

Establishing fire regime characteristics for biomes in southwestern Africa

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DECLARATION

I, Daniel Sarel Boshoff, solemnly declare that this work is original and the result of my own labour. It has never, on any previous occasion, been presented in part or whole to any institution or board for the award of any degree.

I further declare that all information used and quoted has been duly acknowledged by complete reference.

21 November 2022

Signature

Date

DEDICATION AND ACKNOWLEDGEMENTS

This thesis is dedicated to my parents – Piet and Carin – who not only provided unconditional love and support throughout my life, but also taught me to persevere through challenging times.

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- South African National Biodiversity Institute (SANBI) Biodiversity GIS portal
- IRI Climate Lab interactive tools
- National Oceanic and Atmospheric Administration (NOAA) National Center for Environmental Prediction (NCEP) Climate Prediction Center
- Koninklijk Nederlands Meteorologisch Instituut (KMNI) Climate Explorer
- European Centre for Medium-Range Weather Forecasts (ECMWF)
- South African Weather Service (SAWS)

ABSTRACT

Fire has been occurring naturally in all ecosystems on earth before human intervention. Natural fires play a crucial role in the removal of plant litter and regeneration of certain plant species. Vegetation and wildlife mortality from fires affects species composition, habitat quality, biodiversity, seed distribution and migration patterns. In addition, human health, lives, and livelihoods can be severely threatened by fires. Studying fires requires knowledge of fire regimes, which consists of factors such as seasonality, fire intensity, fire frequency, vegetation characteristics, topography, synoptic weather patterns, climate change, soil moisture availability and land use and land cover change (LULCC). Due to the projected climatic changes and LULCC forecast for the western parts of southern Africa, it is crucial to establish the fire regime characteristics for biomes in the region. This study aimed to establish the fire regime characteristics for the biomes in southwestern Africa. Open access data were used with the exception of local weather station data obtained from the South African Weather Service (SAWS). In addition, open-source software packages for example, QGIS and selected Python libraries, were used to extract, analyse, and interpret data. Long-term datasets were extracted and analysed as well as data for five selected case studies in order to determine the relationship between synoptic weather types and fire events. In addition, the pre-fire vegetation conditions and (post-fire) burn severity and burnt areas were also examined. Fire regime characteristics found in this study related to climatic variables, and vegetation conditions prior to fire events. The remotely sensed data identified the seasonality of fires at Knysna to occur in the austral summer, at Cape Town in the austral summer and early autumn and the South-Eastern (SE) Kalahari in the austral winter and early spring. The seasonal occurrences of fires correspond with the literature on the dry seasons across the Fynbos, Savanna and Grassland Biomes. In terms of Fire Return Interval (FRI), the analysis of official records found that the two largest two fires occurred 30 years apart. While irregular FRIs were detected in the official records, the FRIs still correspond with the literature indicating a 2-10 year and 5–50-year FRI in the Fynbos biome. The majority (53%) of the largest fire events in the Western Cape occurred in the years following the El Niño phase of the El Niño Southern Oscillation (ENSO), positive phase of the Southern Annular Mode (SAM) (66%) and below normal seasonal precipitation anomalies (66%). Furthermore, the simultaneous occurrence of these teleconnections and precipitation anomalies were documented for six (40%) of the fire events, with four (27%) of the events took place after La Niña phases of ENSO, negative phases of SAM and below normal seasonal precipitation anomalies. Strong high-pressure (HP) systems were present on the day of ignition across southern Africa for all five of the case studies, and in the 2017 Knysna fire case a strong frontal low-pressure (LP) system had

also been present. In terms of fire extinction, all the fire events, with the exception of the 2021 Cape Town fire, were affected by the presence of a LP system over the region.

Soil moisture volumes were mostly low prior to fire ignition, with the exception of the 2018 Knysna fire where soil moisture volumes were slightly higher than at the other sites. Vegetation was determined to be moderately healthy prior to the Knysna fires and the 2021 Cape Town fire. In contrast, vegetation was under stress prior to the 2015 Cape Town and SE Kalahari fires. The 2021 Cape Town and 2018 Knysna fire events recorded high burn severity, with the latter also classified as the largest fire in terms of burnt area. A moderate-low burn severity was documented for the 2015 Cape Town fire, while the 2017 Knysna and SE Kalahari fires were classified as low severity fires. The low severity fires consumed more hectares than the two Cape Town fires. This thesis contributes to the body of knowledge in the discipline of geography by highlighting the interconnected factors that contribute to fire events, including their occurrence over various spatial and temporal scales.

Keywords: fire weather, land use and land cover change (LULCC), biome characteristics, fire regimes, geography of fire

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CHAPTER 1

INTRODUCTION

1.1 INTRODUCTION AND BACKGROUND

Understanding the occurrence, behaviour and management of fires is not simple. In fact, Hottel stated in 1984 that “a case can be made for fire being, next to life processes, the most complex of phenomena to understand” (Rein, 2013:16). This thesis explores fire regimes across the western parts of southern Africa from a geographical perspective. Chapter 1 details the background, rationale, aim and objectives, and organisation of the thesis.

Fire has been occurring naturally in all ecosystems on earth before human intervention. Natural fires play a crucial role in the removal of plant litter and regeneration of certain plant species (Fidelis, 2020). Ecosystems over the world are affected by fires – whether they are ignited naturally or through human activities.

There are several impacts of fire on humans and the environment, occurring at various scales. Nelson *et al.* (2014) designed a framework to display the impacts of fire on different scales in Figure 1.1 below. The figure shows the impacts extending from local to global scales, including risk to human lives and disruptions of weather patterns.

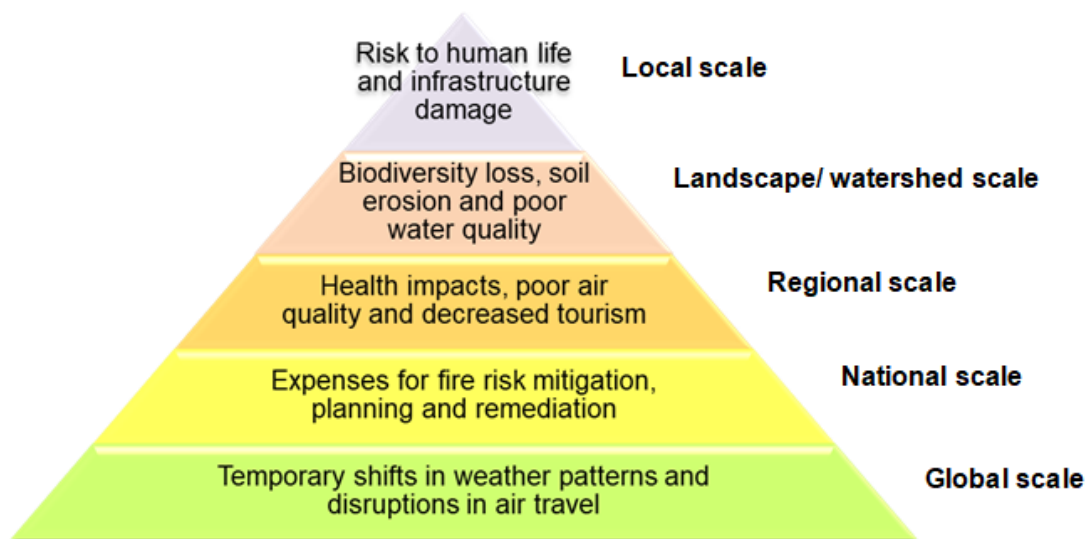


Figure 1.1: Impacts of fire at different scales (Source: Nelson *et al.*, 2014)

In addition, human health, lives and livelihoods can be severely threatened by fires (Edwards *et al.*, 2020). Furthermore, fires can alter ecosystems, habitats, water quality, biodiversity, atmospheric chemistry, biogeochemical cycles, the Earth’s energy budget, biodiversity, as well

as nutrient cycling processes, and lead to disease outbreaks (Holsinger *et al.*, 2016; Silva *et al.*, 2019; Viedma *et al.*, 2020). Fires may lead to heat damage of plant cells, hydraulic tissues and mortality (Midgley and Bond, 2013). Vegetation and wildlife mortality from fires affects species composition, habitat quality, biodiversity, seed distribution and migration patterns (Eskandari *et al.*, 2020). For example, high temperature fires may reduce shallow seed banks such as those in the *Asteraceae* family in the Fynbos biome (Rebelo *et al.*, 2011). Large fire events can also have significant impacts on political stability. In fact, large fire events in Portugal and Greece resulted in restructuring of government administrative bodies and created delays in political elections (San-Miguel-Ayanz *et al.*, 2013).

1.2 PROBLEM STATEMENT AND RATIONALE

Studying fires requires knowledge of fire regimes. The concept of a fire regime has “...developed into a generalized and structured description of the role of fire in ecosystems, mostly involving the parameterization of fire occurrence in a defined space–time window” (Krebs *et al.*, 2010:61). Numerous factors may influence the fire regime of an area. These factors can be linked to seasonality, fire intensity, fire frequency, vegetation characteristics, topography, synoptic weather patterns, climate change, soil moisture availability and land use and land cover change (LULCC) (Chergui, 2018; Duane and Brotons, 2018). In addition, regional climatological events can also play a crucial role in fire regimes, specifically the El Niño Southern Oscillation (ENSO) (Strydom and Savage, 2016; Huffman *et al.*, 2020). Strydom and Savage (2016) mapped fire events occurring in South Africa over an 11-year period and argued that a high fire count in the year 2007 is likely due to the La Niña phase of ENSO occurring in the previous calendar year. This echoes the sentiments of Archibald (2016) supporting the idea that increased precipitation leads to increased biomass that will provide more flammable materials for the next fire season. In their study of fires in the Kavango-Zambezi Transfrontier Conservation Area (only focusing on the regions in Namibia and Botswana), Pricope and Binford (2012) point out that the year with the highest fire count – 2006 – was preceded by three exceptionally dry seasons under the El Niño conditions. In fact, the total annual burnt area was recorded as 34 956km² in 2006, whereas the figure for 2007 is 23 432km². They conclude that El Niño conditions will have a significant impact on fire events under climatic changes (Pricope and Binford, 2012). Climate change may lead to an increase in temperatures and a decrease in precipitation in southwestern parts of Africa, thereby affecting semi-arid and arid biomes (Almazroui *et al.*, 2020). In 2015, Engelbrecht *et al.* (2015) projected that the western parts of southern Africa will experience an increase in heatwave frequency and in high-fire danger days during the far future from 2071 to 2100. In addition, a shift in the rainfall season may occur, which could lead to a prolonged dry season thereby increasing

fire risk (Engelbrecht *et al.*, 2015). These forecasts have been emphasised by the 2021 Intergovernmental Panel on Climate Change (IPCC) Assessment Report Six (AR6) Working Group 1 (WG1) report. Furthermore, warnings about the southern African region becoming a climate change hotspot are signalled in this drought-prone region (Engelbrecht and Monteiro 2021). Figure 1.2 shows that southern Africa, and especially the western part, is expected to become drier under various climate change scenarios (Engelbrecht and Monteiro 2021).

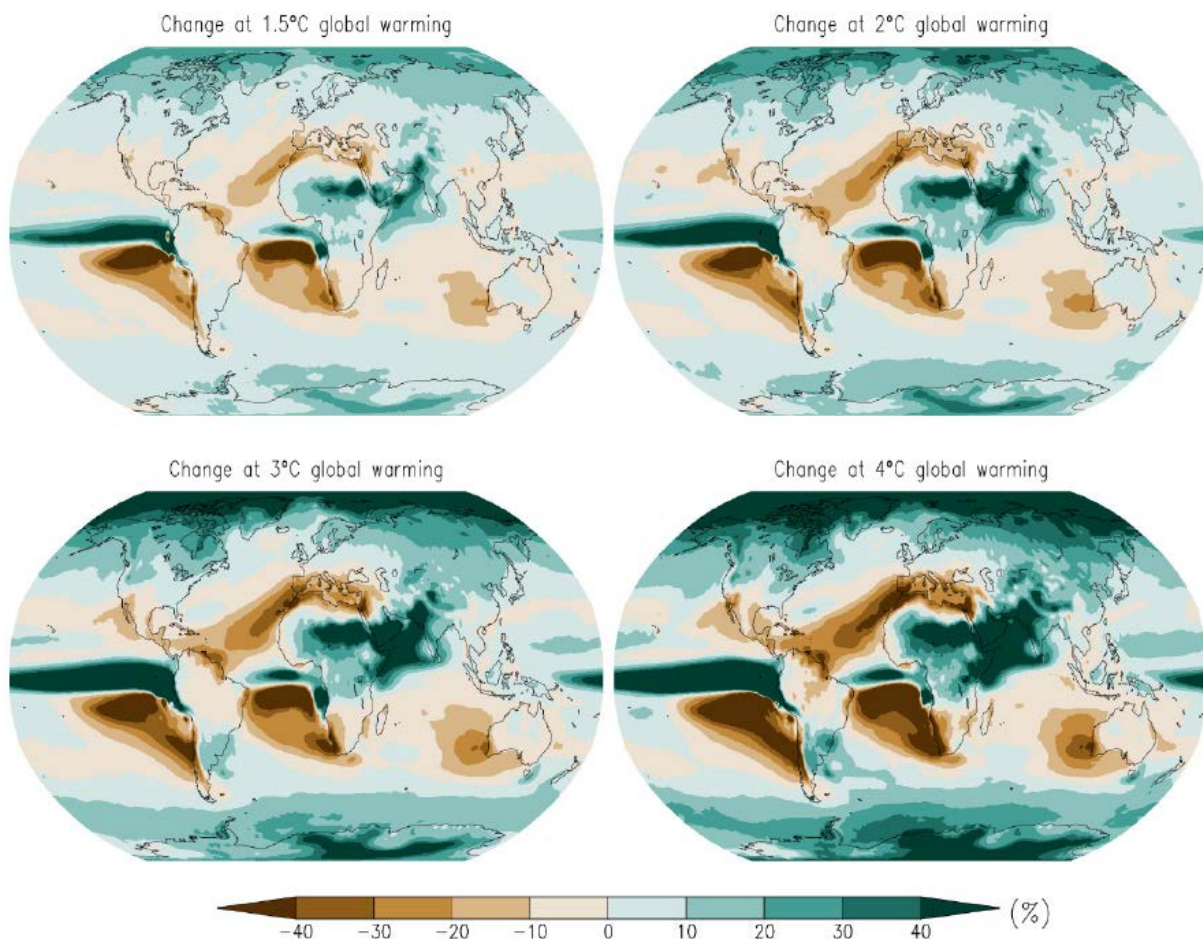


Figure 1.2: Change in precipitation with rising temperatures (Source: Engelbrecht and Monteiro, 2021)

As southern Africa is situated in the subtropics, it is also important to note that the subtropical high-pressure systems (HPs) are projected to expand in the Southern Hemisphere in future (Jury, 2019). The projected warming, reduced precipitation, and presence of strong HPs are key factors to consider when assessing fire regimes in southern Africa. The selected study area features a number of biomes in the western part of southern Africa, which include Fynbos, forest, succulent Karoo, Nama-Karoo, savanna and grasslands.

Multiple studies have been conducted on the pyrogeography of forests, Mediterranean biomes and savanna grasslands; however, not many studies have focused on semi-arid and arid areas (Pricope and Binford, 2012; Amatulli *et al.*, 2013; Alves and Pérez-Cabello, 2017; Kraaij *et al.*, 2018; Rodrigues *et al.*, 2020). Fires occur more frequently in the Fynbos biome than other biomes in the area due to a larger vegetation cover (fuel load), high flammability, and higher moisture levels (Kraaij *et al.*, 2018).

The invasion of grass species from other biomes may increase the fuel load, and therefore the fire frequency of semi-arid and arid biomes (Du Toit *et al.*, 2015). Strydom and Savage (2016) reported an increase in fire frequency in the Northern Cape Province, South Africa. This province contains semi-arid and arid biomes in South Africa and has also been identified as an area that can expect significant in-migration of humans due to prospective mining activities and the establishment of a higher education institution (Ledwaba, 2014; Kleinsmith and Horn, 2015). Human activities have altered fire regimes of many ecosystems, and this has contributed to severe fire events in numerous countries over the last decade (Alvarado *et al.*, 2017; Chaste *et al.*, 2018; Fidelis, 2020; Rodrigues *et al.*, 2020). Management of fire regimes is important to maintain its ecological function, while balancing the socio-economic impacts of fires (Alvarado *et al.*, 2017). A fire event along the Garden Route of South Africa is estimated to have caused ZAR 2 billion in property damages, consumed more than 5 000 ha of forest, 800+ buildings, and resulted in the mortality of seven humans (Kraaij *et al.*, 2018; Forsyth *et al.*, 2018; Frost *et al.*, 2018). Kraaij *et al.* (2018) attribute the severity and impacts of this fire event on inappropriate land management practices with regard to the expansion of the wildland-urban interface (WUI), commercial forestry activities and inefficient control of invasive alien species (IAS). Due to the projected climatic changes and land use and land cover change (LULCC) forecast for the western parts of southern Africa, it is crucial to establish the fire regime characteristics for biomes in the region.

In the past, fires were mapped using ecological modelling, field survey techniques and analyses of aerial photographs. However, these methods have limitations in terms of spatial and temporal scale as well as being costly and not being effective in mapping fires in remote locations (Aroyo *et al.*, 2008). Recently, remote sensing has been employed effectively in mapping fires and fire events due to the large spatial and temporal ranges covered by satellite data, the increased accessibility and developments in processing and displaying large datasets (Çolak and Sunar, 2020; Szpakowski and Jensen, 2019).

The LULCC and projected climate change in the region create the following questions:

- What are the historical and spatial trends or shifts in seasonality of fire regimes in the study area?
- As the temperature rises, are fires becoming more intense or affecting larger areas?
- Are the fire regimes and their main drivers in the different biomes changing in the same manner over time?
- What are the typical surface circulation patterns that occur prior to, during and after fire events?

1.3 AIM AND OBJECTIVES

The research aim is to establish the fire regime characteristics for the biomes in southwestern Africa by using open-sourced data and remote sensing techniques.

The research goal is associated with the following objectives:

- To determine the main drivers of selected fire events in the study area;
- To explore the relationship between synoptic weather types and fire events;
- To analyse the spatial variability and temporal dynamics of fire frequency; and
- To compare the variability of the drivers of fire regimes across the biomes in the study area over time.

1.4 ORGANISATION OF THESIS

The thesis is organised into five chapters. Chapter 2 contains the literature review, whereas Chapter 3 documents the methodology. The results of the study are presented and discussed in Chapter 4. Finally, a summary of findings, conclusions together with recommendations are provided in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Fires are mostly caused by the dynamic relationship between humans and the environment (Jiménez-Ruano *et al.* 2019). In this chapter, the conceptual frameworks for understanding fire regimes together with components of these frameworks are reviewed. Essential components of fire regimes were identified and discussed under the following categories: Climate, geomorphology and hydrology, organisms, and human activities. Furthermore, an examination of the literature on fires and fire regimes focusing on southern Africa is presented towards the end of the chapter.

2.2 FIRE REGIMES

In general, fires are reliant on the climate, availability of combustible biomass and ignition sources (Holsinger *et al.* 2016). However, looking beyond a generalisation or simplification of fire occurrence, spread and characteristics are vital in understanding how, where and why these events take place over larger spatial and temporal scales. This section explores the fundamentals, definitions and conceptualisation of fire regimes.

2.2.1 Conceptualisation

The exact conditions for fires to exist, spread and become extinct are dependent upon a number of variables. While various attempts have been made to present a simplified illustration of important factors at play during fire events, it is necessary to first review core characteristics of fires. Together, these characteristics and factors work in concert to determine the fire regime of an area.

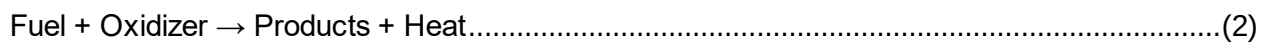
2.2.1.1 Background

Torero (2013:4) defines fire as "...the uncontrolled chemical oxidation of organic fuels that is generally associated with destruction", whereas Park and Allaby (2017) define fire as "the rapid oxidation of a fuel that results in the release of heat, light, and material by-products". In addition, natural fires refer to forest, underground and peat fires. Fires affecting buildings are called structural fires (Torero 2013). Megafires are large fires that spread rapidly, consume plenty of fuel and present significant hazards to humans (Rein 2013).

The process in which fuels and oxidisers react to produce heat and chemical products is called combustion (Torero 2013). According to McGranahan and Wonkka (2021), combustion is essentially the counteraction of the process of photosynthesis, illustrated by the equation below.



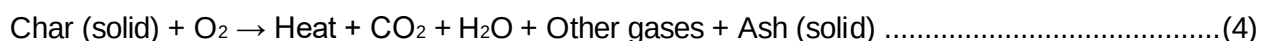
$C_6H_{10}O_5$ is the chemical formula for cellulose, a compound found in the tissues of photosynthesising plants. However, this explanation does not account for the combustion of processed organic materials – such as petrol, timber and plastic (Torero 2013). Both processed organic materials and natural organic materials display the same combustion process, which can be expressed as follows (Torero 2013):



While combustion is an exothermic reaction, pyrolysis is an endothermic reaction (Rein 2013). Pyrolysis refers to the process of breaking down organic material with the addition of heat. This process commences once a fuel particle is heated to approximately 200°C (McGranahan and Wonkka 2021). Rein (2013) points out that, unlike gasification, pyrolysis involves the concurrent alteration of a fuel's physical phase (for example, solid to vapour) and chemical composition (for example, long hydrocarbon chains to short hydrocarbon chains). The products of pyrolysis are both solid materials and gas, as shown by the equation below (Rein 2013):



Pyrolysate consists of a mixture of gases that include particulate matter (PM), hydrocarbons (CH_4 , C_3H_8), polyaromatic hydrocarbons (PAHs), volatile organic compounds (VOCs), carbon oxides (CO_x) and water vapour (H_2O). The solid products from pyrolysis are ash (mineral residue) and char (porous material) (Rein 2013). All the products from pyrolysis can react with oxygen (oxidation). It should be noted that complete combustion hardly ever occurs under natural circumstances that lead, which leads to the formation of gases such as carbon monoxide (CO) and unburnt hydrocarbons (Eq 4). Additionally, the oxidation of pyrolysate may produce nitrogen oxides (NO_x) (Eq 5) (Rein 2013).



When pyrolysate reaches temperatures between 200 and 500°C, flames are produced, and this process is referred to as flaming combustion. In contrast, the decomposition of fuel through

flameless, low temperature burning is called smouldering or glowing combustion (McGranahan and Wonkka, 2021; Rein, 2013). Flaming combustion tends to occur when fuels are less dense, whereas smouldering combustion occurs when fuels are denser (McGranahan and Wonkka, 2021). Notably, flaming and smouldering are intertwined. After a flaming fire has swept through an area, thick materials such as tree branches can smoulder for a while (residual smouldering). Inversely, smouldering can lead to flaming fire events. This may occur when oxygen supply is enhanced, for example by strong winds (Rein 2013).

The heating of materials to a point where it reaches combustion is called ignition (Gorse *et al.* , 2020). It is essential to take note of the term 'propagation'. Propagation refers a transfer of heat energy from already combusted materials to peripheral materials. Subsequently, the peripheral materials reach high temperatures, are ignited and undergo smouldering combustion. When the combustion reaction concludes, a fire reaches its extinction (McGranahan and Wonkka 2021).)

2.2.1.2 Definitions and classification of fire regimes

Definitions of fire regimes vary significantly as many authors struggle to incorporate the essence of what it entails. Oddi (2018) attempted to define a fire regime as “the spatial and temporal pattern of fires and their effects in a given area and over a given time period”. Park and Allaby (2017) elaborate on this concept by contending that a fire regime can be described as “the role that fire plays in an ecosystem, which depends on the frequency and scale of fires, and may include proposals for the controlled use of fire in a given area”. Table 2.1 shows the different factors included by various authors in their attempts to define the term 'fire regime'. Most of the authors underscore the importance of frequency, seasonality, extent and type in definitions. Other factors mentioned in definitions include intensity, severity, burnt area, biomass production and consumption, fire weather, ignition and impacts. Davies (2013) argues that while defining 'fire regimes' is an arduous and complex task, one should take into account that the elements of fire regimes will vary in significance across space, time, biotic and abiotic components of ecosystems.

Bedia *et al.* (2015) argue that fires require four 'switches' that have to occur concurrently: ignition, fire weather, vegetation and flammability of vegetation. Moreover, the flammability of vegetation is greatly dependent upon the moisture content of fine dead organic material. A number of variables can affect the moisture of plant materials, such as solar radiation, relative humidity, precipitation and temperature (Burton *et al.* 2019). It has been estimated that 30% of an ecosystem has to contain flammable materials for a fire to spread. Fire spread can also depend on the vegetation structure, where trees can accelerate the fire spread through their crowns (Flannigan *et al.* 2013).

Table 2.1: Fire regime concept

Author	Frequency (return interval)	Burnt area	Extent	Type	Intensity	Severity	Biomass production and consumption	Fire weather	Seasonality	Ignition	Prescribed burning	Impacts
Keeley (2008)	x	x				x	x		x			
Krebs <i>et al.</i> (2010)	x		x	x	x				x			x
De Groot <i>et al.</i> (2013)	x		x	x	x	x			x			
Davies (2013)	x		x	x	x	x	x		x			
Bedia <i>et al.</i> (2015)							x	x		x		
Liu and Wemberly (2016)	x	x	x									
Park and Allaby (2017)	x		x								x	
Chergui (2018)	x								x			
Oddi (2018)	x		x	x					x			x

The average number of fires taking place in a particular area at a specific time is referred to as fire frequency. On the other hand, fire return interval refers to the time between two fire events in an area (Davies 2013).

Factors that influence the size and extent of the burned area include fuel type, latitude, land use and management, season, and topography (Kassomenos, 2010). There are three broad categories of fire types, which are ground fires, surface fires and canopy fires. When biomass below the soil surface undergoes combustion, this is referred to as a ground fire. Surface fires consume biomass above the soil surface, with fires burning the leaves of standing trees; this is called canopy fires. Torching is the process where the foliage of a standalone tree burns. However, when there is a constant propagation of biomass above the surface, this is referred to as a running crown fire. A high density of trees can lead to the transitioning of surface fires to crown fires (McGranahan and Wonkka, 2021).

Even though fire intensity and fire severity are often used interchangeably, the amount of heat energy released during a fire is referred to as fire intensity (DellaSala 2018). Fire severity refers to the direct impacts of a fire on the environment (Davies 2013). Figure 2.1 below depicts the differences between these two terms.

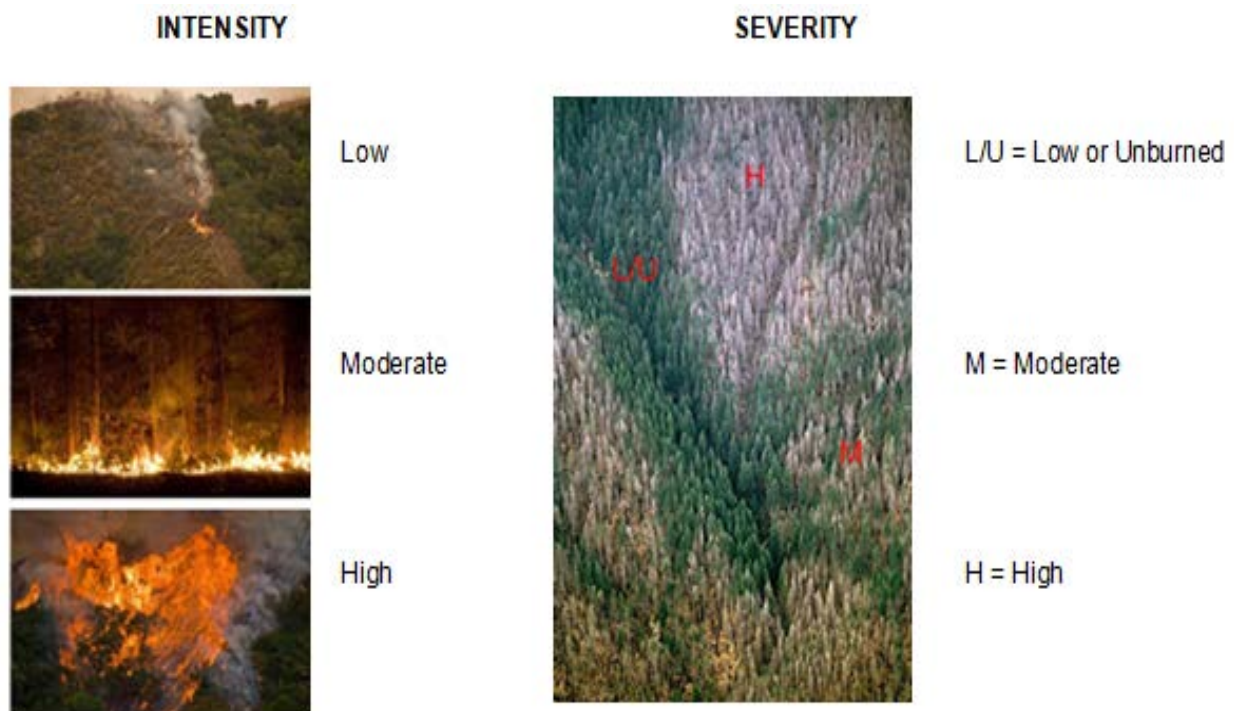


Figure 2.1: Fire intensity and fire severity (DellaSala, 2018)

Natural ignitions can include lightning strikes, spontaneous combustion, earthquakes, volcanoes, friction by rock falls and landslides as well as extra-terrestrial impacts (Belcher *et al.*, 2013; Costafreda-Aumedes *et al.*, 2017). Dry lightning conditions – where little rainfall occurs in the associated thunderstorms – are responsible for igniting many fires globally. It is estimated that more than 80% of the areas burned in Australia and Canada were caused by lightning ignited fires (Couto *et al.*, 2020).

