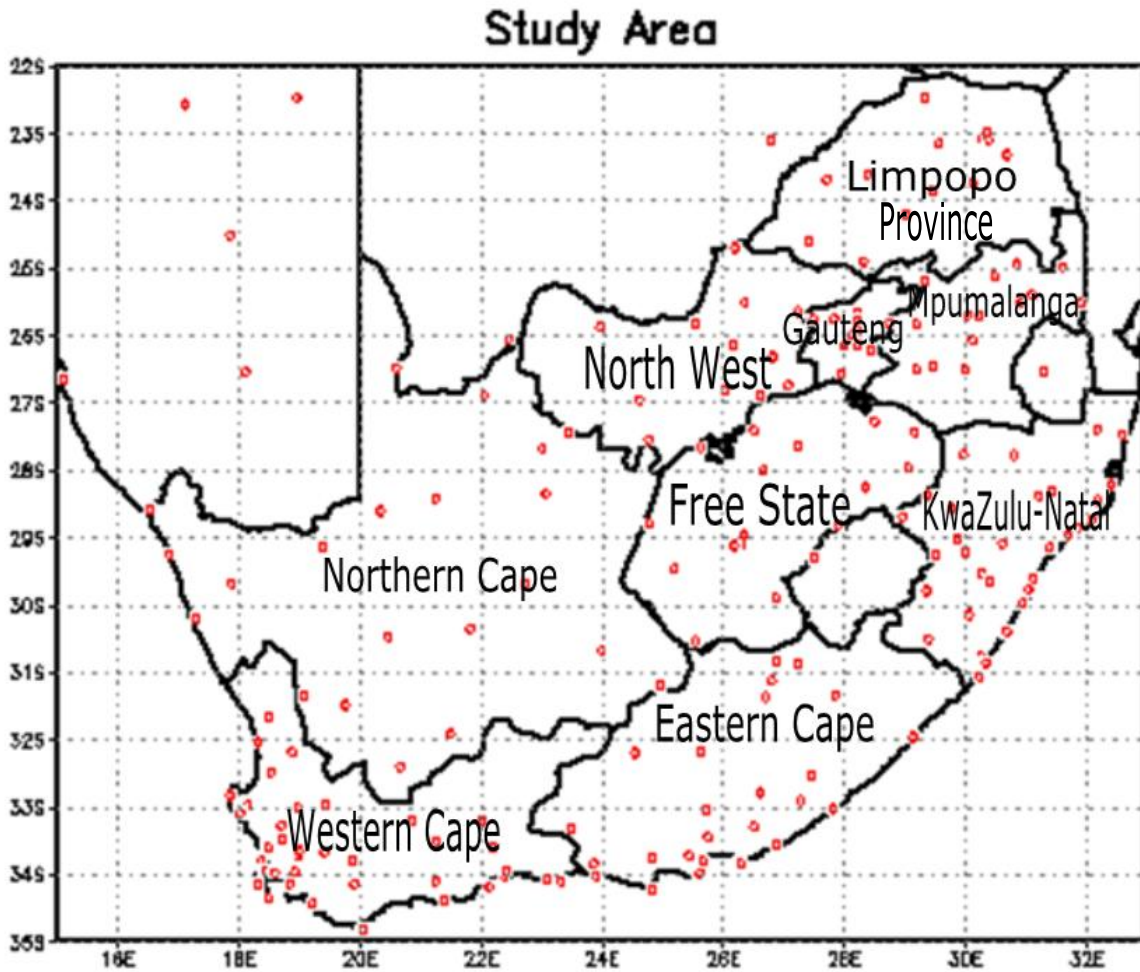


Figure 2.1: Spatial distribution of stations (red circles) used for the study.

meaning that the model is evaluated for its ability to forecast extreme events. The index with the highest skill will be used to develop the heat watch-warning system as well as for further study. The heat wave indices examined include discomfort index from SAWS (SAW), Humiture (HUM), apparent temperature (APT), wet-bulb global temperature (WBG) and the Thom discomfort index (DSI) (Veneckova *et al.*, 2011). The heat indices are used at different weather centres and they each have defined thresholds that are investigated in this study. Table 2.1 depicts the formulae and selected threshold values for these indices. These thresholds are the values that indicate extreme temperatures, and if exceeded for three consecutive days or more, they indicate heat wave phenomena.

SAWS is the authoritative voice on weather and climate in South Africa and has developed, as one of its products, the discomfort index. The index calculates the impact of heat stress on

Table 2.1: Summary of selected Bio-meteorological indices. T=surface temperature (°C), e=water vapour pressure, Td=dew-point temperature (°C) and RH=relative humidity (%) (Veneckova *et al.*, 2011; Bureau of Meteorology, 2014, Steadman, 1994; SAWS, 2014; Brotherhood, 2008; Yousif and Tahir, 2013).

Index	Equation	Threshold
SAW	$2T+RH(T+24)/100$	110
HUM	$T+(e-21)$; where $e=6.11 \times e^{\frac{7.5Td}{273.7+Td}}$	36
APT	$-2.653+0.994T+.368Td^2$	33
DSI	$T-0.55[1-0.01(RH)](T-14.5)$	25
WBG	$0.567T+0.393e+3.94$; where $e=6.11 \times e^{\frac{7.5Td}{273.7+Td}}$	30

humans by taking into account the combined impact of temperature and humidity (SAWS, 2014). Threshold values for the levels of discomfort are: 90-100 =very uncomfortable, 100-110 = extremely uncomfortable and 110+ = hazardous to health (SAWS, 2014).

HUM is used at the Canadian Meteorological Service. The warning system thereof has the following thresholds defined in it: 15-25 °C for low to moderate risk, 26-29 °C for high risk, 30 - 35 °C for very high risk and >36 °C for extreme risk for heat disorders (Brotherhood, 2008). This study identifies all cases with 36 °C or more as extreme cases.

The Bureau of Meteorology, Australia, uses AP to predict and issue heat wave warnings. Apparent temperature is the combined impact of temperature and humidity on humans (Steadman, 1994). For this study, 33 °C is selected as the threshold value for extremely hot events and is used to investigate the model skill in predicting extremely hot events.

TDI is one of the famous formulae for calculating discomfort index based on temperature and relative humidity (Yousif and Tahir, 2013). Discomfort conditions thereof are:

- $TDI < 21$ No discomfort
- $21 \leq TDI < 24$ Less than 50% of people feel discomfort
- $24 \leq TDI < 27$ More than 50% of people feel discomfort
- $27 \leq TDI < 29$ Most of people feel discomfort.
- $29 \leq TDI < 32$ Very strong discomfort
- $TDI \geq 32$ Medical emergency (Thom, 1959). 27 °C was selected as a threshold for extreme events.

WBG is also used at the Canadian Meteorological Service as an indicator of risk to human health due to heat. Indicators of the level of risk are:

- $< 20 =$ Low,
- $21 - 25 =$ Moderate to high,
- $26 - 29 =$ High - Very high, and
- 30 and above = Extreme (Sports Medicine Australia, 2014). 30 °C is used in this study as a threshold for extreme events.

For heat indices in this study, values that the meteorological centres considered as extreme danger/heat values are taken as thresholds for extreme events.

To evaluate the indices above, the first step is to calculate based on the equation/definition, each index for the observations and for the forecasts, e.g. calculate apparent temperature values for observations and for the forecasts. Secondly, the cases when heat waves were observed/forecasted, when certain thresholds were exceeded (i.e. develop a contingency table) were identified, and then the accuracy, reliability and skill for each index was calculated. Table 2.2 depicts the list of evaluation schemes that are used, formulae and skill measures and threshold values thereof.

Forecast verification is the process of evaluating forecast quality by measuring attributes such as bias, accuracy, discrimination, reliability and skill (Wilks, 2006). Bias is the correspondence between average forecasts and average observations. Accuracy measures correspondence between individual forecasts and observations. When an average is taken over all observations, the difference between conditional mean forecasts and unconditional mean forecasts is a measure of discrimination. The correspondence of conditional mean observations and conditional

forecasts averaged over all forecasts is an indication of reliability. Skill indicates how well a forecast performs relative to a climatology or persistence (Wilks, 2006; Jolliffe and Stephenson, 2003; National Research Council, 2006).

Heat waves are considered as rare severe events. Verifying forecasts of rare is complex, partly because scores decline to trivial values as events become rarer (Ferro and Stephenson, 2011). This phenomenon may give the impression that rare events cannot be skilfully forecasted irrespective of the forecasting system being used (Stephenson *et al.*, 2008). To address the shortcomings associated with verifying forecasts for rare events, Ferro and Stephenson (2011) have developed the external dependence index (EDI) and the symmetric external dependence index (SEDI). These are used in this study in addition to the other skill measures.

2.3. The weather systems that caused heat waves over South Africa

2.3.1. NCEP reanalysis 2

NCEP Reanalysis 2 is a dataset of the National Centre for Atmospheric Research's (NCAR) Research Data Archive (RDA). The data is freely available for download online in Grib format (Saha *et al.*, 2011). Reanalysis data combines a numerical model and observations to generate an estimate of the atmosphere and is useful for research and monitoring (Curry, 2011). Atmospheric representation from the weather forecasts derived from reanalysis data has high accuracy and is very close to observations.

To identify the weather systems that caused the recent heat waves over South Africa (from 2011 - 2015), NCEP reanalysis 2 dataset is used (Saha *et al.*, 2011). Geopotential heights at 850hPa and 500hPa, and mean sea level pressure subsets are downloaded for this study and used to plot and identify the weather systems that caused recent heat wave phenomena. The weather systems were analysed at 12:00 GMT when maximum temperatures are measured. The coarser resolution dataset (2.5 x 2.5°) is selected for its smoother appearance (compared to the higher resolution data), which makes it appear much similar to the synoptic maps from SAWS. A composite analysis of the systems is further employed according to the geographical location of the heat wave events in order to better understand the systems that caused heat waves at different locations of the country. The composite analysis also assists in highlighting common features and identify synoptic systems that may be associated with heat waves (González-Alemán *et al.*, 2015; Thomas and Martin, 2007).

Table 2.2: List of evaluation schemes that are used to evaluate the bio-meteorological indices under investigation, where a=number of hits, b=number of false alarms, c=number of misses and d=number of correct negatives (Ferro and Stephenson, 2011; Jolliffe and Stephenson, 2003; National Research Council, 2006).

Scheme		Formula	measure:
		a=hits, b=false alarms, c=misses and d=correct negatives.	
Bias	Bias	$(a+b)/(a+c)$	Bias; perfect score=1, over-forecast>1, under-forecast<1
Critical success index	CSI	$a/(a+b+c)$	accuracy; 0 = worst 1 =best
False alarm ratio	FAR	$b/(a+b)$	Reliability and Resolution 0 = best 1 = worst
Probability of detection	POD	$a/(a+c)$	Discrimination 0 = worst 1 = best
Heidke skill scores	HSS	$2(ad-bc)/((a+c)(c+d)+(a+b)(b+d))$	skill (proportion correct that would be achieved by random forecasts that are statistically independent of the observations) < 0 worse than reference 0 close to reference forecast 1 perfect
Clayton skill scores	CSS	$(ad-bc)/((a+b)(c+d))$	skill - conditional relative frequency of the yes outcome given yes forecasts 1 = perfect forecast 0 = random forecast
Equitable threat scores	ETS	$(a-a_{ref})/(a-a_{ref}+b+c)$; where $a_{ref}=(a+b)(a+c)/n$	Skill - ratio of success 1 = perfect 0 =worst
External dependence index	EDI	$(\log FAR - \log POD)/(\log FAR + \log POD)$	rare events skill 1 -best
Symmetric external dependence index	SEDI	$(\log FAR - \log POD - \log(1-FAR) + \log(1-POD))/(\log FAR + \log POD + \log(1-FAR) + \log(1-POD))$	rare events skill 1 -best

2.4. The heat-health watch-warning system

The heat-health watch-warning system for South Africa comprises of the meteorological forecast and a heat action plan. The meteorological forecasts are based on the heat index that is identified as the most appropriate for South Africa (in Chapter 3). The heat action/prevention plan is derived from a comprehensive literature study from other parts of the world.

2.5. Synopsis

The data for assessing the quality of the model forecasts (model and observational data) have been discussed. Data for studying the weather systems that caused the past recent heat waves and data for developing a heat-action plan that is recommended for South Africa were also discussed. Evaluation schemes for identifying the most suitable heat index for South Africa, hence evaluating the model performance have been outlined. The next chapter gives the results of this model evaluation and the performance of selected heat indices over South Africa.

CHAPTER 3: The performance of different heat indices in predicting extremely hot events over South Africa

3.1. Introduction

In this chapter the results of the evaluation of selected heat indices over South Africa are discussed. The purpose is to identify the most skillful index that could be used to develop a heat watch-warning system for heat waves over South Africa. The final outcome of this work is for the system to be developed and tested and to be made operational at SAWS. Thereafter the information can be disseminated to relevant stakeholders whenever heat waves are forecast.

To identify the most appropriate heat index for South Africa, each one of the selected indices is calculated for each day of the study period (for all available cases) and evaluated against the observations. Evaluation schemes stated in Chapter 2 are utilized. This is done for forecasts up to a 14-day lead-time. An extreme event is identified whenever each threshold in Table 2.1 is exceeded, and those extreme events are used for the study. The assumption is made that any index that can skillfully forecast single-day extreme events can also do the same for prolonged extreme events, i.e. for heat wave events lasting several days.

Since the model data used are derived from the NCEP model, the skill also depends on the quality of the model forecast data. The NCEP model forecasts have been examined over South Africa and been found to have benefit in the skill of the 1-7 day forecasts, in that the ensembles have reduced instances of missing events compared to single deterministic forecasts (Tennant *et al.*, 2006). Ensemble forecasting generally addresses errors associated with numerical model forecasting (Toth *et al.*, 2001).

3.2. Evaluation results

All selected indices (SAW, HUM, APT, WBG and DSI) are evaluated for 1 – 14 day lead-times and the results are summarized in Table 3.1. Evaluation schemes in Table 2.1 are used and the index with a relatively better performance for each scheme and lead-time is entered in the appropriate column (Table 3.1).

Table 3.1: Summary of areal average skill scores per lead-time for each evaluation scheme

Lead-time (days)	1	2	3	4	5	6	7	8	9	10	11	12	13	14
BIAS	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT
FAR	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT	APT
HR	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM
POD	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM
EDI	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM
SEDI	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM
HSS	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM
CSS	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM
ETS	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM
CSI	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	HUM	--	--	--

APT has the least areal average bias and false alarms through all lead times. It is also most reliable and has the highest resolution. HUM shows better scores and skill as far as the rest of the selected evaluation schemes are concerned. This result implies that HUM has the best discrimination (POD and HR), and is most skillful as far as areal average evaluation scores are concerned.

Figure 3.1 depicts the areal average bias scores for all five selected indices. APT bias scores are lowest and closest to 1, the perfect score, through all lead times. The scores follow a decreasing trend (drawing closer to 1) from 1-day to 5-day lead times, and thereafter begin to fluctuate. HUM is second after APT, then WGT. TDI and SDI over-forecast the most through all lead time. All the indices, except APT, over-forecast extreme events at all lead times.

Due to its dependence on the bias, areal average HSS is also one of the schemes that converge to zero for extreme events (Raghavendra, 2014; Stephenson *et al.*, 2008). Figure 3.2 supports this fact clearly. HUM has relatively high scores for HSS. SDI follows, and APT has the lowest scores. Scores generally follow a decreasing trend with increasing lead-time. Skill scores for HUM are above 0.4 only from 1- to 5-day lead-time.

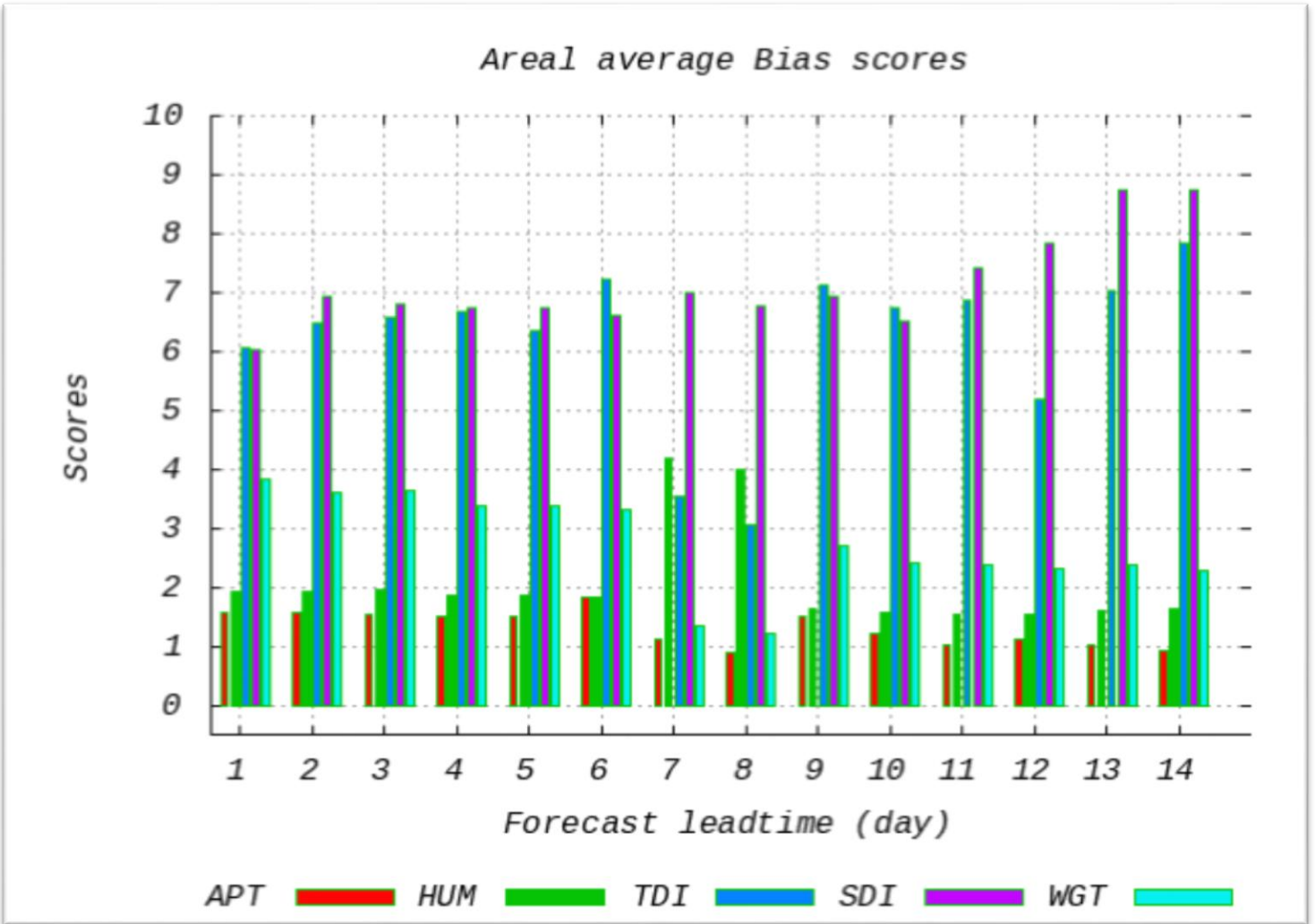


Figure 3.1: Areal average bias scores for selected heat indices through the entire domain.

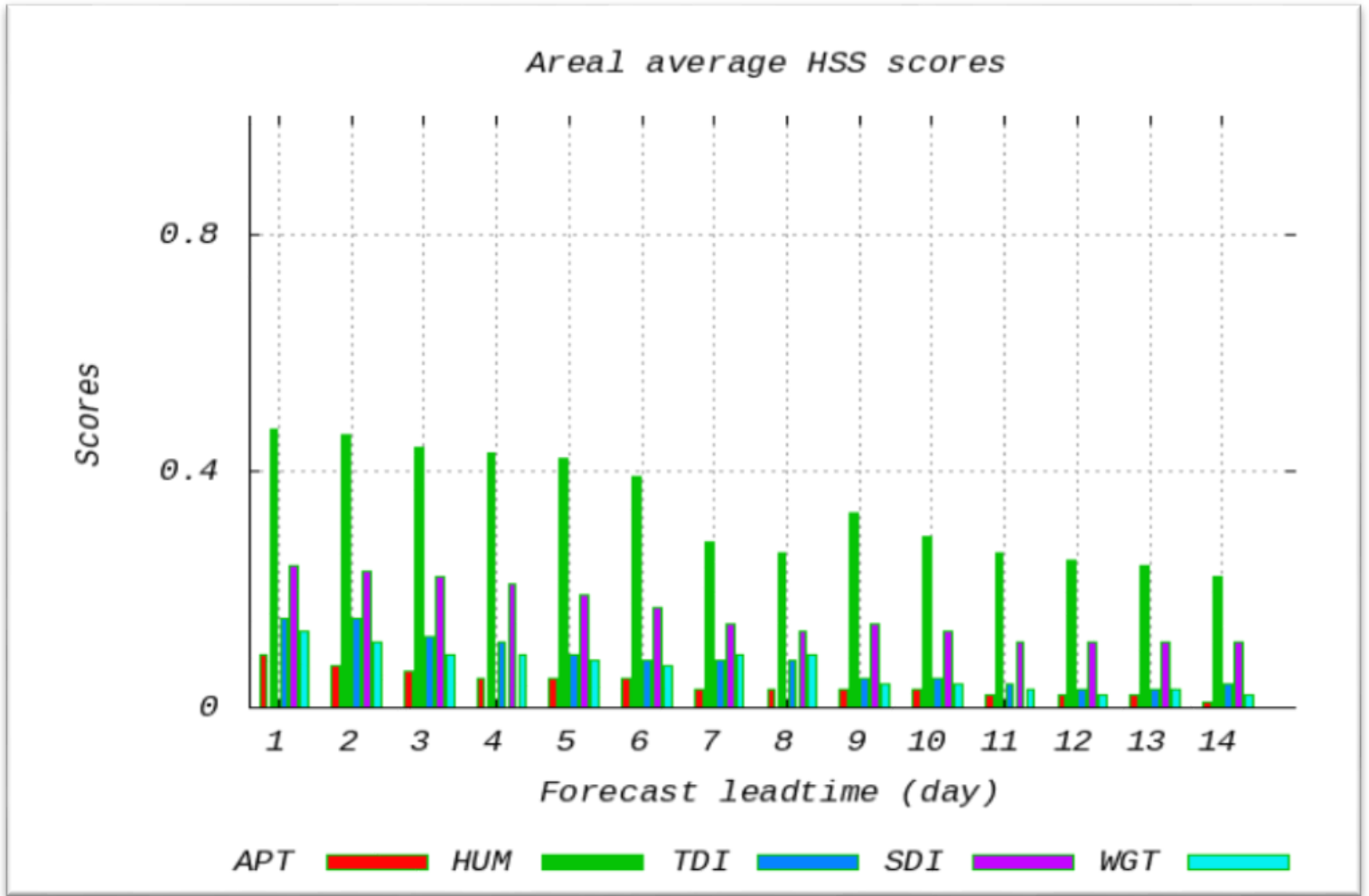


Figure 3.2: Areal average HSS scores for selected heat indices through the entire domain.

Areal average HR (POD) scores are also low (Fig. 3.3). This is expected for rare events, where hits are far less than correct negatives (Doswell *et al.*, 1990). According to Figure 3.3, HUM has the highest discrimination for extremely hot events. It is followed by SDI and the rest, but APT has the lowest level of discrimination. The skill generally becomes lower with increasing lead time. This result is what is expected of forecast skills (Shrestha *et al.*, 2013).

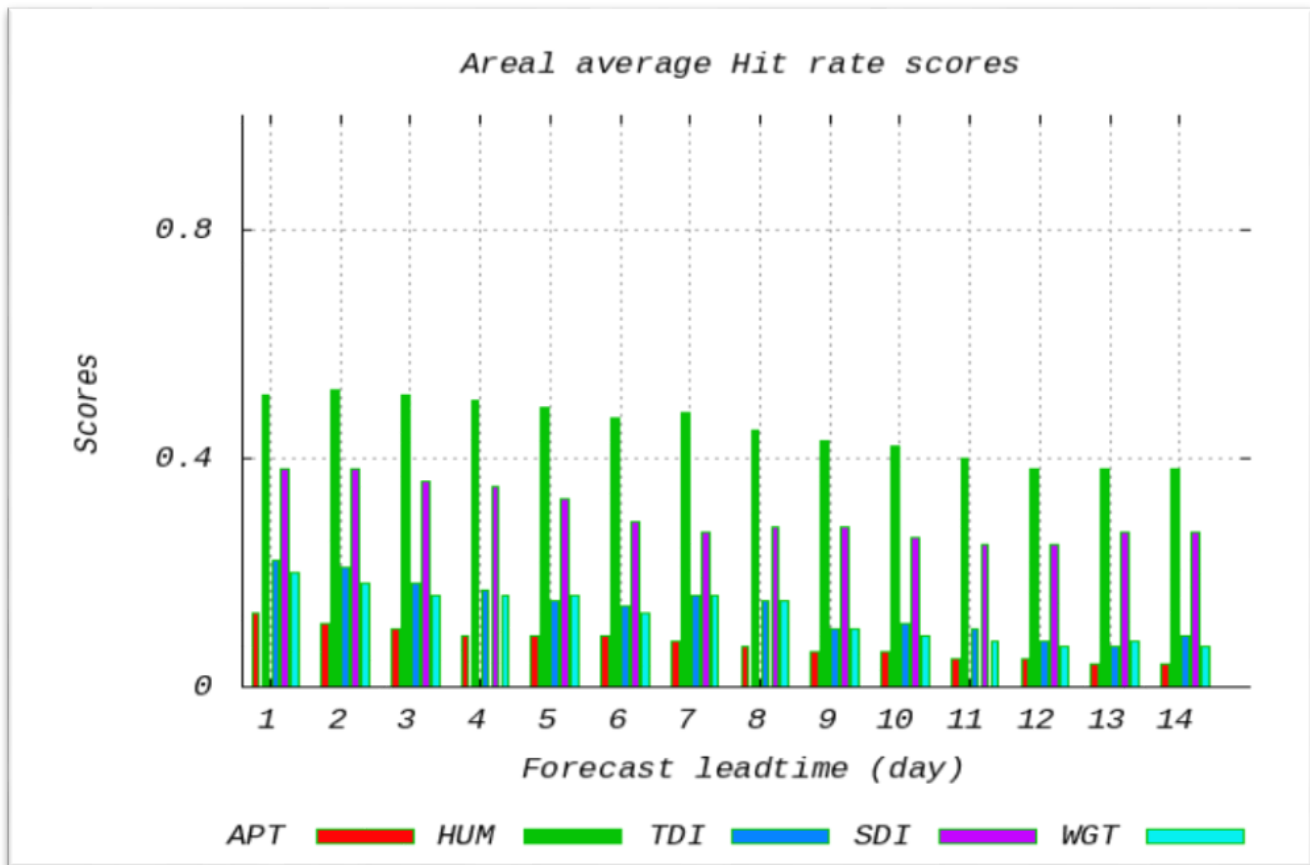


Figure 3.3: Areal average hit rate scores for selected heat indices through the entire domain.

Standard evaluation schemes such as ETS, CSI, POD, etc. approach zero for high threshold amounts (extreme events). This notion is because they are sensitive to bias. However, EDI and SEDI schemes have been proven to be most appropriate for evaluating extreme rare events such as extremely hot events (Raghavendra, 2014; Stephenson *et al.*, 2008). It is interesting to notice that areal average EDI and SEDI skill scores follow a similar trend and that only HUM has some skill (even though it is low) (Fig. 3.4). The other heat indices are always below the line of no skill (zero). This result is because SEDI and EDI scores depend on FAR and POD and their FAR scores are high while their POD is low. HUM has positive EDI and SEDI scores because of its high POD scores. The scores show a slight increase in skill from 1- to 4-day lead-time, and

hereafter follow a decreasing trend with increasing lead-time. A sharp decrease in skill begins at the 6-day lead-time.

ETS is one of the traditional scores used to verify deterministic forecasts of rare binary events such as extremely hot events, but has a disadvantage that it has zero scores for very rare events (Raghavendra, 2014; Stephenson *et al.*, 2008). This, in turn, can lead to a misconception that rare events cannot be evaluated (Raghavendra, 2014). Figure 3.5 below depicts this fact: only HUM has notable scores, and they are very low. APT, TDI, SDI and WGT show no skill as far as ETS is concerned. This result implies that only HUM has a ratio of success in forecasting extremely hot phenomena (Jolliffe and Stephenson, 2003). Figure 3.5 further depicts that the little skill that ETS has generally decreases with increasing lead-time, though there is a slight, insignificant increase between 1- and 4-day lead-times. A sharp decrease in skill with lead-time begins at the 6-day lead-time.

According to Tennant *et al.* (2006) and Candille *et al.* (2007) the use of model-generated probability forecasts are beneficial and display reasonable skill up to 7-day lead-times. In this study, most evaluation schemes generally show great benefit up to 5-day lead-time. This lead-time is believed to be sufficiently long for issuing a heat wave alert and for stakeholders to prepare for it (USEPA, 2006). It is also evident that HUM shows more skill in most cases, hence the spatial distribution of performance is also investigated only for HUM heat index, for 1-5 day lead-times. Areas of interest include the north-eastern interior and coastal areas. The reason is the western and north-western interior are often very hot, so the inhabitants are most likely to adapt easily to extreme heat and least likely to suffer the impacts thereof.

Areal Average EDI and SEDI scores for selected indices

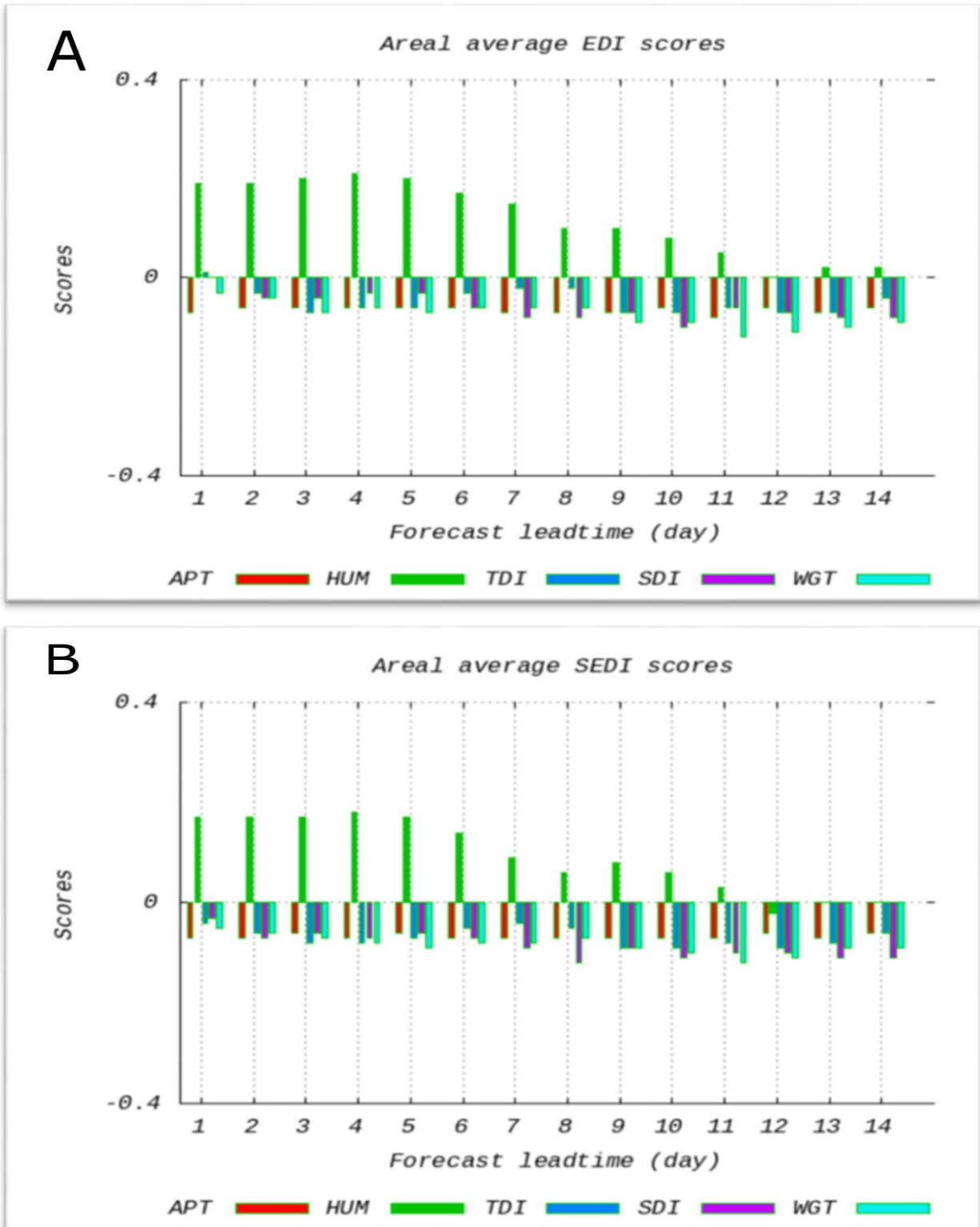


Figure 3.4: Areal average (A) EDI and (B) SEDI scores for selected heat indices through the entire domain.

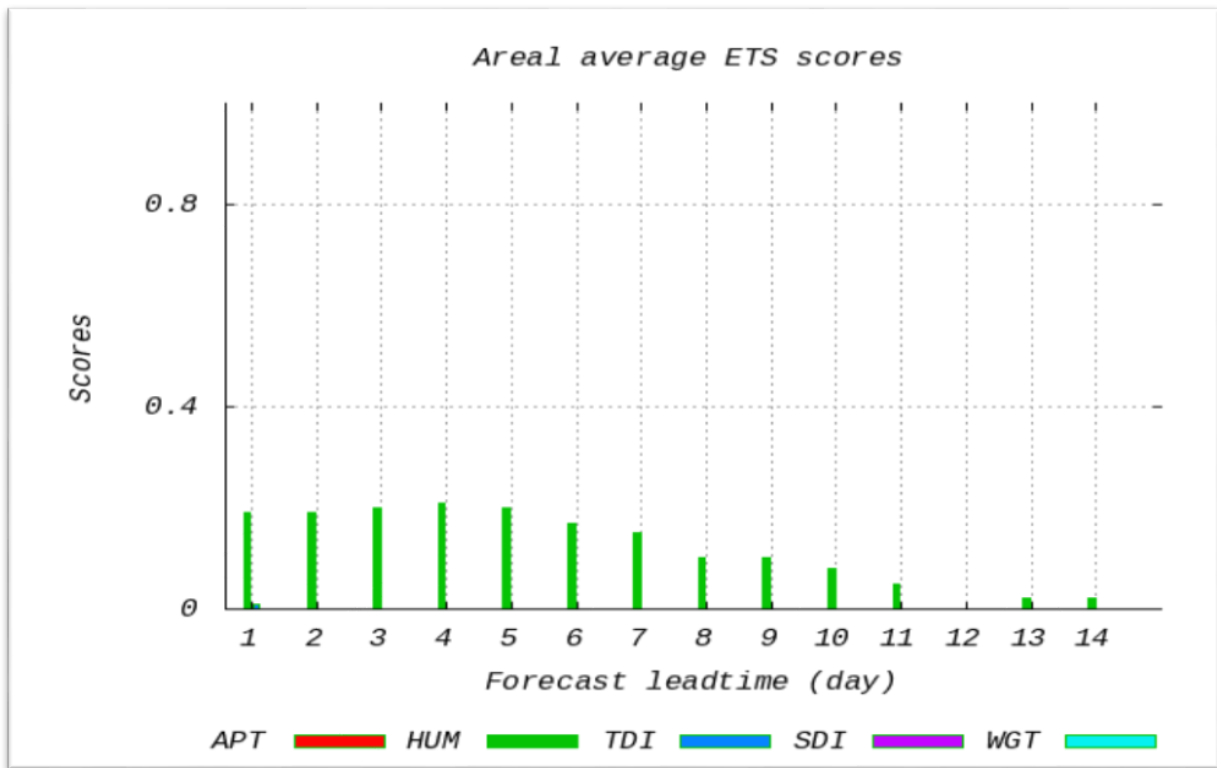


Figure 3.5: Areal average ETS scores for selected heat indices through the entire domain.

CSS generally decreases to zero with increasing lead-time along the areas of interest (Fig. 3.6). Figure 3.6 further depicts that extremely hot events occur more frequently when forecast than when not forecast over the coastal areas (Kliver, 2008). The central interior provinces show no skill throughout as far as CSS scheme is concerned. The Eastern Cape seems to have more skill than the rest of the provinces of interest, and the skill generally vanishes with increasing lead-time. Parts of the Western Cape show significant CSS skill in forecasting extreme events, and it also vanishes with increasing lead-time. KwaZulu-Natal also has some CSS skill, and its magnitude fluctuates through the lead-times.

Clayton skill scores (CSS) for HUM

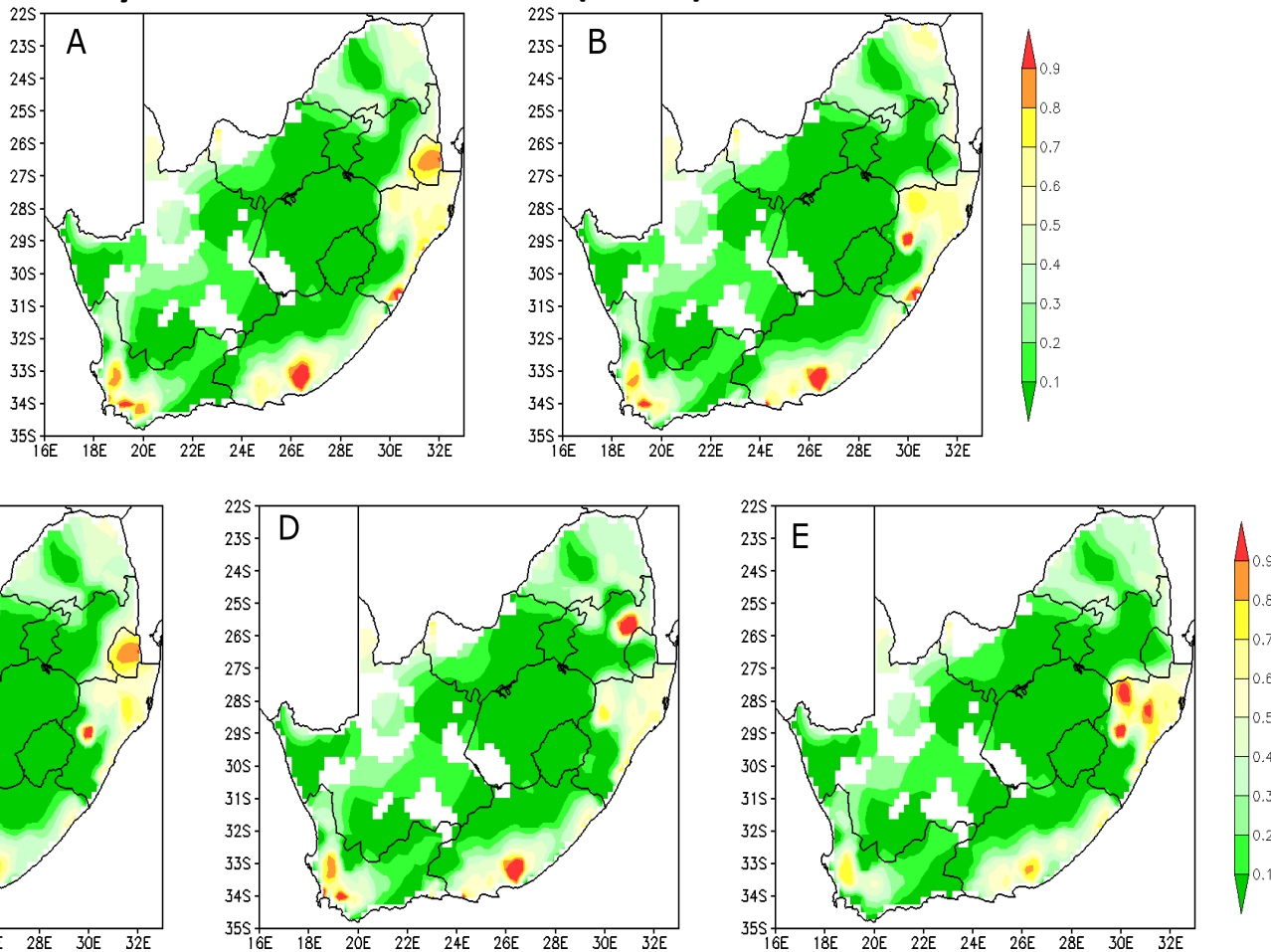


Figure 3.6: The spatial distribution of 1- to 5-day lead-time Clayton skill scores (CSS) for HUM (A-E, respectively).

Skill, as far as CSI is concerned, generally decreases with increasing lead-time over the areas of interest (there are more shades of red-yellow over the coastal and eastern interior at 1-day lead time, and decreases to the least at 5-day lead time) (Fig. 3.7). KwaZulu-Natal shows more skill than all the other provinces of interest, although the skill fluctuates through increasing lead-time. Parts of the Western Cape also show significant CSI skill. These are parts where several heat waves, of which some were fatal, were reported recently (e.g. News24, 2012; eNCA, 2015a; eNCA, 2015b; Eyewitness News, 2015). There is no skill in predicting extreme events over North-West and Gauteng through all the lead-time, and little skill over Limpopo Province and Mpumalanga.

EDI and SEDI scores follow a similar pattern, although EDI values are higher (Fig. 3.8 and Fig. 3.9). This supports the results depicted in Figure 3.4 above. There are higher EDI and SEDI skills over the Limpopo Province on 1-day lead-time, followed by the Western Cape. The skills become lower with increasing lead-time. This result implies that there higher skill and confidence in the forecasts at 1-day lead-time and it decreases with increasing lead-time (Tennant *et al.*, 2006). Parts of the central interior also show some EDI and SEDI skill. The rest of the areas of interest show no EDI or SEDI skill. This finding is due to the high rate of false alarms and fewer hits.

Critical success index (CSI) for HUM

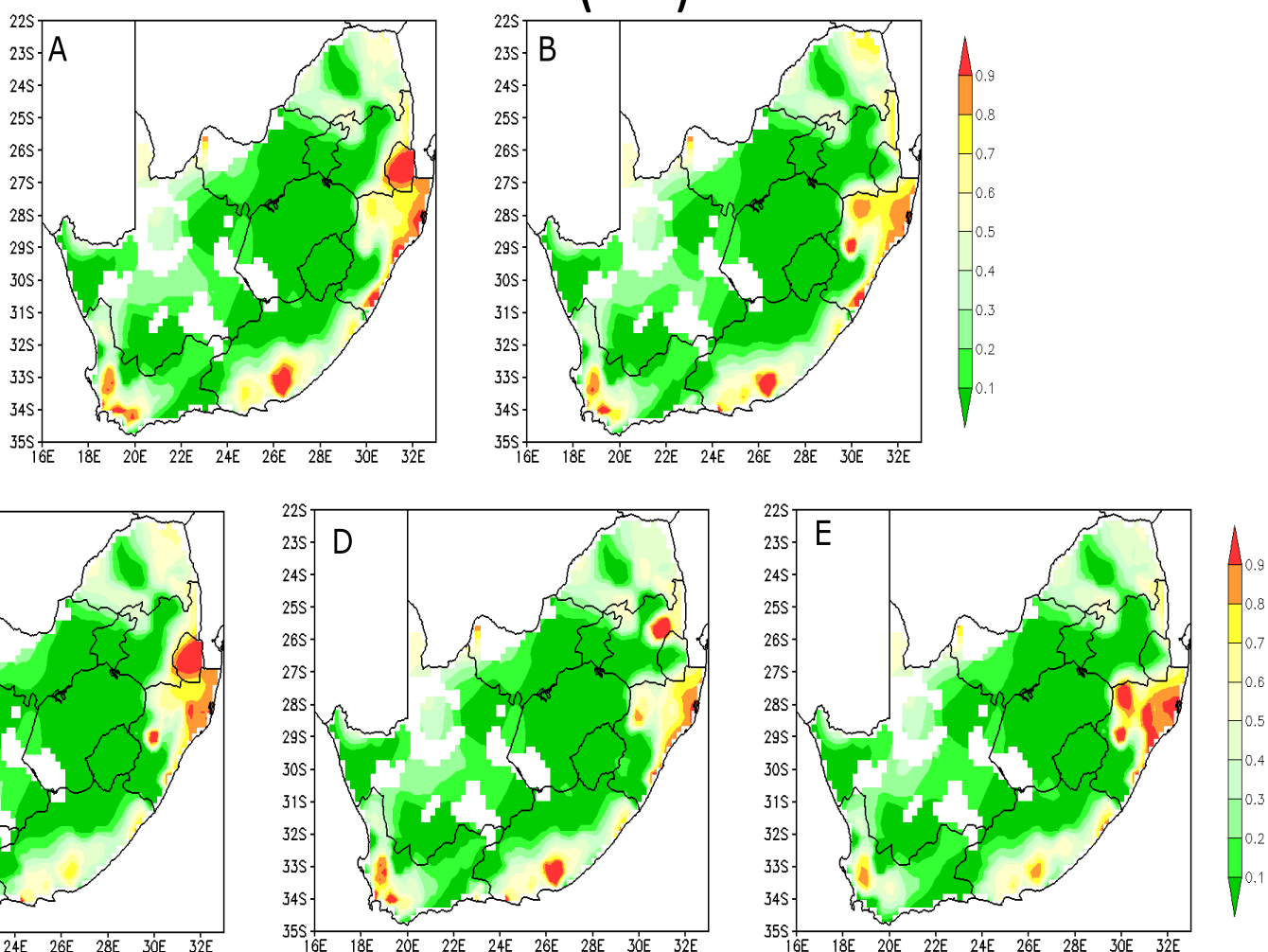


Figure 3.7: The spatial distribution of 1- to 5-day lead-time Critical success index (CSI) for HUM (A-E, respectively).