Miller *et al.* (2019) point out that fires can be ignited by electrical infrastructure faults, arson, accidental escape through campfires and prescribed burns. Army manoeuvres and vehicle accidents may also be ignition sources of fires (Calviño-Cancela *et al.*, 2016). In addition, human-caused fires might be related to live-stock farming and carelessness (Costafreda-Aumedes *et al.*, 2017). Moreover, fires are ignited to clear forests for agricultural land in tropical regions such as Indonesia (Edwards *et al.*, 2020). Distance to infrastructure, roads and cities can also influence human ignitions of fire (Bajocco *et al.*, 2019). Costafreda-Aumedes *et al.* (2017) compared ignition variables on different timescales. Short-term fire occurrence was positively correlated to road

density, holidays, grasslands, shrubs, aspect, temperature, wind speed, fine fuel moisture code (FFMC), fire weather index (FWI) and drought moisture code (DMC). On the longer-term fire occurrence, they found positive relationships between fire events and annual precipitation, days without precipitation, topographic roughness, population density and wildland-urban interface (WUI) (Costafreda-Aumedes *et al.*, 2017). Fires are also lighted in natural parks and conservation areas by poachers to increase the amount of prey they catch (Brooke *et al.*, 2018). Local communities use fires to improve visibility, control pests, cultural rituals and to stimulate revegetation and flowering (Moura *et al.*, 2019). Bowman *et al.* (2011) points out that areas with low population densities may increase ignitions of fires – especially on islands – and therefore the high population density of an area does not necessarily lead to a higher occurrence of fire events.

Bento-Gonçalves *et al.* (2012) summarised three classifications for fire regimes, as indicated in Table 2.2 below. These classifications vary in the total number of fire regimes and rely on the impact of fire on vegetation, fire frequency and time as its scale of measurement.

Table 2.2: Fire regime classifications (Adapted from: Bento-Gonçalves *et al.* 2012)

Seven-class regime	Four-class regime	Five-class regime
Short-interval, stand replacement fires	Understory fire regime	0-35 year frequency and low to mixed severity
Short-interval, low-intensity surface fires	Stand replacement	0-35 year frequency and high severity
Variable interval, variable intensity fires	Mixed: both lethal and non-lethal to vegetation	35-100+ year frequency and mixed severity
Long interval, low-intensity surface fires	No fire regime	35-100+ year frequency and high severity
Long interval, high intensity surface fires		200+ year frequency and high severity
Very long interval, stand replacement fires		
Variable regime: both short interval, low intensity surface fires and long interval, stand replacement fires occur		

Various attempts have been made to simplify or generalise the factors influencing fires on different spatial and temporal scales. The literature is rich on ‘fire triangle’ depictions such as Figure 2.2 below reported by Mouritz *et al.* (2005). The drivers of fire generally refer to the essential requirements for fires to exist – from microscale to macroscale events. As seen in the figure, a small local fire requires oxygen, fuel and heat to exist. On a broader scale, a fire occurs with specific weather, fuel and topographic conditions. At a regional or biome scale, a fire regime can exist and fire events are governed by the climatic conditions, vegetation structures, and ignition sources and frequencies (Moritz *et al.* , 2005). This depiction places ‘ignition’ in a peculiar position. This position implies that ignition occurs at the bigger scale of the factor ‘topography’, whereas both of these factors are essential to the existence of fires. In addition, ‘vegetation’ is mentioned as the biggest in its class of variables, yet a fire lasting for days would require vegetation too.

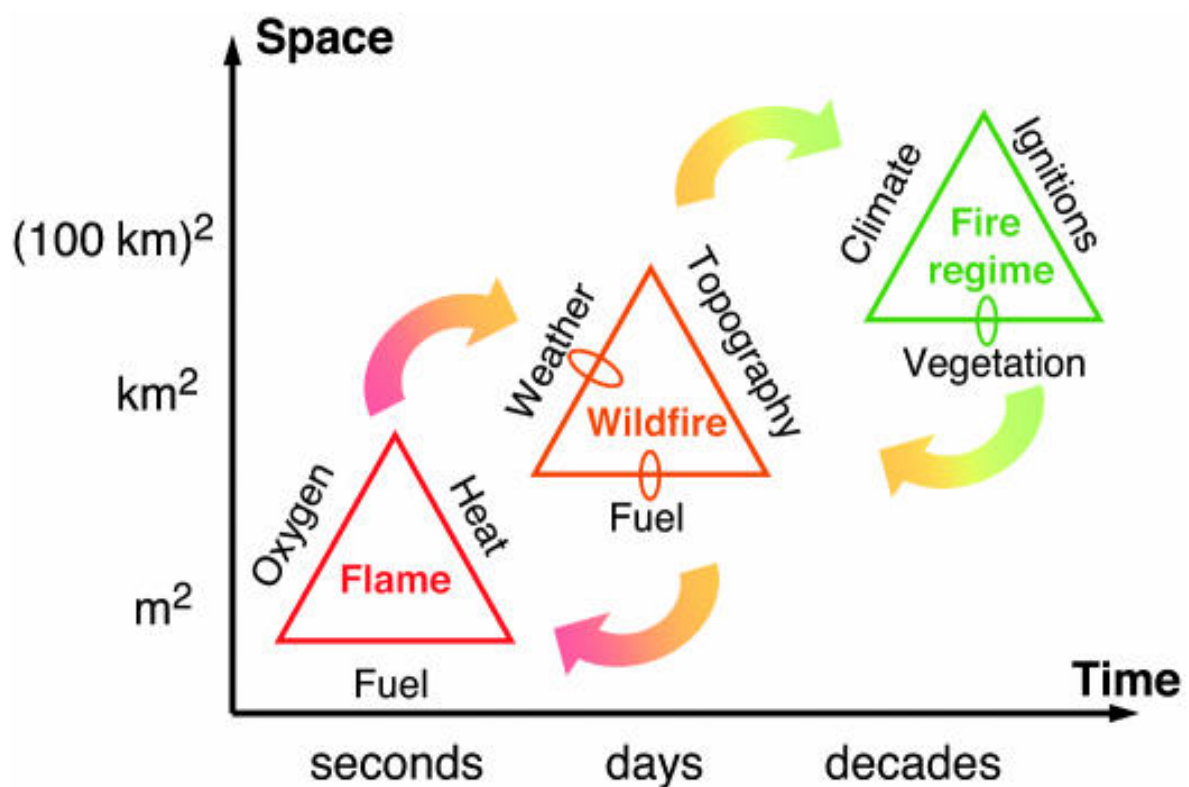


Figure 2.2: Key variables for the existence of fire at different scales (Moritz *et al.*, 2005)

The fire triangle concept has been adjusted by Gomes *et al.* (2018) to include landscape, land-use and microclimate, as shown in Figure 2.3 below. While this representation does well to provide more accurate terminology to distinguish between some of the factors (see for example: Microclimate → Weather → Climate), its representation of land use as the large-scale factor of topography does not make sense.

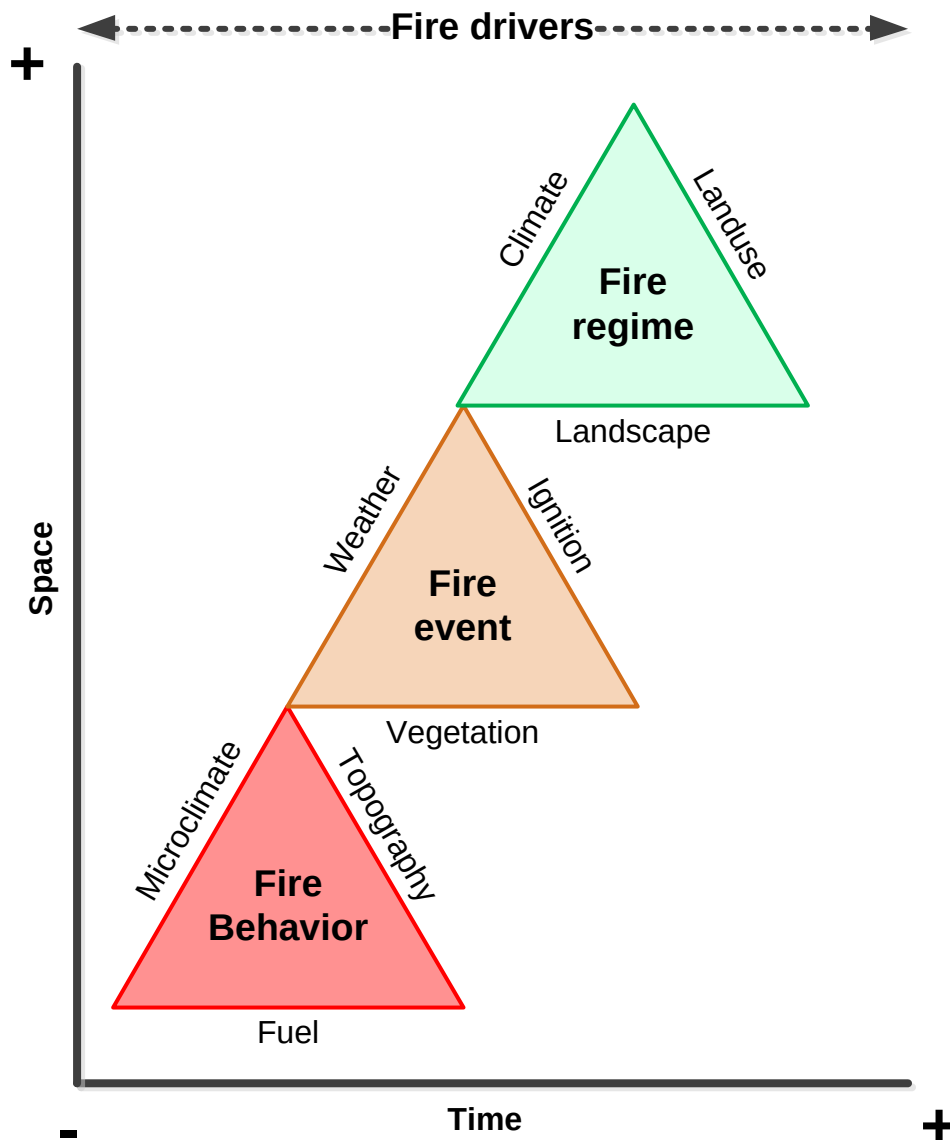


Figure 2.3: Alternative representation of fire triangle (Gomes *et al.*, 2018)

As the influence of humans and their role on not only climate and vegetation, but also on ignitions become more recognised, Bowman *et al.* (2011) developed an evolution of the fire triangle over time in Figure 2.4 below. This framework presents a more dynamic picture of fire occurrence over time, which includes the domestication of fire, plants and animals, agriculture, fire suppression and climate change. However, the role of topography is completely omitted in this representation.

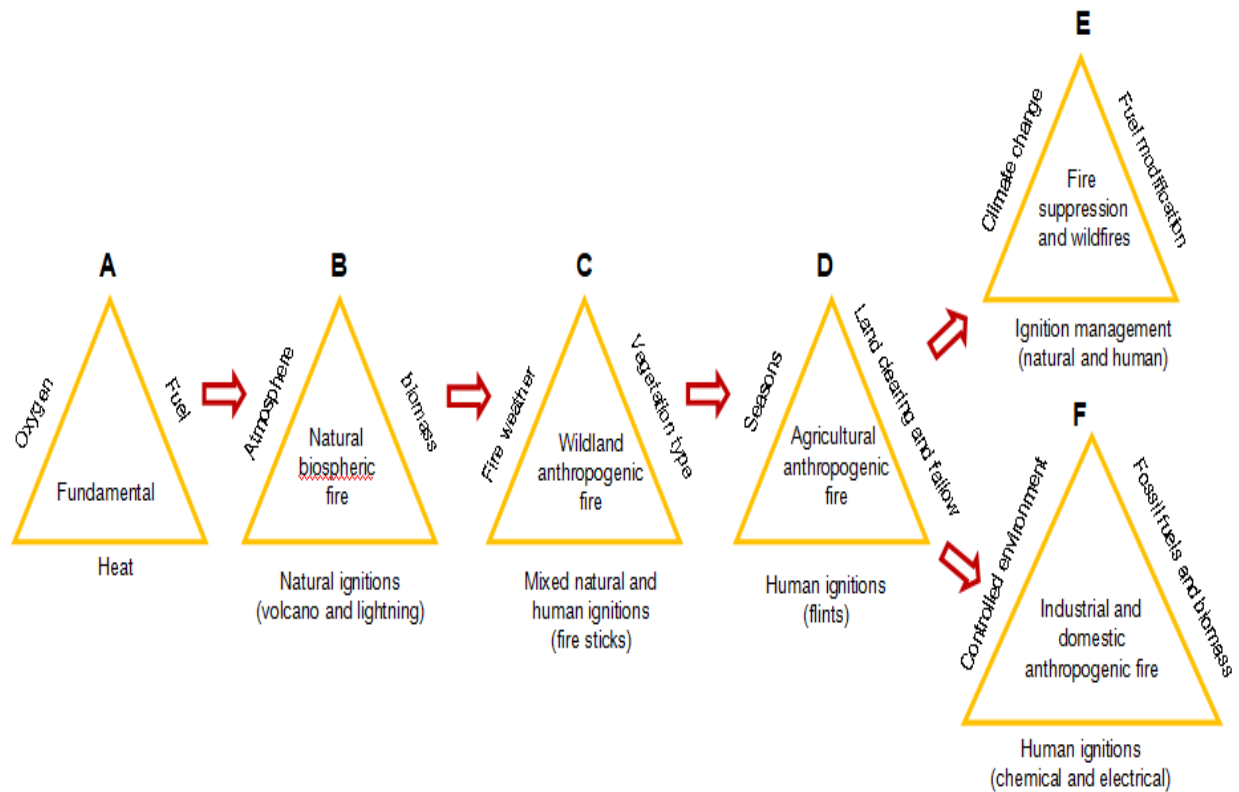


Figure 2.4: Evolution of the fire triangle (Bowman *et al.*, 2011)

Archibald *et al.* (2008) designed a model to portray the factors leading to fire events in the southern African savannas, depicted by Figure 2.5. The curious groupings of variables – especially weather variables – are problematic. For example, wind speed not only influences fire intensity, but also fire size and spread. Additionally, topography can influence wind speed and direction too.

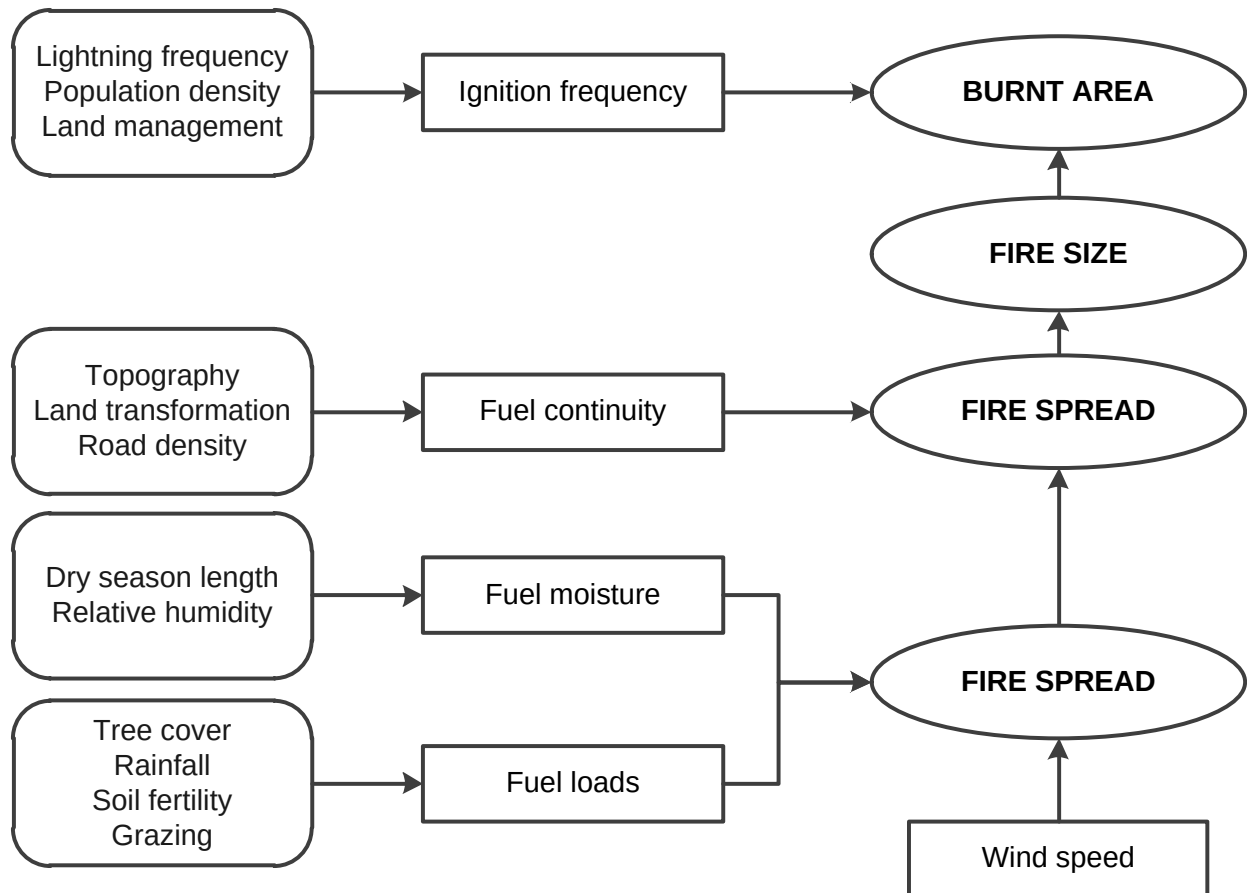


Figure 2.5: Factors affecting fires in savannas (Archibald *et al.*, 2008)

This thesis proposes a new conceptualisation of the fire regime concept. The rationale for this is to include factors that were disregarded and often underestimated in fire occurrence. Figure 2-6 below shows a depiction of this conceptualisation, which resembles a 'fire star'. It should be noted that all the different variables in the fire star can affect each other interchangeably. Five 'classes' of variables are included in this framework. The framework is further expanded upon through a clockwise discussion of these classes in the sections below.

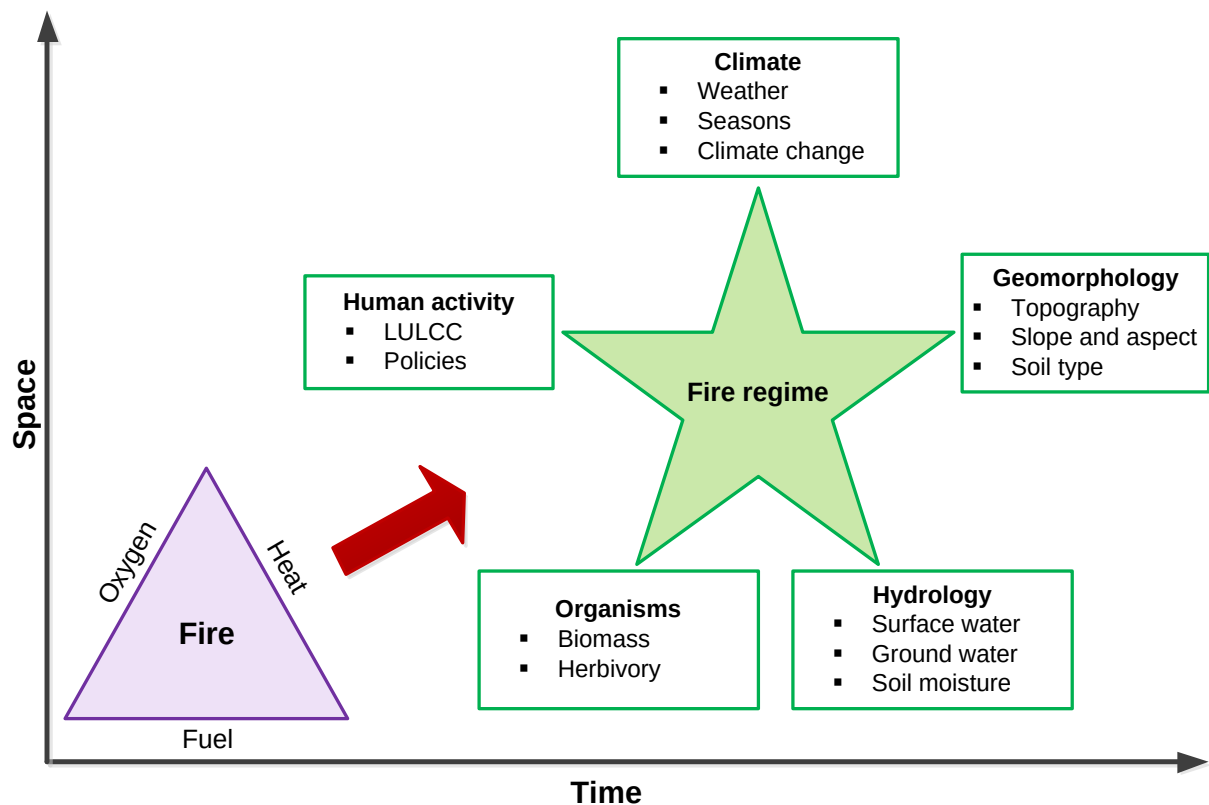


Figure 2.6: Fire regime conceptualisation

2.2.2 Climate

The role of climate in fire regimes is a contentious topic, with some authors claiming that either human activity or the properties and amounts of biomass play a more significant role in fire events than climate does (Archibald *et al.*, 2008; Kraaij *et al.*, 2018). The role of climate in fire regimes is discussed under the subdivisions of weather, seasons, and importantly, climate change.

2.2.2.1 Weather

Weather conditions play a significant role in the ignition and spread of fires. Planas and Pastor (2013) argue that the most important fire weather variables are:

- Air temperature
- Relative humidity
- Solar radiation
- Atmospheric stability
- Wind direction and speed

Weather affects the moisture levels of vegetation (Amatulli *et al.* 2013). Variables of fire weather can include relative humidity, wind velocity and ambient temperature (Bedia *et al.* , 2015). The flammability of vegetation is not only greatly dependent upon the moisture content of plants and dead organic matter, but also on the prevailing short-term weather conditions in the days before a fire event occurs (Duane and Brotons, 2018). Fire events tend to occur on days with strong winds, low relative humidity and high temperatures (Duane and Brotons, 2018).

Extraordinarily little is understood about the role of synoptic weather systems on fire size, location, frequency and spread over time. However, the characterisation of weather conditions – air pressure, temperature, wind velocity and direction, and precipitation – at large spatial scales into synoptic weather types (SWTs) can significantly improve our understanding of current, and prediction of future fire events. Moreover, certain SWTs enhance the development and reliability of fire weather indices, especially with regard to future climatic changes (Duane and Brotons, 2018).

Hayasaka *et al.* (2019) found a strong correlation between fire events in Alaska and the prevailing HP weather systems that bring subsiding, dry air to the surface. The occurrence of HP systems and ridges can become more prominent with climate change in this region (Hayasaka *et al.*, 2016). Large fire events in Mediterranean Europe are closely related to SWTs conducive of strong winds, prolonged drought events and unexpected warm episodes (Rodrigues *et al.*, 2020).

2.2.2.2 Fire seasons

Fire seasons refer to times when fires are more likely to occur. Overall, fuel moisture and weather conditions govern the fire seasonality of a region (Bajocco *et al.*, 2020). Teleconnections such as the El Niño Southern Oscillation (ENSO) and the Southern Annular Mode (SAM) play a significant role in fire seasons where the frequency of large fires increases during dry and warm periods. Regions experiencing hot and dry weather along with strong surface winds may be prone to large fires and burnt areas. When a region experiences high temperatures and below-normal precipitation, the occurrence of droughts can lead to an accumulation of dry vegetation, reduced soil moisture conditions and can increase the flammability of the landscape (Rasilla *et al.*, 2010; Turquety, 2013). Edwards *et al.* (2020) found a strong relationship between an increase in fire events and the dry period of the ENSO in Indonesia. This correlates with the findings of Cattau *et al.* (2016) in their research on peatland fires in Indonesia. In terms of megafires, Rein (2013) reports that approximately 2.57 Gt and 23-76 Mt of carbon gases were emitted by the 1997 and 2006 El Niño events on the Indonesian island of Borneo.

Oscillations in SAM phases can bring about latitudinal shifts in the Southern Hemisphere southwesterlies which affect precipitation in Australia, South America and southern Africa. During the positive SAM phase, the southwesterlies contract towards Antarctica and brings about an expansion of the subtropical HP systems across the southern hemisphere. This means that weather systems associated with the southwesterlies are also shifted more southward than usual. However, during negative SAM phases, the southwesterlies expand towards the tropics, bringing about a northward shift in weather systems (Mariani and Fletcher 2016). While Wang *et al.* (2022) and Squire *et al.* (2021) found correlations between fire events and negative SAM phases in south-eastern and eastern Australia respectively, Holz and Veblen (2011) provide evidence that positive SAM phases contributed to fire events in Patagonia, South America. In addition, Mariani and Fletcher (2016) argue that positive SAM phases coincide with increased fire events in Tasmania, Australia. Moreover, a significant relationship was found between fire events and positive phases of SAM, the Indian Ocean Dipole (IOD) and ENSO (Mariani *et al.*, 2018). The current warming phase of climate change is projected to swing the SAM to more frequent positive phases, which may lead to more drought conditions and potentially increase fire events (Holz and Veblen, 2011; Ibebuchi and Paeth 2021).

2.2.2.3 Climate change

In the past, changes to fire regimes were related to extinctions of herbivores, atmospheric oxygen (O₂) and carbon dioxide (CO₂) levels (Chergui *et al.*, 2018). However, currently, human-enhanced climate change is expected to not only increase extreme weather conditions, but also to extend fire seasons. The intensity and frequency of fires are also predicted to increase (Burton *et al.*, 2019; Filkov *et al.*, 2020). Significant amounts of air pollution – particularly carbon-based substances, such as carbon oxides (CO_x) and methane (CH₄) – are emitted by fires. Additionally, fires also emit precursor gases of ozone production (Dhandapani and Evers, 2020; Edwards *et al.*, 2020; Turquety 2013). Even though it is difficult to quantify the gases emitted by fires globally, Turquety (2013) attempts to explain the role of these emissions on changes in climate. Aerosols may either absorb or scatter radiation – which affects the surface albedo (Turquety, 2013). Deforestation may lead to longer dry seasons, which can increase the flammability of the landscape, as documented in the Amazon forests (Belcher *et al.*, 2013).

Anticyclonic circulations during warm and dry seasons are expected to increase with climate change, thereby creating more heatwave conditions (leading to fire) (Duane *et al.*, 2019). Increased fire activity may alter vegetation compositions of biomes, especially for species reliant on fire for regeneration (Burton *et al.*, 2019). Higher temperatures reduce the levels of water tables

and increase rates of evapotranspiration, thereby decreasing soil and vegetation moisture content. This enhances the flammability of fuels (Flannigan *et al.*, 2013).