External Dependence index (EDI) for HUM

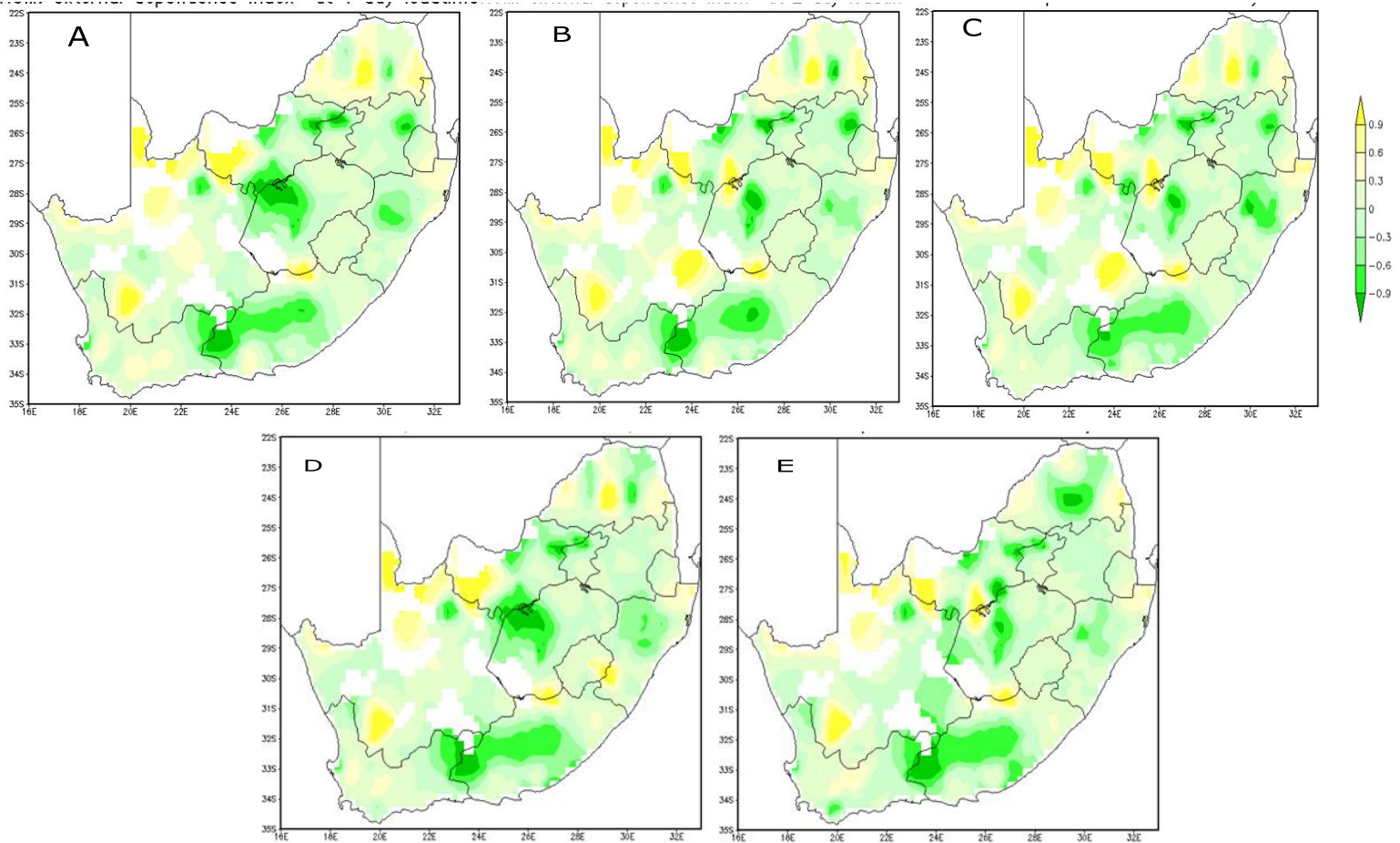


Figure 3.8: The spatial distribution of 1- to 5-day lead-time External dependence index (EDI) for HUM (A-E, respectively).

Discrimination for extremely hot events, as defined by POD, has notable spatial extent of high scores over large parts of the country (Fig. 3.10). Discrimination over the areas of interest is highest over large parts of Limpopo and vanishes with increasing lead-time. North-West, the Western and Eastern Cape, and the Free State possess discrimination that fluctuates through the

lead-times. On average, POD decreases slightly with lead-time. Gauteng and Mpumalanga show no discrimination throughout.

Symmetric External Dependence index (SEDI) for HUM

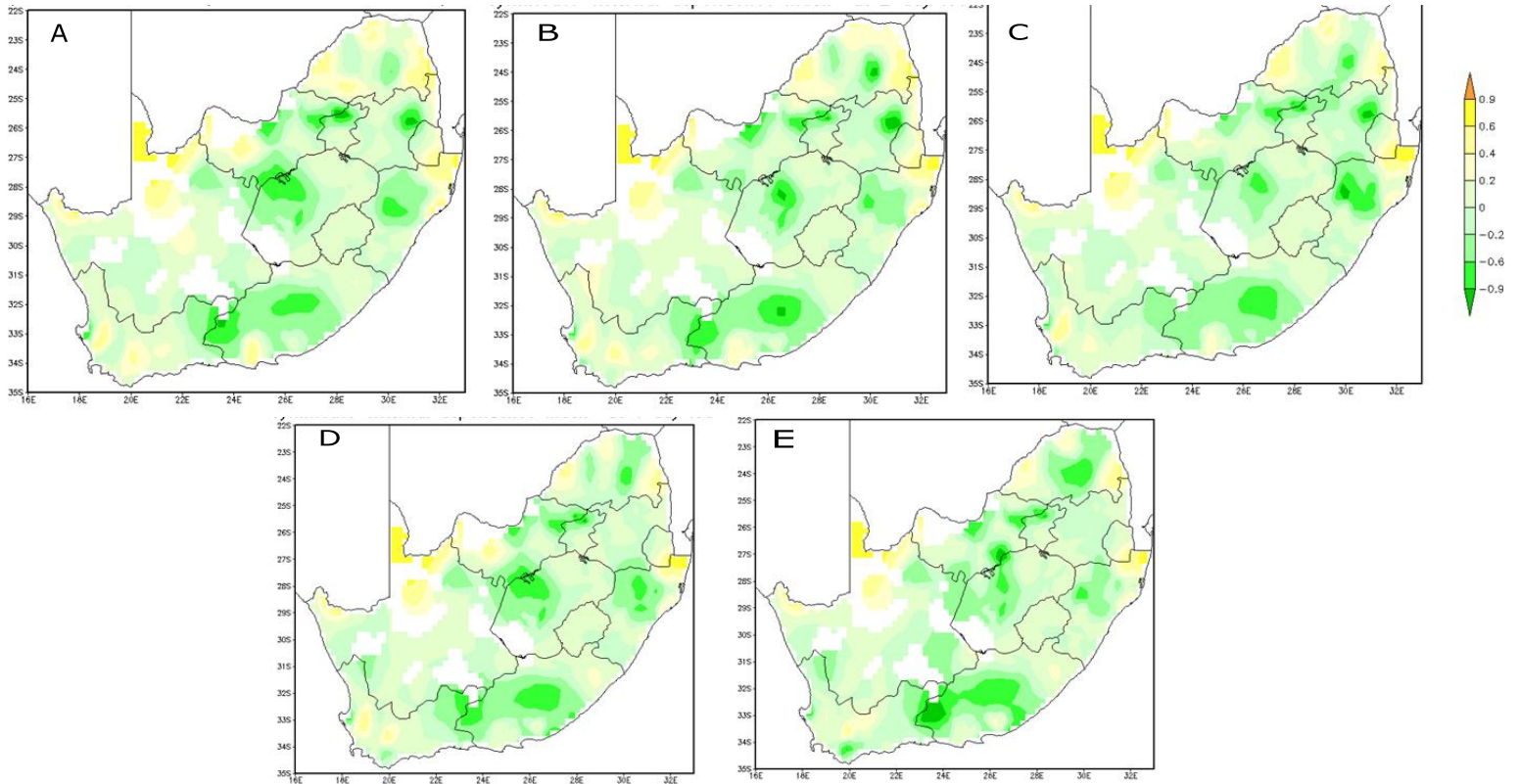


Figure 3.8: The spatial distribution of 1- to 5-day lead-time External dependence index (EDI) for HUM (A-E, respectively).

Probability of detection (POD) for HUM

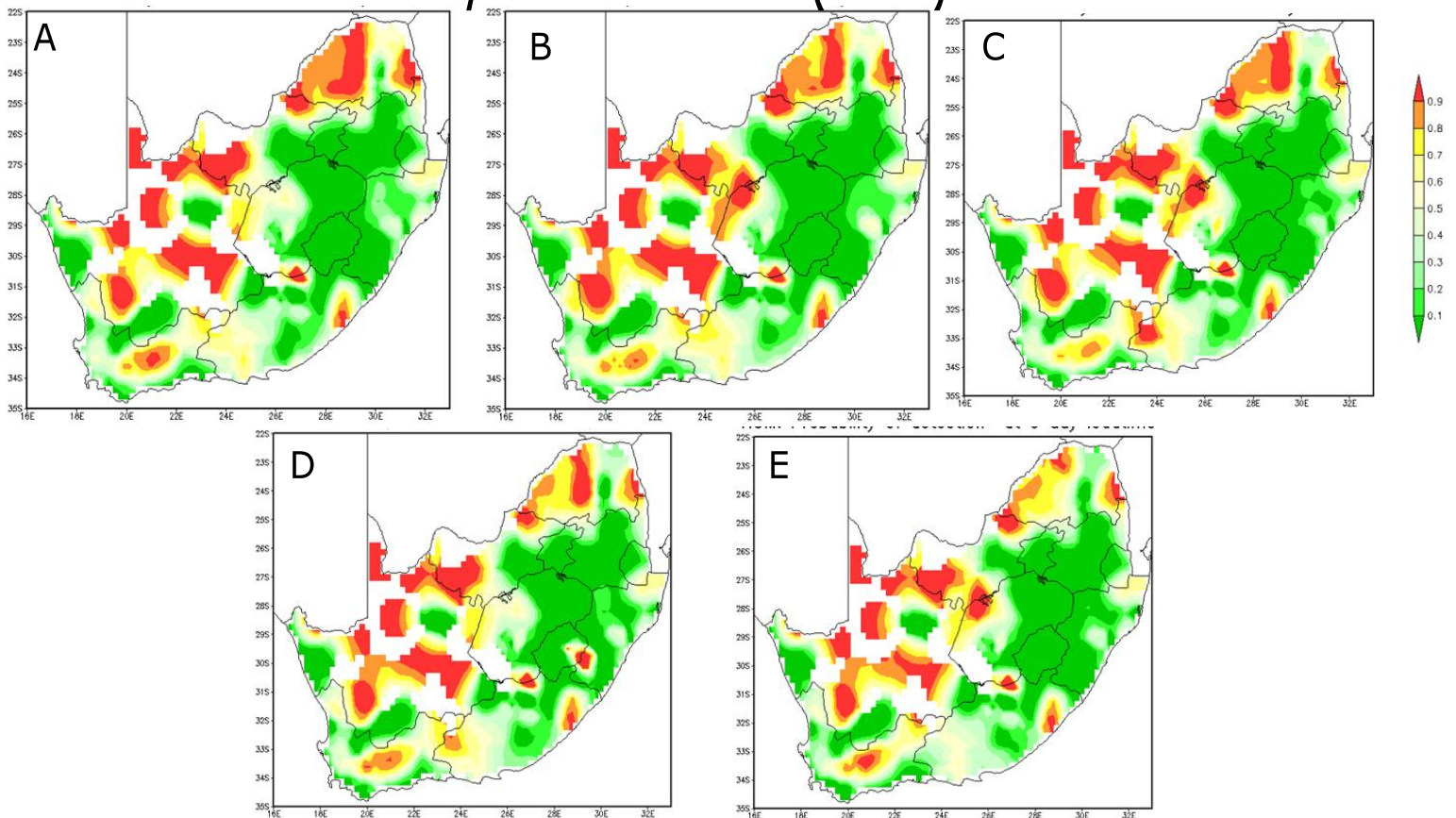


Figure 3.10: The spatial distribution of 1- to 5-day lead-time Probability of detection (POD) for HUM (a-e, respectively).

3.3. Synopsis

Based on the results of the evaluation of selected heat indices on their ability to predict extremely hot events, HUM has, for the most part, the best performance compared to the rest of the indices. For this reason, it was decided to further develop an operational heat wave forecast system at SAWS based on the HUM only. HUM is also selected for further use in this study. All the indices are underperforming. This result could be caused by the fact that extremely hot events are rare, have “hits” that are far less than “correct negatives” or any other unidentified cause (Doswell *et al.*, 1990).

It is important to note, however, that HUM only takes into account the effects of temperature and humidity. This may be a limiting factor as the same temperature and humidity can have different effects in different parts of the world. Demography and adaptation are other factors to consider when developing heat forecast systems since South Africa is geographically located in an area of variable climatic conditions (Dyson, 2000; Victorian Government Department of Human Services, 2009). All these factors should be taken into account when developing the operational heat wave forecast system (not part of this study).

The performance generally decreases with increasing lead-time. It is interesting to note that the performance of HUM is generally skillful up to 5-day lead-time, which is still sufficient period for stakeholders to prepare for a forecasted extremely hot event, and heat waves in particular. It is also notable that parts of the Western Cape have significant performance in predicting extremely hot events. EDI, SEDI and POD schemes show that the Limpopo Province has the highest performance (skill and discrimination). The model shows little to no ability in predicting extremely hot events over Gauteng and the Free State.

To further add value to the skillful model forecasts, there is need to understand that the occurrence of heat waves is dependent on the meteorological conditions. Further study on the weather systems that cause heat waves over South Africa is also done and is discussed next. This will help weather forecasters stay on the lookout for heat waves whenever such systems are forecasted or observed. The model skill for predicting such weather systems is expected to be good up to five days ahead of the event.

CHAPTER 4: The weather circulation patterns that caused heat waves over South Africa

4.1. Introduction

The knowledge and understanding of weather systems that cause heat waves are critical to weather forecasters and atmospheric scientists. Due to its geographical location, South Africa is influenced by tropical, subtropical and temperate weather circulation systems (Taljaard, 1995a). The circulation patterns include subtropical anticyclones, easterly lows, and subtropical lows/troughs, westerly waves, ridging anticyclones, west-coast troughs, thunderstorms and tropical cyclones (Tyson and Preston-Whyte, 2000).

The subtropical anticyclones are high-pressure circulations that are deep and tilted upward from the surface towards the north-west (Tyson and Preston-Whyte, 2000). They are associated with divergence in the near-surface wind field, strong subsidence throughout a deep layer, the occurrence of inversions, fine clear conditions and little or no rainfall. When prevailing for extended periods in summer, subtropical anticyclones may produce severe heat waves and aridness. Subtropical anticyclones in the upper air are most likely during dry summers and are associated with subsidence (Karoly, 2015; Tyson and Preston-Whyte, 2000). When these high-pressure systems are located in the upper air in summer, they produce clear, fine weather (Tyson and Preston-Whyte, 2000).

Tyson and Preston-Whyte (2000) showed that easterly waves and lows are usually associated with the Inter-Tropical Convergence Zone (ITCZ) and the warm humid easterly winds between the ITCZ and the subtropical high-pressure belt. Typically in summer, they extend from Namibia to the central interior of the country and are also flanked by the Indian Ocean high and the Atlantic Ocean high (Taljaard, 1995a). West of the easterly waves and lows are clear skies, hot conditions with no rainfall. Thunderstorms may occur within a convergence zone, extending 200-300 km north-eastward of the trough and often form squall lines that advance from the south-west. Subtropical lows, westerly waves, ridging anticyclones, thunderstorms and tropical cyclones tend to produce heavy rainfall over South Africa during summer months (Tyson and Preston-Whyte, 2000).

Ridging anticyclones are associated with berg winds over the south and south-east coasts when they are located over the central interior, and berg winds over the Western Cape when they are located over the southern parts of the country (Tyson and Preston-Whyte, 2000). They are also associated with subsidence with clear, fine and hot weather.

In this chapter, the weather systems that caused heat waves in the recent years are identified. Such understanding will help meteorologists stay on the lookout for heat waves whenever such systems are forecasted or observed, so they can issue warnings to relevant stakeholders.

4.2. The weather patterns responsible for observed heat waves

In this study, cases that were reported mainly by SAWS and the media between 2011 and 2015 are used to investigate the weather systems that influenced heat waves in different parts of South Africa. Identified cases are 24-26 October 2011, 13-15 November 2011, 15-18 January 2012, 23-28 January 2013, 16-18 January 2014, 14-17 February 2014, 7-11 February 2015, 4-12 October 2015 and 7-12 November 2015 (SAWS, 2016; eNCA, 2014; Health24, 2015; News24, 2015a; The Citizen, 2015; eNCA, 2015a; eNCA, 2015b, eNCA, 2015c, News24, 2011; News24, 2015b; IOL, 2015; News24, 2015c; SABC, 2011; de Jager, 2015; The Sowetan, 2013; News24, 2013; SABC, 2014; News24, 2012). From these cases, it can be seen that 2015 has experienced the longest heat waves of all selected. Based on the cases above, the average duration of each heat wave event is four days.

Table 4.1 depicts the spatial distribution of the heat wave cases that were reported by SAWS and other media between 2011 and November 2015. Most of these heat waves occur over the north-eastern interior, with Gauteng experiencing the most of them. No heat wave was reported in the Eastern Cape during this period. Heat waves that occurred in the Western Cape have a much smaller spatial extent compared to the ones in the north-eastern interior and has observed heat waves during mid-January and February. January has the highest number of heat wave events for the study period, followed by February. Heat waves that occurred at the end of spring and beginning of the summer season (October and November) occurred in the north-eastern interior.

4.2.1. The average circulation patterns

To further understand the nature of heat waves over South Africa, NCEP reanalysis data are used (Saha *et al.*, 2011). In order to understand the circulation patterns from sea level to the upper

Table 4.1: Location/spatial distribution of heat waves that were recorded in the media and by SAWS between 2011 and November 2015 (eNCA, 2014; Health24, 2015; news24, 2015; The Citizen, 2015; SAWS, 2016; eNCA, 2015a; News24, 2011; News24, 2015a; IOL, 2015; News24, 2015b; SABC, 2011; de Jager, 2015; Sowetan, 2013; News24, 2013; SABC, 2014; News24, 2012).

Heat wave case	Location
24-26 October 2011	Gauteng Province
13-15 November 2011	Free State, Gauteng, Limpopo, Mpumalanga and North West Province
15-18 January 2012	Western Cape (Cape Town)
23-28 January 2013	Gauteng, Limpopo, the Northern Cape and North West
16-18 January 2014	Gauteng, Free State, North West province, Northern Cape and Limpopo
14-17 February 2014	Western Cape (Cape Peninsula)
7-11 February 2015	Gauteng and North West
4-12 October 2015	Limpopo, Mpumalanga and Gauteng
7-12 November 2015	Gauteng, Mpumalanga, Limpopo and parts of North West

atmosphere, geopotential heights (GPH) at 850 hPa and 500 hPa, and mean sea-level pressure (MSLP) are plotted for the study. The events are grouped and averaged according to their location: heat waves over the Western Cape and events over the north-eastern parts, respectively, in order to investigate further the general circulation patterns influencing heat waves over each location. This analysis is conducted for identified cases at 12:00 GMT of each case.

General patterns causing the heat waves listed above over the Western Cape are depicted in Figures 4.1 and 4.2. Figure 4.3 depicts the spatial distribution of average maximum temperatures during the heat wave days. It can be seen that temperatures were highest over parts of the Western Cape where heat waves were reported (Fig. 4.3). On average, the weather patterns that influence heat waves at mean sea level are a ridging anticyclone (Atlantic Ocean high), accompanied by a tropical trough (Fig 4.1). The ridging high (centered south of the country) extends to the eastern parts of the country, while the tropical trough extends from Namibia to the south-west coast. Ridging highs are characterized by subsidence over the Western Cape, which results in clear, fine and hot weather (Tyson and Preston-Whyte, 2000). The two weather systems

are positioned in an offshore area of the Western Cape, accompanied by an easterly to north-easterly flow. Berg winds are most likely under such conditions, and they are also characterized by subsidence and very hot conditions (Taljaard, 1995b).

Average MSLP for cases that were reported over the WC

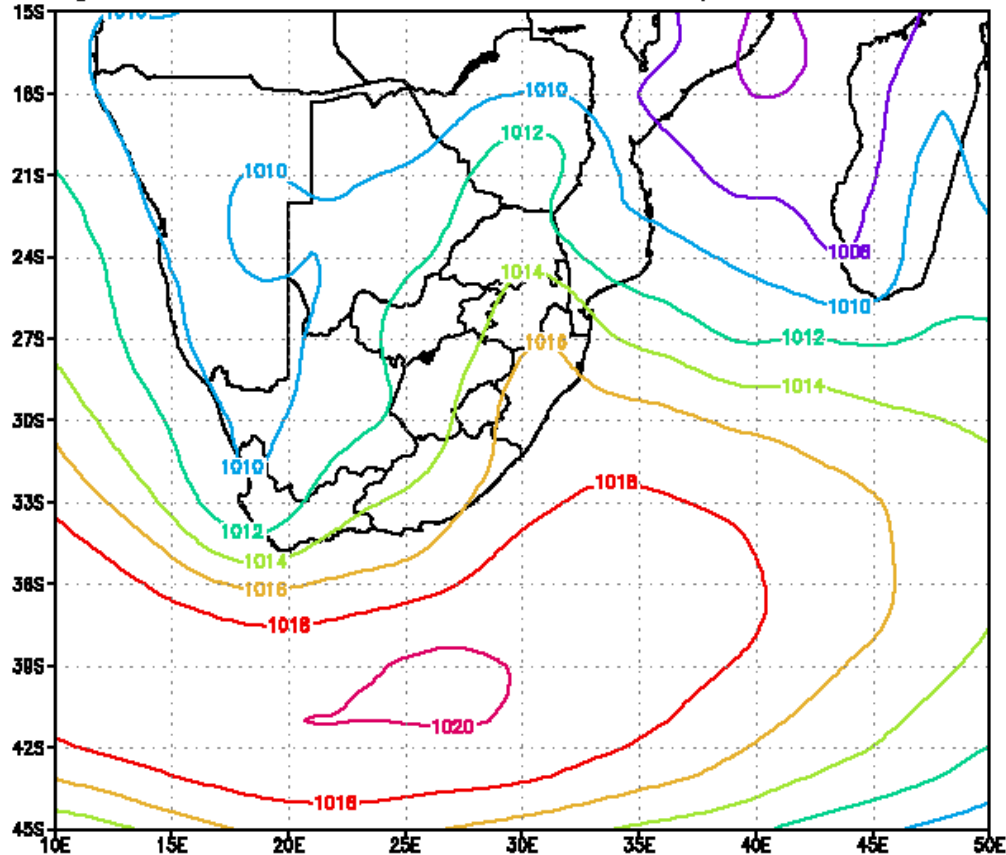


Figure 4.1: General circulation patterns at mean sea level pressure for heat wave events that were reported over the Western Cape from 2011 to November 2015. The averaging was done for each day of the heat wave events over the Western Cape as depicted in Table 4.1 above. The average is for 12:00 GMT of each case day for the NCEP reanalysis.

At 850 hPa, a ridging high-pressure system, with its center located over the south-eastern parts of the country (slightly northeast of the mean sea-level one), with a tropical low-pressure system located over northern Namibia places the Western Cape in an area of offshore flow (Fig. 4.2). At 500 hPa, an upper-air high is located directly above the Western Cape (Fig. 4.2). This high is slightly northwest of the surface high. This configuration of the high-pressure systems supports the theory stated by Tyson and Preston-Whyte (2000), that anticyclones are tilted north-west towards the north-west. As stated above, these systems are associated with strong subsidence, with fine, hot and clear conditions. When these anticyclones are observed for extended periods,

they are known to bring heat waves and desiccation (Tyson and Preston-Whyte, 2000). This finding is also in line with the definition that heat waves are very hot conditions that are observed for extended periods (at least three days) (Peng *et al.*, 2011).

Cases where heat waves were observed over the central, eastern and north-eastern parts of the country during the study period are also averaged and depicted in Figures 4.4 and 4.5. Figure 4.6 depicts the average maximum surface temperatures for the cases. During this period, the composite map shows the highest temperature over parts of the north-eastern interior, where the heat waves were experienced. At mean-sea level, a deep trough extends from the tropics to the central interior and the Atlantic high is ridging over the southern tip of the country (Fig. 4.4). The flow along the east coast is parallel to the coastline. A tropical low is located over Namibia and connects to a surface low (heat low) south-eastern parts of the country (Fig. 4.5). A high-pressure system (continental high) is situated over the north-eastern parts of the country; with a flow parallel to the coastline further north (Mozambique) and an offshore flow over the east coast. This is in agreement with the study of Taljaard (1995a) concerning the mean January (summer) patterns at 850 hPa, except that there is no influx of moisture from the Indian Ocean. A broad upper-air high is situated over the northern parts of the country at 500 hPa (Fig. 4.5). This corresponds to the theory for upper-air patterns for fine weather during summer as shown by Tyson and Preston-Whyte (2000). The systems above are situated in such a way that the north-eastern and eastern parts of the country are in an area of subsidence. The flow along the east coast is offshore. This creates favourable conditions for berg winds and strong subsidence along the east coast, subsidence with fine and dry weather conditions over large parts of the interior or even heat waves if they persist for extended periods (Tyson and Preston-Whyte, 2000).