Several models have projected an increase in fire risk as the Mediterranean region is expected to experience warmer and drier weather conditions coupled with more heatwave episodes (Amraoui *et al.*, 2015). In fact, Jiménez-Ruano *et al.* (2020) report that Mediterranean Europe experienced its warmest fire season in 2018. Dupire *et al.* (2017) predict that the frequency and intensity of fire danger days will increase in the French Alpine region as a result of climate change. Heatwave conditions and droughts in summer have been positively linked to the occurrence of large fires in Greece (Gouveia *et al.*, 2016). Liu and Wemberly (2016) project that climate change will increase the amount of flammable vegetation in the western parts of the USA, thereby creating a more flammable landscape with more frequent and severe fires. The Cerrado grasslands in Brazil will experience more extreme weather conditions and droughts as a result of climate change and will therefore experience more severe fires (Silva *et al.*, 2019). Tan *et al.* (2019) report that climate change in boreal regions – especially in the Rocky Mountains – is causing increased temperatures in summer and spring as well as shifting the spring snowmelt to earlier in the season. These events can increase the number of fire danger days in Canada (Tan *et al.*, 2019).

2.2.3 Geomorphology and hydrology

Landforms can have a significant effect on not only fire weather conditions but also on the production of biomass. For example, canyons and steep-sided ravines can increase local wind speeds. Slope and aspect may also play a significant role in soil and fuel moisture conditions, depending on the amount of solar radiation. Slopes receiving more solar radiation are generally drier, thereby creating ideal conditions for grassy vegetation. In contrast, slopes receiving less solar radiation may contain more moisture and therefore host more woody plant species. The result of this may affect fire intensity, spread, and fire type (MacGranahan and Wonkka 2021).

The amount of rocks and the topography of a landscape can play major roles in fire temperature and oxygen supply (via local winds) (Rebelo *et al.*, 2011). Fires can enhance or alter mass movement processes such as landslides, debris flows and soil creep (Doerr and Shakesby, 2013). Rocks that are exposed to fires may experience extreme temperature gradients, which result in thermal expansion (physical weathering) (Doerr and Shakesby, 2013). Stine (2016) reports that fires can alter weathering, erosion and runoff rates, and soil properties. According to Dhandapani and Evers (2020) fires can increase soil pH levels and macronutrients; however, it may also lead to a loss of carbon and redox potential. Fires with a temperature between 270 and 400°C may disrupt the soil structure as organic material undergoes oxidation. This increases the erodibility of

the soil. In addition, fire can affect the soil carbon balance (Doerr and Shakesby 2013). Doerr and Shakesby (2013) point out that areas with high amounts of soil moisture are less likely to burn as the moisture has to be evaporated before the vegetation can be ignited.

Water quality of freshwater bodies may become subject to increases in sedimentation and eutrophication in the aftermath of a fire event (Eskandari *et al.*, 2020). The most significant aspect of hydrological disturbances from fire events is soil water repellence. Burnt areas experience lower infiltration rates than unburnt areas do. This may be due to an absence of organic matter, which reduces surface water and increases run-off (Doerr and Shakesby, 2013).

2.2.4 Organisms

The properties of vegetation or fuel are essential in understanding its role in fires. These properties are depicted by Table 2.3 from Planas and Pastor (2013). While fuel moisture content and fuel bed or fuel arrangement are often highlighted as the most important characteristics influencing fires, it is interesting to note the other fuel properties that are often overlooked by the literature.

Table 2.3: Fuel characteristics influencing fire behaviour (Planas and Pastor 2013)

Intrinsic fuel properties	Extrinsic fuel properties	Fuel state
Chemical composition	Fuel load	Fuel moisture content
Density	Shape and size	Live to dead fuel ratio
Thermal properties: • Conductivity • Heat capacity • Heat of combustion	Bulk density and compactness	
	Fuel arrangement	

Fuels are also classified according to size by a surface area:volume ratio (MacGranahan and Wonkka, 2021). This classification includes the categories as indicated in Table 2.4 below:

Table 2.4: Fuel sizes (Adapted from MacGranahan and Wonkka 2021)

Time	Particle diameter
1 hour	<0.6 cm
10 hours	0.6-2.5 cm
100 hours	2.5-7.6 cm

Fuel moisture plays a vital role in fire events. Not only does fuel moisture fluctuate diurnally, but also seasonally. Additionally, the moisture contained in live plant materials slows down the ignition of the fuel bed. The fuel bed refers to the three-dimensional structure of plant material, which affects not only the combustion of materials, but also the spread of fires (MacGranahan and Wonkka 2021). Small fuel particles are easier to burn as they have a more porous texture (Planas and Pastor, 2013).

The flammability of a landscape is defined as a “group of plant characteristics that influence fire probability and behaviour” (Burton *et al.*, 2019:2). Flammability can be determined by leaf size, leaf moisture content, dead leaves on the surface and secondary chemical compounds (Midgley and Bond 2013). Moreover, fire spread is determined by the continuity of fuel (Argibay *et al.*, 2020). Herbivores can affect the fuel bed in terms of fuel load, size and connectivity (MacGranahan and Wonkka 2021). Moreover, they change species composition and structure of vegetation (Rebelo *et al.*, 2011).

Fire regimes are often considered to be either climate-driven or fuel driven (Bedia *et al.*, 2015). Several biomes are prone to sporadic large fire events that represent the majority of fire activity over time (Bedia *et al.*, 2015). The spatial distribution of fires is dependent on the relationship between fuel-limited and climate-limited fire landscapes. This is sometimes also referred to as the productivity and aridity gradient. Climate-limited areas are considered as highly productive systems – in terms of vegetation – and also areas where significant amounts of precipitation curb the occurrence of fire, for example tropical rainforests. On the other hand, arid areas – such as deserts – receive low amounts of precipitation and therefore have a low productivity of vegetation, limiting the amount of fuel that can be burnt. However, biomes experiencing distinct seasonality in terms of precipitation and temperature provide ideal conditions for fires to occur – two primary examples are the savanna and Mediterranean biomes (Prichard *et al.*, 2017). The human influence on the distribution of fire has altered the representation of this spatial distribution of fires

to such an extent that areas previously regarded as 'climate-limited' or 'fuel-limited' have become more fire prone as indicated by Figure 2.7 (Mcwethy *et al.*, 2013).

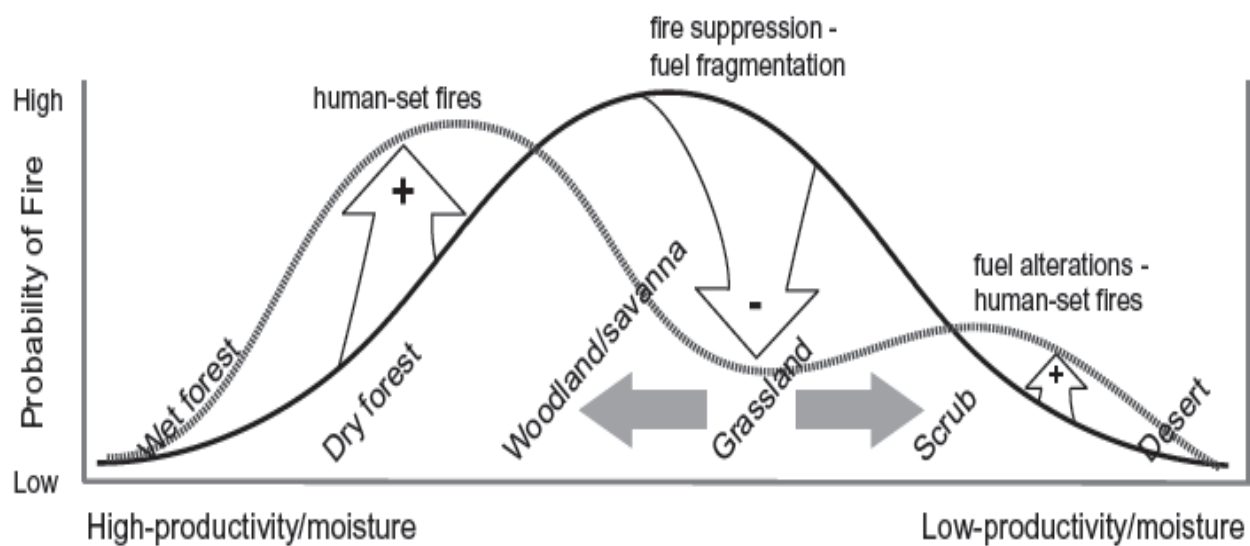


Figure 2.7: Fire probability across various landscapes (Mcwethy *et al.*, 2013)

According to Midgley and Bond (2013), fires lead to the abundance of C4 grasses (species adapted to grow in warm seasons) in tropical savannas. Other impacts of fires on plants include post-fire germination, re-sprouting and flowering (Midgley and Bond 2013). Alvarado *et al.* (2017) state that the fire regimes in African savannas are controlled by fuel availability, whereas those occurring in savannas in South America are moisture dependent.

The diversity of fire regimes worldwide is largely determined by precipitation, droughts and seasonality (Argibay *et al.*, 2020). Biomes across the world are experiencing more fires as the global ambient temperatures increase. Significant increases in the burned area of tropical rainforests, savannas, Australian eucalypt forests, boreal forests, and forests in the western USA have been recorded recently (Prichard *et al.*, 2017). Cattau *et al.* (2016) notes that the two regions most sensitive to disturbances brought by fire are tropical and subtropical forests.

Drivers of fire on semi-arid and arid ecosystems include drought, invasion of alien species, fire management policies, livestock farming and climate change (Aslan *et al.*, 2018). Generally, the occurrence of fires has been rare in semi-arid and arid ecosystems due to their limited fuel loads. However, an increase in fuel load due to an invasion of grass species can drastically increase fire events and severity. Examples of this phenomenon are increased fires in the USA due to the invasive *Bromus tectorum* and *Pennisetum ciliare* grass species. Additionally, some invasive grass species in Mexico and Australia display a short return growth periods that also increase fire frequency (Aslan *et al.*, 2018).

Laris *et al.* (2018) estimate that approximately 2.8 million km² of savannas are burned annually, making this the biome with the most burned area. In spite of its continuous fuel bed with flammable materials, savanna fires tend to occur in patches (Laris *et al.* 2018). Savanna fires occurring in the late dry season (LDS) are more detrimental to tree species than early dry season (EDS) fires. However, the last few decades have seen a significant trend towards LDS fires in this biome (Schmidt and Eloy, 2020). Prichard *et al.* (2017) report that the invasion of alien grass species *Urochloa mutical* and *Andropogon gahyanus* are increasing the flammability, size and spread of fires in the savanna in Australia. According to Archibald (2016), the replacement of large herbivores by cattle and livestock has increased the burned areas in wet savannas in Africa.

2.2.5 Human activities

The role of human activities in fire regimes mostly relates to LULCC and fire management policies. However, fire management policies often rely on the prediction of fire danger, and therefore the prediction of fires through weather indices is also considered here.

2.2.5.1 LULCC

While it is important to take note of the biophysical variables of fire regimes, the role of humans has become more evident over time. Human activities through habitat fragmentation, warfare, introduction of IAS, deforestation, erection of artificial barriers, treatment of fuels and patch burning play a significant role in altering fire regimes (Bowman *et al.*, 2011). Changes to fire regimes from human activities before and after the Industrial Revolution are compared in Table 2.5 below. According to their synthesis, Bowman *et al.* (2011) contend that fires have increased across the globe in most of the biomes – with the exception of tropical savannas.

Table 2.5: Changes in fire regimes across biomes are summarised by (Bowman *et al.*, 2011)

Biome	Pre-industrial fire regime	Post-industrial fire regime
Tropical rain forest	Very infrequent, low-intensity fires with negligible long-term effects on biodiversity	Frequent surface fires associated with forest clearance causing a switch to flammable grassland or agricultural fields
Tropical savanna	Frequent fires in dry season, causing spatial heterogeneity in tree density	Reduced fire due to heavy grazing causing increased woody species recruitment

Biome	Pre-industrial fire regime	Post-industrial fire regime
Mid-latitude desert	Infrequent fires following wet periods that enable fuel build-up	Frequent fires due to introduction of alien flammable grasses
Mid-latitude North American seasonally dry forests	Frequent, low-intensity surface fires limiting recruitment of trees	Fire suppression causing high densities of juveniles and infrequent high-intensity crown fires
Boreal forest	Infrequent high-intensity crown fires causing replacement of entire forest stands	Increased high intensity wildfires associated with global warming causing loss of soil carbon and switch to treeless vegetation

In the 20th century, humans have implemented fire-suppression policies that created build-up of fuel, thereby altering fire seasons (Holsinger *et al.* 2016; Batista *et al.*, 2018).

Zones where urban areas lie within close proximity of natural landscapes are often referred to as the wildland urban interface (WUI). As human-caused ignitions of fire may increase with an increase in population density, WUIs are becoming essential in fire management (Calviño-Cancela *et al.*, 2016). In addition, Damasceno and Fidelis (2020) report that invasive species can outcompete indigenous species in a fire-prone landscape.

Forestry and logging activities may also affect fire regimes. Forestry may increase the number of large fuels and increase the likelihood of crown fires, whereas logging can reduce crown fire events (MacGranahan and Wonkka, 2021).

Bajocco *et al.* (2019) contend that human activities are virtually solely responsible for fire ignitions in Mediterranean Europe and it has overcome the role of climate in fire regimes. San-Miguel-Ayanz *et al.* (2013) report that the establishment of holiday homes in rural areas has increased the WUI and ignition probability in Mediterranean Europe. The maintenance of seasonal fires in Mediterranean Europe provided employment opportunities and subsequent lack of fire management is closely related to fire events in the region. Disputes over land use and ownership are also linked to fire occurrence in Spain and Portugal (San-Miguel-Ayanz *et al.*, 2013). LULCCs such as afforestation, abandonment of agricultural land and urbanisation have increased fire hazards and fire events in the northern and western parts of the Mediterranean recently (Viedma *et al.*, 2017).

Calef *et al.* (2017) point out that even though human-caused fire ignitions in Alaska have decreased, there has been an increase in the duration of fire events and the burned area.

A reluctance to enforce environmental laws together with political encouragements of deforestation played a significant role in the 2019 widespread fires in Brazil (Schmidt and Eloy, 2020).

2.2.5.2 Fire danger ratings

San-Miguel-Ayanz *et al.* (2013) state that even though substantial efforts and resources were used to fight the large fire events in Greece, Spain and Portugal, the fires were only contained once the fire danger conditions diminished. It is therefore important to consider the variables related to fire danger via fire weather indices (FWI), regional weather and climate phenomena and the impact of climate change on fire occurrence.

Fire weather indices (FWI) are valuable tools in providing fire danger information for present and future fires (Bedia *et al.*, 2015). One index developed to forecast fires and their spread is the Canadian Forest Fire Weather Index (CFFWI) (Amatulli *et al.*, 2013). Figure 2.8 below illustrates the relationship between the variables of this index (Carvalho *et al.*, 2011) which include wind, temperature, relative humidity and precipitation. These variables are then used to calculate important fuel moisture codes, such as the drought code (DC), fine fuel moisture code (FFMC) and the Duff moisture code (DMC). From the fuel moisture codes, fire behaviour indices – initial spread index (ISI) and build-up index (BUI) – are used to calculate the fire weather index (FWI) (Carvalho *et al.*, 2011).

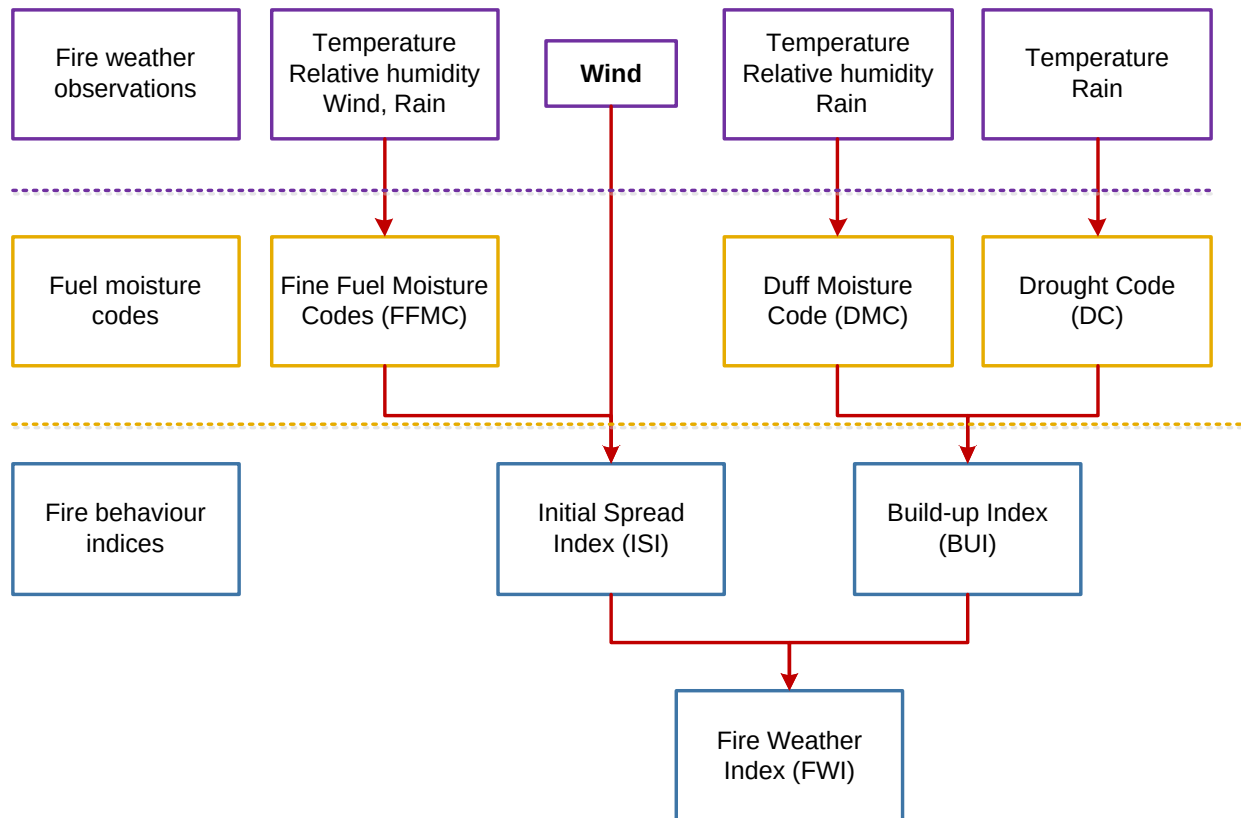


Figure 2.8: Components of the CFWI (Carvalho *et al.* 2011)

The McArthur forest fire danger index (FFDI) relies on variables such as relative humidity, precipitation, wind velocity, air temperature and soil moisture deficit. Mount's soil dryness index (SDI) or Keeth Byram's drought index (KBDI) are used to calculate the soil moisture deficit (Clarke *et al.*, 2019). There is a strong correlation between soil moisture conditions and fuel moisture and therefore it is important to include soil moisture variables in fire weather indices (Häusler *et al.*, 2019).

FWIs often rely on fuel models and the characterisation of fuels. Planas and Pastor (2013) summarised the fuel models used in FWI and fire danger predictions in the US, Canada and Australia in Table 2.6 below.

Table 2.6: Fuel characteristics in different models (Adapted from Planas and Pastor, 2013)

US	Canada	Australia
7 categories of fuel types: • Non-burnable • Grass • Grass-shrub • Shrub • Timber-understorey • Timber litter • Slash-blowdown	6 fuel-bed strata: • Canopy - o Trees - o Snags - o Ladder fuels • Shrub - o Primary layer and secondary layer • Non-woody fuels - o Primary layer and secondary layer • Woody fuels - o All woody - o Sound wood - o Rotten wood - o Stumps - o Woody fuel accumulation • Litter - o Litter - o Lichen - o Moss • Ground fuels - o Duff - o Squirrel middens - o Basal accumulations	5 layers of vegetation: • Surface - o Leaf - o Twigs - o Bark • Near-surface - o Grasses - o Low shrubs - o Creepers - o Collapsed understorey • Elevated - o Tall shrubs • Intermediate tree and canopy - o Trees with crowns below or extending into the crowns of the overstorey trees • Overstorey tree and canopy - o Uppermost canopy of the forest
Fuel parameters: • Fuel load by size and category (live and dead) • Surface area-to-volume ratio (SAV) for live woody, live herbaceous and dead fuels with diameter <0.6 cm • Fuel-bed depth • Dead fuel extinction moisture content • Heat content of live and dead fuels	Fuel parameters: • Percentage cover • Height • Foliar moisture content • Density • Diameter • Width • Length • Depth • Species (canopy)	4 Attributes are considered when assessing hazard score: • Thickness of fuel elements • Degree of horizontal and vertical continuity • Proportion of dead fine fuel in fuel bed • Height of the most continuous stratum

2.2.5.3 Fire management policies

Fire management strategies are nowadays focused on sustainable fuel management to improve ecosystem resilience. One fuel management technique is prescribed burning. Duane *et al.* (2019:69) define prescribed burning as “...the planned use of fire to achieve defined objectives.” Its main intention is to limit the impacts, or severity of fires (Hiers *et al.* , 2020) However, the efficiency of prescribed burning is contentious and difficult to quantify (Duane *et al.* , 2019).

Human interventions in fire regimes – most notably land use and land cover change (LULCC) and fire suppression policies – have made landscapes more susceptible to fires from unexpected weather events. The perception of fires as agents of environmental degradation influenced the widespread adoption of fire suppression policies across the globe. While advancements in biogeographical knowledge have proven the important role of fires in ecosystems, some conservation areas in Brazil are still managed by zero-fire management practices (Fidelis *et al.* , 2018). Emotional reporting of the 2019-2020 fires in Australia also added fuel to the perception that fires are mainly negative agents of ecosystems (Fidelis, 2020). In addition, fire suppression policies do not significantly reduce the aftermath of large intensity fires (Duane *et al.* , 2019). Fire suppression often leads to an accumulation of fuel that cause large fires with significant impacts on human lives and the environment. Furthermore, large fires become more frequent with the growth of the WUI, population increases and widespread occurrence of invasive alien plants (Kraaij *et al.* , 2018).

Fire suppression policies were prevalent in Mediterranean Europe over the last few decades (Aquilué *et al.* , 2020). Jiménez-Ruano *et al.* (2020) note that budgets for fire management – specifically prevention and suppression of fire – are increasing in the USA and EU. Therefore, decision-makers in these administrative regions are expecting an increase in fire events in the near future.

Aslan *et al.* (2018) compared the changes in fire dynamics of a few biomes. They contend that fire suppression in the savannas and grasslands leads to encroachment of woody vegetation that will increase severe fire events and high-intensity fires. The forest biomes can also expect an increase in large and severe fires as a consequence of fire exclusion policies and accumulation of flammable materials. The invasion of alien grass species in arid and semi-arid ecosystems can increase fire size, frequency and intensity in the future (Aslan *et al.* , 2018). According to Viedma *et al.* (2017), fire management issues in tropical ecosystems and forests are related to exclusion of fires, and in Mediterranean Europe, it is related to a decrease in prescribed burning in rural areas.

The Brazilian Cerrado biome has been managed under integrated fire management approaches since 2012. These strategies aim to protect both livelihoods and biodiversity by promoting artificial fires that mirror natural fire events. Therefore, a heterogeneous mosaic landscape is created – curbing the impact of intense, LDS fires (Franke *et al.*, 2018).

The management of fires have changed in certain areas, such as those in the Kruger National Park, South Africa – located in the African savanna biome. The fire management policies are summarised in Table 2.7 below and entail an evolution from no policy to an adaptive management strategy. Attorre *et al.* (2015) summarised the changes in fire management policies in the Kruger National Park, South Africa – located in the African savanna biome below:

Table 2.7: Fire management policies in KNP (Attorre *et al.*, 2015)

Period	Fire policy	Description
1926-1947	No official policy	Following the creation of the Park (in 1926), areas were occasionally burnt mainly to provide new fodder for grazing.
1948-1956	Fire exclusion	From 1948, a fire-suppression policy was implemented that, however, led to some very large and dangerous fires.
1957-1980	Fixed prescribed burning system	In 1957, regular prescribed burnings were applied at three-year cycles on fixed areas (454 burning blocks) during the spring. The policy was aimed at assuring 'cold' fires in order to minimise damage to flora and fauna. However, it led to some unexpected effects such as the growing dominance of species of grass characteristic of very poorly managed range and a decline in large tree densities.
1981-1991	Flexible burning system	Fires in burning blocks were timed to account for fuel loads, post-fire age, and mean annual rainfall, and it was meant to encourage a more variable fire return interval, a longer fire return interval in drier areas and a wider seasonal distribution of fires.
1992-2001	'Natural' (lightning-driven) fire regime	All lightning-ignited fires were allowed to burn freely, while other fires were to be suppressed looking for a more variable, less intense and more 'natural' fire regime.

Period	Fire policy	Description
2002-2011	Adaptive management	A 2001 assessment of the nine years of 'natural' fire management made clear that the objectives of that policy were not being achieved, and that the anthropogenic ignitions dominated over the lightning ones. Therefore, the lightning-driven 'natural' policy was replaced by an 'adaptive' approach, entailing patch ignitions tailored on biomass and two-year preceding rainfall (see the text for major detail), whose implementation was monitored through a set of thresholds of potential concern (TCPs) for the entire Park.
2012-present	Adaptive management; implemented by fire zones	Still patch-mosaic fires, as during the preceding policy, but with fire objectives, associated TCPs and management actions now variable for ecologically delineated management zones (i.e. delineation based on historical fire frequency, rainfall and geology)

2.3 SOUTHERN AFRICA

Marumbwa *et al.* (2019) analysed rainfall trends across various biomes in southern Africa for the period 1981-2016. They detected an overall decrease in rainfall in the tropical rainforest, desert, Succulent Karoo, Nama Karoo and Fynbos biomes. This corresponds with the models developed by Almazroui *et al.* (2020), which predict a warmer and drier future for the western parts of southern Africa. However, the analysis from Marumbwa *et al.* (2019) shows a trend of increasing rainfall in the western and central savanna biome.

Du Toit *et al.* (2015) studied fire events in the Nama-Karoo biome and argue that the forecasted encroachment of grass species from other biomes may not occur due to fire activity.

According to Archibald (2016), a warmer climate will result in a decrease of fire activity, especially in the Fynbos and savanna biomes. She contends that high temperatures and decreased precipitation will lead to a reduction in biomass (fuel), thereby limiting the number of fire events (Archibald, 2016).

Kraaij *et al.* (2018) claim that the role of humans in fire regimes may supersede the role of climate in fire events. Additionally, it is maintained that climate change is 'blamed' for an increase in fire activity (Kraaij *et al.*, 2018). Gillson *et al.* (2020) assert that due to its intrinsic properties, many Fynbos species are resilient to dry conditions and therefore may not be significantly reduced by a warming climate.

Brooke *et al.* (2018) established a 10-year fire regime (2007 to 2016) for the Pondoland-Ugu Sandstone Coastal Grassland along the Indian Ocean Coastal Belt. Their focus was on fire size, frequency, seasonality and human-caused ignitions (2007 to 2016) (Brooke *et al.*, 2018). In their study, a fire danger index (FDI) was compiled from weather variables (relative humidity, maximum temperature, rainfall and average wind speed) measured at a station 30 km northeast of the study area. This method of extracting weather variables may not be representative of the local weather conditions as the study site is located in an area with an undulating landscape and steep river gorges (Mucina and Rutherford *et al.* 2011). Therefore, the role of both climate and geomorphology on the fires at the chosen location is greatly undervalued and underestimated by Brooke *et al.* (2018).

2.4 MAPPING FIRES

Creating maps of fire events holds its own set of challenges due to the complexity and multitude of parameters affecting fires and fire activity, as discussed above. Fires were traditionally mapped according to fuel types by making use of aerial photo interpretations, field surveys and ecological modelling. While each of these methods have their own advantages, mapping fires according to fuel types are complex activities that can become expensive and very time consuming. The potential of using remote sensing techniques to improve upon the mapping of fire events was recognized during the 1960s (Aroyo *et al.*, 2008). One of the biggest advantages of using remote sensing to map fires is the ability of these techniques to cover large spatial and temporal scales, enabling time-series analyses. Other advantages include free, open-accessed data with high spatial resolution and using satellites with multispectral sensors. Disadvantages of using remote sensing for fire mapping include the differences in spatial resolution from different satellites and the lack of canopy penetration with regards to forest fires (Szpakowski and Jensen, 2019). Nevertheless, a number of variables and factors influencing fire events can be mapped with remote sensing techniques such as topography, vegetation cover, roads, urban areas and meteorology (Çolak and Sunar, 2020). Recently, advances in the processing of large datasets and cloud computing mechanisms have been deployed to improve upon the mapping of fires from remotely sensed data. Bui *et al.* (2018) illustrated a method to use machine learning methods on remotely sensed data in order to predict future forest fires. Further explanation of the remote sensing methods employed by this study are discussed in the following chapter.