General circulation during heat waves over the WC

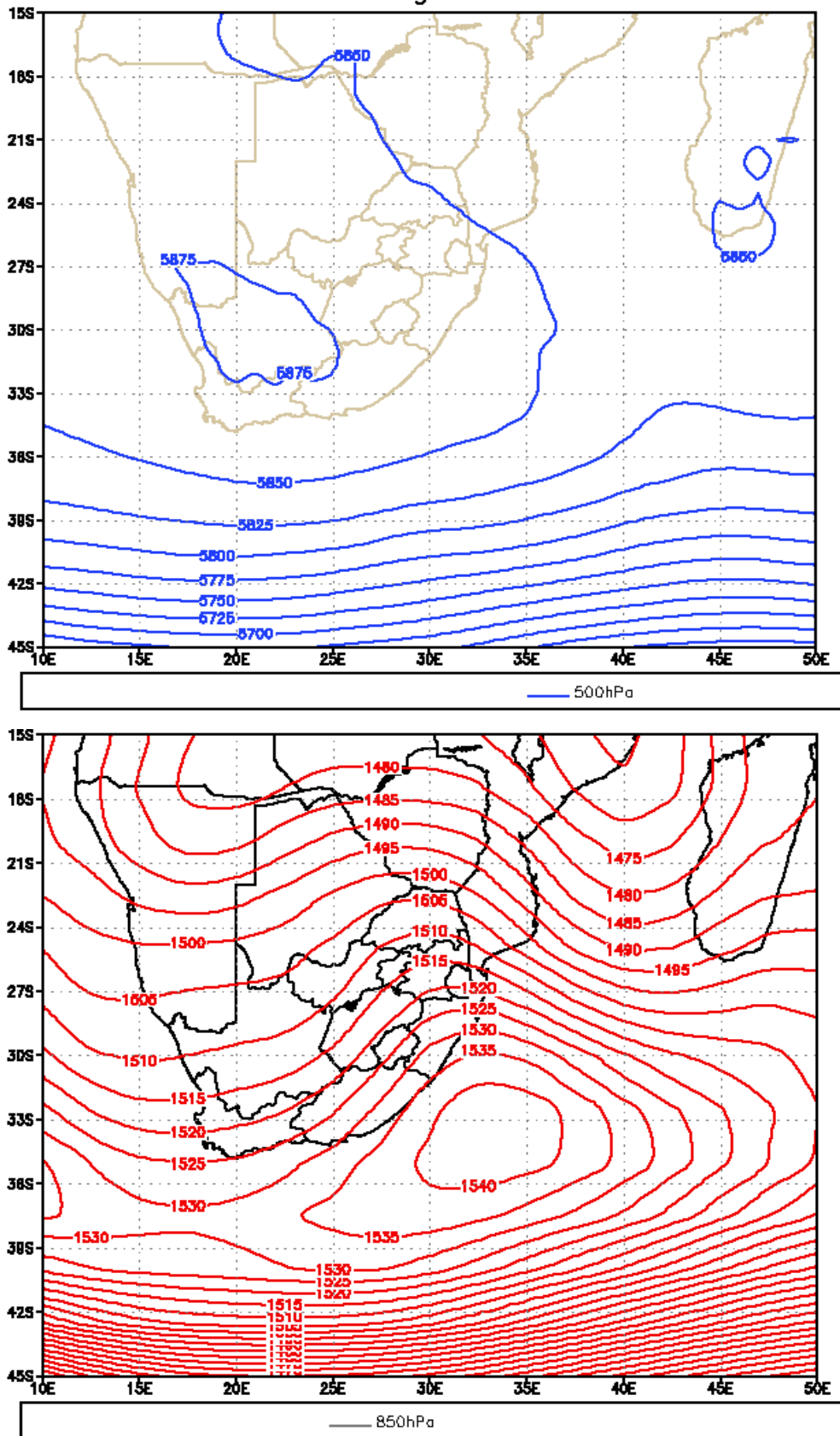


Figure 4.2: The average circulation patterns that caused heat wave events over the Western Cape from 2011 to November 2015, at 500h Pa (top) and 850 hPa (bottom).

Average Surface temperature for cases over the WC of SA

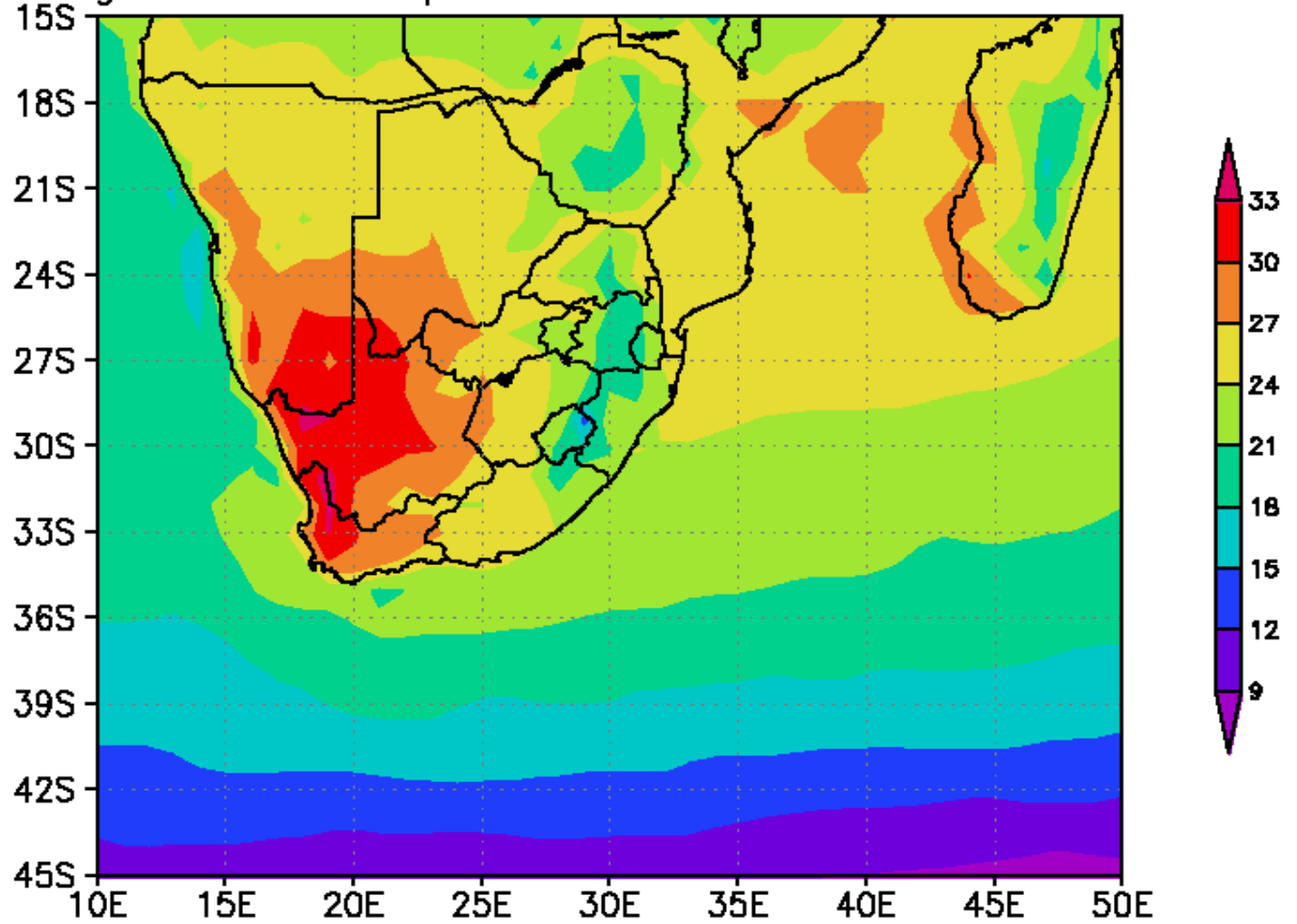


Figure 4.3: The average surface temperature for heat wave events that were reported over the Western Cape from 2011 to November 2015.

Average MSLP for cases that were reported over the NE of RSA

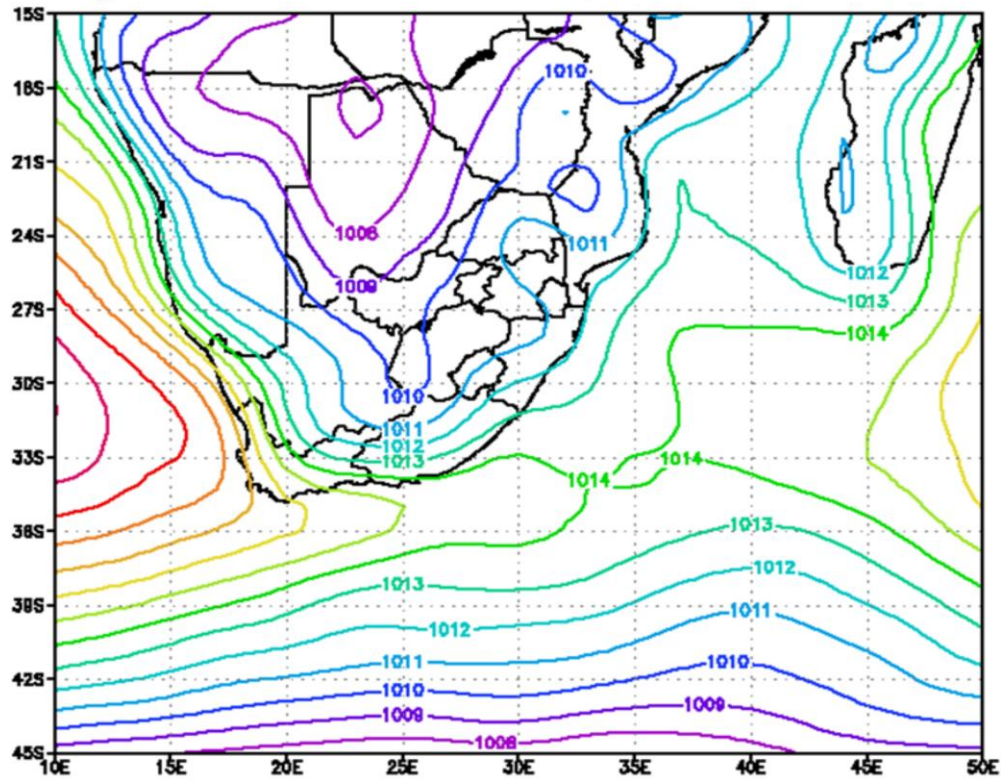


Figure 4.4: General circulation patterns at mean sea level pressure for heat wave events that were reported over the eastern and north-eastern parts of the country

Average Surface temperature for cases over the NE of SA

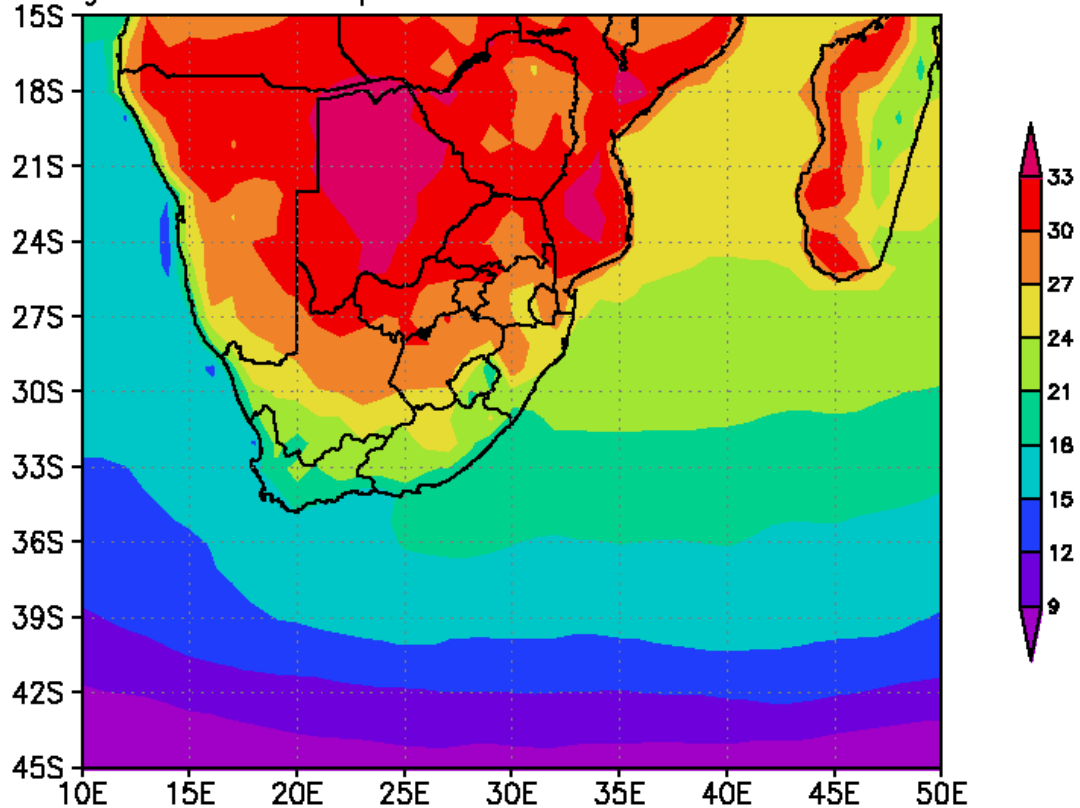


Figure 4.6: The average surface temperature for heat wave events that were reported over the eastern and north-eastern parts of the country between 2011 and November 2015.

4.2.2. Case studies

To further study the weather systems that influence heat waves over different parts of South Africa, a few of the cases listed in Table 4.1 above were selected for further study. One case was selected for a heat wave over the Western Cape, another one for a heat wave over the Northern Cape and KwaZulu-Natal and the last case for a heat wave that affected the north-eastern interior of the country.

On 15 – 18 January 2012, a severe heat wave was reported over the Western Cape, in which a fatality of a 55 year-old male construction worker, due to heat exhaustion, was reported in Paarl and five of his colleagues were admitted to hospital (News24, 2012; SAWS, 2016). Temperatures

in parts of the Western Cape reached the upper 30's and lower 40's. A deep trough at mean sea level, extending from the tropics across the western interior to the west coast was observed throughout the heat wave event, placing the Western Cape in an area of strong offshore flow (Fig. 4.7a-d). This created favourable conditions for hot weather as well as berg winds.

At 850 hPa, a trough extended from the tropics to the western interior, flanked by a ridging anticyclone over the south-eastern parts of the country from the 15th to the 18th (Fig. 4.8a-d). The ridging Indian Ocean high was situated south of the country on the 15th (Fig. 4.8a) and gradually moved off the south-east coast from the 16th to 18th (Fig. 4.8b-d). An upper-air high was tilting north-west of the surface high and centered over the south-west coast on the 15th (Fig. 4.8a). It broadened and moved eastwards so that it tilted north-west of the surface high from the 16th to 17th (Fig. 4.8b-c). By the 18th, the upper-air high was located off the south-east coast, slightly above the surface high (Fig. 4.8d). Throughout the period, the Western Cape was located in the area of strong offshore flow at the surface and strong subsidence.

Mean Sea level pressure patterns 15 - 18 January 2012

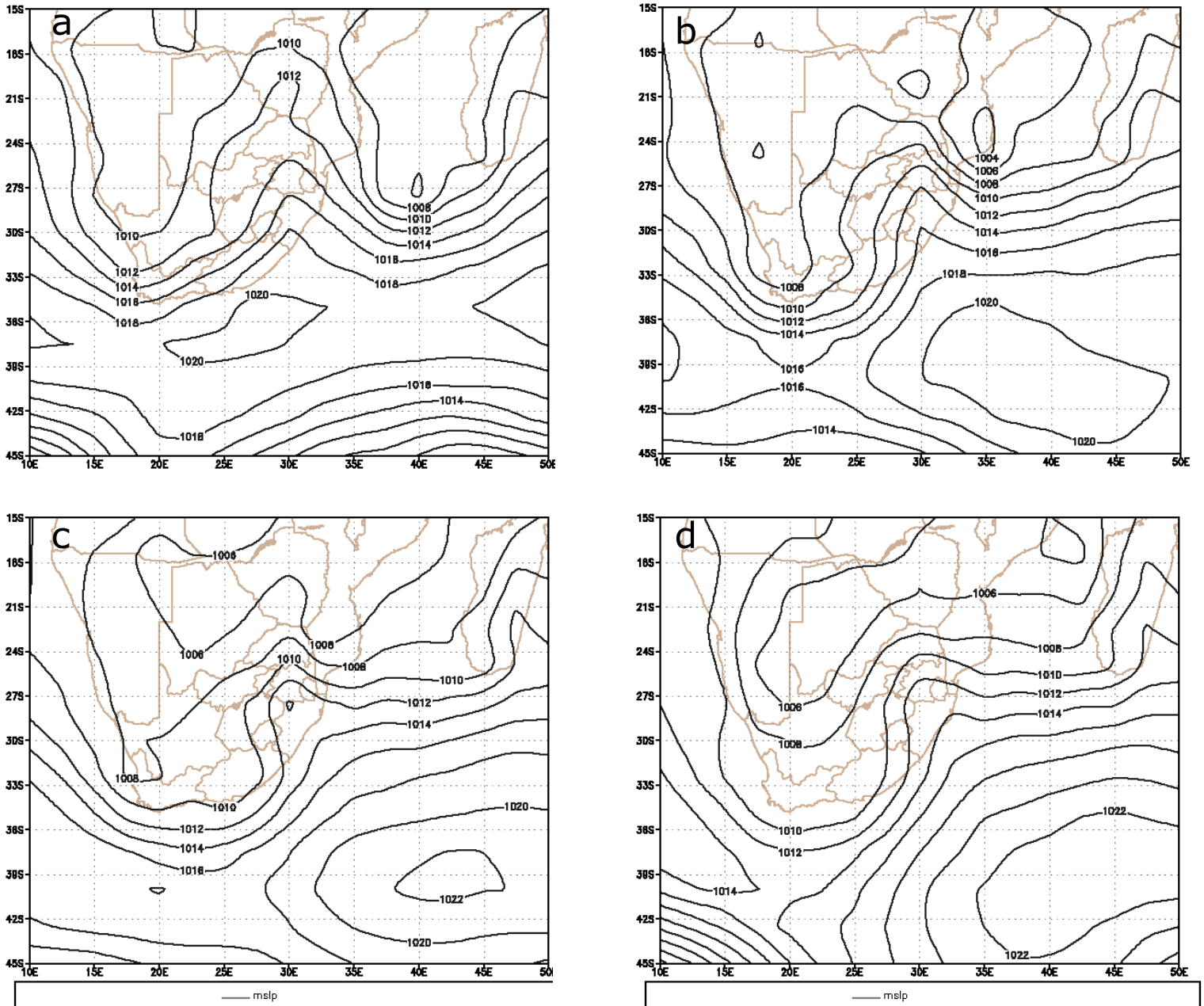


Figure 4.7: The average circulation patterns at sea level that caused the heat wave over the Western Cape on (a) 15th, (b) 16th, (c) 17th and (d) 18th January 2012.

Circulation patterns for 15 - 18 January 2012

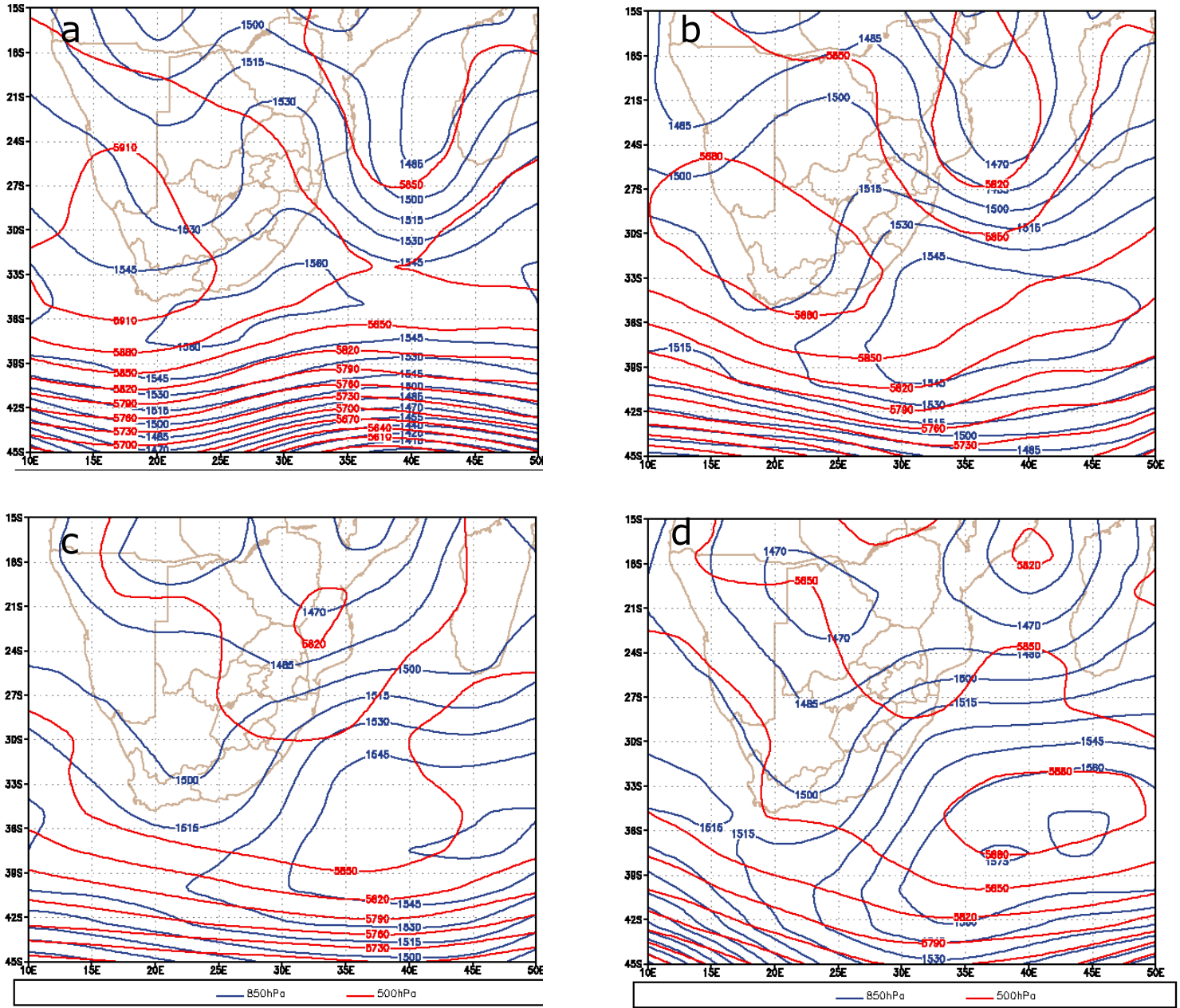


Figure 4.8: The circulation patterns at 850 hPa (blue) and 500 hPa (red) that caused the heat wave over the Western Cape on (a) 15th, (b) 16th, (c) 17th and (d) 18th January 2012.

On 16 – 18 January 2014, parts of the Northern Cape, Gauteng, KwaZulu-Natal, Limpopo, North West, and the Free State were hit by a heat wave (SAWS, 2016; eNCA, 2014). This was a short-lived, wide-spread heat wave. A report given to eNCA (2014) by weather authorities from SAWS stated that the heat wave was due to an upper-air high-pressure system. Mean sea-level pressure patterns depict a tropical cyclone over Madagascar, and it moved south from the 16th to the 18th (Fig. 4.9a-c). A broad trough extended over the western interior from the 16th to the 17th, flanked by the Atlantic Ocean high ridging over the south-west coast on the 16th (Fig. 4.9a-b). The Atlantic Ocean high ridged further eastward on the 17th (Fig. 4.9b) and reached the east coast by the 18th, forcing the trough to move to the central interior (Fig. 4.9c). There was an offshore flow over the east coast on the 16th and 17th. On the 18th, the surface trough at mean sea level over the central interior continued to strengthen, flanked by the ridging high that extended to the east coast (Fig. 4.9c). As a result, the east and south coasts experienced air flow parallel to the coastline (no moisture influx), the eastern interior was located east of the trough with no moisture influx from the east coast, and the Northern Cape was located at an area of subsidence.