2.5 SUMMARY

In summary, fires occur most frequently in savanna and Mediterranean biomes. However, human activities have altered vegetation, the biophysical landscape and climate to such an extent that

other biomes are increasingly exposed to more frequent fire events. In fact, some authors contend that the human influence on fire regimes has become more prominent than the role of climate.

Drivers of fire are dependent upon the vegetation (fuel), climate (oxygen) and ignition sources (heat). These drivers are dynamic and subject to change through climatic, vegetation and human activities. In order to predict the occurrence and spread of fire events, classifications have been made to group fires into fire regimes. One recent fire regime classification uses fire frequency and the severity of fire on vegetation as its classification criteria. A new framework for understanding fire regimes has been proposed. This framework includes the often-overlooked variables – such as the geomorphology and hydrology of an area. While geomorphology is often presented by only topography, other important processes, including mass wasting, weathering and soil properties, do not receive sufficient attention in the literature. Additionally, the disagreement about which driver of fire is the most significant will need further exploration. In southern Africa, research conducted on fire events seems to be conducted mostly from an ecological perspective (Archibald, *et al.*, 2016, Du Toit, 2015; Brooke *et al.*, 2018; Kraaij *et al.*, 2018), that often undermines the role of climate, geomorphology and hydrology of an area. Furthermore, the role of seasonality through ENSO cycles and climate change must be evaluated and considered more closely when synthesising fire events – especially those events that receive national and international attention through popular media publications.

CHAPTER 3 METHODOLOGY

3.1 INTRODUCTION

This methodology chapter presents the data collection and data analysis techniques as well as a description of the study areas. Traditionally, data from remotely sensed products had been expensive, inaccessible, and restricted to the government agencies who acted as custodians of the data. However, since 2008, there has been a concerted effort to improve not only access to the data but also to make it freely available – most notably Landsat data from the United States Geological Survey (USGS). Additionally, websites and tools to manipulate remote sensing data were developed and these combined efforts led to a substantial increase in the use of satellite products in academic publications (Turner *et al.*, 2015). With the improved access to high quality data from freely available web portals, the researcher used almost exclusively open-sourced data and software for this study. This due to the ease of access and time required to find reliable and accurate datasets. Data collection and analyses techniques are discussed below for the study area, fire data, climate and weather data and remotely sensed images.

3.2 STUDY AREA

This section details how maps were generated for the study area as well as a description of the study area.

3.2.1 Study Area Maps

The NASA SRTM Digital Elevation 30m dataset was downloaded from the USGS portal (NASA SRTM 2022). The elevation data was then opened and merged using Quantum GIS (QGIS) version 3.24.3 software in order display the topography across South Africa. This particular dataset was selected as it is an improvement upon previous elevation models as a result of a void-filling process (Farr *et al.*, 2007). The map displaying biomes across South Africa was created by adding a shapefile of the 2018 National Vegetation Map to a base layer of the NaturalEarth Plugin in QGIS. The shapefile was downloaded from the Biodiversity GIS website and was created by SANBI (SANBI 2018). The topographic and vegetation maps are discussed further in the section below.

3.2.2 Description of study area

The synoptic patterns influencing the climate over southern Africa are generally classified into three broad 'control' systems: subtropical HPs, subpolar low pressures (LPs), and tropical LPs.

The subtropical HP systems dominating over the study area are associated with dry subsiding air. However, since two of the high pressures – the South Indian and South Atlantic High – are located over oceans, their circulation and seasonal shifts enable them to play a significant role in precipitation across the region (Xulu *et al.*, 2020). Ridging HPs are responsible for almost half of the annual rainfall along the south coast of the Eastern and Western Cape Provinces of South Africa (Engelbrecht *et al.* 2015; Pohl *et al.*, 2018). The western parts of southern Africa are often subjected to regional scale synoptic systems formed in the subpolar LP. One of the most common systems is a cut-off low (COL). COLs have the ability to produce large amounts of precipitation, which can lead to flash flooding (Singleton and Reason, 2006). In South Africa, the winter rainfall zone as well as the southern Cape region receive the majority of its precipitation from ridging HPs and COLs (Engelbrecht and Landman, 2016).

Southern Africa experiences many tropical-temperate troughs (TTTs) in the summer rainfall zone. TTTs can provide ideal conditions for precipitation to occur (Hart *et al.*, 2010). Occasionally, cut-off LP systems (COLs) can produce rainfall over the region during summer (Pohl *et al.*, 2018). Summer rainfall is linked to strong convection forces along with the Angola LP (Hart *et al.*, 2010).

The climate of the region is influenced by the cold Benguela current to its west and the warm Agulhas current, moving southwards along the east coast of southern Africa. Precipitation in the region occurs in different seasons with the south-westerly section of the study area receiving most of its rainfall during the austral winter (Finch and Meadows 2019). However, the majority of precipitation across southern Africa occurs during the austral summer (Ratna *et al.*, 2012). The region receiving its precipitation in the austral summer is separated from the winter rainfall area by a region receiving precipitation throughout the year and is known as the 'year-round rainfall' region.

Southern Africa has narrow coastal plains – along with an extensive coastal plain in Mozambique – and interior plateaux (Moore *et al.*, 2009), as shown in Figure 3.1. The topography of the region plays a significant role in the regional weather systems and moisture fluxes. In particular, the movement of air from high pressure systems over the plateau towards the coastal regions can increase fire danger conditions as it brings along dry, hot air often associated with high wind speeds (Moore *et al.*, 2009).

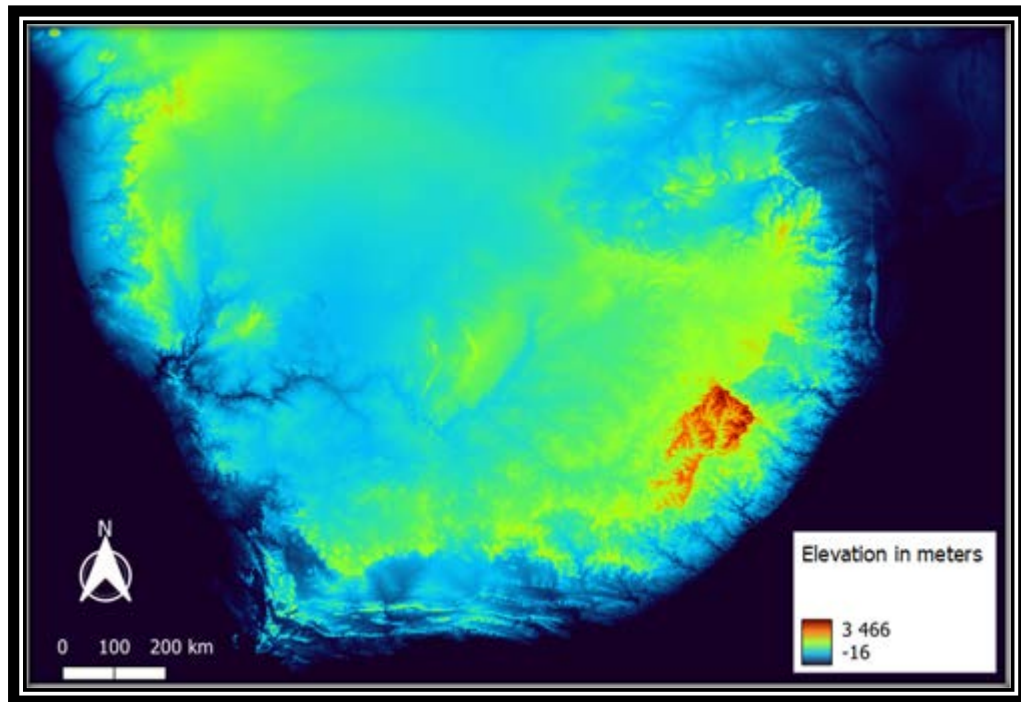


Figure 3.1: Topography over South Africa

This thesis focuses on three selected study areas, located west of the 27°E meridian. Even though Namibia and Botswana are also found in the western parts of southern Africa, this study only included sites located in South Africa due to the availability of observational data from the South African Weather Service (SAWS). Figure 3.2 depicts the three study areas and their location within various biomes in South Africa. The southwestern Cape is located within the winter rainfall zone, the Garden Route is located within the year-round rainfall zone, and the South-Eastern Kalahari Bushveld is situated in the summer rainfall zone. All three regions possess unique landscape and vegetation types, and experience different weather systems (for example, different dry seasons). As a result, a useful comparison can be made for fire events across the western parts of southern Africa. Fire events were selected based on their prominence in popular media reports and the use of higher spatial resolution data from the most recent satellite products, as discussed in the remotely sensed data section below (Goddard 2020, Hosken 2018, Kraaij 2018, Le Grange 2021). Brief summaries of the biomes which are located in the western parts of South Africa are discussed below as fire events occur within these biomes or within transition zones between two biomes. For example, Knysna is located in an area where the Forest, Fynbos and Albany Thicket biomes intersect. It is important to note that while three study areas were selected for long-term trend and recent fire event analyses, official fire records for the Western Cape region were also discussed as it assists with producing a more comprehensive understanding of fire regimes in western southern Africa.

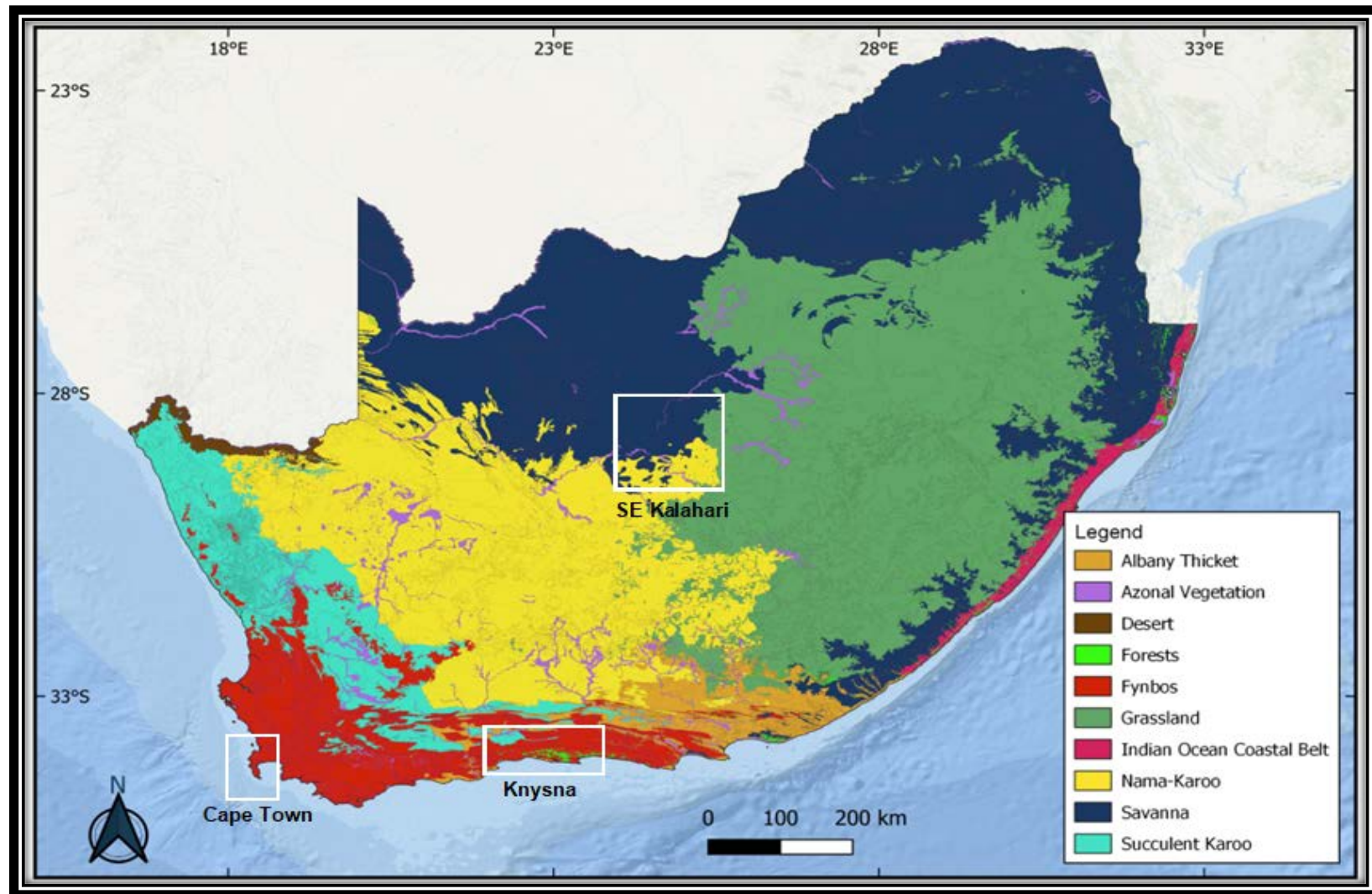


Figure 3.2: Study areas across biomes of South Africa

3.2.2.1 Fynbos

The Fynbos biome – a biome that is endemic to South Africa – encompasses the Cape Fold Belt Mountain range as well as the low-lying areas towards the Atlantic (west) and Indian Oceans (south). Climatically, the Fynbos biome is very similar to the North African Mediterranean biome. Both of these regions are subjected to subtropical HP systems, which leads to hot and dry summers. During winter, the region is influenced by low-pressure (LP) systems in the form of cold fronts that bring precipitation with them. Orographic rainfall can also occur during autumn and spring to areas south of the Cape Fold Mountains. A diversity of soil types is found in this biome, which include silcrete, ferricrete, shale, quartzites and colluvial and aeolian soils. The ecology of the Fynbos biome is dependent upon four unique characteristics, namely:

- 1) Cool, wet winters and hot, dry summers
- 2) A combination of nutrient poor and nutrient rich soils
- 3) A multifaceted network of plant-animal interactions
- 4) Fire return intervals of two to 10 years in Renosterveld areas, and five to 50 years in the rest of the biome.

Fynbos vegetation is adapted to fires through the release of seeds after fire events (serotiny). In this biome, natural fires usually take place towards the end of the dry season, i.e., late summer and early autumn. When fires occur in spring, serotinous plant seeds become vulnerable to predation by avifauna and rodents. IAS – particularly shrubs and large trees such as *Acacia*, *Australian Hakea* and *Pinus* species – increase the flammability of the landscape. These species consume large amounts of water, which results in decreased soil and vegetation moisture levels. Additionally, these species increase fuel loads and the risk of crown fires (Rebelo *et al.*, 2011).

3.2.2.2 Forest

The forest biome in South Africa is very diverse and occurs mostly in the eastern parts of the country and along the south coast of the Western Cape. The biome's subunits can appear as 'islands' within other biomes such as Fynbos and grassland. The flora within the Southern Cape Afrotemperate Forest is adapted to cool, humid conditions, and occur in moist mountainous terrain. The forest biome is spread across the winter, summer and all-year rainfall areas of South Africa, with the Southern Afrotemperate Forests occurring in the all-year rainfall region, in the vicinity of Knysna. Steep gradients of mountain ranges provide ideal conditions for the orographic precipitation – mostly through rainfall, but also through mist occurring within this biome. Soil types of this biome are mostly nutrient poor and formed from aeolian sands, quartzitic sandstone, shale,

mudstone, granite-gneiss, dolerites, dolomite, conglomerate and schist (Rutherford *et al.*, 2011). Rutherford *et al.* (2011:590) claim that “in principle, the South African forests (in particular the afrotemperate ones) as we know them today are non-flammable by nature”. This is ascribed to the low-fat content and high moisture content of leaves of forest species. Human activities have significantly reduced forest cover in South Africa. This relates to construction of dams, firewood collection, timber production, and commercial forestry. However, the remaining forests are attractions for ecotourism activities (Rutherford *et al.*, 2011).

3.2.2.3 Succulent Karoo

The Succulent Karoo biome extends from Luderitz in Namibia to the Cape Fold Mountains in South Africa, mostly to the west of the Great Escarpment. It also occurs to the north of the Outeniqua, Baviaanskloof, Tsitsikamma, Langeberg and Groot Winterhoek Mountains. Precipitation through rain and snow mostly occurs in winter, while small sections of the biome are located in the all-year-round rainfall region. Fog can occur along the Namaqualand coast. Soils in this biome include calcareous sands, stony, acid soils, alcaic, salic and gypsic. Desert pavements also occur. The Succulent Karoo biome hosts a rich biodiversity of dwarf leaf succulents and shrubs (Mucina *et al.*, 2011).

3.2.2.4 Albany Thicket

Albany Thicket occurs within the semi-arid regions of the Western and Eastern Cape. It is also found in valleys and may represent the transition between subtropical vegetation and the dry Nama-Karoo vegetation. This biome includes areas that fall under two rainfall regions of South Africa: the summer rainfall region and the all-year rainfall zone. Maximum precipitation occurs in autumn and spring. The Cape Fold Mountain Belt plays a significant role in the topography and soil development processes of this biome. In the mountains, the slopes are shallow and rocky, whereas soils in the floodplains and valley floors are deep and fine-textured. Semi-succulent, woody and dense vegetation dominates in this biome. A high biodiversity of species is located in this biome, with estimates indicating that 365 species of plants are endemic (Hoare *et al.*, 2011).

3.2.2.5 Savanna

The savanna biome is the largest biome in southern Africa. The climate of this biome displays a distinct seasonality in terms of precipitation with dry winters and wet summers and low occurrence of frost. Therefore, savannas are found in the summer rainfall region of South Africa. The majority of the savanna biome occurs below 1 500m. A wide variety of soils are found as the precipitation gradient decreases from east to west. Shallow soils appear frequently, along with red soils with high amounts of base cations and sandy soils. The vegetation in this biome consists of open tree

areas with grass. According to Mucina *et al.* (2011), fires maintain the height of trees and prevent bush encroachment – where tree density increases to the detriment of grass species. The occurrence of frost and late winter frost can lead to an increase in grass mortality, which can result in an increased intensity of fires when it is followed by a dry season (Mucina *et al.*, 2011).

3.2.2.6 Nama-Karoo

The Nama-Karoo biome occurs in the western parts of South Africa – mostly in the Northern Cape Province – and southern parts of Namibia. It is located on the interior plateau and has a continental climate. The precipitation in this biome occurs in summer, with the majority of rainfall occurring in March. Soil development of this biome relies on the weathering of sedimentary rocks and igneous intrusions. Due to the high evaporation rates and low precipitation, soils tend to be lime-rich and contain many cations. In addition, soils are mostly shallow and sandy. Vegetation in the Nama-Karoo mainly consists of low shrubs, succulents, grasses and geophytes. Rocky outcrops can also provide ideal conditions for small trees to grow. Although fires occur in the eastern parts of the biome, it is very rare in the western parts. It is claimed that fires in the eastern parts occur as a result of recurrent seasons with normal to above normal precipitation together with light grazing (Mucina *et al.*, 2011).

3.2.2.7 Grassland

The grassland biome occurs on the Highveld of South Africa, with some parts of it along the Great Escarpment Areas in the KwaZulu-Natal and Eastern Cape Provinces. Precipitation occurs in summer and frost occurs in winter. Topographically, the grassland consists mostly of flat to gently undulating terrain and includes some mountainous terrain in the east. Soils are derived from sedimentary rocks and alluvial depositions. Fire frequency is estimated to be one to four years, with fire events peaking in July to September. The grassland biome not only contains dominant grasses from the Poaceae and Panicoideae families, but also woody vegetation with high resistance to fire, such as those from the Protea, Cussonia and Vachellia genera (Mucina *et al.*, 2011).

3.3 HISTORICAL FIRE EVENTS

This section outlines the data collection and analyses techniques deployed to investigate historical fire events across the study area. Firstly, the long-term trends of fire events were considered, followed by the official records of fire events.

3.3.1 Long-term trends

The Normalized Difference Vegetation Index (NDVI) and Normalized Burn Ratio (NBR) indices were selected to establish long-term trends of fire events from Landsat data. NDVI was selected to detect the vegetation health and NBR was selected due to its efficiency in identifying burnt areas and burn severity. NBR values close to 1 indicate healthy vegetation, while values below 0, indicate burnt areas (UN n.d.) It should therefore be noted that NDVI values tend to be closer to 1 during the growing (wet) season (except during droughts) and closer to 0 during the dry season or after a fire event. Due to the large amount of data required to extract seasonality from remotely sensed images – for example, Batista *et al.* (2018) downloaded 455 images for their study, Argibay *et al.* (2020) downloaded 306 images and Bajocco *et al.* (2020) downloaded 276 images – along with the timely nature of processing and analysing all the images, it was decided to use a novel, big data approach to extract seasonality for three selected points across the study area. The Geextract Python library was used to extract and calculate the NDVI and NBR indices from Landsat data for three selected points, with a buffer zone of 500m (Dutrieux 2017). All three of the selected points are located within areas that experienced fire events since 2017, and their coordinates are listed below:

- Knysna: -33.9973, 22.92236
- Cape Town: -34.0852, 18.4452
- SE Kalahari: -28.6143, 25.0641

In Table 3.1 the Landsat Bands are summarised according to the different satellites. Landsat 5 and 7 used the same bands, while Landsat 8 used bands with slightly different wavelengths (NASA n.d.). All the data extracted from Landsat products came from its Collection 2 as it supersedes the Collection 1 data in terms of data processing, quality and accuracy (NASA 2022).

Table 3.1: Landsat Bands used to calculate timeseries

LANDSAT/LT05/C02/T2_L2 and LANDSAT/LE07/C02/T2_L2			
Name	Wavelength (µm)	Spatial resolution (m)	Description
SR_B1	0.45-0.52	30	Band 1 (blue) surface reflectance
SR_B2	0.52-0.60	30	Band 2 (green) surface reflectance
SR_B3	0.63-0.69	30	Band 3 (red) surface reflectance
SR_B4	0.77-0.90	30	Band 4 (near infrared) surface reflectance
SR_B5	1.55-1.75	30	Band 5 (shortwave infrared 1) surface reflectance
SR_B7	2.08-2.35	30	Band 7 (shortwave infrared 2) surface reflectance
LANDSAT/LC08/C02/T2_SR			
Name	Wavelength (µm)	Spatial resolution (m)	Description
B1	0.435-0.451	30	Band 1 (ultra blue) surface reflectance
B2	0.452-0.512	30	Band 2 (blue) surface reflectance
B3	0.533-0.590	30	Band 3 (green) surface reflectance
B4	0.636-0.673	30	Band 4 (red) surface reflectance
B5	0.851-0.879	30	Band 5 (near infrared) surface reflectance
B6	1.566-1.651	30	Band 6 (shortwave infrared 1) surface reflectance
B7	2.107-2.294	30	Band 7 (shortwave infrared 2) surface reflectance

Table 3.2 displays the formulae used to calculate the Landsat Timeseries. Data from different satellites were used in order to construct a comprehensive timeline of NDVI and NBR Landsat 5 was used for the timeframe 1984/03/05 – 1999/05/31, Landsat 7 for 1999/06/01 – 2013/03/31, and Landsat 8 for 2013/04/01 – 2021/12/31.

Table 3.2: Formulae used for Landsat Timeseries

Index	LT5 (1984, 3, 5 – 1999, 5, 31)	LE7 (1999, 6, 1 – 2013,3, 31))	LC8 (2013,4,1-2021,12,31)
NDVI	NDVI = (NIR - R) / (NIR + R)		
	NDVI = (Band 4 – Band 3) / (Band 4 + Band 3)		NDVI = (Band 5 – Band 4) / (Band 5 + Band 4)
NBR	NBR = (NIR - SWIR) / (NIR + SWIR)		
	NBR = (Band 4 – Band 7) / (Band 4 + Band 7)		NBR = (Band 5 – Band 7) / (Band 5 + Band 7)

Landsat data were imported into R statistical software to plot timeseries. Data were seasonally decomposed using additive decomposition model. Additive decomposition was selected as the seasonal changes in vegetation health is relatively constant over large time periods. In addition, this model has been applied successfully to remotely sensed images with abrupt changes in vegetation cover – such as fire events – showing up clearly in the trend component of the decomposed data (Verbesselt et al 2010). The formula used for the time series composition is $Y=T+S+R$, where Y is the raw data, T represents the trend-cycle, S reflects the seasonal components and R is the remainder or residual component. Trends and seasonal components for each of the sites were interpreted.

Timeseries for fire events were also extracted from the Fire Information for Resource Management System (FIRMS) which uses the brightness temperature of fire pixels by using MODIS channels 21 and 22 (NASA 2022). FIRMS data were exported and plotted via the Javascript Editor tool on the Google Earth Engine (GEE) platform. This source only contained data from the year 2000, however seasonal fluctuations in brightness temperature were detected and discussed from the plots.

3.3.2 Official fire records

Data for officially recorded fire events were accessed and extracted from the South African National Biodiversity Institute (SANBI) Biodiversity GIS portal. The specific dataset used from this portal was the archived data on fires held by CapeNature (SANBI 2022). Recorded fire events do not cover all the study sites, however, it contained valuable information regarding fire events across most of the study area and fire events in the Western Cape, in particular. Maps of fire events were created and overlaid on a layer showing biomes within the Western Cape, using the same shapefile used for creating the biome map in the description of the study area (SANBI

2018). QGIS software was employed to create maps showing the spatial distribution of fire events as well as the sizes of the fire events across the Western Cape over time. The attribute table of the shapefile containing the officially recorded fires in the Western Cape was extracted from QGIS and imported into the pandas library of Python. This enabled the researcher to extract descriptive statistics, large fire events in terms of burnt area, a timeline of fire events and a histogram showing the seasonality of the fire events from the attribute table. The Python library known as matplotlib was employed to plot the data extracted from the attribute table. The pandas and matplotlib libraries were chosen to process and plot the data due to their capability to handle big datasets (Hunter 2007, NumFocus 2022).

3.4 CLIMATE AND WEATHER DATA

Seasonal Precipitation Anomalies were mapped using the IRI Climate Lab interactive tools. Data from the National Oceanic and Atmospheric Administration National Center for Environmental Prediction (NOAA NCEP) Climate Prediction Center were used to plot 3-month seasonal precipitation anomaly values at 2.5° resolution, using the timeframe of 1991-2020 as a base period (Janowiak and Xie 1999). The data was derived from the Climate Anomaly Monitoring System-Outgoing Longwave Radiation Precipitation Index (CAMS-OPI). Despite the reliance of this index on both rain gauge and satellite observations, it has proven to efficiently monitor and predict variations in rainfall (Sohn *et al.*, 2012).

European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 climate reanalysis datasets were plotted and displayed via the KMNI Climate Explorer for the synoptic variables of Mean Sea Level Pressure (Mean SLP), Geopotential Height (z500) and Maximum Temperature (TMax). The synoptic variables were plotted for the domain 10°-50°S and 10°-50°E and the resolution of the data is a 0.5° x 0.5° grid. ENSO and SAM phases were also plotted using the KMNI Climate Explorer. ENSO phases were plotted using the relative Niño3.4 index due to its wide use to measure the El Niño and La Niña cycles and eliminates the global warming trend which is contained within the Niño3.4 index (Van Oldenborgh *et al.* 2021). SAM phases were plotted from ERA5 observational data as the ECMWF data recorded at the 40°S latitude were proven to be of higher accuracy than other reanalysis products (Marshall 2003). After ENSO and SAM phases were plotted on a timeline, the officially recorded fire events in the Western Cape were added to the timelines.

Weather station data were obtained for each fire event from the SAWS. The rationale for using this data is due to the observed weather parameters on a local scale close to fire events, thereby improving the accuracy of fire event analyses. Station data were imported into the pandas library

in Python and plotted in meteograms by the matplotlib library of Python. For each fire event case study, data were plotted for the day before ignition, ignition day, day before extinction and the extinction day. One station, closest to each of the fire events was selected as displayed by Table 3.3 below.

Table 3.3: SAWS weather stations

Station name	Coordinates	
SA Astronomical Observatory (2015 Fire)	-33.9336	18.4775
Knysna (2017 and 2018 Fires)	-34.049	23.0815
Kimberley (2020 fire)	-28.8061	24.7698
Molteno Reservoir (2021 Fire)	-33.9377	18.4109

Volumetric soil moisture levels top layer of soil (0-7cm below the surface) for the days prior to the fire events were downloaded from the ECMWF ERA5-Land climate reanalysis dataset via the Copernicus Climate Data Store. The spatial resolution of this dataset has been fitted to a 0.1x0.1° latitude-longitude grid. The data was then imported into the Grid Analysis and Display System (GrADS) for the creation of soil moisture maps.

3.5 REMOTELY SENSED IMAGES

The USGS portal was used to download remotely sensed images from the Landsat 8 (2015 fire) and Sentinel-2A (2017, 2018, 2020 and 2021 fires) products. This method has been used widely for accessing and processing data about fire events (Alves and Pérez-Cabello 2017, Argibay *et al.*, 2020, Downing *et al.*, 2017). The rationale for selecting Sentinel-2A images is the higher spatial resolution than the products from Landsat and MODIS (European Space Agency n.d.), for example the Landsat-8 bands summarized in Table 3.1 have resolutions of 30 m, whereas the majority of the Sentinel-2A bands have a spatial resolution of either 10 or 20 m as seen in Table 3.4 below.

Table 3.4: Sentinel-2A MSI Bands

Name	Central wavelength (nm)	Spatial resolution (m)	Description
B1	442,7	60	Aerosols
B2	492,7	10	Blue
B3	559,8	10	Green
B4	664,6	10	Red
B5	704,1	20	Red Edge 1
B6	740,5	20	Red Edge 2
B7	782,8	20	Red Edge 3
B8	832,8	10	NIR
B8A	864,7	20	Red Edge 4
B9	945,1	60	Water vapour
B11	1613,7	20	SWIR1
B12	2202,4	20	SWIR2

For every fire event, a pre-fire and post-fire image was downloaded. The remote sensing tile references are shown in Table 3.5 below. Both fire events in the Knysna area were recorded in the same remote sensing tile.

Table 3.5: Tile References

Fire event	Tile or Path number	Row number
Knysna 2017 and 2018	T34HFH	R078
Cape Town 2015	P175	R084
Cape Town 2021	T34HBH	R121
SE Kalahari 2020	T35JLJ	R035

On the USGS portal, a mask was applied to select images with <10% cloud cover. Spatial data, including remotely sensed data, are prone to include distortions and errors (Manjula *et al.*, 2013). Prior to the analysis of these datasets, series of data pre-processing methods are usually recommended. These methods include geometric, relative and absolute corrections (Young *et*

al., 2017). After the remote sensing images were downloaded, it had undergone pre-processing and processing before analyses were made as depicted by Figure 3.3 below.

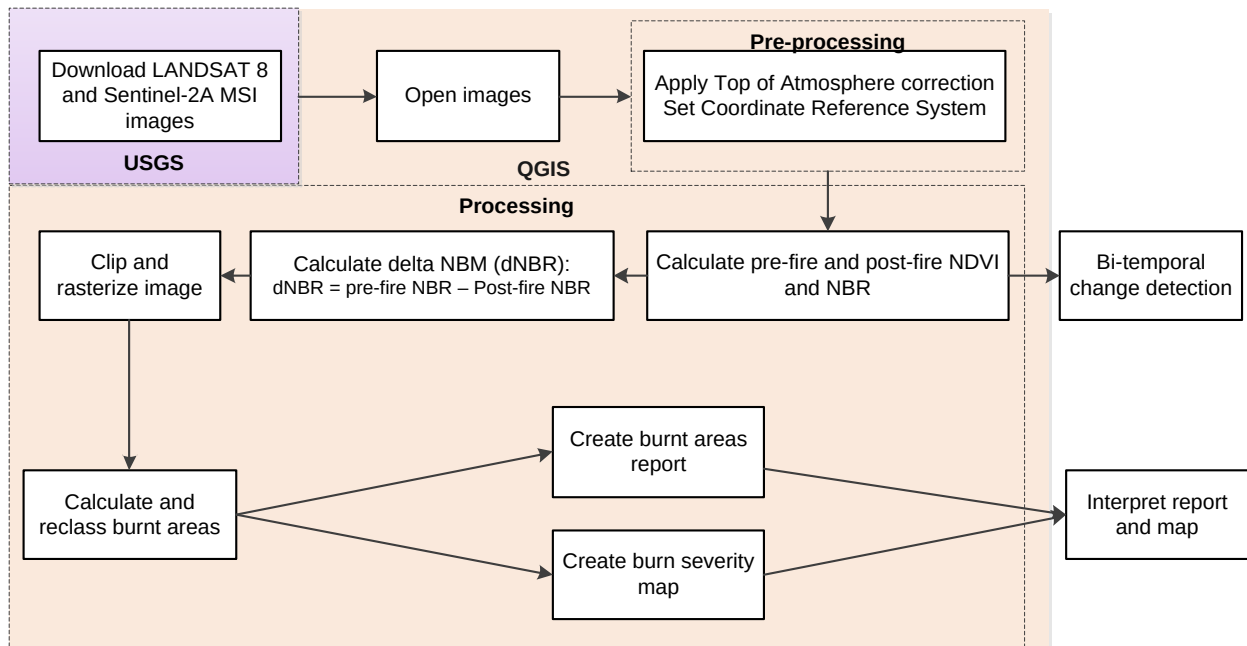


Figure 3.3: Remote sensing methodology

QGIS was employed to pre-process and process data. Specifically, the Semi-Automatic Classification Plugin was used for atmospheric correction, setting coordinate reference systems, calculating vegetation indices and clipping the images. Vegetation indices were calculated using the band mathematics operation to apply the formulae outlined in Table 3.6 below.

Table 3.6: Formulae used for band mathematics

Formula	Sentinel-2A MSI (2017-2021 fires)	Landsat 8 (2015 fire)
NDVI	$NDVI = (NIR - R) / (NIR + R)$	
	$NDVI = (B8 - B4) / (B8 + B4)$	$NDVI = (Band\ 5 - Band\ 4) / (Band\ 5 + Band\ 4)$
NBR	$NBR = (NIR - SWIR) / (NIR + SWIR)$	
	$NBR = (B8 - B12) / (B8 + B12)$	$NBR = (Band\ 5 - Band\ 7) / (Band\ 5 + Band\ 7)$

Pre-fire and post-fire NDVI and NBR images were created in order to conduct a bi-temporal change detection. This analysis technique was selected due to its ability to detect abrupt changes and efficient use in studying vegetation changes before and after fire events (Thonfeld *et al.*, 2015, Pérez-Cabello *et al.*, 2021). For NDVI, vegetation health was classed according to

Cherlinka (2019) as summarized by Table 3.7 below. The bitemporal change detection method was used to compare the vegetation health according to the NDVI images for each fire event. NBR images were assessed similarly and proved to be successful in identifying burnt areas.

Table 3.7: NDVI Classes

NDVI Values	Description
-1 – 0	Dead plants or barren land
0 – 0,33	Unhealthy vegetation
0,33 – 0,66	Moderately healthy vegetation
0,66 – 1	Very healthy vegetation

In order to establish the severity of each fire event, the delta NBR (dNBR) was calculated using the Raster Calculator function in QGIS. The formula for calculating dNBR is:

$$\text{dNBR} = \text{pre-fire NBR} - \text{post-fire NBR}$$

After the dNBR was calculated, the image was clipped, rasterized and classified into the USGS burn severity classes in QGIS. In order to calculate the burnt area, the USGS reclass rules were applied via the Raster Calculator in QGIS as recommended by UN (n.d). The reclass rules are contained in Table 3.8 below. As this research did not focus on post-fire regrowth, the regrowth classes were grouped into the “unburnt” category.

Table 3.8: USGS reclass rules

dNBR values	Class	Category
- 1000 to 99	0	Unburnt
100 to 269	1	Low Severity
270 to 439	2	Moderate-Low Severity
440 to 659	3	Moderate-High Severity
660 to 1300	4	High Severity

Burnt areas were then calculated in hectares (ha) and displayed in the burnt area report according to the categories in Table 3.8. The same categories were used for the legend of each burnt area map, as applied through the Layer Styling options in QGIS. Subsequently, interpretations of the burnt area reports and maps were made.

3.6 LIMITATIONS

Limitations of this study relate mostly to the time and storage space required for downloading and storing remotely sensed images from the USGS website. In addition, the processing of data via QGIS was time consuming.

The comparison of fire events across three study areas in order to provide a baseline for fire regime analysis resulted in the limitation of parameters included in the study. For example, a focus on fire events in one particular rainfall zone may provide the opportunity to include more dimensions to understanding fire regimes, such as topographical variables and the role of human activities in fire events.

3.7 ETHICS

As the data collection and analyses of the study do not involve interaction with humans, animals or fieldwork, ethics approval was granted, and the study declared a no risk study. The NWU ethics number is NWU-01503-20-A9.

3.8 SUMMARY

In this chapter, the methodology of the study was explained, together with the study area demarcation and limitations of the study. Due to its location in the subtropics, the influence of subtropical HP systems plays an important role in not only the overall climatology of southern Africa, but also the establishment of fire danger conditions. These conditions can occur when a HP system located on the interior plateau moves air below the Great Escarpment towards a coastal LP system, which leads to adiabatic heating of air. Fire events examined in this study occurred in seven biomes across South Africa, excluding the desert and Indian Ocean Coastal Belt biomes. While fires occur more frequently in the Fynbos, savanna, grassland and eastern parts of the Nama-Karoo biomes, they have also been detected in the succulent Karoo, forest and Albany Thicket biomes.

Open access data were used with the exception of local weather station data obtained from the SAWS. In addition, open-source software packages were used to extract, analyse, and interpret data for example QGIS and selected Python libraries.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 INTRODUCTION

This chapter focuses on the analysis of selected fire events within the southwestern part of southern Africa. Even though some reports claim that the 2017 Knysna fire had been ignited by lightning (Forsyth *et al.*, 2018 and Frost *et al.*, 2018) and therefore a natural ignition, this has been contrasted by evidence linking human ignition – specifically arson – to this event (Manuel 2017). Furthermore, all the other case studies were associated with arson (Goddard 2020; Le Grange 2021 and Xulu *et al.*, 2021). Although this research does not focus on the human dimension of fire regimes across the study area, it is important to acknowledge the role it played in the fire events. The organisation of this chapter mimics the layout of the previous chapter. However, the results are presented and interpreted first with an overall synthesis of the results discussed towards the end of the chapter. Results for the long-term trends in fire events are presented first, followed by historical fire records, the relationship between large fire events and teleconnections, synoptic weather conditions and lastly, burn severity.

4.2 LONG-TERM TRENDS

4.2.1 Remotely sensed data

4.2.1.1 Cape Town

The Landsat timeseries show a clear seasonality but an irregular trend of NDVI as in Figure 4.1 below. While the NBR values in Figure 4.2 show a similar seasonal pattern, the trend of the values appears to have been higher in the mid-1990s to mid-2000s and from 2012 onwards.

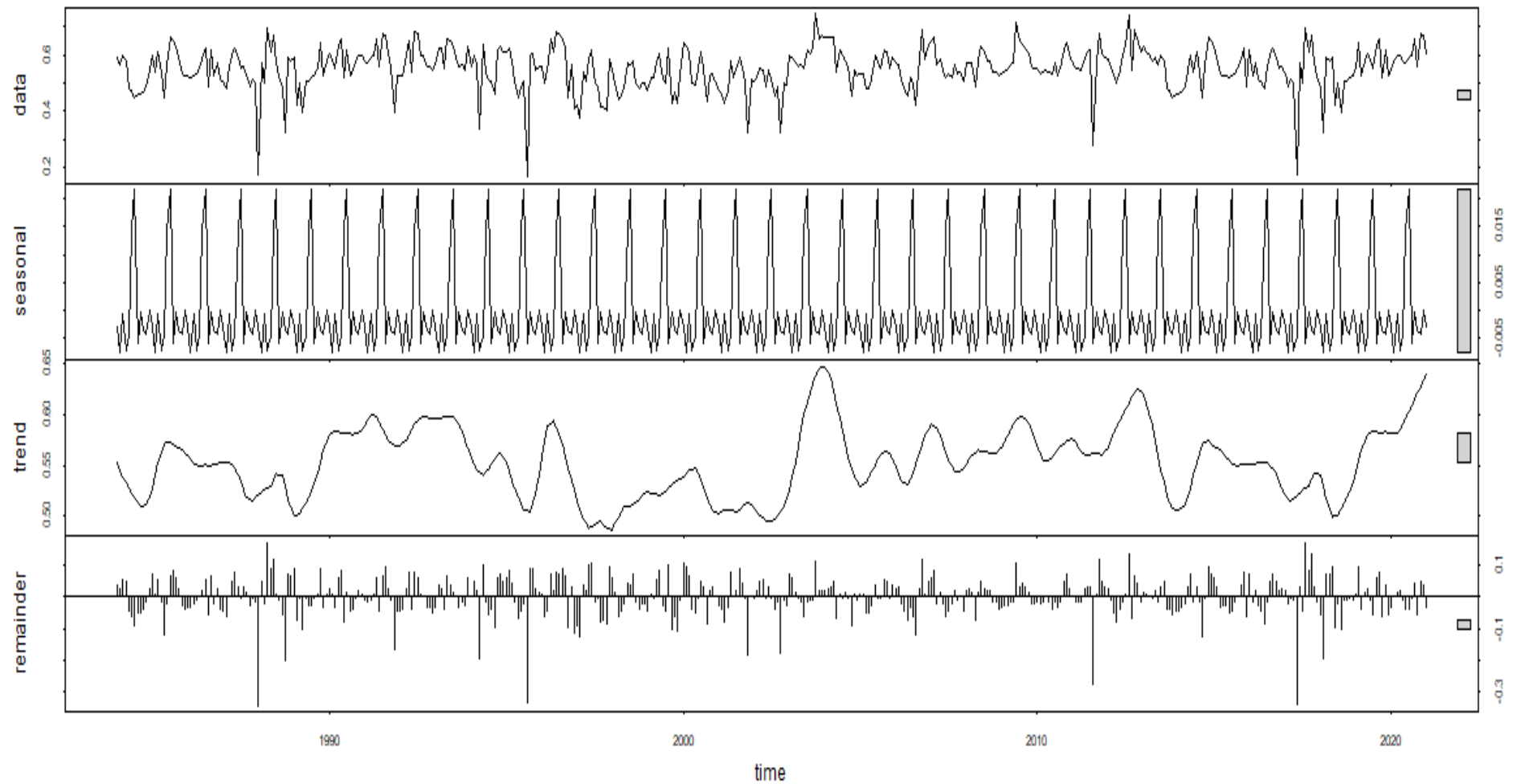


Figure 4.1: Landsat NDVI Timeseries of Cape Town Peninsula

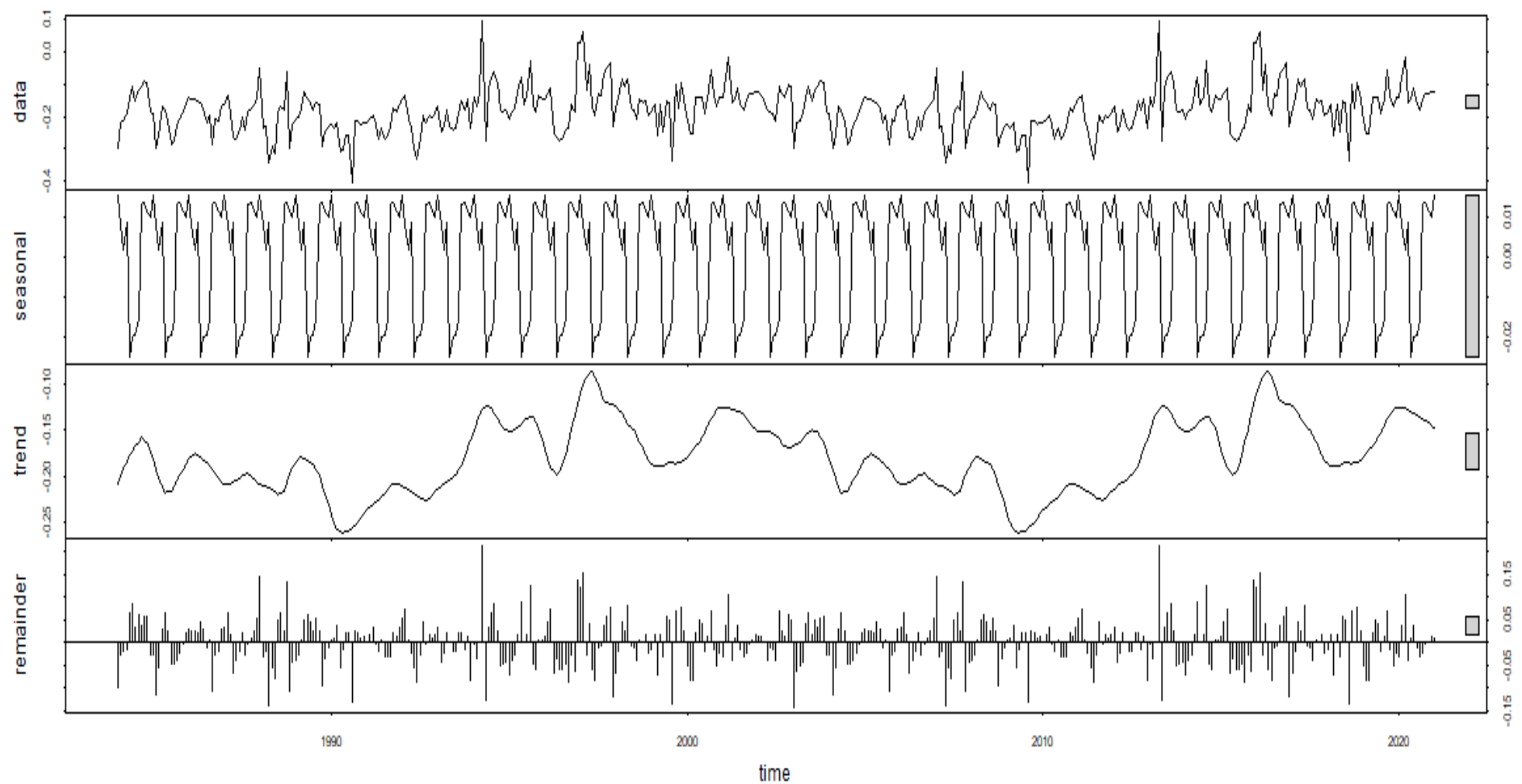


Figure 4.2: Landsat NBR Timeseries of Cape Town Peninsula

The long-term trend in fire pixel counts in the Cape Town Peninsula region are shown in Figure 4.3 below. The long-term trend reveals a tendency of more fire pixel counts in the early 2000s and in the latter part of the 2010s.

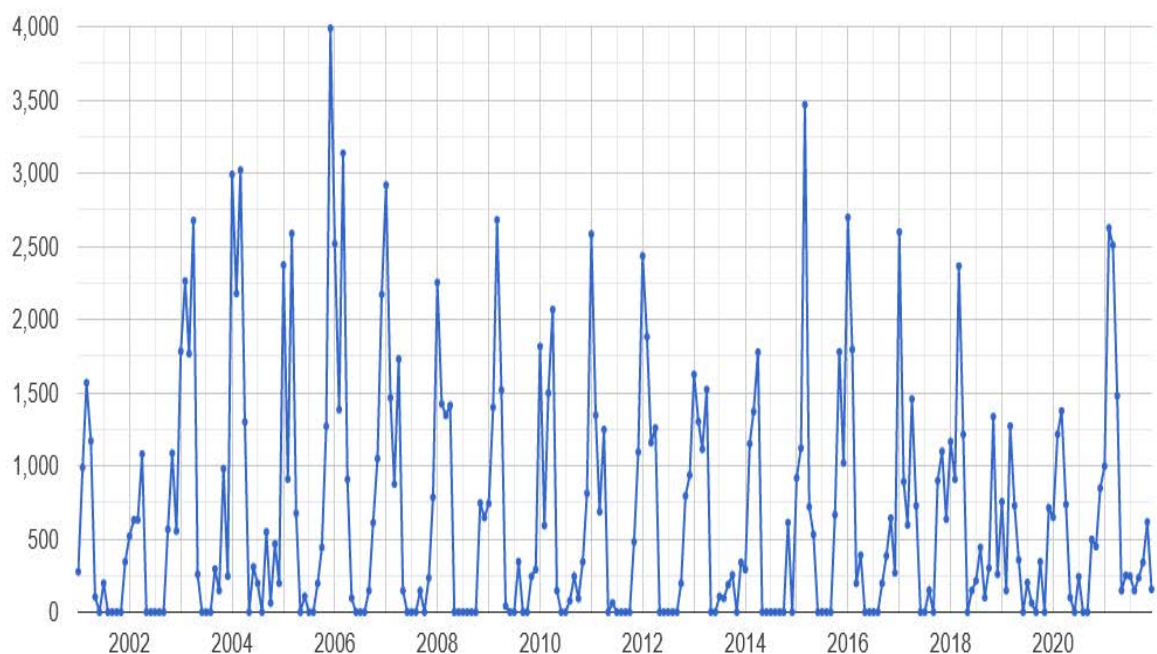


Figure 4.3: Fire pixel counts over the Cape Town Peninsula from 2000 to 2021

Over the 22-year period, the highest amount of fire pixel counts was recorded in December 2005, followed by March 2015 as shown in Table 4.1 below. Overall, fire pixel counts appear to be more prominent in the months of January to March.

Table 4.1: Highest fire pixel count months in the Cape Town Peninsula

Months	Number of burnt pixels
January 2004	2990
March 2004	3020
December 2005	3989
March 2006	3135
March 2015	3467

4.2.1.2 Knysna

Figure 4.4 shows the Landsat timeseries of NDVI for the Knysna site. A seasonal pattern was detected, and the trend shows a gradual increase in values that had been interrupted by a dip in the mid-2000s. The NBR values remained fairly stable as shown in Figure 4.5 with a seasonal pattern detected. However, significantly higher values were recorded in the period where the data had been derived from the Landsat 7 instruments.

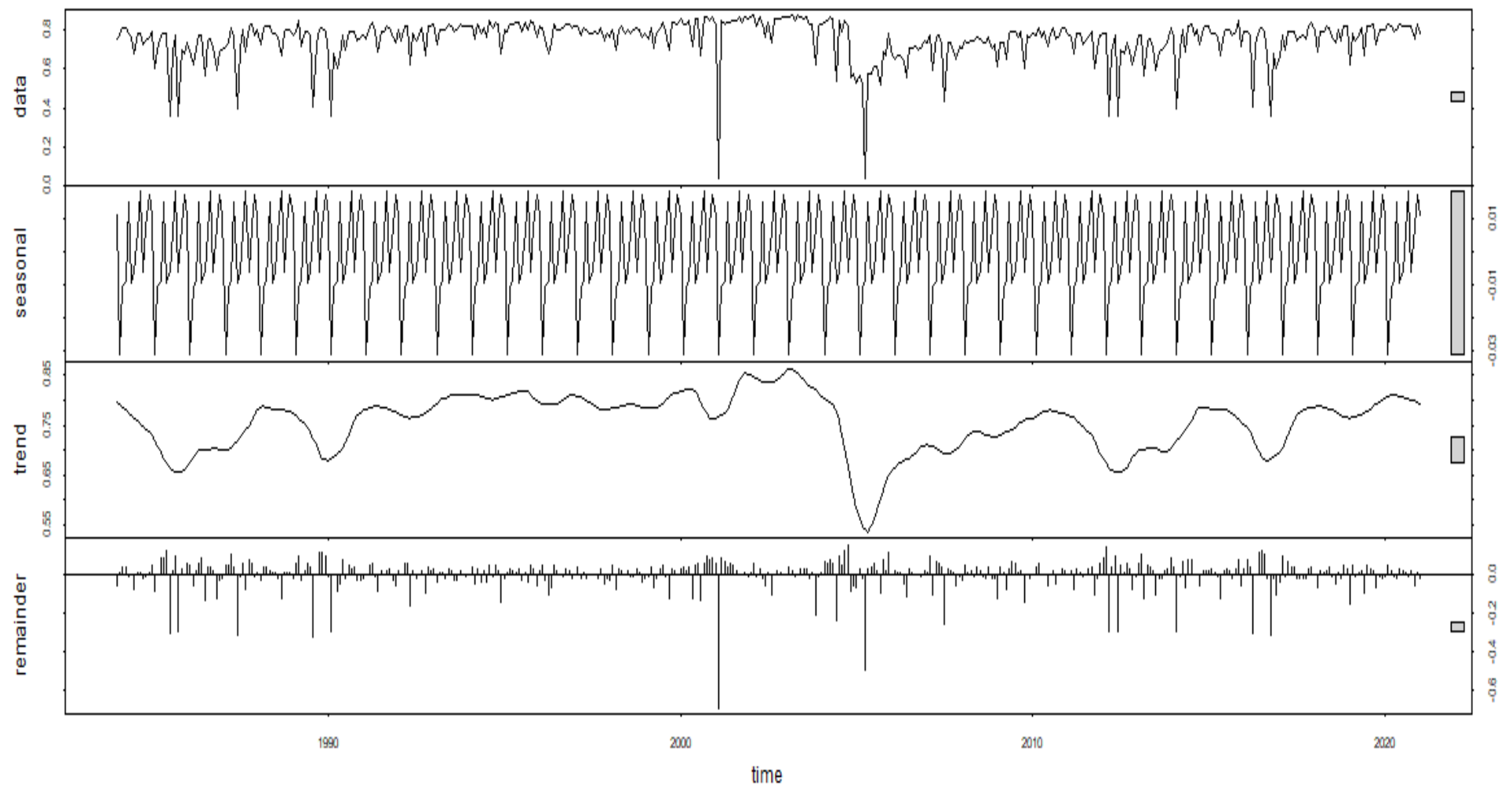


Figure 4.4: Landsat NDVI Timeseries of Knysna

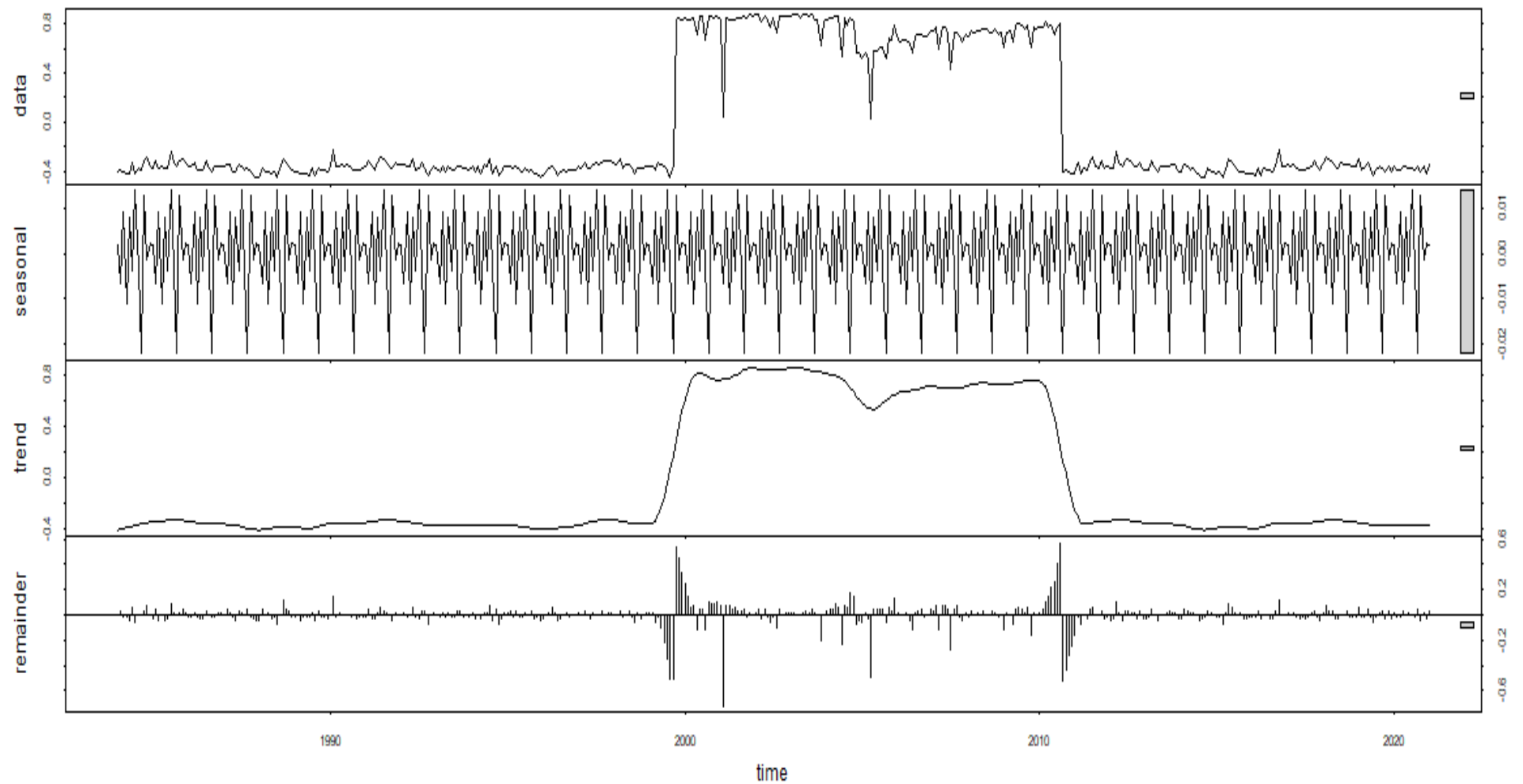


Figure 4.5: Landsat NBR Timeseries of Knysna

The fire pixel counts over the Knysna region appears to have been relatively consistent over the longer term, with significant increases in fire pixel detections in 2017 and 2018 as shown in Figure 4.6.