Figure 4.10 depicts the weather circulation patterns for the 16 – 18 January 2014 at 850 hPa and 500 hPa. At 850hPa, a high-pressure system was located along the west coast, and it moved eastward from the 16th to the 18th, placing the parts of the country that reported a heat wave east of the 850 hPa high (Fig. 4.10a-c). An upper-air high, at 500 hPa, had settled over the country from the 16th to the 18th, causing strong subsidence over the country. This supports the report given to eNCA (2014) above. The position of the upper-air high (at 500 hPa) and the broad surface trough at mean sea level created favourable conditions for the heat wave over parts of the country. Throughout the heat wave phenomenon, a low-pressure system was evident over Madagascar area, where the tropical system was located. This tropical cyclone may have contributed to the occurrence of the heat wave, since tropical cyclones are associated with fine and dry conditions to their west, over the central and western plateau (Tyson and Preston-Whyte, 2000).

The last case was a prolonged heat event in the hottest year on record (WMO, 2016; Health24, 2015; News24, 2015c; The Citizen, 2015; SAWS, 2016; eNCA, 2015c). It was reported over the Limpopo Province, Mpumalanga and Gauteng on 4 - 12 October 2015. The heat wave had severe impacts ranging from restrictions in water supply in several municipalities, drowning of 11 children and one adult, the entire farming industry and wildfires in parts of the Limpopo Province (SAWS, 2016). Figures 4.11 and 4.12 depict the weather-circulation patterns that caused this heat wave. Mean sea-level pressure patterns show that a broad trough over the country was dominant throughout the heat wave event (Fig. 4.11a-i). The trough was located over the western interior

on the 4th (Fig. 4.11a). On the 6th, the trough moved further north as a high-pressure system moved into the eastern parts of the country (Fig. 4.11b). The trough broadened to cover the entire country by the 8th (Fig. 4.11c). The trough extended to the east coast on the 10th, as a cold front was passing over the western interior with the Atlantic High ridging behind it (Fig. 4.11d). After the cold front had passed, the Atlantic Ocean High ridged into the east coast, allowing the trough to cover large parts of the country (Fig. 4.11e). By the 12th, the surface trough extended from the tropics to the central interior (Fig. 4.11f). Throughout the heat wave event, the Limpopo Province, Gauteng and Mpumalanga were located in an area of generally northerly flow and subsidence, experiencing extreme heating and receiving no moisture.

The general patterns at 850hPa show that a ridging high over the north-eastern parts of the country was dominating throughout the heat wave event, placing Limpopo, Gauteng and Mpumalanga in an area of subsidence (Fig. 4.12). An upper air high extended to the northern and north-eastern parts of the country, and it tilted upwards towards the north to north-west of the surface ridging high (Fig. 4.12). The high pressure systems were associated with subsidence over the northern and north-eastern parts of the country, particularly Limpopo, Gauteng and Mpumalanga. They also caused the clear conditions and subsidence in the area. This also supports the findings on the average circulations that affect heat waves over the north-eastern interior in Fig. 4.4 and 4.5.

Mean sea-level pressure patterns for 16 - 18 January 2014

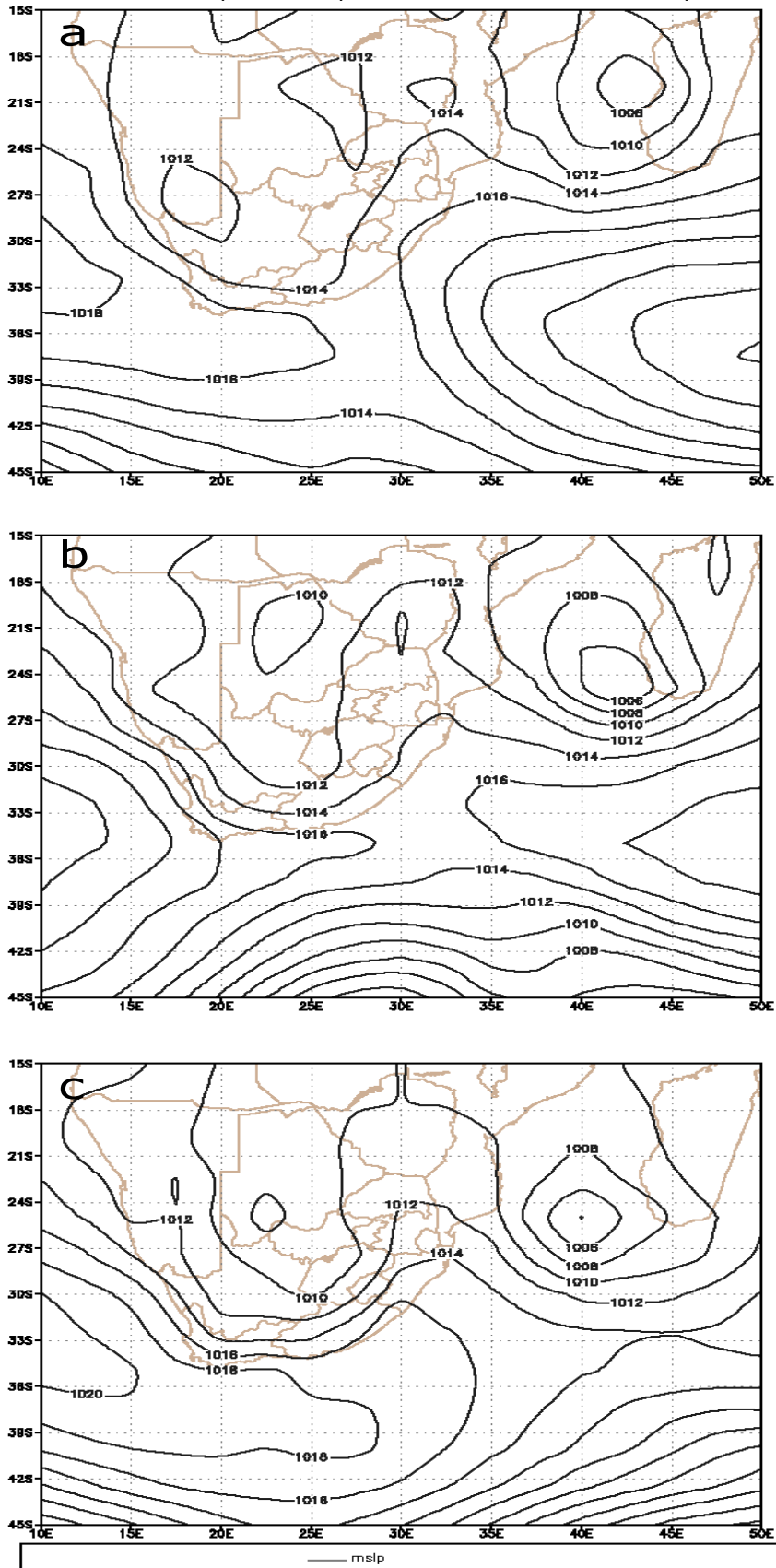


Figure 4.9: The circulation patterns at sea level that caused the heat wave over large parts of the country on (a) 16th, (b) 17th and (c) 18th January 2014.

Circulation patterns for 16 - 18 January 2014

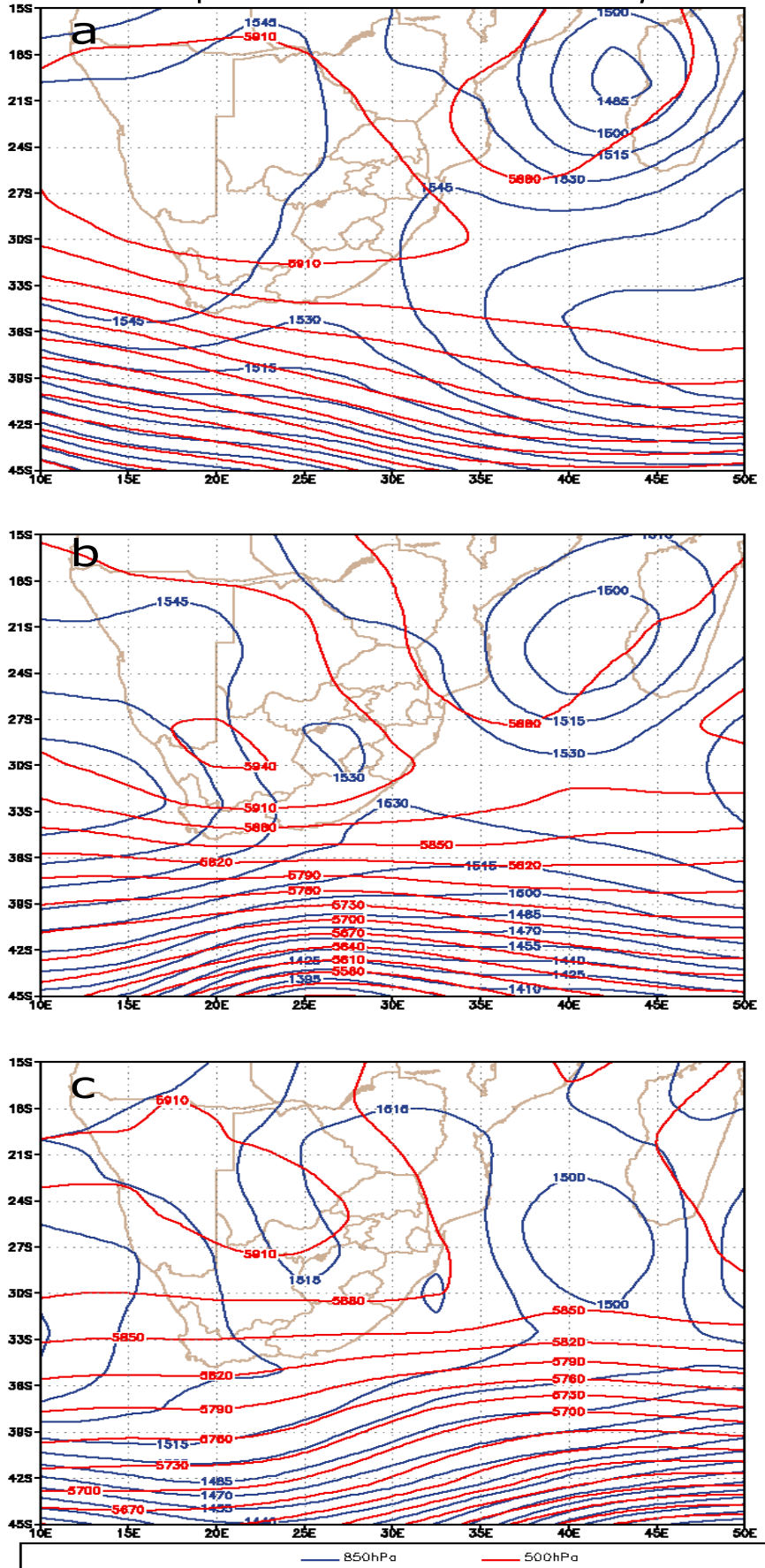


Figure 4.10: The circulation patterns at 850 hPa (blue) and 500 hPa (red) that influenced the heat wave over large parts of the country on (a) 16th, (b) 17th and (c) 18th January 2014.

Mean sea-level pressure patterns for 4 - 12 October 2015

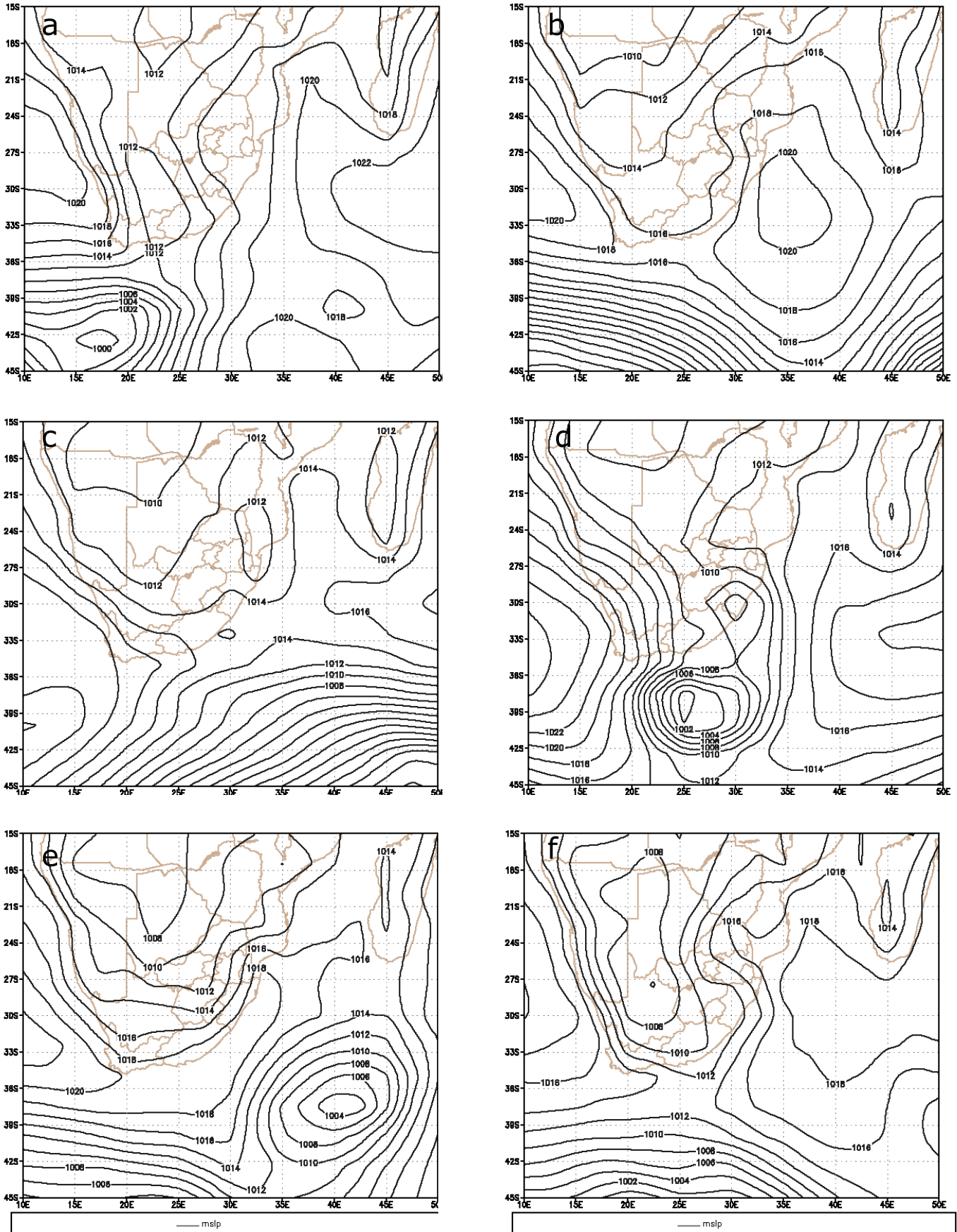


Figure 4.11: The circulation patterns at sea level that caused the heat wave over the eastern interior on the 4th (a), 6th (b), 8th (c), 10th (d), 11th (e) and 12th (f) October 2015.

Circulation patterns for 4 - 12 October 2015

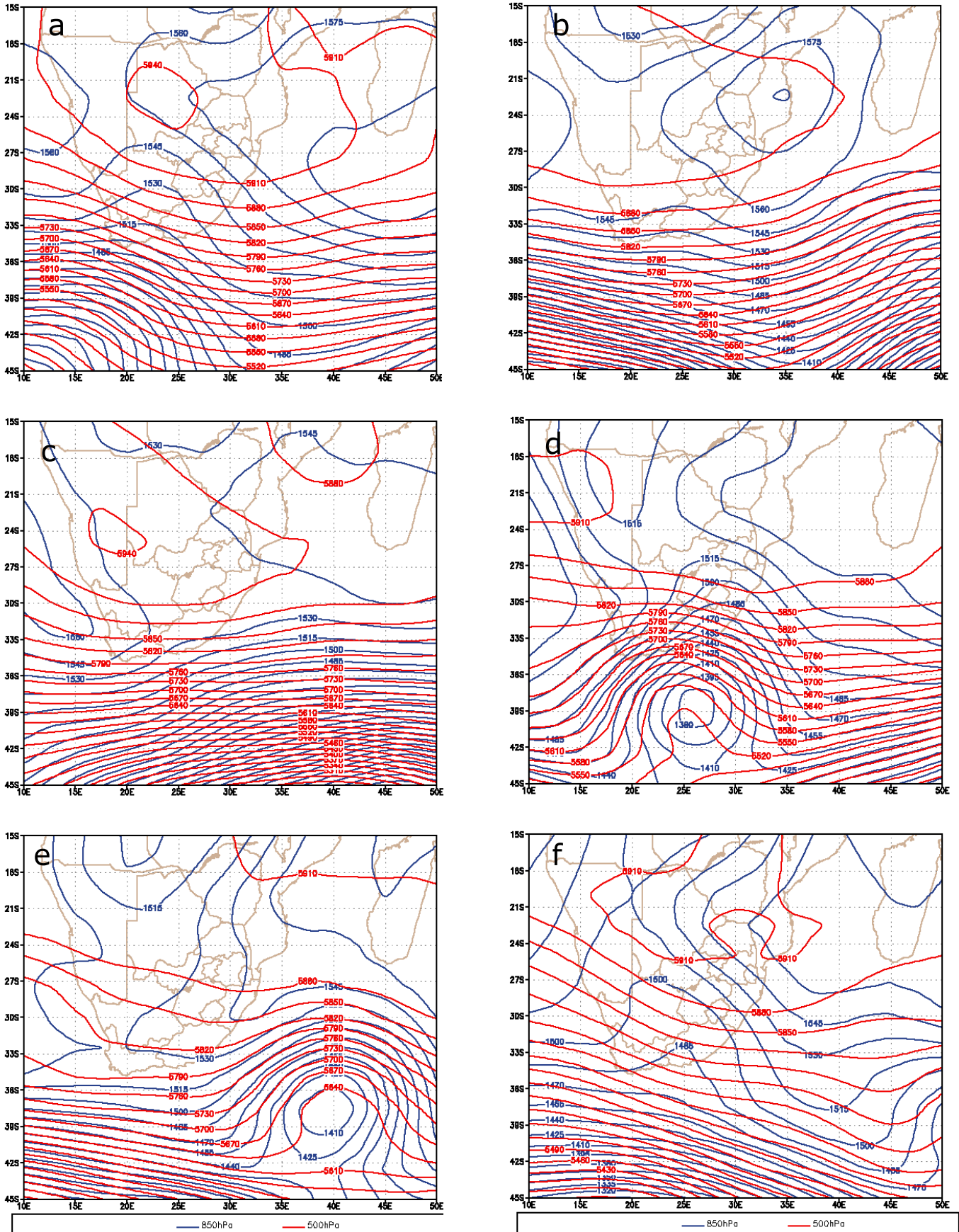


Figure 4.12: The circulation patterns at 850 hPa (blue) and 500 hPa (red) that caused the heat wave⁵¹ over the eastern interior on the 4th (a), 6th (b), 8th (c), 10th (d), 11th (e) and 12th (f) October 2015.

4.3. Synopsis

It is evident from the cases reported over South Africa between 2011 and November 2015 that the eastern interior, and particularly Gauteng, is most likely to experience heat waves. October and January are the months with the highest number of the heat waves. Heat waves over the Western Cape had a small spatial extent, whereas the heat waves over the north-eastern parts of the country mostly had a large spatial extent. The heat waves (over the Western Cape) were observed during the months of January and February.

All the heat waves observed were characterized by a strong upper-air high-pressure system over the affected area. The upper-air high was coupled with other weather systems at mean sea level and at the surface:

- Western Cape

Heat waves observed over the Western Cape were caused by a broad trough over the western interior coupled with a ridging high over the southern to south-eastern parts of the country at mean sea level and at 850 hPa. This synoptic configuration allows for strong offshore flow (easterly flow), subsidence, adiabatic heating of subsiding air, berg winds and clear skies. If these conditions continue for extended periods, they result in heat waves occurring.

- East coast

A ridging high over the east coast or continental anticyclone, located in such a way that the east coast experiences an offshore flow (westerly flow), caused heat waves over the east coast. These conditions are favourable for subsidence, strong heating and clear skies. The east coast may also experience berg winds.

- Eastern interior

Heat waves over the eastern interior resulted from a broad trough extending from the tropics to the central interior, with a northerly flow over the north-eastern interior, flanked by a ridging high over the southern parts of the country at mean sea level. Under these conditions, no moist air from the Indian Ocean flows into the north-eastern parts of the country, and the upper-air high causes strong heating and subsidence.

It is also important to note that based on the work on Lyon (2009), heat waves are also very likely during El Nino events when droughts are expected.

Information on synoptic configurations leading to heat waves is useful to meteorologists, in order for them to stay on the lookout for heat waves whenever weather conditions associated with such synoptic systems are expected or observed for a period of three or more days. In order to make weather forecasts/alerts for heat waves effective, meteorologists need to collaborate with other

stakeholders that can assist in heat hazard mitigation/prevention and to identify the best practices for heat mitigation over South Africa. The next chapter outlines these based on literature studies from other parts of the world.

CHAPTER 5: The heat-health watch-warning system for South Africa

5.1. Background

Heat waves have hazardous impacts on a wide spectrum of sectors including agriculture, economy, environment, water, power supply, and human and domestic animal health (Sheridan and Kalkstein, 2004; Jendritzky, 2000). Heat waves can cause a significant increase in human mortality (Hattis *et al.*, 2012). In addition, it is projected that heat wave events will increase in frequency and intensity due to climate change (Risbey and Tryhorn, 2006; Peng *et al.*, 2011). Therefore, there is a need for attention from meteorologists and all sectors that can assist in mitigating the effects of heat waves. This is especially relevant for South Africans as many like to spend their summer days in swimming pools and beaches, others are outdoor workers, and others have pre-existing medical conditions that put them in great danger during heat waves. The young and elderly are also most likely to suffer severely during heat waves (Nicholls *et al.*, 2009).

The purpose of this chapter is to study the different heat action plans that were implemented in other parts of the world and highlight aspects that are most relevant to South Africa. Heat-health watch-warning systems are aimed at better preparing affected citizens for an upcoming heat wave, information sharing and coordinating response. This will help alleviate the impacts of heat waves on the health of affected populations.

5.2. Understanding heat waves

5.2.1. Defining heat waves

As stated earlier in chapter 1, there is no internationally accepted definition of heat waves (Peng *et al.*, 2011). This is because local factors such as humidity, demographics, urban or rural design issues and acclimatization may result in different health impacts of the same temperatures on populations at different geographical locations (Department of Human Services, 2009; Pascal *et al.*, 2005). For this reason, it is important to have a localized definition of heat waves that takes in to account local factors. Accurately defining and forecasting heat waves is one aspect that determines whether the heat-health watch-warning and response system will be effective or not (USEPA, 2006).

In this study, it was discovered that, of all the indices that were investigated, humidex is the most appropriate. Humidex only takes into account temperature and relative humidity. The heat wave forecast system that will be developed for SAWS comprises a meteorological forecast and health aspect (estimated impacts/health implications of the heat waves and their preventative measures). The meteorological forecast will be improved to take into account factors such as local climate for more accuracy, skill and value. Therefore heat waves are defined whenever the humidex threshold for at least 36°C is forecast for at least three consecutive days countrywide.