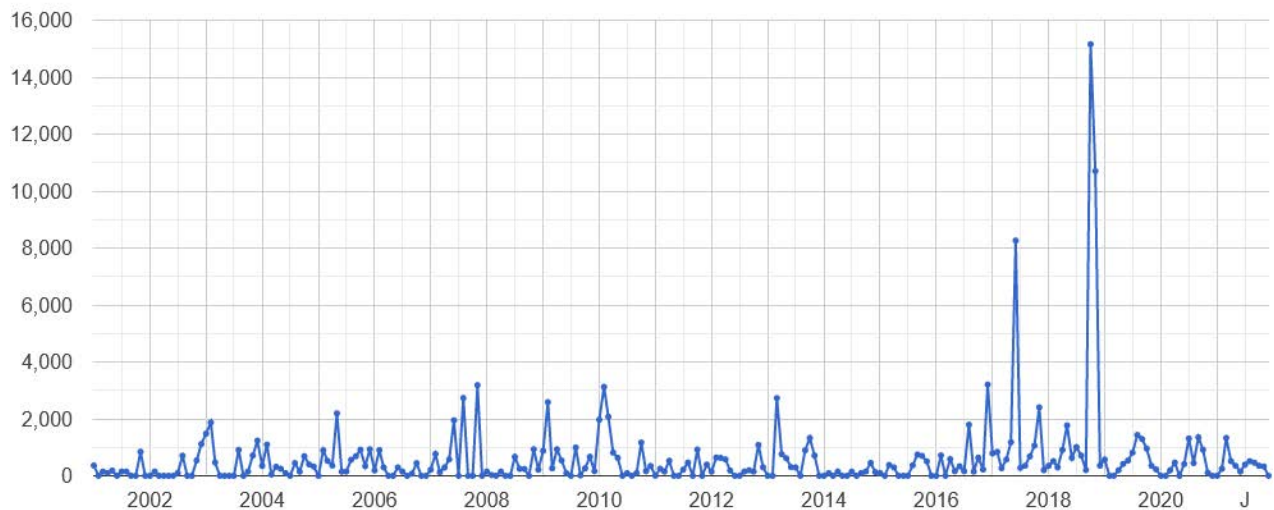


Figure 4.6: Fire event activity in the Knysna region from 2000 to 2021.

A closer look at the numbers, in Table 4.2, reveal the four months with the highest detected fire pixels were spaced across two years, from December 2016 to November 2018. Most of the fire events appear to occur in the austral summer.

Table 4.2: Highest fire count months in the Knysna area

Months	Number of burnt pixels
November 2007	3186
December 2016	3204
June 2017	8261
October 2018	15158
November 2018	10701

4.2.1.3 SE Kalahari

Figure 4.7 shows the Landsat timeseries for NDVI at the selected point in the SE Kalahari region. According to this figure, a clear seasonal pattern exists within the data and an increase in the trend from the mid-2000s with a higher fluctuation of values occurring. The NBR shown in Figure 4.8 shows a similar pattern to the NDVI timeseries. While the trend in values tended to dip around the year 1990, it gradually increased and fluctuated from the mid-2000s.

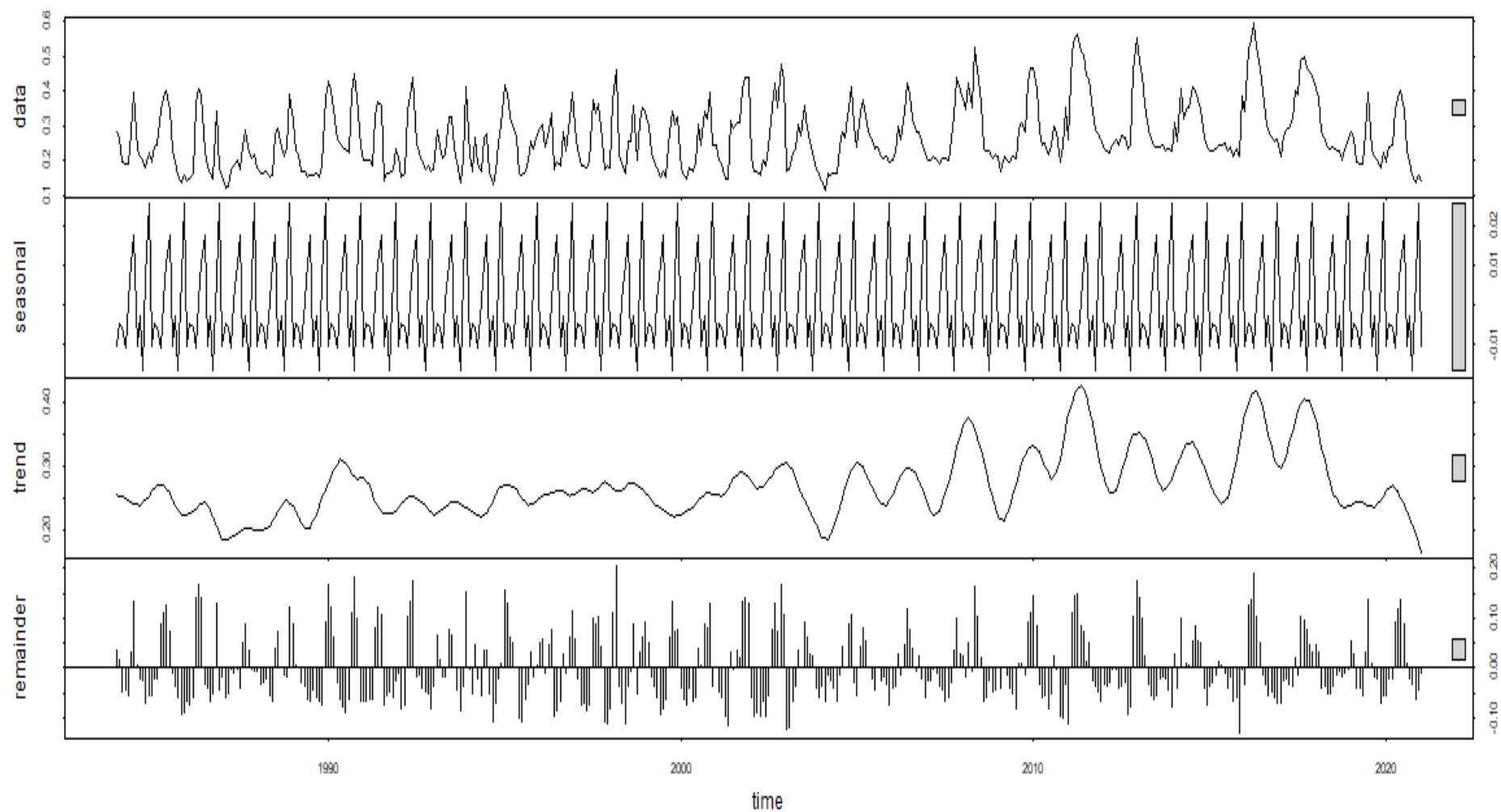


Figure 4.7: Landsat NDVI Timeseries of SE Kalahari

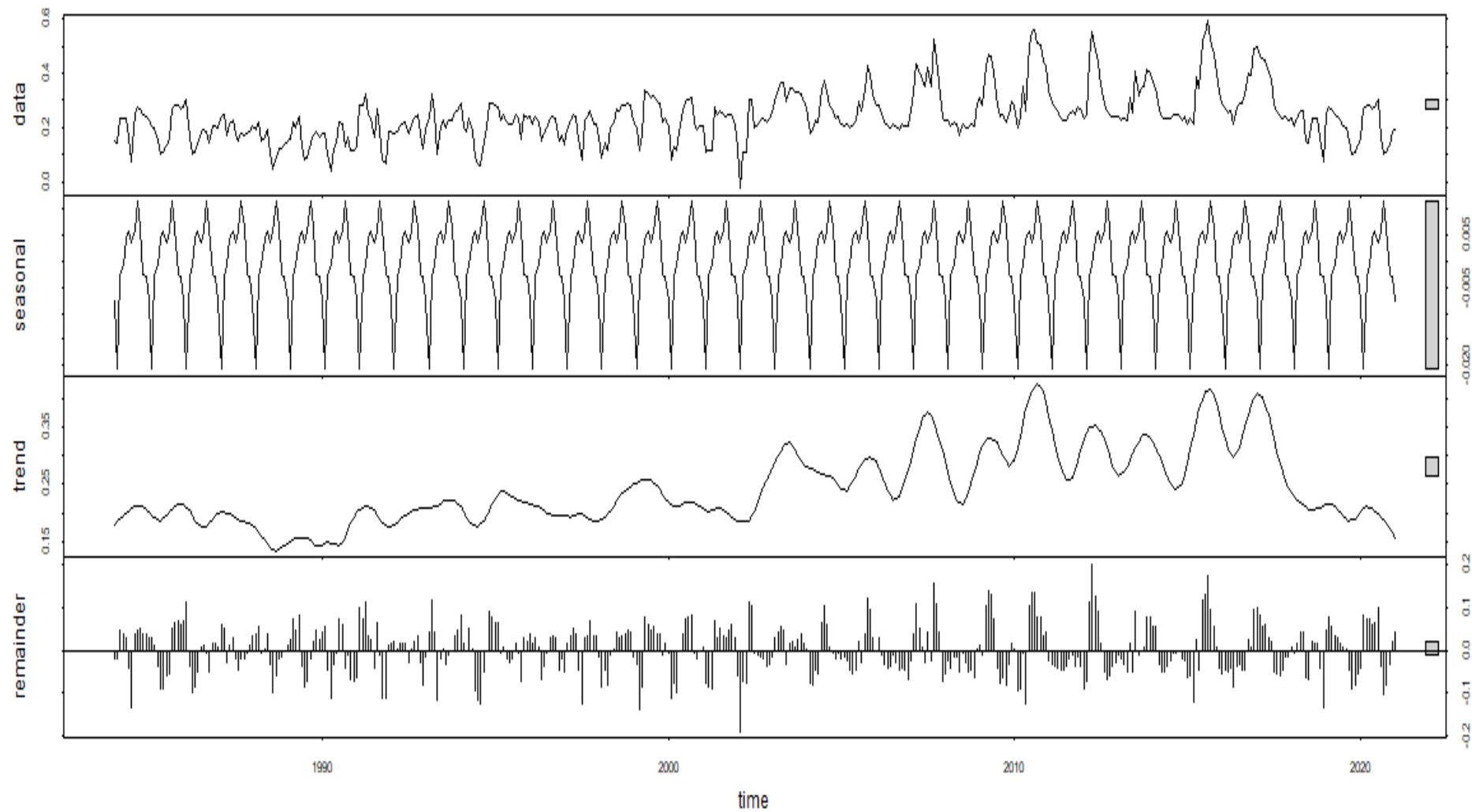


Figure 4.8: Landsat NBR Timeseries of SE Kalahari

Over the SE Kalahari region, the amount of fire pixel counts appears to have increased recently, with numbers peaking in 2020 and 2021 as shown in Figure 4.9.

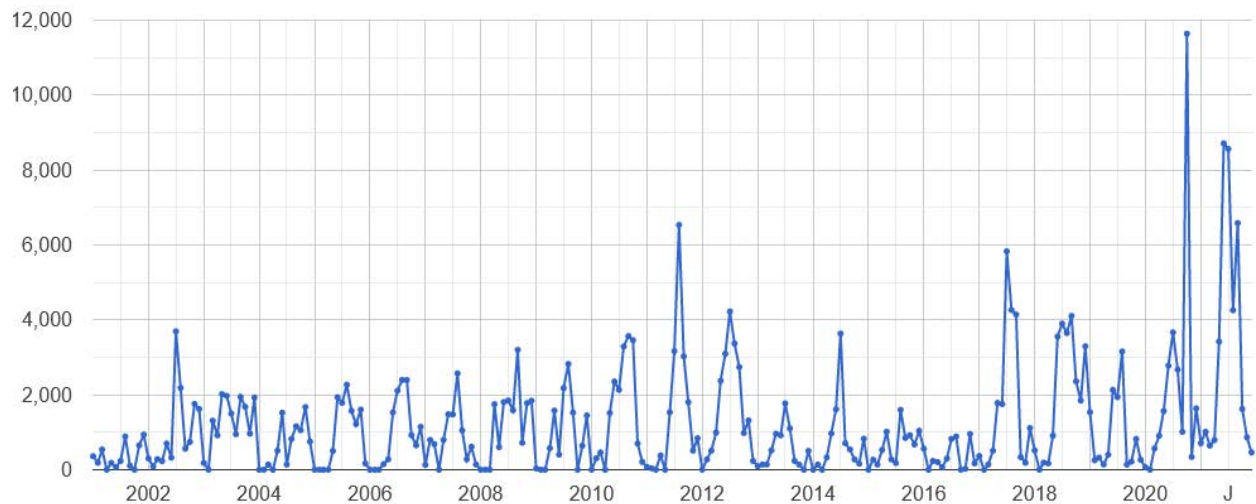


Figure 4.9: Fire pixel counts in the SE Kalahari region from 2000 to 2021

Fire pixel counts appears to have been the most significant for three months of 2021 – June, July and September, while the highest burnt pixel counts were recorded in October 2020 as shown in Table 4.3. A clear trend in seasonality was detected from Figure 4.9. The late dry season – in this case the austral winter and spring – provided more ideal conditions for fires to occur.

Table 4.3: Highest fire count months

Months	Number of burnt pixels
August 2011	6535
October 2020	11638
June 2021	8709
July 2021	8565
September 2021	6585

4.2.2 Official records

Figure 4.10 shows the spatial distribution of reported fire events in the Western Cape, overlaid on a map of the biomes of South Africa. The fire events mostly occur in the interior and within the Fynbos biome. Other biomes where fires occurred are the Forest biome and fringes of the Nama-Karoo biome. Small patches of fire activity appear to have occurred in the Succulent Karoo biome.

It should be noted that the fires recorded in both the Nama-Karoo and Succulent Karoo biomes were on the fringes of the Fynbos biome, which naturally contains more fire-prone vegetation.

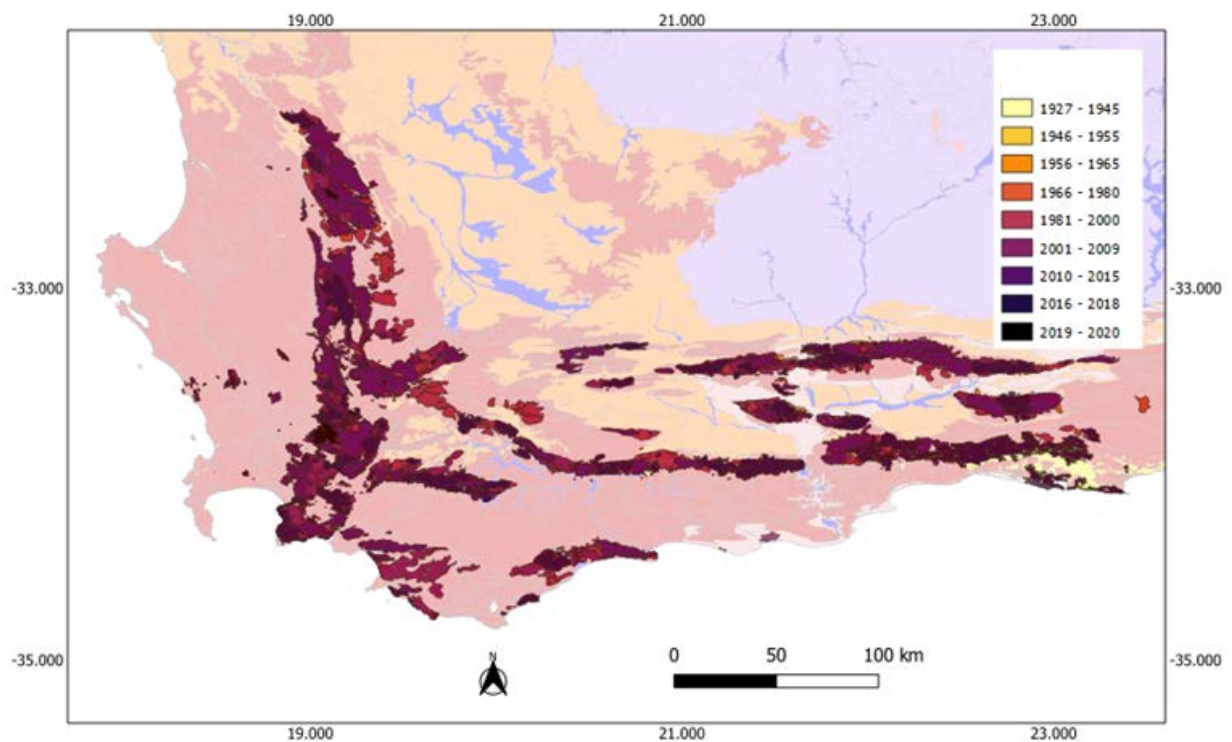


Figure 4.10: Spatial distribution of reported fires

The total burnt area of the reported fires are depicted by Figure 4.11 below. From 1927 to 1988, no fire event consumed more than 20000 hectares(ha).

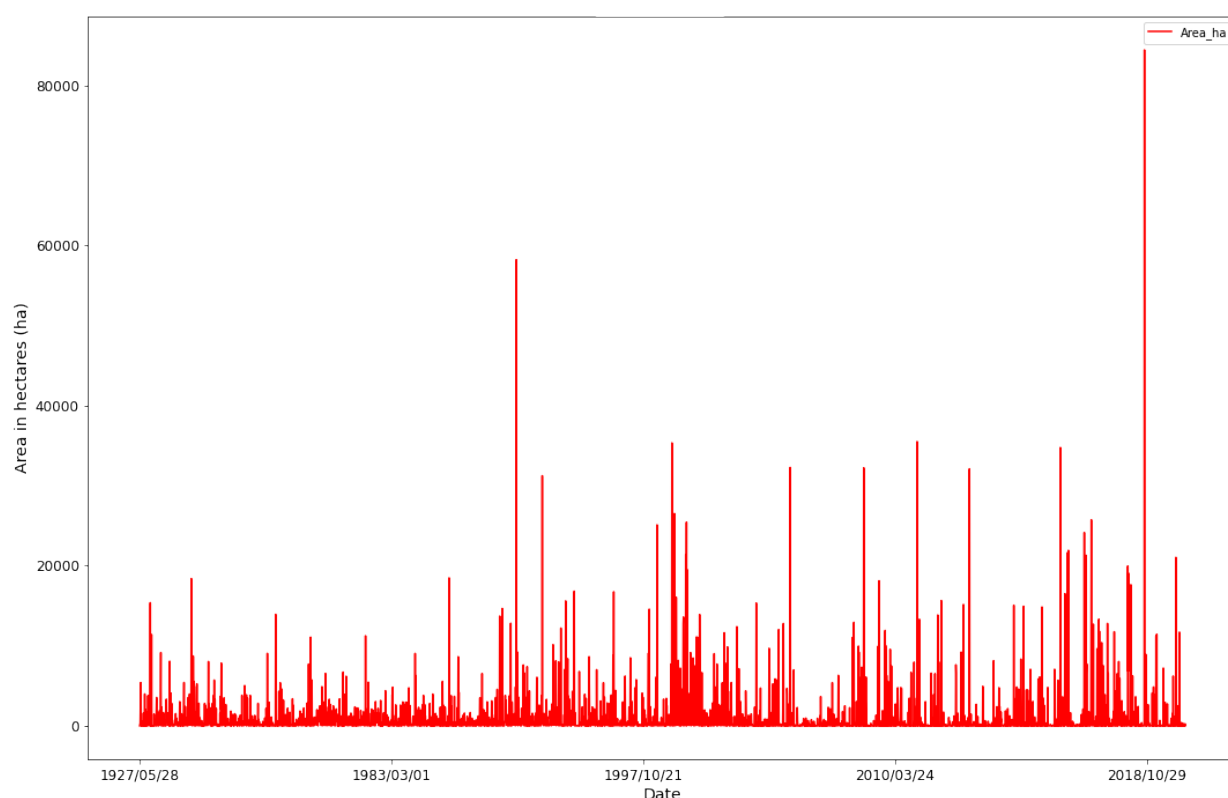


Figure 4.11: Reported fires and burnt areas in the Western Cape over time

The descriptive statistics of the reported historical fire record in Table 4.4 shows the mean burnt area amount to 1003,879 ha, with a median of 108,164 ha. The largest fire event consumed 84402,069 ha.

Table 4.4: Descriptive statistics of burnt areas over time

	Area (ha) burnt
Min	0.00003
Mean	1003.879
Standard deviation	3152.822
Q1	9.282
Q2 (Median)	108.164
Q3	626.224
Max	84402.069

Data from the historical record was filtered to isolate the 15 largest fire events and is depicted by Figure 4.12 below. Only two fire events consumed more than 50000 ha – the 1988 fire in the Cederberg Wilderness Area (58203,287 ha) and the 2018 fire in the Witfontein Nature Reserve (84402,069 ha). The time lapse between these two events are 30 years. Between these two events, the largest recorded fire consumed 35494,661 ha (2011 fire in the Haweqwa Mountain Catchment Area). Six other fires consumed more than 30000 ha, while an equal amount of fire events consumed less than 30000 ha. Three of the large fire events occurred in the years 1999 and 2016, with another large fire event occurring in early 2017.

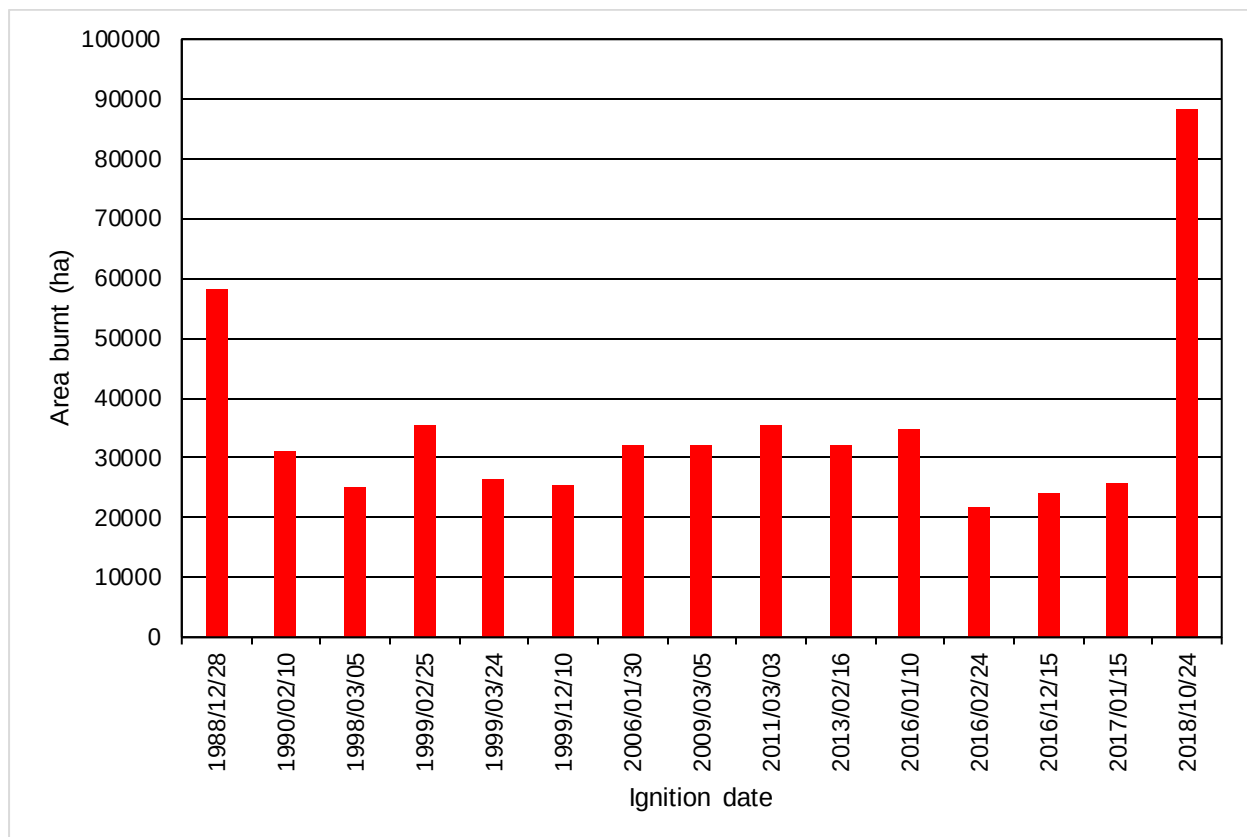


Figure 4.12: Largest reported fire events over time

The spatial distribution of burnt areas are shown in Figure 4.13 below. Large fire events were recorded in the Cederberg Wilderness Area, Haweqwa Mountain Catchment Area and Witfontein Nature Reserve. It is important to take note that the largest fire event occurred in the Forest biome (Witfontein Nature Reserve).

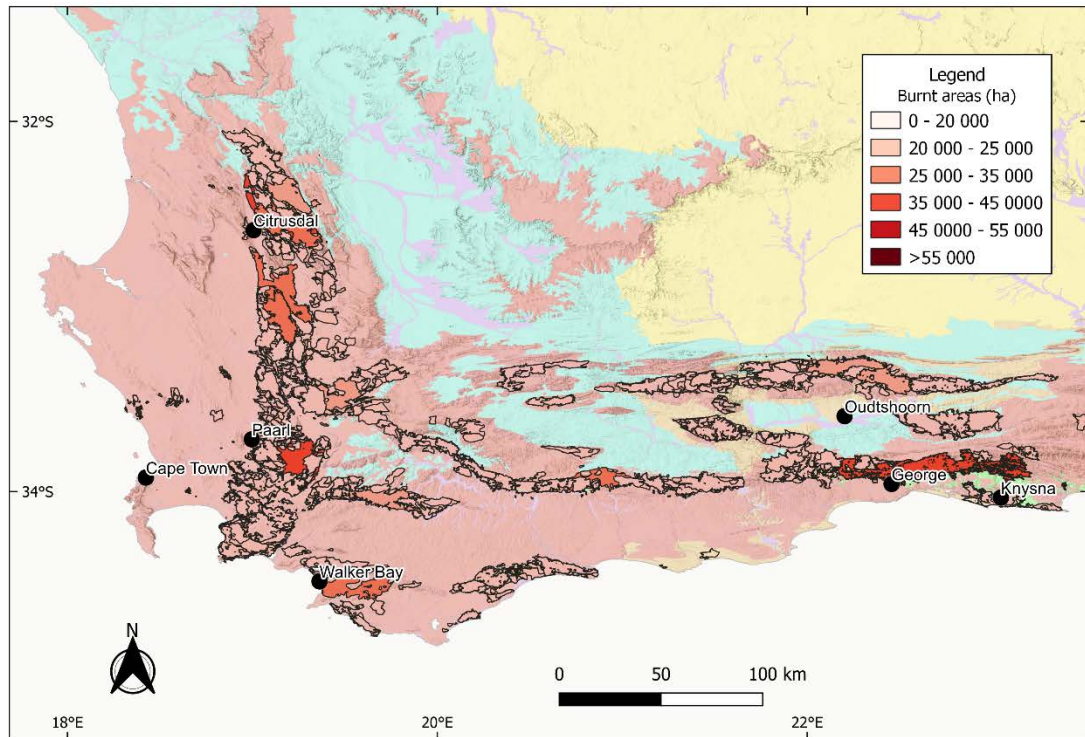


Figure 4.13: Distribution of burnt areas of reported fires

Some of the largest fire events across the region occurred at the same place, or in the same region as indicated in Table 4.5 below. Fires recorded in the Citrusdal area (Cederberg Wilderness Area and Matjiesrivier Nature Reserve) showed an irregular time interval. The time lapse between the first two large fires was almost 10 years, followed by a 15-year gap between the second and third large fire, and then by a 3-year gap between the third and fourth largest fire event. Fires in the Haweqwa Nature Reserve occurred with a 21-year gap between them, and the burnt areas were almost the same (31230,015 ha in 1990 and 35494,661 ha in 2011). In the Grootwinterhoek Wilderness Area, large fire events occurred with an almost 7-year and 1-year gaps in between. This does not show a clear pattern of fire frequency at a certain area over time.

Table 4.5: Location of largest fire events

Date of fire ignition	Area burnt (ha)	Location
1988/12/28	58203,287	Cederberg Wilderness Area - NE of Citrusdal
Interval: 13 months, 13 days		
1990/02/10	31230,015	Haweqwa Nature Reserve - SE of Paarl
Interval: 8 years, 23 days		
1998/03/05	25097,914	Cederberg MCA Southern Cederberg
Interval: 11 months, 21 days		
1999/02/25	35330,392	Theewaters Nature Reserve - SE of Franschhoek
Interval: 1 month		
1999/03/24	26503,559	Jonkershoek Nature Reserve - E of Stellenbosch
Interval: 8 months, 17 days		
1999/12/10	25424,957	Boosmansbos Wilderness Area - E of Barrydale
Interval: 6 years, 1 month, 20 days		
2006/01/30	32260,132	Walker Bay Nature Reserve - N of Gansbaai
Interval: 3 years, 1 month, 5 days		
2009/03/05	32215,875	Grootwinterhoek Wilderness Area - N of Tulbagh
Interval: 1 year, 11 months, 26 days		
2011/03/03	35494,661	Haweqwa MCA SE of Paarl
Interval: 1 year, 11 months, 13 days		
2013/02/16	32088,187	Matjiesrivier Nature Reserve - NE of Citrusdal
Interval: 2 years, 10 months, 25 days		
2016/01/10	34750,522	Grootwinterhoek Wilderness Area - N of Tulbagh
Interval: 1 month, 14 days		
2016/02/24	21911,115	Groot Swartberg Nature Reserve - NE of Oudtshoorn
Interval: 9 months, 21 days		
2016/12/15	24138,376	Cederberg Wilderness Area - NE of Citrusdal
Interval: 1 month		
2017/01/15	25722,941	Grootwinterhoek Wilderness Area - N of Tulbagh
Interval: 1 year, 9 months, 9 days		
2018/10/24	88402,069	Witfontein Nature Reserve N of George

A histogram showing the fire event distribution according to months of the year is displayed in Figure 4.14 below. This shows the months recording the most fire events are December to March (>400) and the least amount of fire events were recorded during the months of May to August. The higher frequency of fire events corresponds with the late-dry season of the Fynbos biome, where the majority of the fire events occur. When looking at the 15 largest fire events, one can see a similar pattern where almost all of these events occurred in the months between December and March – with the exception of the 2018 fire, an event occurring in the Forest biome.

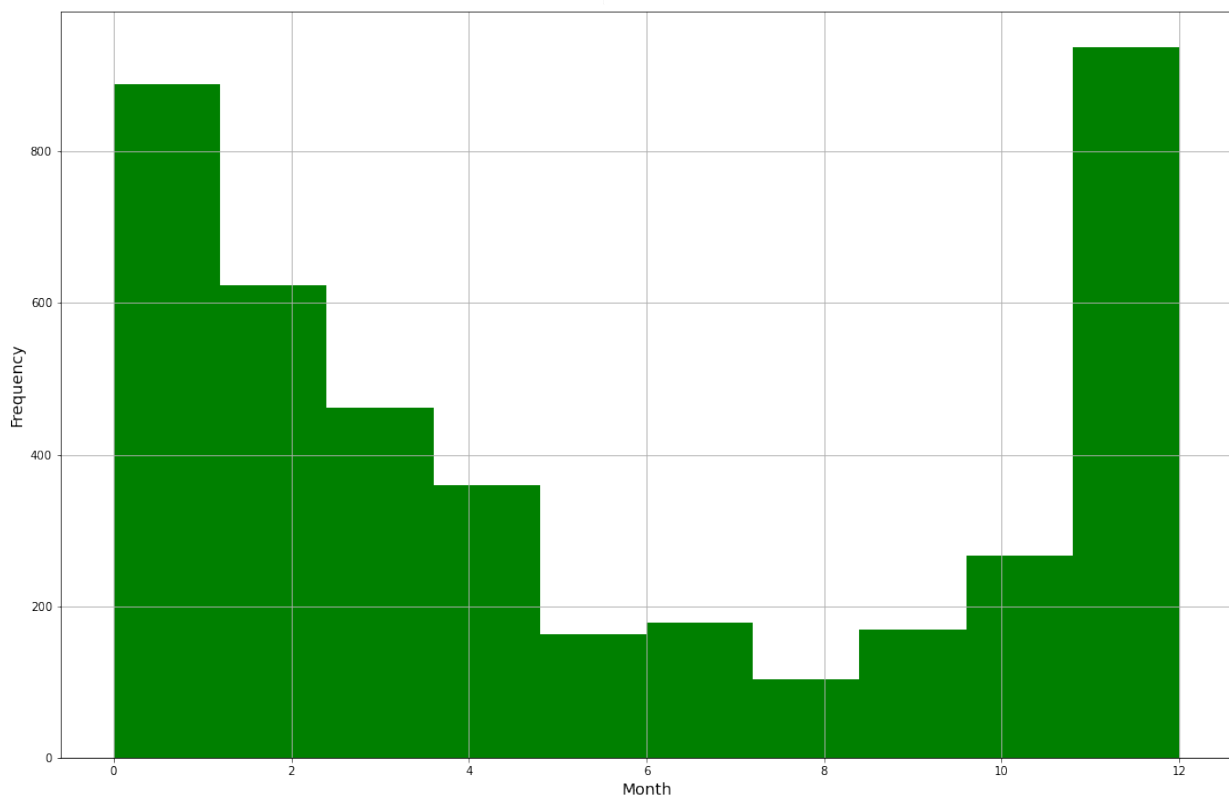


Figure 4.14: Histogram showing seasonality of reported fires

Seasonality of fire events may also encompass periods where a particular region experienced precipitation anomalies. The majority of the fire events occurred after seasons recording below normal precipitation. The two largest fires (1988 and 2018) occurred after seasons where below normal precipitation had been recorded over the region. No seasonal anomalies were recorded in the seasons preceding five large fire events. Above normal precipitation anomalies were recorded in the seasons preceding two large fire events. These phenomena are associated with the 2006 and 2009 fire events. The Figures 4.15-4.20 display the precipitation anomalies associated with fire events. Figure 4.15 shows below normal precipitation over the south-western Cape, with above normal precipitation occurring along the east coast of South Africa and Mozambique during the months of May to August 1988. In Figure 4.16 below normal precipitation

over the south-western Cape is depicted for the periods July to September 1997 and Jun to September 1998. Below normal precipitation conditions also occurred over the Eastern Cape during the 1997 period. Above normal precipitation occurred during March to June 2005 over the southwestern and southern Cape as well as southern Namibia and the SE Kalahari as depicted by Figure 4.17. This figure also shows below normal precipitation occurring over the Limpopo and KwaZulu-Natal provinces.

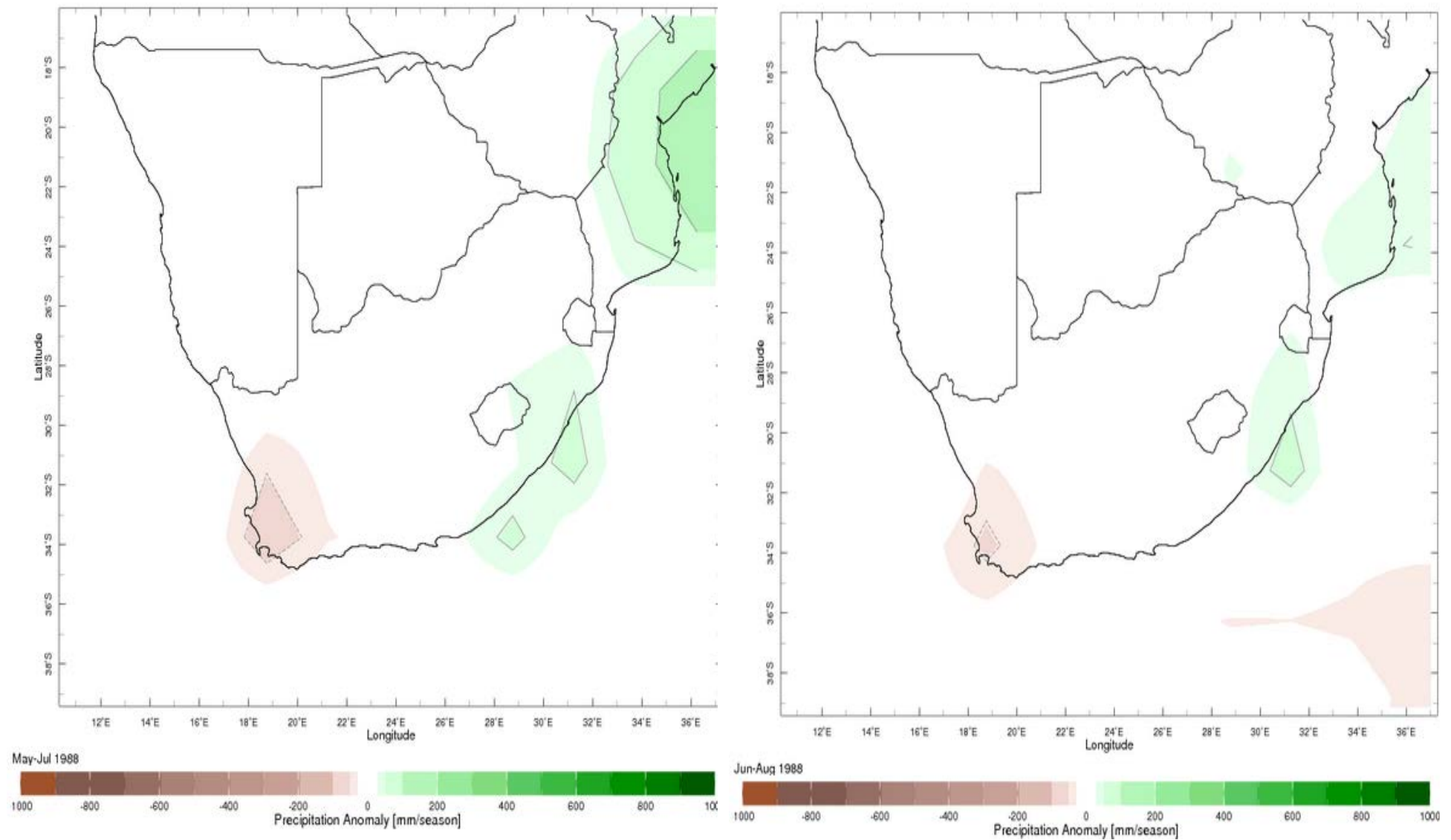


Figure 4.15: Seasonal precipitation anomalies for the large fire in 1988

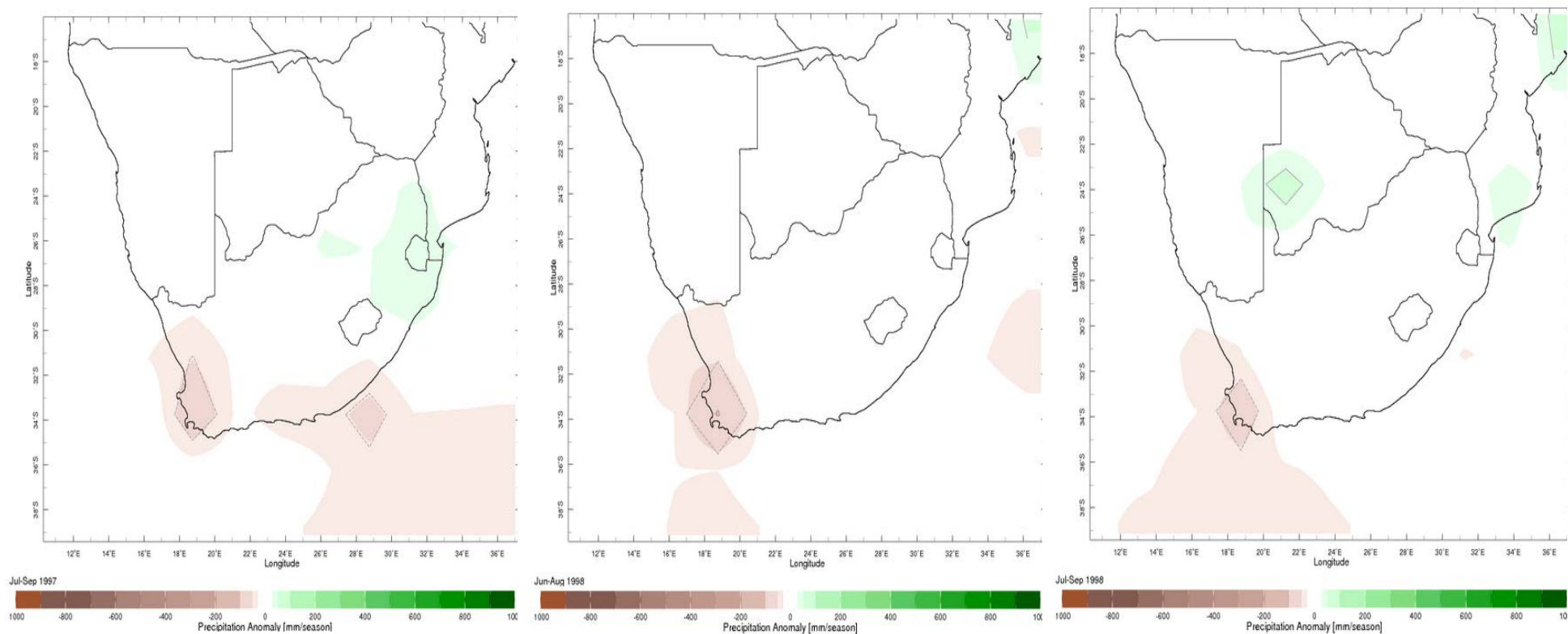


Figure 4.16: Seasonal precipitation anomalies linked to large fires in 1999

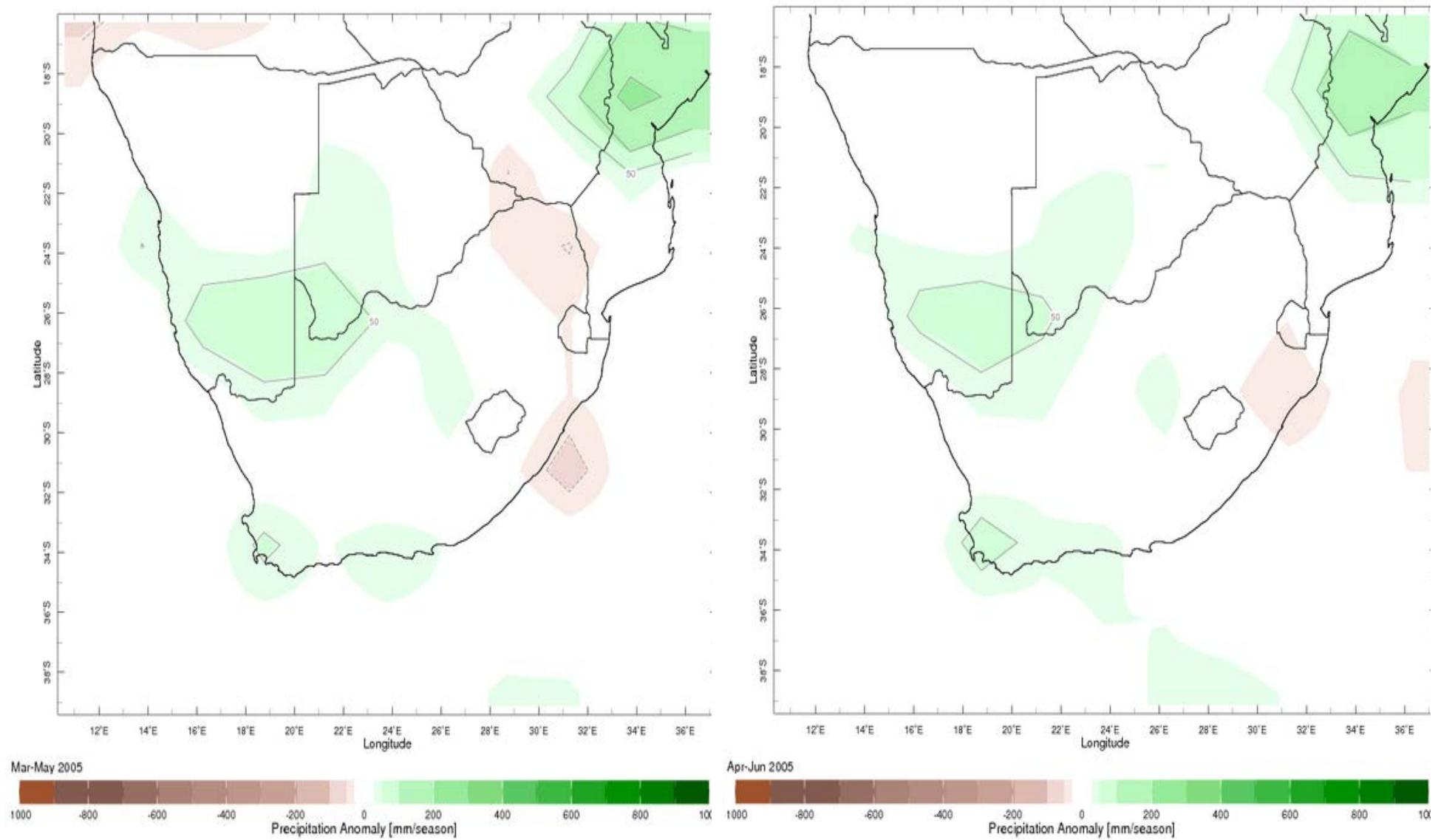


Figure 4.17: Seasonal precipitation anomalies linked to the large fire in 2006

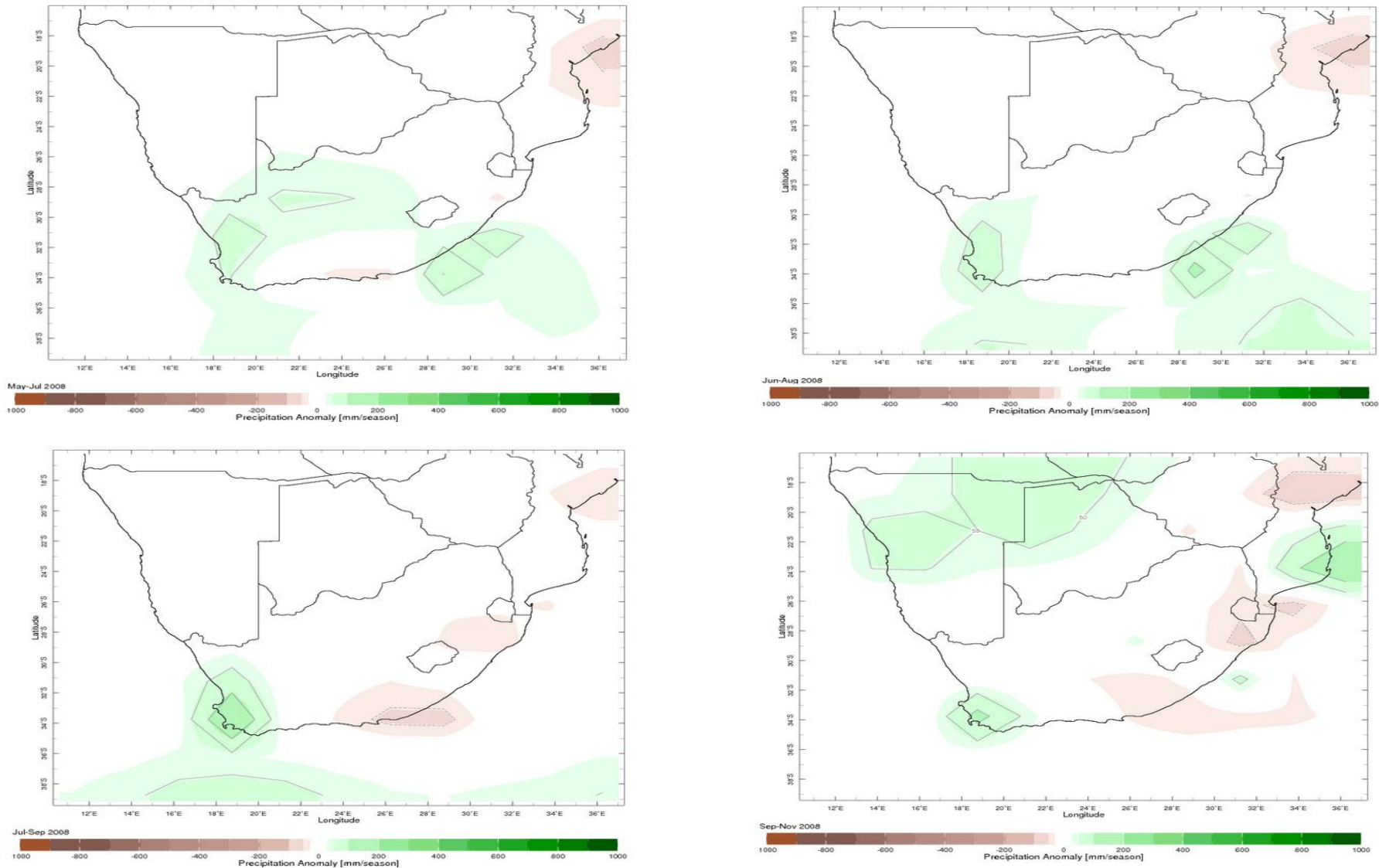


Figure 4.18: Seasonal precipitation anomalies linked to the large fire in 2009

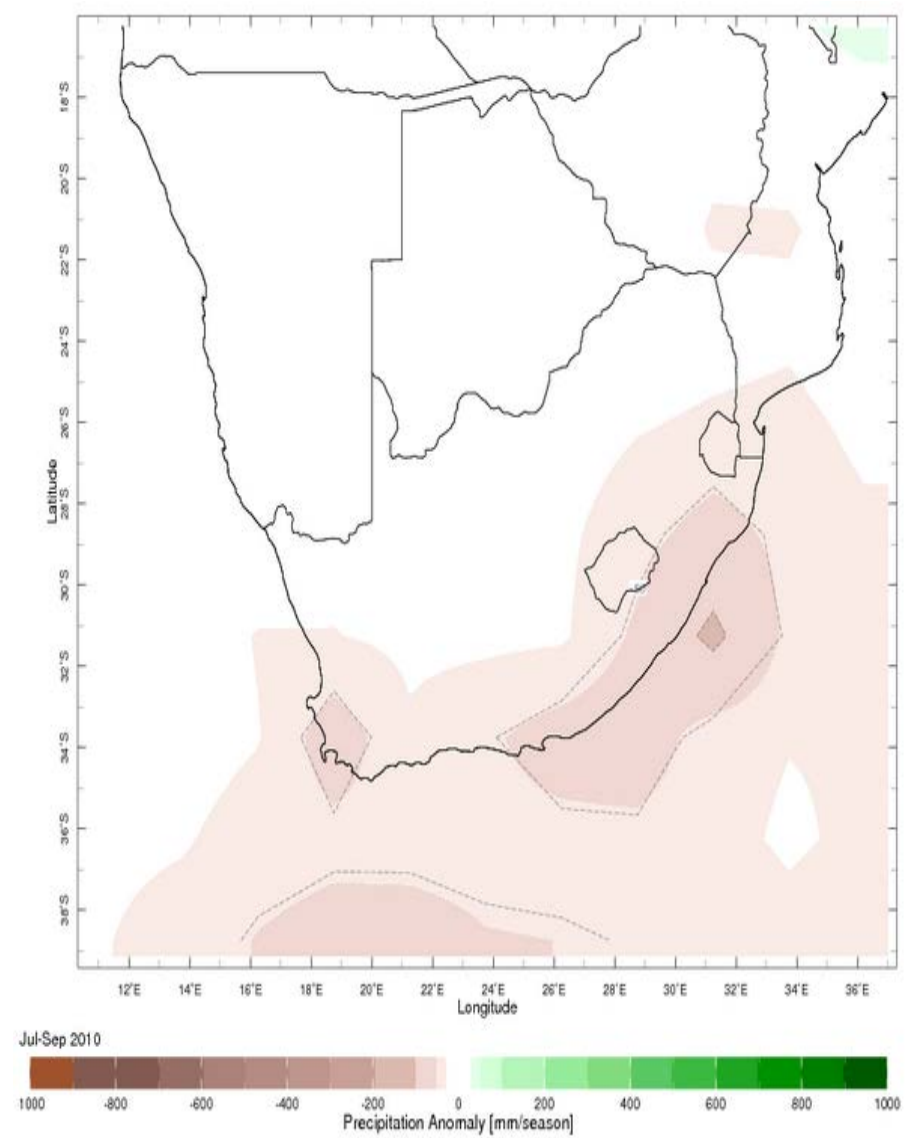
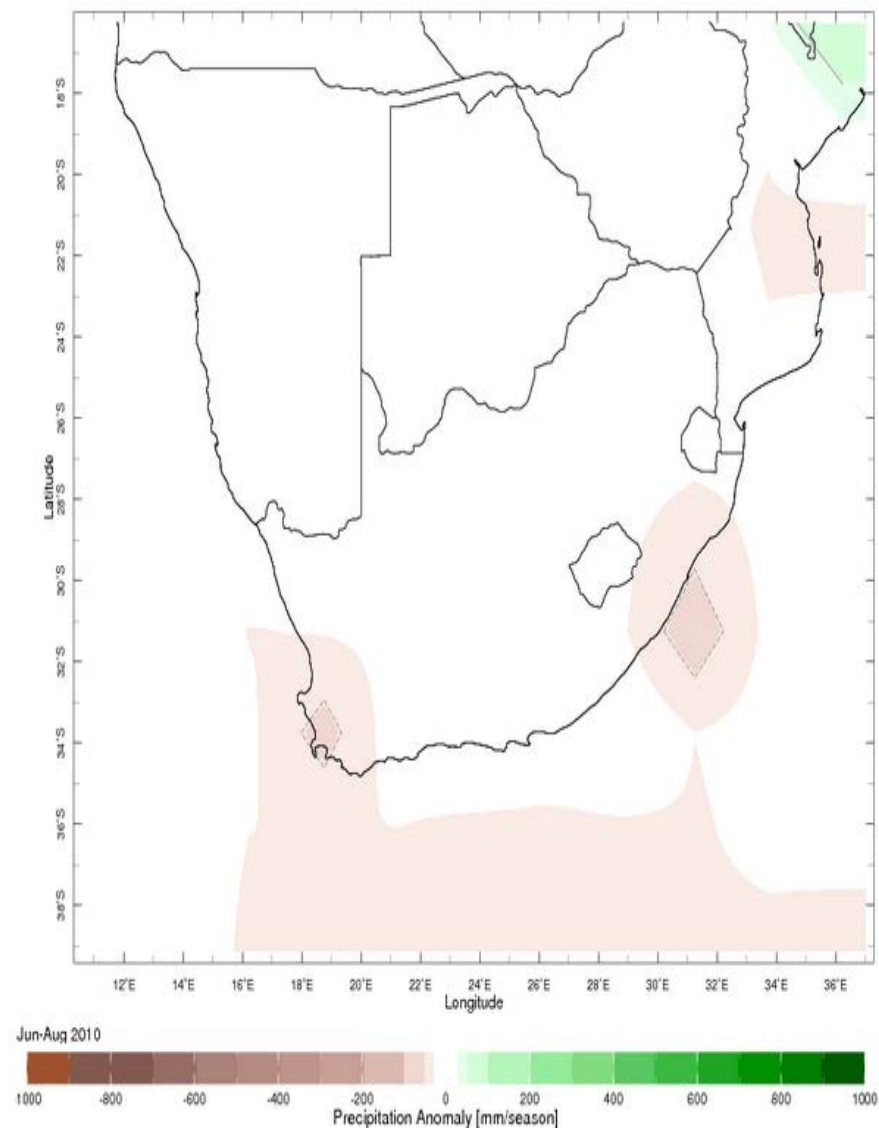