As further research is done to improve the forecast, such as including other meteorological factors and studying local health impacts, localized humidex thresholds will be identified and will be used instead. Localized humidex thresholds are the local humidex values/temperatures that are most likely (assumed) to result in health outcome, such as mortality, on the local populations. At these humidex values health outcome increases, e.g. mortality increases. These are the same humidex

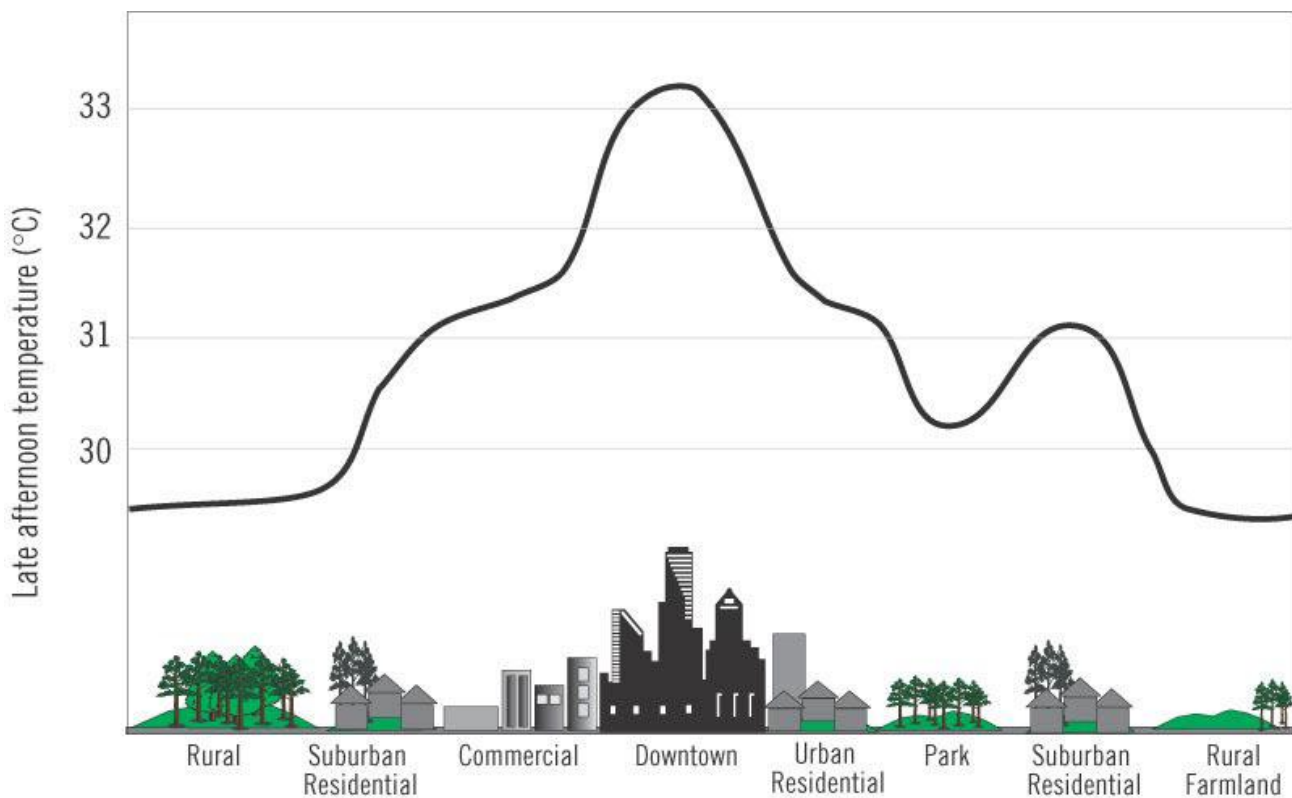


Figure 5.1: Effects of urban heat island (Taken from Department of Human Services, 2009).

values at which the heat wave alerts will be issued and they take into account climatic conditions amongst other characteristics of each location (USEPA, 2006). This is because South Africa is located in an area of variable climatic conditions.

It is most critical for health experts to be involved in the development of a heat wave forecast system. Their inputs will provide the most accurate localized health impacts of the expected heat waves, which SAWS can then incorporate into the weather forecasts. It is important that epidemiological studies are conducted for each part of the country would have to be conducted before the exact health impacts of each humidex threshold are definite (Department of Human Services, 2009).

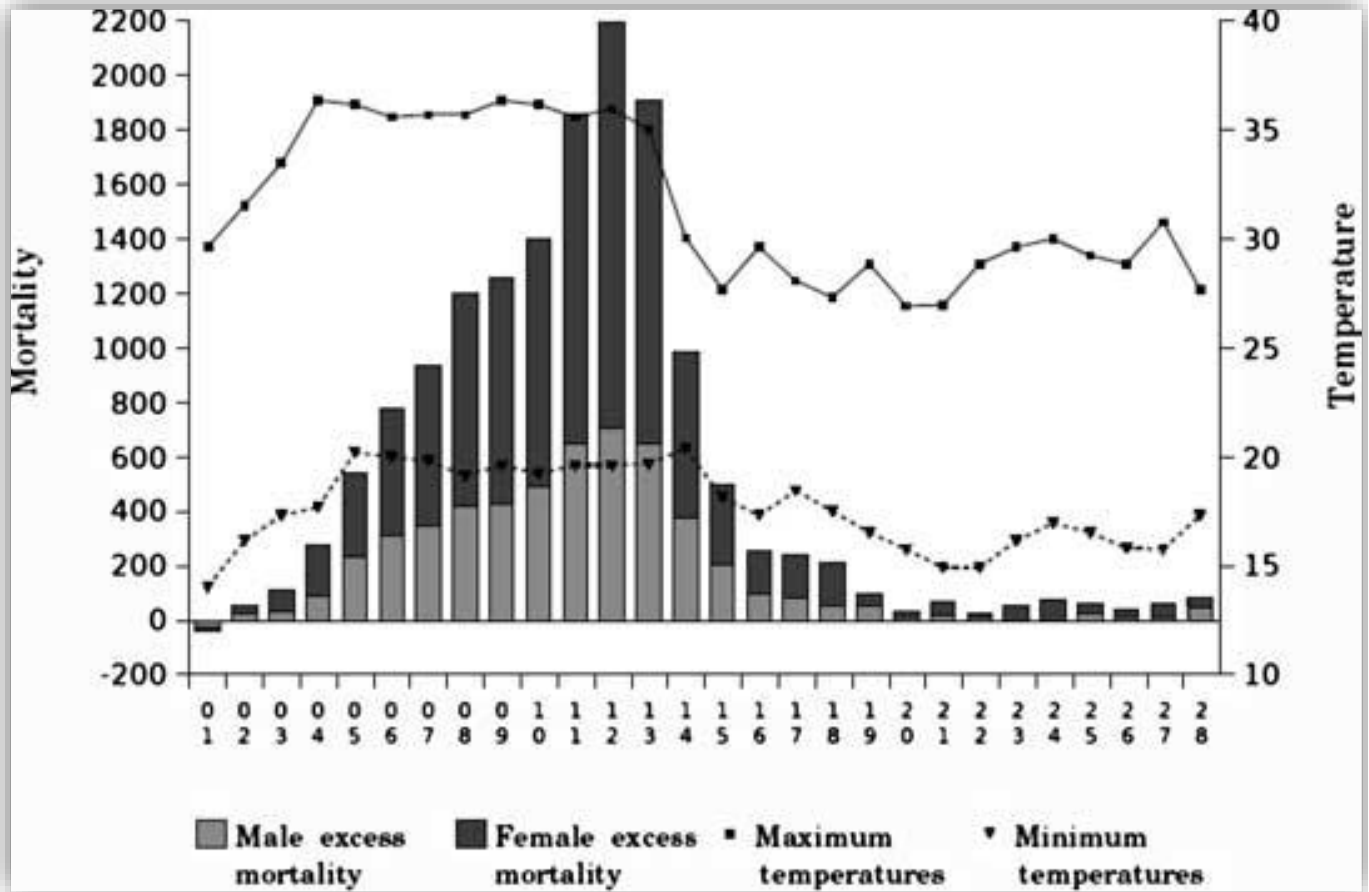


Figure 5.2: Daily excess mortality and outside temperatures in France in August 2003 (Poumadere *et al.*, 2005). The x-axis is the days of the month.

5.2.2. The heat-health watch-warning system

A heat-health watch-warning system is a weather-forecast system that is used to issue public alerts whenever heat wave phenomena are expected, with the aim to prevent or mitigate heat-related impacts on human health (Kovats and Kristie, 2006). It links heat wave (meteorological) forecasts with public-health action plans. Implementation of public-health measures for heat wave phenomena is essential and it helps to prevent heat-related illnesses and mortalities in the community and in institution that care for vulnerable individuals, e.g. the elderly and the sickly (Kovats and Kristie, 2006).

In many countries, heat-health watch-warning systems have been developed (e.g. Nicholls *et al.*, 2009; Greene *et al.*, 1996). In order for a heat-health watch-warning system to be effective, it must comprise:

- An accurate weather forecast for the region of interest,
- A comprehensive heat-health action plan,
- Effective response measures and
- Stakeholder involvement (Kovats and Kristie, 2006).

This implies that for an effective heat-health watch-warning system for SOUTH AFRICA weather forecasters would have to collaborate with health experts and other relevant stakeholders that can easily communicate or assist the affected public. This includes the media, caregivers at old age homes, caregivers to young children and hospitals.

Since it was shown in this the study that the model can confidently forecast extreme temperatures up to 5 days in advance, it means that heat wave forecasts will be issued from 1-5 days before the event. The heat wave forecast systems in Toronto and Philadelphia, US, also issue heat wave warnings 1-5 days ahead and they were proven to be effective (USEPA, 2006). It is important to note, however, that predicted heat waves will need to be monitored continuously in case of any changes in the forecasts.

5.2.3. Potential heat-health risk factors

It is essential to investigate and understand the factors that increase the risk of heat-related illnesses or deaths (Nitschke *et al.*, 2013). Factors that can increase heat illnesses and mortality include physiological factors and age, socio-economic factors, pre-existing medical conditions, adaptation to extreme heat, gender, medication and behaviour (McGregor *et al.*, 2015). These are potential health factors and their impacts may differ from one location to another. These factors are assumed for SOUTH AFRICA until epidemiological studies are done to identify the factors that are applicable to each part of the country. These factors can be divided into factors

on heat waves, which in turn affect human health and potential factors on humans. Factors on heat waves include the timing, duration and intensity of the phenomenon and the urban heat island (Zacharias *et al.*, 2014; Menne and Matthies, 2009; Chinganon *et al.*, 1996; Steffen *et al.*, 2014).

- The duration and intensity of the phenomenon: The longer the duration of heat waves, the higher the mortality they cause (Zacharias *et al.*, 2014). Heat wave events that last longer and are more intense have a greater impact on mortality (Menne and Matthies, 2009).
- Urban heat island: Heat islands, because of their nature to retain heat, intensify the heat waves in cities. Elderly people in urban areas are amongst those who are most vulnerable to the impacts of heat waves (Chinganon *et al.*, 1996). Figure 5.1 depicts the effects of a heat island. Though the temperature is more pronounced during the night, the figure depicts that urban areas are most likely to suffer the impacts of high temperatures because of the construction materials thereof (Department of Human Services, 2009). During heat waves, overnight temperatures are high, providing no relief from the daytime heat (Steffen *et al.*, 2014). Heat waves may put stress on power supply in urban areas, which in turn may result in citizens not able to operate air conditioning and refrigerators (Jendritzky, 2000).

Potential factors on humans include:

- Age: Several studies have shown that the elderly (65 years old and above) and young (under the age of five) are very prone to the effects of heat waves (Kovats and Kristie, 2006; Palecki *et al.*, 2001; Menne and Matthies, 2009; Westcott, 2011; Department of Human Services, 2009). Elderly people are most vulnerable because their bodies have reduced ability to regulate its internal temperature, and they are most likely to be unfit, have pre-existing illnesses, disabled or on medication (Ebi and Meehl, 2007). Ebi and Meehl (2007) further explain that children are also most vulnerable to heat waves because they are most likely to suffer dehydration. Elderly people are also most prone to hyperthermia and heat stroke, which most likely cause mortality (Loughnan *et al.*, 2012). Most of the fatalities that occurred during a heat wave over the US, occurred in 1999 and were females over 70 years old (Palecki *et al.*, 2001). A study by LoVecchio *et al.* (2005) shows that 6% of the deaths that occurred as a result of heat waves between 1979 and 2002 in the United States were children. Wichmann (2017) conducted a study that confirmed that even in SA, the elderly (≥ 65 years old) are more vulnerable to heat exposure.

- Gender: Females are said to be more prone to heat mortality and illnesses (Kovats and Kristie, 2006; Zacharias *et al.*, 2014; Menne and Matthies, 2009). A study done by Poumad`ere *et al.* (2005), depicted in Figure 5.2 shows that there were more female mortalities during the French heat wave in 2003. A study by Wichmann (2017) found that elderly women from Cape Town are most vulnerable to heat exposure. However, a study in the US shows that more men than women died during the heat wave in 1995 (Palecki *et al.*, 2001).
- Behaviour: Outdoor workers and people that engage in excessive outdoor exercise are exposed to a lot of heat because they are outside and are most likely to suffer dehydration, which may cause dizziness and even death (Dash and Kjellstrom, 2011; Xiang *et al.*, 2015). Sufficient intake of non-alcoholic fluids is critical for reducing dehydration and chances of dying as a result during heat waves (Ebi and Meehl, 2007). Eating heavy or hot meals can increase the rate of metabolism, which may increase the amount of heat the body must dissipate (USEPA, 2006). Staying in a vehicle, especially with closed or slightly opened windows can cause hyperthermia, which may even result in death (NOAA, 2015). According to NOAA (2015) children, the elderly and the sickly are at an increased risk of dying due to staying in vehicles for a long time during hot weather. People who have air conditioning but decide not to use it are also prone to heat illnesses (Department of Human Services, 2009). Wearing heavy, dark clothing can lessen the body's ability cool itself through evaporation of perspiration and wearing clothing that overly exposes the skin to the sun can limit the body's ability to evaporative cooling by increasing the risk of sunburn (USEPA, 2006).
- Socio-economic factors: There is some evidence that humans with a lower socioeconomic status and those with less social support (e.g. single, divorced, widowed) are at an increased risk of illness or mortality during heat wave events (Menne and Matthies, 2009). Individuals living in low-income areas usually do not have air conditioners to keep themselves cool during heat waves, or cannot afford to operate them and cannot use windows for ventilation at night due to high chances of crime in the area (Chinganon *et al.*, 1996; USEPA, 2006). As a result, this places them at a high risk of heat illness or mortality during heat waves.
- Unfit or overweight: Unfit and overweight people also have difficulty in regulating their body temperature due to their low physical activity or their fatty tissues' limited ability to conduct heat (their tendency to retain more heat), preventing a proper heat flow (Ebi and Meehl, 2007; US Department of Health & Human Services, 2016).

- Pre-existing medical conditions: Conditions such as cardiovascular and respiratory diseases may lead to fatalities during heat waves (Ebi and Meehl, 2007). Persons with diabetes, kidney disease or mental illness are also likely to suffer severely during heat waves (Department of Human Services, 2009).
- Medication: People on medication for conditions such as asthma, depression, insomnia, diabetes, heart conditions and epilepsy, overweight and obesity may experience major challenges during heat waves (Palecki *et al.*, 2001; Ebi and Meehl, 2007; Department of Human Services, 2009). This is because the medication can cause dehydration or alter central thermoregulation, hence affecting physiological and behavioural responses or may even have side effects that can cause them to be unaware of their bodies' inability to cope with extreme heat (Ebi and Meehl, 2007). Some medication can also cause drowsiness and lessen the ability to avoid heat or change blood pressure, which may cause dizziness and fainting (Kovats and Kristie, 2006; Sports Medicine Australia, 2008).

5.2.4. Preventative measures for heat waves

Recent heat waves over South Africa have had drastic impacts on human health, some even caused fatalities (e.g. News24, 2012; eNCA, 2015a; eNCA, 2015b; Eyewitness News, 2015). Such incidents are preventable and can be prevented in the future, but effective prevention requires a hands-on approach to preparedness, planning and response, and it requires the involvement of multiple disciplines (WHO, 2006; WHO, 2009). Recognizing the risk and applying the preventative measures could reduce the effects of heat waves on human health (Akompab *et al.*, 2013). Some preventative measures against heat-related illnesses or death include (Nitschke *et al.*, 2013, Akompab *et al.*, 2013; USEPA, 2006; US Department of Health & Human Services, 2016):

- Using wet cloth on neck and face;
- Staying indoors and keeping blinds and curtains closed;
- Reducing/avoiding outdoor activities, or even limit them to morning and evening hours as much as possible;
- Staying in cooler places;
- Opening the house in the evenings;
- Regular intake of fluids, preferably water. This helps replace salts and minerals that the body loses through heavy sweating. Patients whose doctors have put on water pills or restricted the fluid intake amount should enquire how much they should drink during hot weather;
- Individuals working in the heat should continually check on each other's condition;

- Avoiding meals that are hot and rich in protein since they increase metabolic rate. This, in turn, increases the amount of heat that the body must dissipate;
- Children, the elderly and the sickly should not be left unattended in a parked car, even if the windows are cracked open. This is because cars have a tendency to heat up fast, placing them at a risk of heat stroke or even death;
- Avoid drinking alcohol since it has an impairing effect on the brain and individuals cannot discern when they are experiencing the negative impacts of heat;
- Limit intake of very cold drinks as they can cause stomach cramps;
- Wearing light-weight, light-colored, loose-fitting clothing and avoid exposing skin to the sun. Sun burn causes loss of body fluids, reduces the body's ability to cool itself, and causes pain and damage to skin;
- Putting on light-colored, wide-brimmed sun hats or umbrellas with sunglasses;
- Health attendants or organizations should preferably communicate with electricity- and water-supply services providers to ensure services are not cut off during severe heat waves;
- The medical services should also increase the number of staff on duty during heat waves;
- Swimming pools should extend their operating hours; and
- In order to assist the vulnerable, e.g. the elderly, increase social contact.

5.3. International heat wave notification and response plans

Heat waves, and any other severe meteorological events, may be well-understood and well-forecasted, but if there has been insufficient preparation and response they may still cause severe negative impacts on human health (USEPA, 2006). It is therefore, critical to have a response plan that also outlines preparations that will help prevent or mitigate the negative consequences of heat waves whenever they are observed.

A recent study on the impacts of heat on human mortality over parts of South Africa (Cape Town, Johannesburg and Durban) has shown that higher apparent temperature values have increased on mortality, especially the elderly (Wichmann, 2017). There is no evidence of other studies on the impacts of heat on human health in South Africa. For this reason, it is not known exactly how heat waves have affected the different populations over South Africa. However, from studies in other parts of the world, it can be concluded that heat waves are a health hazard and can be life-threatening (e.g. Guirguis *et al.*, 2014; NOAA, 2012; Westcott, 2011; Sheridan and Kalkstein, 2004; Nicholls *et al.*, 2009; Voogt, 2004; Palecki *et al.*, 2001; Ebi and Meehl, 2007). It is also

understood from these studies that many of the negative health impacts of heat waves can be prevented or lessened through effective notification and response plans or programs (USEPA, 2006; Nicholls *et al.*, 2009; Greene *et al.*, 1996; Matthies and Menne, 2009; Palecki *et al.*, 2001). The plans developed in other parts of the world generally comprise preparedness (planning and raising awareness of heat wave hazards), prevention (eradicating/lessening the negative health impacts), response (ways to respond to heat waves impacts, providing rescue and relief in cases of emergency) and recovery (to assist affected humans to recover and function at an effective level) (Department of Human Services, 2009). These plans all start with a meteorological forecast that has high reliability, a good understanding of the heat-health relationship and end up with a comprehensive heat action plan (notification and response plan) (Pascal *et al.*, 2005).

USA Department of Human Services (2009) studied the different strategies that were used in heat wave planning internationally, and they are summarised in Table 5.1. Each one of these heat wave plans starts with a meteorological forecast and involves the participation of other stakeholders. Stakeholder involvement increases the value of a weather forecast because the affected populations are able to take necessary preventative actions or respond more effectively.

Table 5.1: Summary of heat wave planning strategies used internationally (Department of Human Services, 2009; USEPA, 2006; WHO, 2009; Pascal *et al.*, 2005).

Area	Heat wave planning strategy
<p>Canada (Department of Human Services, 2009)</p>	<p>Hot weather response plan:</p> <ul style="list-style-type: none"> • Providing heat alerts and safety measures to relevant stakeholders (general public, pet owners, boarding homes). • Collaboration with stakeholder (e.g. to cease utility disconnections for owing citizens, to provide cooling centers and transport to cooling centers, to ensure that fountains have sufficient water). • Planning roles and responsibilities of different response agencies. • Follow-up from previous summer using reports and reviews.

<p>England (Department of Human Services, 2009)</p>	<p>Heatwave Plan for England – Health protection and Reducing Harm from Extreme Heat and Heatwaves:</p> <ul style="list-style-type: none"> • During summer months the Met Office issues meteorological forecasts and collaborates with institutions such as the Department of Health to determine the health impacts and levels of response. • Other stakeholder participation includes the Department of Health disseminating advice and information to the general public, and social and health-care professionals that work directly with vulnerable populations; hospitals and nursing homes ensuring that vulnerable citizens under their care stay in cooled areas; and the media disseminating heat wave alerts and advice before and during heat waves. • Buddy checks amongst the citizens was also encouraged. • The plan also includes a long-term, multi-agency planning for adaptation and mitigation of the impacts of climate change.
<p>Victoria, Australia (Department of Human Services, 2009)</p>	<p>Victorian Heatwave Strategy developed by the Department of Human Services:</p> <ul style="list-style-type: none"> • The department established a heat-alert system that issues heat wave alerts to councils and departmental staff. • Developed a heat wave planning guide in local councils. • Stakeholder participation includes the media in providing information to the general public, ambulance and other emergency services' involvement, and encouraging utility agencies not to cease service even to owing citizens during heat waves. • The department went further to organize a climate change conference where heat wave health impacts were discussed, commissioned research to further improve heat wave forecasting and funded 13 pilot projects to develop and implement heat wave plans in 22 local councils.
<p>Europe (WHO, 2009)</p>	<p>Extreme weather/heat wave warning and public response improvement — EuroHEAT:</p>

	<ul style="list-style-type: none"> • It includes a timely and accurate alert system. • Stakeholder involvement: to provide heat-related health information plan, provide/monitor of cooling areas, provide care for vulnerable populations, the involvement of health and social care specialists, and real-time evaluation of the system. • Stakeholder involvement and periods when they are required have been clearly defined, e.g. local meteorological services issue/update warnings whenever thresholds are expected to be reached, local health care authorities communicate the warnings, General practitioners/health care professionals advice on changes of medication/treatment whenever temperatures require so, special follow-up of vulnerable individuals by health services and health centers throughout the summer season, etc. • Communication strategy includes printed leaflets, information distribution via vast media, and information and advice to medical specialists via the internet. • During heat waves, health data for the further understanding of its impacts and for monitoring of the effectiveness of the heat action plan is collected. This includes mortality data, hospital admissions, and emergency phone calls. • The EuroHeat includes a long-term urban planning to reduce heat wave impacts.
<p>US (Philadelphia and Toronto) (USEPA, 2006; Department of Human Services, 2009)</p>	<p>Extreme Heat Events (EHE) plan</p> <p>The program comprises four main aspects:</p> <ul style="list-style-type: none"> • Prediction – where a weather forecast for heat waves is issued 1-5 days in advance and is made accessible to relevant stakeholders. • Risk assessment – where health specialists work together with weather forecasters in estimating (developing criteria

	<p>for) the health impacts the forecasted EHE, identifying high-risk individuals and identifying heat-related deaths.</p> <ul style="list-style-type: none"> • Notification and response – where the timing, severity, and duration of EHE are broadcasted to the public, along with appropriate mitigation and safety/response measures. • Mitigation – where reduction measures for the effects of heat island are developed and promoted. Only mitigation has not been evaluated.
<p>France (Pascal <i>et al.</i>, 2005)</p>	<p>The Heat Health Watch Warning System:</p> <p>The system is activated yearly from 1 June – 30 September. This is done at four levels of the action plan:</p> <ul style="list-style-type: none"> • Level 1: Where it is run for caution throughout the season. • Level 2: When the thresholds at any location are expected to be reached within three days. • Level 3: When the thresholds are reached. • Level 4: When the thresholds are reached and the phenomenon is prolonged, or even reach exceptional levels such as drought. <p>The plan was based on a study conducted for June – August 1970-2003, using both meteorological and mortality data. The forecast system was found to be reliable up to 5 day lead time.</p>

5.4. Heat-related illness and treatment (response measures)

Heat waves may have direct (e.g. heat illnesses such as heat cramps and heat stroke) or indirect impacts (e.g. worsen heart diseases) on human health (Pascal *et al.*, 2005). The ability to recognize the symptoms of heat illnesses is critical in order to take necessary actions to prevent further impacts and mortality, and also to commence treatment (City of Casey, 2015). Table 5.2 shows the different symptoms of heat-illnesses and the treatment thereof. If the first four categories of heat-illness symptoms do not cease after using recommended treatment then it is recommended that the patient immediately seeks assistance from a health professional (City of Casey, 2015). These symptoms may be caused by dehydration as a result of strenuous activities during heat waves, and heatstroke may be fatal because the body is unable to prevent its temperature from rising rapidly (Department of Human Services, 2009).

Table 5.2: The direct impacts of heat waves: symptoms of heat illnesses and the treatment thereof (City of Casey, 2015; Department of Human Services, 2009; Pascal *et al.*, 2005; US Department of Health and Human Services, 2016).

Symptoms	Description	Treatment
Heat rash	Heat rash is a skin irritation that results from excessive sweating during hot, humid weather. It has an appearance of a red cluster of pimples or blisters on the neck, upper chest, in the groin, under the breasts or in elbow crinkles.	This is usually not a serious condition and may be treated by moving to a cool, drier environment.
Sunburn	Skin turns red, becomes painful and very warm due to heat exposure.	Sunburn usually causes minor discomfort and may heal within a week, but it may also be severe, causing fever, fluid-filled blisters or severe pain. See a doctor in this case or if sunburn occurs in children less than one year old. Make sure not to break blisters and avoid repeated sun exposure.
Cramps and Oedema	Cramps – muscle pains/spasm in the abdomen, arms or legs. Oedema - swelling of feet and ankles	Rest and take more fluids.
Syncope and Exhaustion	Syncope - fainting and dizziness Exhaustion – muscle pains/spasm in the abdomen, arms or legs. It may cause rapid heart rate, muscle cramps, weakness, dizziness, headache, nausea, vomiting or fainting.	Lay the person down, remove clothing that can prevent them from breathing properly, give them cool fluids and use a wet cloth.
Heatstroke	Heatstroke – it occurs when the body is no longer able to regulate its temperature and may occur within 24 hours of heat exposure. Symptoms of	Immediately seek assistance from a health professional. While waiting for a health professional,

	<p>heatstroke include an extremely high body temperature, no sweating, rapid, strong pulse, dizziness, nausea, confusion or fainting, and severe headache. Heat stroke may cause permanent disability or death if not treated urgently.</p>	<p>try as much as possible to cool down the victim by taking them to a shady area, fanning them vigorously, placing them in a cool shower, sponging or spraying the person with cool water.</p>
--	---	---

Factors that may cause heat-related illnesses include environmental and job-specific factors (US Department of Labour, 2016). Environmental factors include high temperature and humidity, direct sun exposure or extreme heat and lack of breeze or wind. Job-specific factors include the type of work (how strenuous it is), and the type of clothing and equipment being used. This applies especially to outdoor workers or individuals involved in outdoor activities, and can be prevented through their employer’s involvement in providing water and shade at their work sites, allowing them to do the hardest work during the mornings and evenings, and through training their workers on the risk factors of heat waves and related preventative measures (US Department of Labour, 2016). Training resources need to be made available by the Weather Service or Health Department.

5.5. The heat-health watch-warning system for South Africa

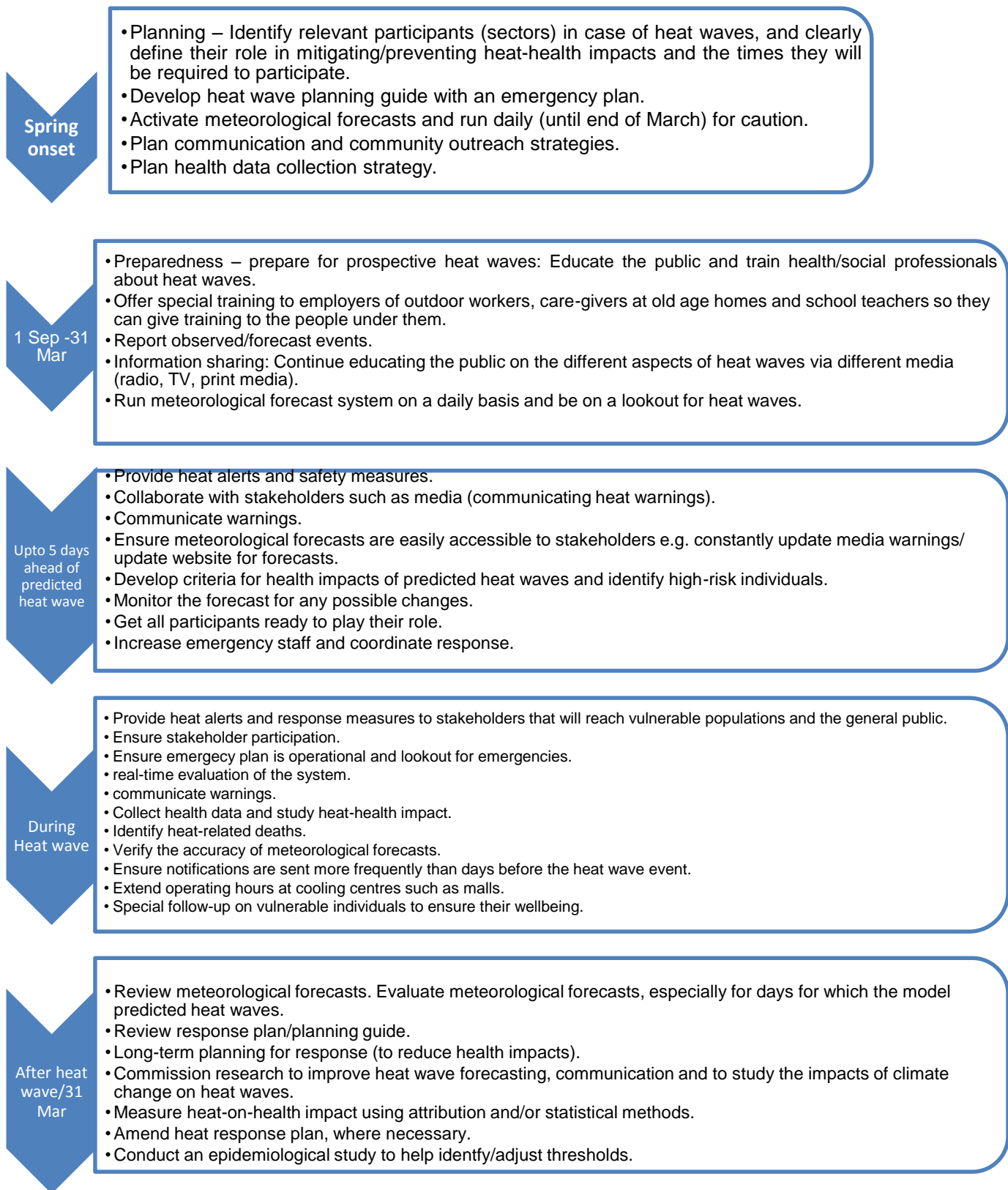
Heat-health watch-warning systems assist in preventing and mitigating the negative impacts of heat waves if weather forecasts for heat waves are incorporated with effective notification and response plans (Greene *et al.*, 1996). To propose a system for South Africa, a number of actions from other parts of the world (listed in Table 5.1) were selected. This system is developed for meteorologist, and they are supposed to collaborate with other stakeholders such as health professionals, hospitals, media and social caregivers. The system is currently built for the whole country and it requires review on a regular basis in order to make necessary adjustments that take into consideration local factors that influence the impacts of heat waves on human health. There is need to conduct epidemiological studies to help improve the system. Regular reviews of the system by meteorologists and related stakeholders will help identify other relevant stakeholders and vulnerable individuals, who will help make necessary adjustments to the system.

One of the most critical components of the system is identifying heat-related deaths and illnesses. During heat waves, health examiners would have to state if the primary cause or main contributing

factor to morbidity/mortality heat exposure for internal body temperatures exceeding 40 °C or if the person experienced illness or mortality after staying in an enclosed area without adequate cooling (USEPA, 2006). This is referred to as direct attribution method episode analysis (Sarofim *et al.*, 2016; WHO, 2003). With regards to mortality, excess mortality is projected by taking away expected mortality from observed mortality (WHO, 2003). Statistical methods are another way to identify heat-related deaths and illnesses. These methods involve investigating if the heat conditions were associated with increased illness or death compared to the longer-term average (Sarofim *et al.*, 2016).

Previous records for heat waves show that heat waves over South Africa are most likely to occur between September and March (SAWS, 2014; SAWS, 2016). For this reason, the heat-health watch-warning system is planned to be activated between spring and fall. The meteorological forecasts for the system are run daily for caution and heat alerts are issued 1-5 days ahead of forecasted heat wave events. Though health data collection for further study is continuous, health professionals should ensure that it is collected during heat waves events in affected areas.

5.5.1. Proposed considerations and structure for a heat-health watch-warning for South Africa



Stakeholder education during seasons when heat waves are likely to occur and during heat wave events is one of the most critical components of this action plan. This includes educating the general public, and it is discussed further below. In this heat action plan, outdoor and community workers should receive specialized training that advises them on how to avoid heat illness for themselves. The training should include teachings on risk factors, heat-related illness, symptoms, treatment, and prevention procedure. Caregivers for other vulnerable populations should also receive similar training and online questionnaires. Online questionnaires are aimed at giving feedback that will help evaluate the effectiveness of the system. Children may be further educated using posters or pamphlets, games and graphics at schools, on television or print media. Employers of community/outdoor workers can further mitigate or prevent heat illness by providing water and shade, and allow the workers to rest often or even do the hardest work in the mornings and evenings.

5.5.2. Implementation

Heat waves are most likely to occur between spring and autumn every year. For this reason, the heat-health watch-warning system in this study is proposed to run operationally from September of every year until April of the following year. The HUM index is used, and the heat wave forecast system will continually be revised and improved to cater for the differences in the climatic conditions in various parts of South Africa and the population's ability to adapt to local climate (Kovats and Kristie, 2006; USEPA, 2006). The heat watch-warning is activated once HUM exceeds the threshold at each location.

The first step in developing or issuing an effective and reliable heat watch-warning system is to issue a timely, accessible and accurate meteorological forecast (USEPA, 2006). Based on Chapter 3, the forecasts can be relied on for up to five days ahead. Hence, the public and stakeholders will be notified whenever the model forecasts heat wave events five or fewer days ahead. This should allow everyone affected ample time to prepare and avoid the negative impacts of heat waves as much as possible.

The second step is to issue appropriate heat impact warnings (to explain what are the most likely heat impacts for area expecting heat waves) for each HUM threshold and location. The impact warnings are currently based on literature studies and it is recommended that health specialists

do further research on this issue and get accurate impacts of each HUM index at each station location. In the USA, a weather-response committee that comprises of different agencies and specialists was formed, and they define health impacts for heat waves at the onset of summer and evaluate them after the season has passed to see if there is a need for corrections/adjustments (USEPA, 2006).

Another step that needs to be taken is to identify other necessary participants in developing and improving the system. They would have to assist in the notification, response and mitigation. This includes the media (internet, television, radio, and newspapers - to send out weather forecasts from meteorologists, and expected health impacts and response measures from health specialists), ambulance and emergency services (to provide assistance and to operate a toll-free telephone line in cases of emergency), hospitals (to increase staff during heat waves), agencies that work with the general public (to extend notifications to the general public, especially the technologically disadvantaged), government agencies (water and sanitation, electricity, transport – to ensure services are provided during heat waves), swimming pool services (to keep swimming pools open for extended hours during heat waves), social care agencies such as nursing homes (to give extra care to the elderly during heat waves), etc. (Department of Human Services, 2009; USEPA, 2006).

5.5.3. Target population

Heat waves may cause life-threatening diseases such as heat stroke, heart diseases, and heat cramps, or even cause mortalities in the elderly, the sickly, the overweight, and young children (Nicholls *et al.*, 2009). Low-income and poor population groups are also prone to the effects of heat waves because they do not have sufficient means to combat the effects of heat waves. The climate in towns and cities makes the citizens thereof prone to the effects of heat waves (Nicholls *et al.*, 2009). Populations in areas of low water supply may suffer severe dehydration during periods of sustained heating, resulting in many hospital admissions or even deaths. Decreased water quality and supply may also have a negative impact on irrigation, commercial forestry plantations, mining, industry, power generation as well as domestic sectors (CSIR, 2010).

Heat waves are most likely to affect some people more than others, depending on different factors. In order to establish the exact impacts of heat waves on human health and mortality, and to identify the exact citizens that should take extra caution during heat waves at specific locations over South Africa, there would be a need for epidemiologic studies to be conducted at such locations (Benmarhnia *et al.*, 2015). The study should also aim to identify methods to classify

heat-related mortality for each location and how they should be reported (Azhar *et al.*, 2014). Until the study is done, citizens or caregivers to citizens listed in the paragraph above and in section 5.2.3 are advised to take extra caution during heat waves and it should be ensured that they are well educated whenever heat waves are forecasted.

5.5.4. System evaluation

In order to monitor the effectiveness of the heat-health watch-warning system and to identify its shortcomings, it needs to be evaluated whenever heat waves are observed. Other countries that have evaluated their heat-health warning systems include Italy (relationship between meteorological forecasts and mortality), Hungary (the effectiveness of communication strategy in the heat action plan), France, and England (awareness of the heat action plan in the social and healthcare sectors) (WHO, 2009). The heat wave forecast system comprises of mainly two aspects, the meteorological (weather forecast for the spatial and temporal distribution of expected heat waves) and health aspect (estimated impacts/health implications of the heat waves and their preventative measures), each one requiring a specialized evaluation.

The meteorological forecast system for heat waves is evaluated after every incidence of a heat wave event by meteorologists at SAWS. Evaluation methods as discussed in chapter 3 are used. It is essential to evaluate the performance of a public weather forecast to ensure that it efficiently and effectively meets the public's needs and it is forecast accurately (Wilks, 2006; Jolliffe and Stephenson, 2003).

The second part of the system, assessing the health impacts on human health, would be led by health professionals. For effective evaluation, they will need to use suitable quantification methods as well as accurate health data (USEPA, 2006). The third part is to evaluate the effectiveness of the communication strategy by using methods such as questionnaires and surveys. These can be made available online, especially for caregivers and those who are technologically advanced. Hard copies can also be made available in public areas such as libraries, swimming pools, hospitals, etc. and collected by relevant professionals for further study and improvements of the system. This can be done during and after the heat waves.

5.5.5. Public awareness and education of heat waves

Lack of understanding of the implications of heat waves and their impacts may result in the public taking poor response measures or even ignoring/not being aware when they are being negatively

impacted by heat waves. It is, therefore, critical to ensure stakeholders are educated about the risk, impacts and response measures for heat waves (USEPA, 2006).

One way to ensure stakeholders are educated may be via the media, such as radio/television where meteorologists or/and health specialists may host a teaching session and also open discussion for questions (USEPA, 2006). Other strategies recommended by USEPA (2006) include organizing programs for schools, special education for caregivers to the vulnerable populations (listed in 5.2.3 above) and special education to employers of community/outdoor workers.

5.6. Discussion

There is a great need for improved understanding of mortality and morbidity patterns as a result of heat waves over South Africa. There is a need to understand how heat illness and mortality can be avoided and how the preventative measures differ between different parts of the country. This can be done by applying and continuously improving the recommended heat-health watch-warning system for South Africa.

Stakeholder involvement is highly necessary for a heat-health action plan to be effective. It is therefore recommended that SAWS meteorologists collaborate with the media, health department and health care professionals, hospitals, caregivers at old age homes and pre-schools, emergency and ambulance services, utility agencies, and other relevant stakeholders. Messages sent the public should also encourage buddy checks, especially to elderly and isolated populations.

One of the most important stakeholders that meteorologists need to work with is health professionals because they can study, map vulnerability and develop heat thresholds that are relevant to each location, which will take into account all the other factors that affect human health during heat waves (in addition to meteorological factors). Examples of studies that investigated health impacts and the methods thereof include WHO 2003; Basu and Samet 2002; Rooney *et al.*, 1998; Chinganon *et al.*, 1996; Greene *et al.*, 1996; Medina-Ramón *et al.*, 2006; and Zacharias *et al.*, 2014. The media can be the most useful and effective source of communication to the general public since most communities have access to it in one way or the other.

Water and electricity are very critical utilities during heat waves, so it will be needful for the relevant stakeholders or meteorologists to communicate with and encourage utility agencies not to cease services to anyone during heat waves. Since parts of South Africa, especially rural areas, suffer water scarcity in general, water and utility departments should then be requested to make special provision for water in those areas and to ensure that the supply is available throughout the heat wave events. This practice is necessary because water is essential for alleviating the effects of heat waves. If the departments supply water by vehicle or at a central point for a large population, then they should ensure supply in the early hours or later in the day when it is cooler to minimize heat exposure during heat waves. South Africa has been experiencing load shedding in the recent years. It is recommendable that requests be sent to Eskom to ensure electricity supply throughout the heat wave event.

Social-care professionals should also be requested to provide cooling centers and the transport department to make transport to these cooling centers easily accessible. Communications and advices sent to the public should include buddy checks to ensure that the sickly, elderly and isolated are given sufficient attention and care during heat waves. The relevant stakeholders have an additional task for public awareness and to ensure the public and all relevant stakeholders are educated on heat waves and their impacts.

CHAPTER 6: Discussions and conclusions

A study to identify the most suitable index for forecasting heat waves over South Africa and to examine the NCEP EFS has been conducted. Additionally, synoptic systems were identified that caused heat waves over different parts of the country. A proposed heat-health action plan to mitigate or prevent the negative impacts of heat waves have also been outlined. This chapter summarises the findings of this study and also outlines the recommendations.

6.1. The performance of different heat indices in predicting extremely hot events over South Africa

The spatial and temporal evaluation of selected heat indices from different parts of the world, for the study period, reveals that the HUM has the best performance compared to the rest of the indices. This is the heat index that is proposed for developing an operational heat wave forecast system for South Africa and it is reliable up to 5 days ahead. It is notable that all of the selected indices have poor performance in evaluating extremely hot events. This is most likely to be as a result that extremely hot events are rare, with hits far less than correct negatives.

6.2. The weather circulation patterns that caused heat waves over South Africa

Understanding the weather systems that caused heat waves over South Africa in the past will help meteorologists stay on the lookout for heat waves whenever such weather patterns are observed or forecast. From cases that were reported between 2011 and 2015, it can be noted

- that no heat waves were reported over the Eastern Cape,
- most of the heat waves were reported over the north-eastern interior with Gauteng experiencing most of them, and
- heat waves over the Western Cape have a much smaller spatial extent.
- January has the highest number of heat waves and these heat waves been on a general increase in duration and frequency in the recent years.

This confirms the projections for the impacts of climate change.

Grouping the heat wave events into heat waves over the Western Cape and heat waves over the north-eastern (which includes the central interior and east coast) show that heat waves over the Western Cape were characterized by a ridging Atlantic Ocean high accompanied by a trough that extends from the tropics, through Namibia to the Western Cape at sea level and 850 hPa level, and an upper air high at 500 hPa level centred over the Western Cape. These are the same

conditions that are most likely to cause veld fires and berg winds. General circulation patterns during heat waves over the central, eastern and north-eastern parts of the country were a deep surface trough extending from the tropics to the central interior accompanied by a ridging high over the southern coast at mean sea level and an upper-air high at the 500 hPa level. Selected individual cases show the same results. A case for the east coast shows that there was an anticyclone ridging into the eastern parts of the country (causing an offshore flow) over the east coast at mean-sea level and an upper air high situated over the central interior to the east coast. In all occurrences of heat waves, there was an upper air high over the affected area associated with other surface circulation patterns.

6.3. The heat-health action plan for South Africa

The heat-health watch-warning system comprises two aspects, i.e. the meteorological forecast and a heat wave guide. The heat wave guide outlines a list of actions to reduce the risks to human health, the stakeholders that are required and their responsibilities. The stakeholders include the health sector, social-care sector, some other public agencies, professionals working with vulnerable individuals and the general public. Applying the steps recommended in this heat action plan is sure to reduce the impacts of heat waves on human health and mortality. The system also requires continual improvements that take into account other factors of heat on human health.

6.4. Recommendations

- The health sector should be consulted with regards to the current considerations and structure for a heat-health watch-warning for South Africa.
- Further study on the weather systems that cause heat waves need to be conducted in order to quantify the findings of this study.
- Since the existing heat wave forecast system only takes into account temperature and relative humidity, other local factors such as demography and adaptation to local climate need to be considered in order to increase the quality of the forecasts. Other factors such as demography and adaptation need to be taken into account when developing the operational heat wave forecast system.

CHAPTER 7: References

- Akompab, D.A., Bi, P., Williams, S., Grant, J., Walker I. A., & Augoustinos, M. (2013). Heat Waves and Climate Change: Applying the Health Belief Model to Identify Predictors of Risk Perception and Adaptive Behaviours in Adelaide, Australia. *Int. J. Environ. Res. Public Health.*, 10, 2164-2184. doi:10.3390/ijerph10062164
- Australia Sports Medicine. (2015). *Beat the heat: playing and exercising safely in hot weather fact sheet*. Retrieved from Sports Medicine Australia: www.sma.org.au
- Azhar, G.S., Mavalankar, D., Nori-Sarma, A., Rajiva, A., Dutta, P., Jaiswal, A., Sheffield, P., Knowlton, K., & Hess, J.J. (2014). Heat-Related Mortality in India: Excess All-Cause Mortality Associated with the 2010 Ahmedabad Heat wave. *PLoS ONE*, 9(3), e91831.
- Basu, R & Samet, J.M. (2002). Relation between Elevated Ambient Temperature and Mortality: A Review of the Epidemiologic Evidence. *Epidemiol Rev*, 24(2), 190-202.
- Benmarhnia, T., Deguen, S., Kaufman, J.S., & Smargiassi, A. (2015). Vulnerability to Heat-related Mortality: A Systematic Review, Meta-analysis, and Meta-regression Analysis. *Epidemiology, Lippincott, Williams & Wilkins*, 26(6), 781-793.
- Brotherhood, J. (2008). *Beat the Heat - playing safely in hot weather*. Retrieved from Sports Medicine Australia: <http://sma.org.au/resources/policies/hot-weather/>
- Bureau of Meteorology. (2012). *Urban design. Department of Environment, Sport and Territories*. Melbourne: Bureau of Meteorology. Retrieved from http://reg.bom.gov.au/info/leaflets/urban_design.pdf
- Bureau of Meteorology. (2014). *Thermal Comfort observations*. Retrieved from Bureau of Meteorology: http://www.bom.gov.au/info/thermal_stress/
- Burgess, P. (2009). Variation in light intensity at different latitudes and seasons, effects of cloud cover, and the amounts of direct and diffused light. *Continuous Cover Forestry Group (CCFG) Scientific Meeting 29 September 2009*. Westonbirt Arboretum, Gloucestershire: Continuous Cover Forestry Group.
- Burkart K., Breitner S., Schneider A., Khan M.M., Krämer A. & Endlicher W. (2014). An analysis of heat effects in different subpopulations of Bangladesh. *Int J Biometeorol.*, 58(2), 227-37. doi: 10.1007/s00484-013-0668-5
- Candille, G., Côté, C., Houtekamer, P.L. & Pellerin, G. (2007). Verification of an Ensemble Prediction System against Observations. *American Meteorological Society*, 135, 2688-2699.
- Chinganon, S. A., Kunkel, K. E. & Reinke, B. C. (1996). Impacts and responses to the 1995 heat wave: A call to action. *Bulletin of the American Meteorological Society*, 77(7), 1497-1506.
- City of Casey. (2015). *Preparing for Heatwaves*. Retrieved from Health promotion: <http://www.casey.vic.gov.au/health-safety/health-promotion/heatwaves>
- Confalonieri, U., Menne, B., Akhtar, R., Ebi, K. L., Hauengue, M., Kovats, R. S., Revich, B. & Woodward, A. (2007). *Human health. Climate Change 2007: Impacts, Adaptation and Vulnerability*. Cambridge, UK: Cambridge University Press.

- CSIR. (2010). *A CSIR perspective on water in South Africa – 2010*. Pretoria, South Africa: CSIR Report No. CSIR/NRE/PW/IR/2011/0012/A.
- Curry, J. (2011). *Climate Etc*. Retrieved June 21, 2016, from Reanalyses.org: <https://judithcurry.com/2011/08/17/reanalyses-org>
- Dash, S.K. & Kjellstrom, T. (2011). Workplace Heat stress in the context of rising temperature in India. *Current science*, 101(4).
- de Jager, E. (2015). *General Information: Heatwave conditions*. Pretoria: South African Weather Service. Retrieved from http://www.unisa.ac.za/news/wp-content/uploads/2015/11/SA-Weather-Service__Continuation-of-heat-wave.pdf
- Department of Human Services. (2009). *Heatwave Planning Guide: Development of heatwave plans in local councils in Victoria*. Melbourne Victoria Australia: Environmental Health Unit, Victorian Government Department of Human Services.
- Doswell, C. A., Davies-Jones, III, R. & Keller, D. (1990). On summary measures of skill in rare event forecasting based on contingency tables. *Wea. Forecasting*, 5, 576–585.
- Dyson, L. (2000). *A dynamical forecasting perspective on synoptic scale weather systems over southern Africa*. Pretoria: MSc dissertation, University of Pretoria.
- Ebi, K. L. & Meehl, G. A. (2007). *Heatwaves and Global climate: The Heat is On: Climate Change & Heatwaves in the Midwest*. Arlington, VA 22201: Pew Center on Global Climate Change.
- eNCA (eNews Channel Africa). (2014). *Heatwave to persist over weekend*. Retrieved October 13, 2015, from <https://www.enca.com/south-africa/heatwave-persist-over-weekend>
- eNCA (eNews Channel Africa). (2015a). *What caused Tuesday's record-breaking heat?* Retrieved from eNCA: <https://www.enca.com/weather/what-caused-tuesdays-record-breaking-heat>
- eNCA (eNews Channel Africa). (2015b). *Cape Town's hottest day in a century*. Retrieved from eNCA: <https://www.enca.com/south-africa/its-hottest-day-cape-town-century>
- eNCA (eNews Channel Africa). (2015c). *Watch: Heat wave expected to continue*. Retrieved from eNCA: <https://www.enca.com/media/video/watch-heat-wave-expected-continue>
- Eskom. (2010a). *DSM – Air-conditioning facts Revision 2*. Sandton, South Africa.: Eskom. Retrieved from http://www.eskom.co.za/content/DSM_0002AirConFactsRev2~1.pdf
- Eskom. (2010b). *Environment – Understanding Pollution Revision 7*. Sandton, South Africa: Eskom. Retrieved from http://www.eskom.co.za/content/GI_0002EnvUderstPollRev7~1.pdf
- Eyewitness News. (2015). *SA weather confirms record high temperatures for CT*. Retrieved from Eyewitness News: <http://ewn.co.za/2015/03/04/CT-weather-office-records-highest-temperature-ever>
- Ferro, A.T. & Stephenson, D.B. (2011). Extremal Dependence Indices: Improved Verification Measures for Deterministic Forecasts of Rare Binary Events. *Amer. Meteor. Soc*, 26, 699-713.
- Frich, P., Alexander, L. V., Della-Marta, P., Gleason, B., Haylock, M., Klein Tank, A. M. G. & Peterson, T. (2002). Observed coherent changes in climatic extremes during the second half of the twentieth century. *Climate Research*, 19, 193–212.

- Ghiasi, M. (2011). Social Risk Factors for Heat Wave Mortality Among the Elderly: A case study of the 2003 heat wave in Paris, France. *Public health*.
- González-Alemán, J. J.F. , Martín-León, V. F. & Evans, J. L. (2015). Classification and synoptic analysis of subtropical cyclones within the northeastern Atlantic Ocean. *J. Climate*, 28, 3331–3352.
- Gordon, N. & Morimoto, J. (2000). *Guidelines On Performance Assessment Of Public Weather Services*. Geneva, Switzerland: World Meteorological Organization.
- Greene, J.S., Kalkstein, L.S., Jameson, P.F., Libby, J. & Robinson, L. (1996). The Philadelphia hot weather-health watch/warning system: Development and application, summer 1995. *Amer. Meteor. Soc*, 77, 1519 – 1528.
- Guirguis, K., Gershunov, A., Tardy, A., & Basu, R. (2014). The Impact of Recent Heat Waves on Human Health in California. *J. Appl. Meteor. Climatol*, 53, 3–19.
- Hattis, D., Ogneva-Himmelberger, Y., & Ratick, S. (2012). The spatial variability of heat-related mortality in Massachusetts.. . *Applied Geography*, 33, 45-52.
- Health24. (2015). *How to survive the Gauteng heatwave*. Retrieved from <http://www.health24.com/News/Public-Health/Heatwave-about-to-hit-Gauteng-20151005>
- IOL. (2015). *Heatwave in Gauteng, North West*. Retrieved from <http://www.iol.co.za/news/south-africa/gauteng/heatwave-in-gauteng-north-west-1815437>
- Jendritzky, G. (2000). *Impacts of extreme and persistent temperatures – cold waves and heat waves*. In “*Proceedings of the WMO/UNESCO Sub-Forum on Science and Technology in Support of Natural Disaster Reduction*”. Geneva, 6–8 July 1999: World Meteorological Organization.
- Jolliffe, I.T. & Stephenson D.B. (2003). *Forecast verification: A practitioner’s guide in atmospheric science*. Wiley.
- Kanamaru, H. & Kanamitsu, M. (2007). Scale-selective bias correction in a downscaling of global analysis using a regional model. *Monthly Weather Review*, 135, 334–350. doi:10.1175/MWR3294.1
- Karoly, D. (1998). *Meteorology of the Southern Hemisphere* (1st ed.). American Meteorological Society. doi:0065-9401
- Karoly, D. (2015). *Meteorology of the Southern Hemisphere*. Boston: American Meteorological Society.
- Kliver, D. (2008, April). *Skill Scores*. Retrieved April 6, 2016, from udel.edu/~daria/Statistics_Weather_Forecasting_3.pptx
- Kovats, R.S & Kristie L E. (2006). Heatwaves and public health in Europe. *European Journal of Public Health*, 16, 592–599.
- Loughnan, M., Nicholls, N. & Tapper, N. . (2012). *Hot Spots Project: A spatial vulnerability analysis of urban populations to extreme heat events*. Victoria, Australia: Monash Climate, School of Geography and Environmental Science, Monash University.
- LoVecchio, F., Stapczynski, J.S., Hill, J. & Haffer A.F. (2005). Heat-related mortality—Arizona, 1993–2002, and the United States, 1979–2002. *Mortality and Morbidity Weekly Report*, 54, 628-630.

- Lyon, B. (2009). Southern Africa summer drought and heat waves: observations and coupled model behavior. *Amer. Meteor. Soc.*, 22, 6033-6046.
- Matthies F, Bickler G, Cardeñosa Marín N. & Hales S. (2008). *Heat–Health Action Plans. Guidance*. Copenhagen: World Health Organisation Regional Office for Europe.
- McGregor, G.R., Bessemoulin, P., Ebi, K. & Menne, B. (2015). *Heatwaves and Health: Guidance on Warning-System Development*. Geneva, Switzerland: World Meteorological Organization and World Health Organization.
- Medina-Ramón, M., Zanobetti, A., Cavanagh, D.P. & Schwartz, J. (2006). Extreme Temperatures and Mortality: Assessing Effect Modification by Personal Characteristics and Specific Cause of Death in a Multi-City Case-Only Analysis. *Environ Health Perspect.*, 114(9), 1331–1336.
- Menne, B. & Matthies, F. (2009). *Improving public health responses to extreme weather/heat-waves – EuroHEAT. Technical summary*. Denmark: World Health Organization.
- Michelozzi, P., de' Donato, F., Accetta, G., Forastiere, F., D'Ovidio, M. & Perucci, C. (2004). *Impact of Heat Waves on Mortality --- Rome, Italy, June--August 2003*. Atlanta, GA : Centers for Disease Control and Prevention.
- Michelozzi P, de Donato F, Bisanti L, Russo A, Cadum E, et al. (2005). The impact of the summer 2003 heatwaves on mortality in four Italian cities. *Eurosurveillance*, 10, 161–65.
- Mucina, L., Adams, J.B. , Knevel, I.C. , Rutherford, M.C., Powrie, L.W., Bolton, J.J., van der Merwe, J.H., Anderson, R.J. Bornman, T.G., le Roux, A. & Janssen, J.A.M. (2006). Coastal Vegetation of South Africa. *Strelizia*, 19, 660-697.
- National Research Council. (2006). *Completing the Forecast: Characterizing and Communicating Uncertainty for Better Decisions Using Weather and Climate Forecasts*. Washington, DC: The National Academies Press.
- News24. (2011). *Gauteng sizzles in heat wave* . Retrieved from <http://www.news24.com/SouthAfrica/News/Gauteng-sizzles-in-heat-wave-20111024>
- News24. (2012). *News24. Heatwave claims labourer 5 others in hospital*. Retrieved October 14, 2015, from <http://www.news24.com/SouthAfrica/News/Heatwave-claims-labourer-5-others-in-hospital-20120118>
- News24. (2013). *Heatwave warning for parts of SA*. Retrieved March 24, 2016, from <http://www.news24.com/SouthAfrica/News/Heatwave-warning-for-parts-of-SA-20130124>
- News24. (2015a). *Furious heatwave short-lived*. Retrieved October 13, 2015, from <http://www.news24.com/SouthAfrica/News/Furious-heatwave-short-lived-20150209>
- News24. (2015b). *Heatwave warning for SA*. Retrieved March 24, 2016, from <http://www.news24.com/SouthAfrica/News/Heatwave-warning-for-SA-20111113>
- News24. (2015c). *Near week-long heatwave to hit parts of SA*. Retrieved March 22, 2016, from <http://www.news24.com/SouthAfrica/News/near-week-long-heatwave-to-hit-parts-of-sa-20151109>
- Nicholls, N., Loughnan, M. & Tapper N. (2009). *Hot Spots Project: A spatial vulnerability analysis of urban populations to extreme heat events*. Melbourne: Monash Climate, School of Geography and Environmental Science, Monash University.

- Nitschke, M., Hansen, A., Bi, P., Pisaniello, D., Newbury, J., Kitson, A., Tucker, G., Avery, J. & Grande, E.D. (2013). Risk Factors, Health Effects and Behaviour in Older People during Extreme Heat: A Survey in South Australia. *Int. J. Environ. Res. Public Health*, *10*, 6721-6733. doi:10.3390/ijerph10126721
- NOAA (National Oceanic and Atmospheric Administration). (2012). *Heat Wave: a major summer killer*. Retrieved from US Department of Commerce: www.noaawatch.gov/themes/heat.php
- NOAA (National Oceanic and Atmospheric Administration). (2015). *Heat: A major killer*. Retrieved from NWS heat safety tips: <http://www.nws.noaa.gov/os/heat/index.shtml>
- NOAA's National Weather Service. (2016). *Glossary*. Retrieved from National Oceanic and Atmospheric Administration: National Weather Service: <http://w1.weather.gov/glossary/index.php?word=heat+wave>
- Palecki, M.A., Changnon, S.A. & Kunkel, K.E. (2001). The Nature and Impacts of the July 1999 Heat Wave in the Midwestern United States: Learning from the Lessons of 1995. *Bulletin of the American Meteorological Society*, *82*, 1353- 1367.
- Pascal, M., Laaidi, K., Ledrans, M., Baffert, E., Caserio-Schönemann, C., Le Tertre A., Manach, J., Medina, S., Rudant, J. & Empereur-Bissonnet, P. (2005). France's heat health watch warning system. *Int J Biometeorol* , *50*, 144–153.
- Peach, H. (1997). *Air Quality and Human Health*. Canberra: Dept of the Environment.
- Peng, R. D., Bobb, J. F., Tebaldi, C., McDaniel, L., Bell, M. L. & Dominici, F. (2011). Towards a quantitative estimate of future heat wave mortality under global climate change. *Envir. Health Perspect.*, *119*, 119-701.
- Poumad`ere, M., Mays, C., Le Mer, S & Blong, R. (2005). The 2003 HeatWave in France: Dangerous Climate Change Here and Now. *Risk Analysis*, *25*, 1483-1493.
- Raghavendra, A. (2014). Cases of Extreme Rainfall during Monsoon and their Verification. *Sixth WMO International Verification Methods Workshop*. New Delhi, India: WMO. Retrieved from Available at: <http://www.ncmrwf.gov.in/verif2014/day-1.php>
- Resosudarmo, B. P., Syahril, S. & Tomo, H. S. (2002). *Future Trends, Health Impacts, Economic Value and Policy Options*. Jakarta, Indonesia: Asian Development Bank.
- Risbey, J. & Tryhorn, L. (2006). Heat wave distribution over the Australian region. *Aust. Met. Mag.*, *55*, 167-182.
- Rooney, C., McMichael, A.J., Kovats, R.S. & Coleman, M.P. (1998). Excess mortality in England and Wales, and in Greater London, during the 1995 heatwave. *J. Epidemiol. Community Health*, *52*, 482–486.
- SABC (South Africa Broadcasting Corporation). (2011). *Gauteng cooks in heat wave*. Retrieved March 24, 2016, from <http://www.sabc.co.za/news/a/acfd518048ce2d3485d0854585ed271e/Gauteng-cooks-in-heat-wave--20111024>
- SABC (South African Broadcasting Corporation). (2014). *Cape Town heat wave to ease in the Peninsula*. Retrieved March 24, 2016, from <http://www.sabc.co.za/news/a/82458d0042f3bc0badfbbf895990ad13/CapeundefinedTo>

wnundefinedheatundefinedwaveundefinedtoundefinedeaseundefinedinundefinedtheund
efinedPeninsula-20141602

- Saha, S. Moorthi, S., Wu, X., Wang, J., Nadiga, S., Tripp, P., Behringer, D., Hou, Y., Chuang, H., Iredell, M., Ek, M., Meng, J., Yang, R., Mendez, M. P., van den Dool, H., Zhang, Q., Wang, W., Chen, M., & Becker, E. . (2011). *updated daily. NCEP Climate Forecast System Version 2 (CFSv2) 6-hourly Products*. Retrieved October 14, 2013, from <http://dx.doi.org/10.5065/D61C>
- Sarofim, M.C., Saha, S. Hawkins, M.D. Mills, D.M. Hess, J. Horton, R. Kinney, P. Schwartz, J. & St. Juliana, A. (2016). *Ch. 2: Temperature-Related Death and Illness. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment*. Washington, DC: U.S. Global Change Research Program.
- SAWS (South African Weather Service). (2012). *World MET Day Celebrations 2012, King Shaka Weather Office and SAWS Alumni Launch*. Retrieved from South African Weather Service: <http://intranet.saws.co.za/?p=1032>
- SAWS (South African Weather Service). (2014a). *What is the discomfort index?* Retrieved from South African Weather Service: <http://www.weathersa.co.za/learning/educational-questions/58-what-is-the-discomfort-index?recache=1>
- SAWS (South African Weather Service). (2016). *Caelum: NOTABLE WEATHER AND WEATHER-RELATED EVENTS FROM 1991 TO 2016*. Pretoria: South African Weather Service.
- Sheridan, S. C. & Kalkstein, L. S. (2004). Progress in heat watch–warning system technology. *Bull. Amer. Meteor. Soc.*, *85*, 1931-1941.
- Shrestha, D. L., Robertson, D. E., Wang, Q. J., Pagano, T. C. & Hapuarachchi, H. A. P. (2013). Evaluation of numerical weather prediction model precipitation forecasts for short-term streamflow forecasting purpose. *Hydrol. Earth Syst. Sci*, *17*, 1913–1931.
- Southern AER. (2001). *A Quarterly Activity Bulletin of The South Carolina Department of Natural Resources-Southeast Regional Climate Center*. Retrieved from Southern AER: http://science-class.net/Lessons/Space/Space%20Cycles/Seasons/Earth_Sun_Geometry.pdf
- Sports Medicine Australia. (2008). *Sports Medicine Australia*. Retrieved from Beat the heat: playing and exercising safely in hot weather fact sheet: www.sma.org.au.
- Sports Medicine Australia. (2014). *HOT WEATHER GUIDELINES For sporting clubs and associations and the physically active*. Retrieved from Sports Medicine Australia: <http://sma.org.au/wp-content/uploads/2009/05/hot-weather-guidelines-web-download-doc-2007.pdf>
- State of Victoria. (2009). *January 2009 Heatwave in Victoria: an Assessment of Health Impacts*. Melbourne, Victoria: Victorian Government Department of Human Services.
- Steadman R.G. (1994). Norms of apparent temperature in Australia. *Aust. Met. Mag*, *43*, 1-6.
- Steffen, W., Hughes, L. & Perkins, P. (2014). *HEATWAVES: HOTTER, LONGER, MORE OFTEN*. Australia: Climate Council of Australia Limited. Retrieved from <http://www.climatecouncil.org.au/uploads/9901f6614a2cac7b2b888f55b4dff9cc.pdf>

- Stephenson D. B., Casati, B, Ferroa, C. A. T. & Wilson, C. A. (2008). The extreme dependency score: a non-vanishing measure for forecasts of rare events. *Meteorol. Appl*, 15, 41–50.
- Taljaard, J. (1995a). *Atmospheric circulation systems, synoptic climatology and weather of South Africa: Part 3 The synoptic climatology of South Africa in January and July*,. Pretoria: Soth African Weather Bureau.
- Taljaard, J. (1995b). *Atmospheric circulation systems, synoptic climatology and weather phenomena of South Africa: Part 4 Surface pressure and wind phenomena in South Africa*. Pretoria: South African Weather Bureau.
- Tennant, W.J., Toth, Z., & Rae, K. (2006). Application of the NCEP Ensemble Prediction System to Medium-Range Forecasting in South Africa: New Products, Benefits, and Challenges. *American Meteorological Society*, 22, 18-35.
- The Citizen. (2015). *Keep cool – heatwave expected*. Retrieved March 22, 2016, from <http://www.citizen.co.za/802288/keep-cool-heatwave-expected/>
- The Sowetan. (2013). *Heatwave hits SA*. Retrieved March 24, 2015, from The Sowetan: <http://www.sowetanlive.co.za/news/2013/01/25/heatwave-hits-sa>
- Thom, E. (1959). The Discomfort Index. *Weatherwise*, 12, 57-60. Retrieved from <http://dx.doi.org/10.1080/00431672.1959.9926960>
- Thomas, B. C., & Martin, J. E. (2007). A synoptic climatology and composite analysis of the Alberta clipper. *Wea. Forecasting*, 22, 315–333.
- Tiriolo, L., Torcasio ,R.C., Montesanti, S. & Federico, S. (2015). Verification of a Real Time Weather Forecasting System in Southern Italy. *Advances in Meteorology*, 2015. Retrieved from <http://dx.doi.org/10.1155/2015/758250>
- Toth, Z., Kalnay, E., Tracton, S.M., Wobus, R & Irwin J. (1996). A synoptic evaluation of the NCEP ensemble. *Wea. Forecasting*, 12, 140-153.
- Toth, Z., Zhu, Y., & Marchock, T. (2001). The use of ensembles to identify forecasts with small and large uncertainty. *Wea. Forecasting*, 16, 436-477.
- Tyson, P. D. & Preston-whyte, R.A. (2000). *The atmosphere and weather of Southern Africa*. (2nd ed.). Cape Town: Oxford University Press Southern Africa.
- US Department of Health & Human Services. (2016). *Extreme Heat Prevention Guide*. Retrieved from Emergency Preparedness and Response: http://emergency.cdc.gov/disasters/extremeheat/heat_guide.asp
- US Department of Labour. (2016). *Training Workers*. Retrieved from Occupational Safety & Health Administration: https://www.osha.gov/SLTC/heatillness/heat_index/training_workers.html
- USEPA (United States Environmental Protection Agency). (2006). *Excessive Heat Events Guidebook*. Washington, DC: United States Environmental Protection Agency. Retrieved from <http://www.epa.gov/heat-islands/excessive-heat-events-guidebook>
- Vaneckova, P., Neville, G., Tippett, V., Aitken, P., Fitzgerald, G. & Tong, S. (2011). Do biometeorological indices improve modeling outcomes of heat-related mortality? *J Appl Meteor Climatol*, 50, 1165–1176.
- Victorian Government Department of Human Services. (2009). *Development of Heatwave Plans in Local Councils in Victoria*. . Retrieved from Department of Human Services:

<https://www2.health.vic.gov.au/about/publications/policiesandguidelines/Heatwave%20Planning%20Guide%20Development%20of%20heatwave%20plans>

- Voogt, J. (2004). *Urban Heat Islands: Hotter Cities*. Canada: American Institute of Biological Sciences, University of Western Ontario.
- Wescott, N. (2011). The prolonged 1954 Midwestern U.S. heat wave: Impacts and responses. *Amer. Meteor. Soc.*, 3, 165-176.
- Westcott, N.E. (2011). The prolonged 1954 Midwestern U.S. heat wave: Impacts and responses. *Amer. Meteor. Soc.*, 11, 165-176.
- WHO (World Health Organization). (2003). *The health impacts of 2003 summer heat-waves: Briefing note for the Delegations of the fifty-third session of the WHO Regional Committee for Europe*. Vienna, Austria: WHO.
- WHO (World Health Organization). (2005). *WHO Air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide, World Health Organization Regional Office for Europe*. Geneva, Switzerland: WHO Press.
- WHO (World Health Organization). (2006). *Preventing harmful health effects of heat-waves*. Geneva, Switzerland: World Health Organization.
- WHO (World Health Organization). (2009). *Improving public health responses to extreme weather/heat-waves – EuroHEAT*. Copenhagen Ø, Denmark: World Health Organization.
- Wichmann, J. (2017). Heat effects of ambient apparent temperature on all-cause mortality in Cape Town, Durban and Johannesburg, South Africa: 2006-2010. *Sci Total Environ.*, 587-588, 266-272. doi:10.1016/j.scitotenv.2017.02.135
- Wilks, D.S. (2006). *Statistical methods in the atmospheric sciences* (Second Edition ed.). Elsevier: Department of Earth and Atmospheric Sciences, Cornell University.
- WMO (World Meteorological Organization). (2016). *2015 is hottest year on record*. Retrieved from WMO web site: <http://public.wmo.int/en/media/press-release/2015-hottest-year-record>
- Xiang, J., Hansen, A., Pisaniello, D. & Bi, P. (2015). Perceptions of workplace heat exposure and controls among occupational hygienists and relevant specialists in Australia. *PLOS*, 10(8).
- Yousif, T. A. & Tahir H. M. M. (2013). Application of Thom's Thermal Discomfort Index in Khartoum State, Sudan. *JOURNAL OF FOREST PRODUCTS & INDUSTRIES*, 2(5), 36-38.
- Zacharias, S., Koppe, C. & Mücke, H. (2014). Influence of Heat Waves on Ischemic Heart Diseases in Germany. *Climate*, 2, 133-152.