Figure 4.19: Seasonal precipitation anomalies linked to the large fire in 2011

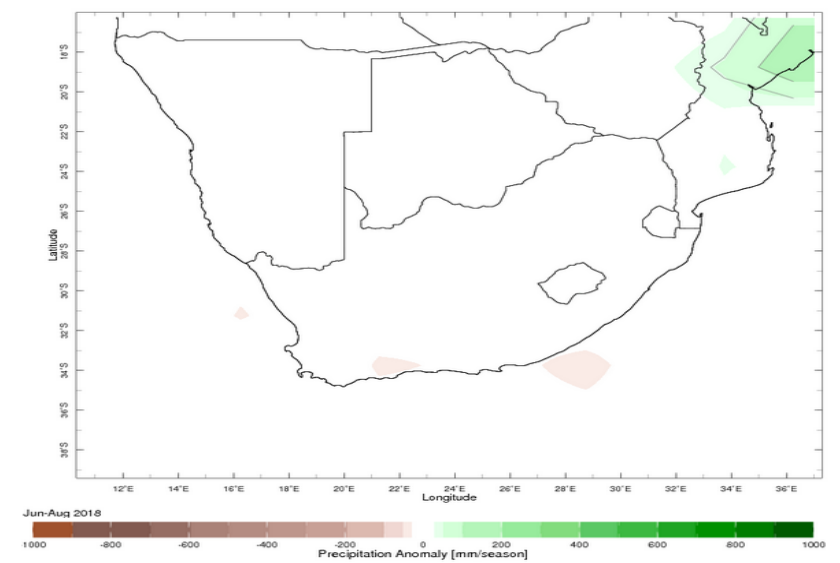
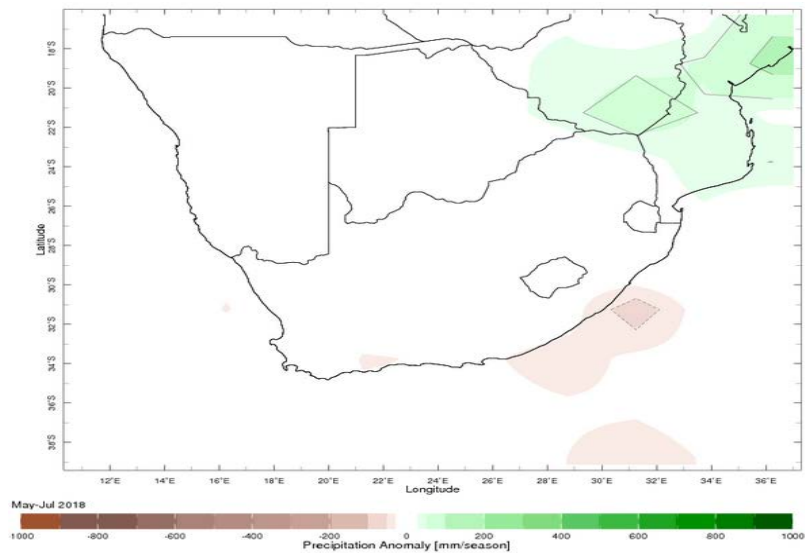
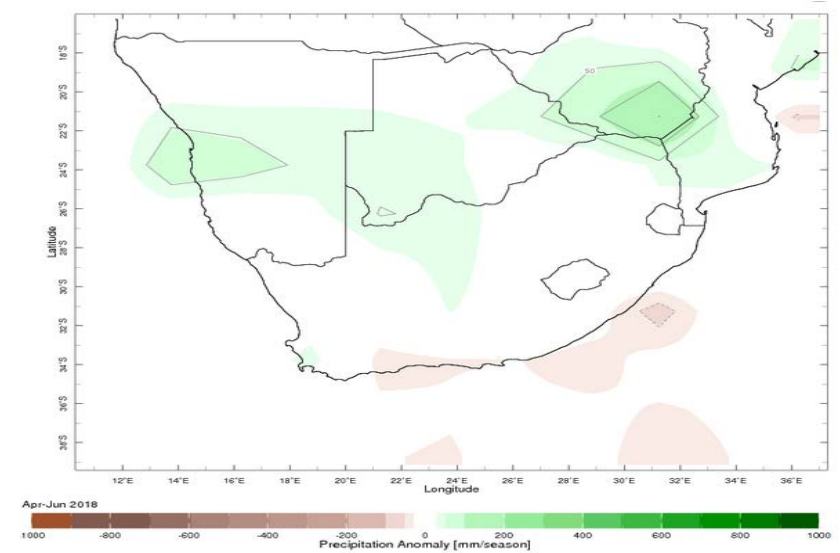
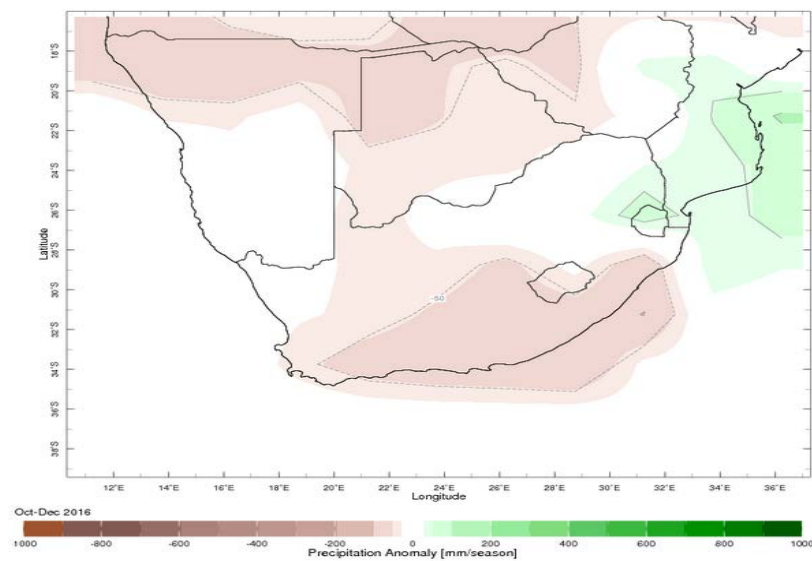


Figure 4.20: Seasonal precipitation anomalies linked to large fires in 2016, 2017 and 2018

Figure 4.18 shows the above normal precipitation occurring over the southwestern Cape, Northern Cape and coastal regions of the Eastern Cape and KwaZulu-Natal provinces during the period of May to November 2008. During the latter part of this period, above normal precipitation conditions were recorded over large parts of Namibia and Botswana. The southern coast recorded slightly below average precipitation amounts. Figure 4.19 displays the below average precipitation conditions that were recorded over the southwestern Cape and coastal regions of KwaZulu-Natal during the period June to August 2010, while the period July to September 2010 shows the precipitation anomaly occurred over large parts of the Western Cape, Eastern Cape and KwaZulu-Natal provinces. The period October to November 2016 recorded a significant below normal precipitation over much of Namibia, Botswana and South Africa as shown in Figure 4.20. Slightly above normal precipitation values were recorded over Mozambique and eSwatini over this time. In addition, Figure 4.20 also depicts the below normal conditions that occurred over the southern coast during the periods April to August 2018. Above normal precipitation values were recorded over Zimbabwe and Mozambique during this time.

ENSO cycles may play a significant role in the occurrence of precipitation anomalies. The occurrence of large fires in the Western Cape has been added to the timeline of the ENSO cycles created by the NOAA in Figure 4.21 below.

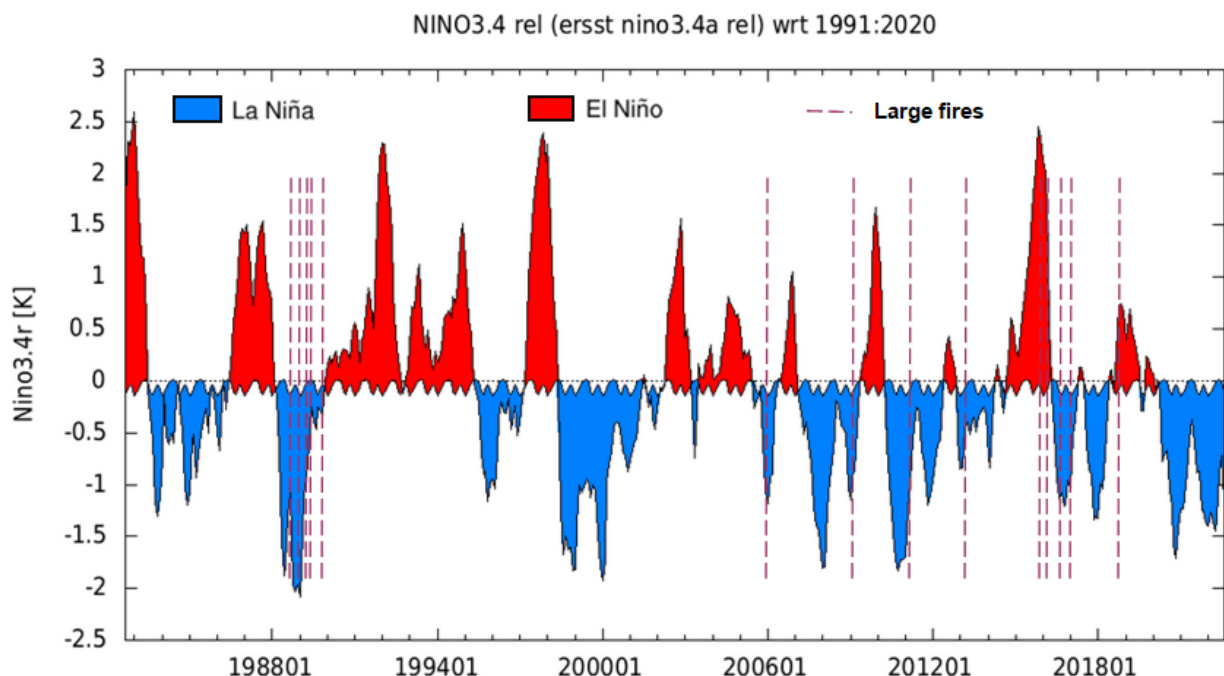


Figure 4.21: Large fire events on an ENSO timeline

While eight of large fire events occurred following an El Niño phase of ENSO (1988, 1998, 2006, 2011, 2016 and 2018 fires) – which is associated with below normal precipitation over southern

Africa – one of the fire events (2013 fire) occurred in the neutral phase of ENSO. The remaining six fire events occurred after La Niña phases of ENSO (1990,1999, 2009 and 2017 fires).

In terms of the case studies selected, the 2015 and 2018 fires occurred a few months after an El Niño phase commenced, while the 2020 and 2021 fires occurred after and during La Niña phases as shown by Figure 4.22. The 2017 fire occurred after a La Niña phase which had been followed by a slightly neutral phase of the ENSO. However, it should be noted that the El Niño phase of 2015 was particularly strong and lasted until the autumn of 2016 (Trenberth 2019).

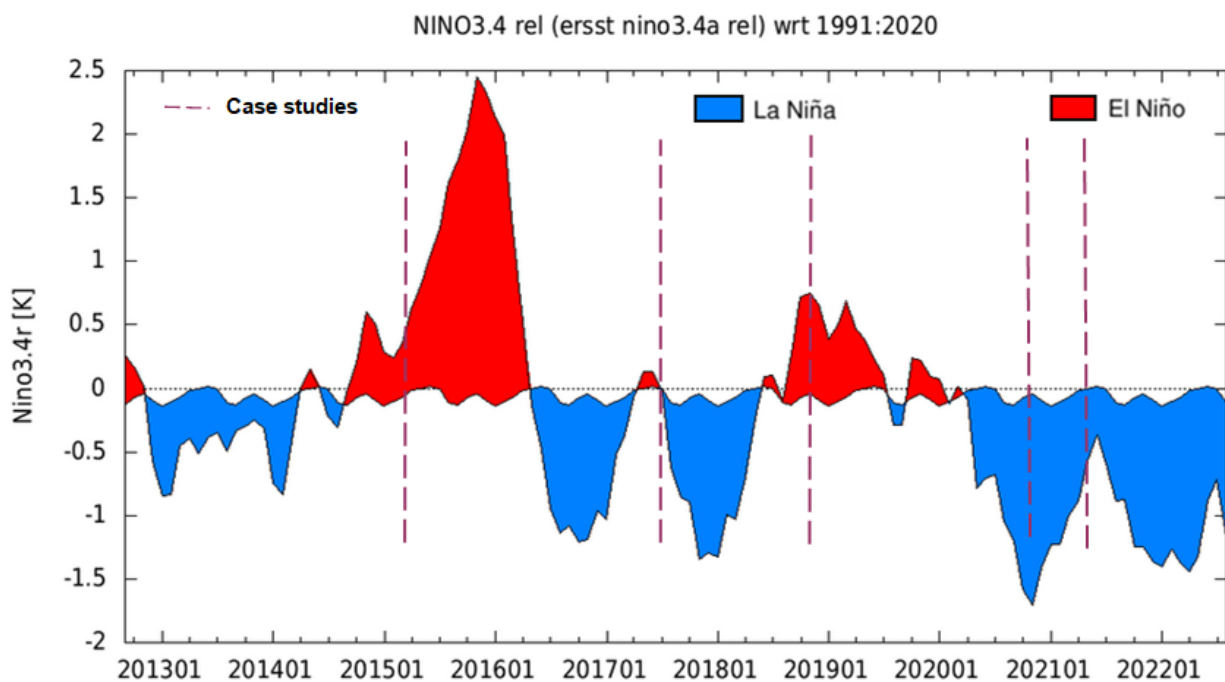


Figure 4.22: Selected fire events on an ENSO timeline

Figure 4.23 below shows the occurrence of large fire events with respect to the official recorded large fire events. In total, 10 of the 15 large fire events in the Western Cape occurred after the positive SAM phases. In contrast, only five of the large fire events occurred after a negative SAM phase in the preceding year. In addition, four of the largest fires in terms of burnt area, occurred after positive SAM phases (1999, 2011, 2016 and 2018).

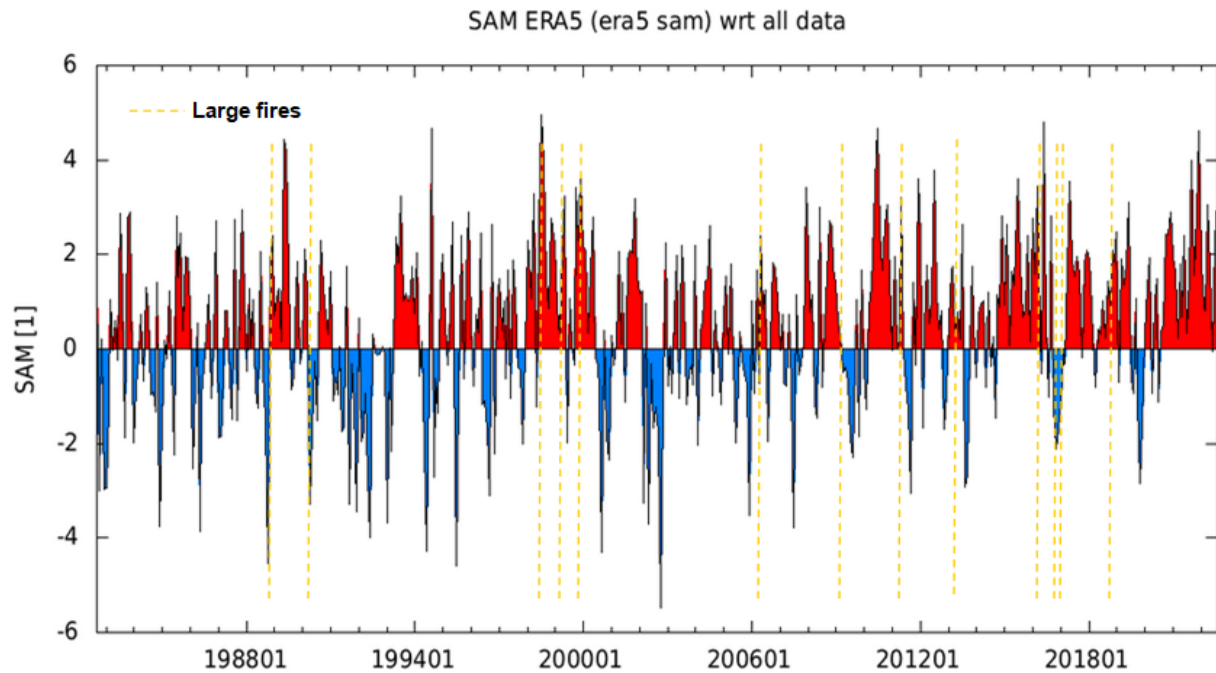


Figure 4.23: Large fire events during SAM phases.

Figure 4.24 Depicts the SAM phases for the selected case studies. According to this figure, three of the fire events occurred after negative SAM phases and two after positive phases.

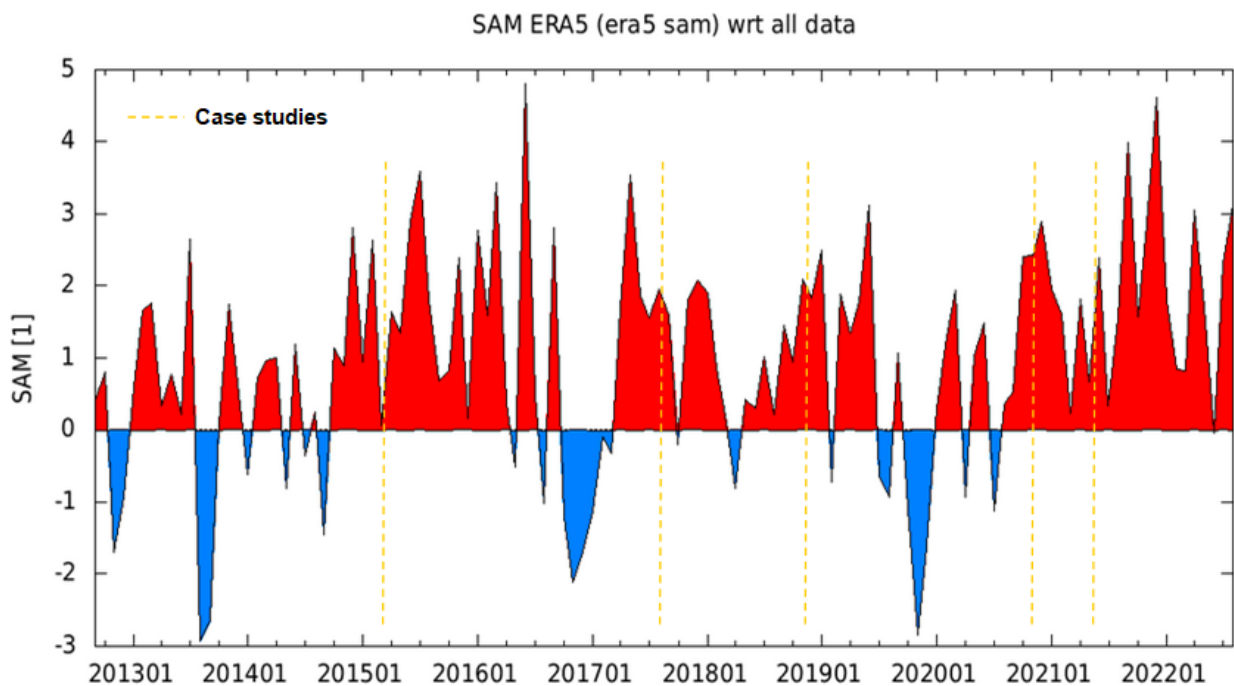


Figure 4.24: SAM phases during the selected case studies

4.3 FIRE EVENT 1: CAPE TOWN 2015

4.3.1 Weather and soil moisture

The Cape Town fire was ignited on the 1st of March 2015. During the previous wet season, above normal precipitation anomalies were recorded in the south-western Cape, with the anomalies reaching more than 50mm for both time periods (April to June and June to August) as shown by Figure 4.25 below. Figures 4.26 and 4.27 below show a LP extending from the interior over the south-western Cape region on the ignition day, while the development of a ridging HP system can be seen towards the southwest of the country. By the 3rd of March, the HP system dominates the weather over the region. Over the next few days, a surface trough starts developing and moving across the western part of South Africa on the day of extinction – the 9th of March. Figure 4.28 shows the maximum temperature on the day of ignition had been high over the western interior and remained stable for the following days while some slight lowering of the maximum temperatures occurred on the day of extinction.

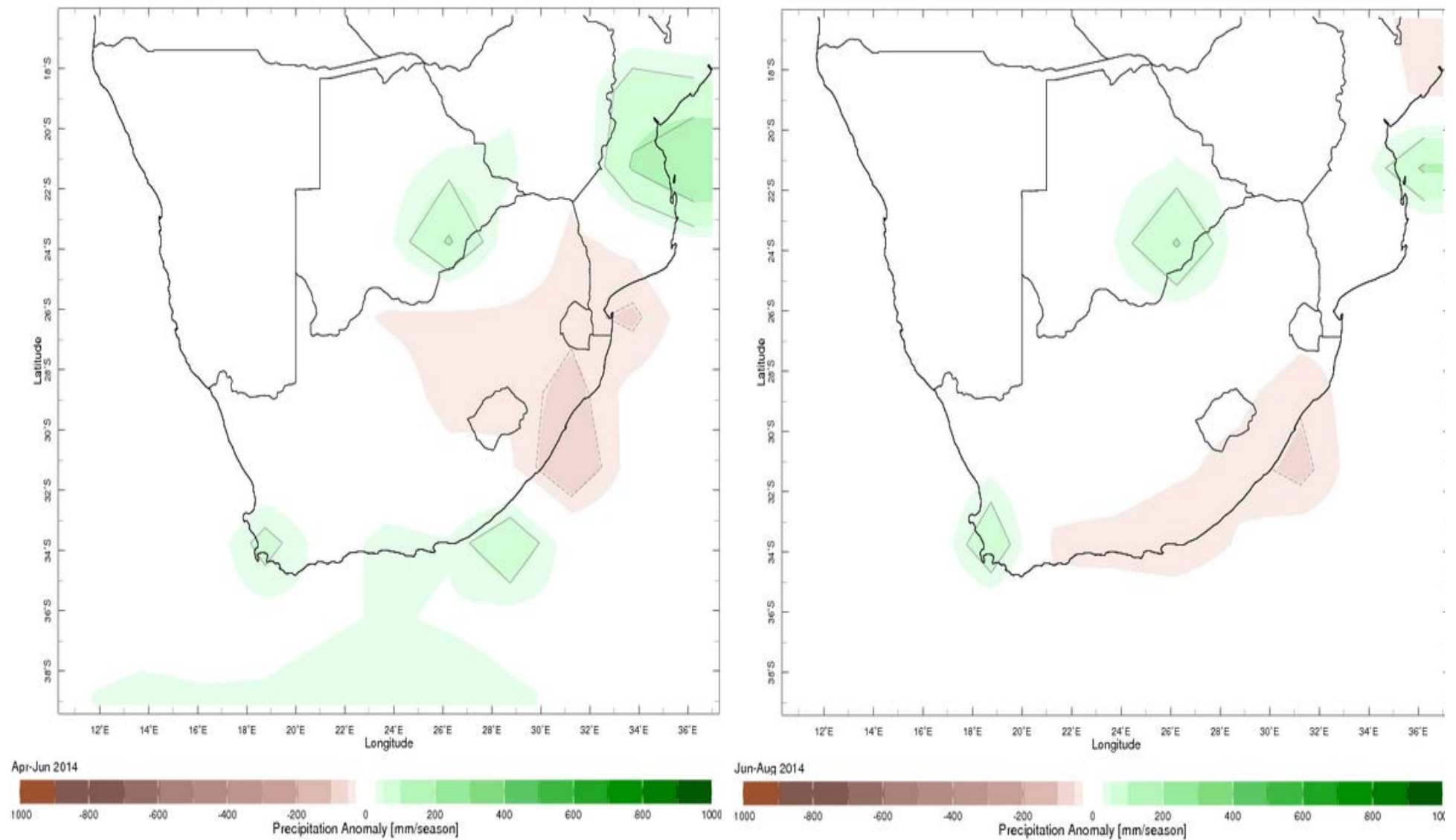


Figure 4.25: Seasonal precipitation anomalies recorded in 2014

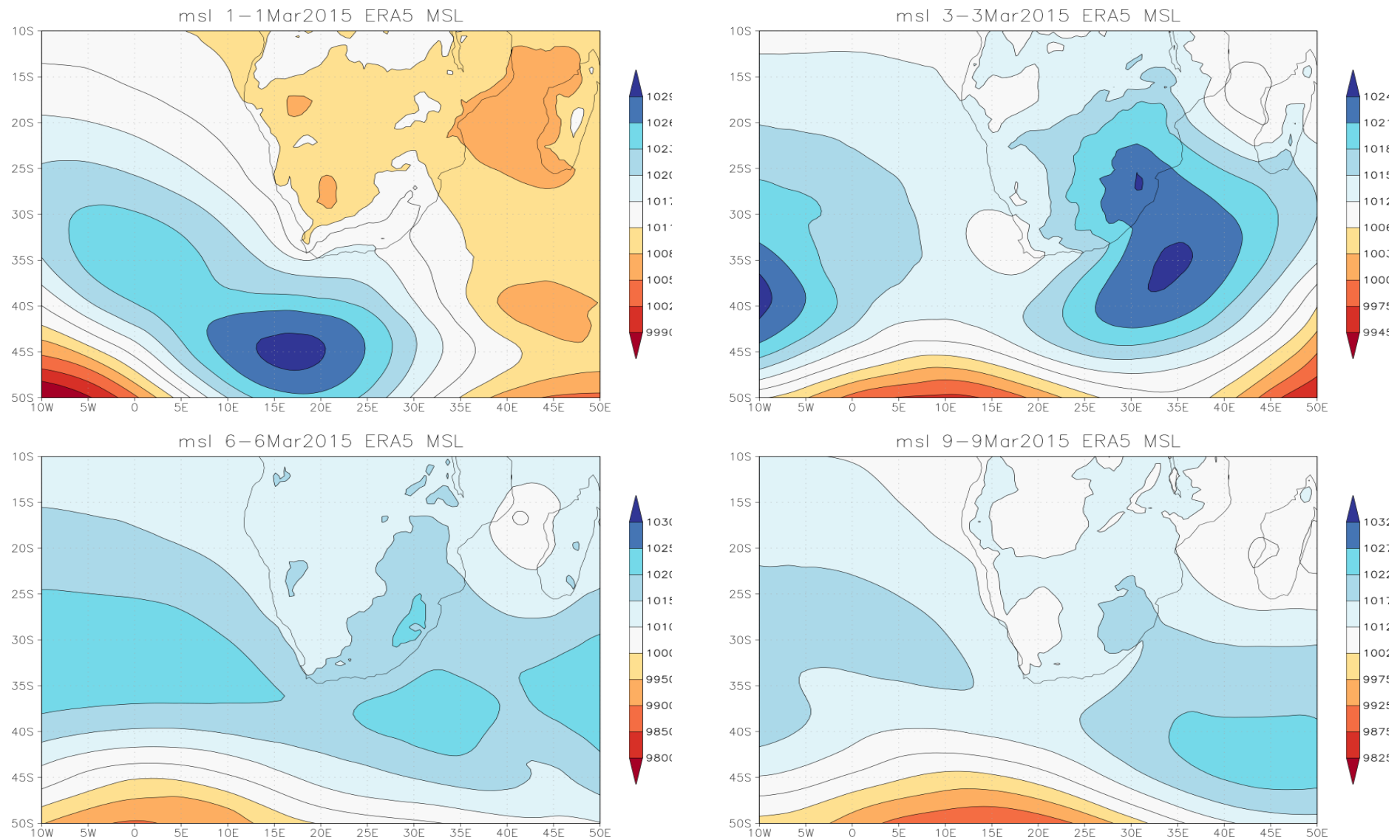


Figure 4.26: Mean-Sea-Level Pressure over South Africa for selected days in March 2015

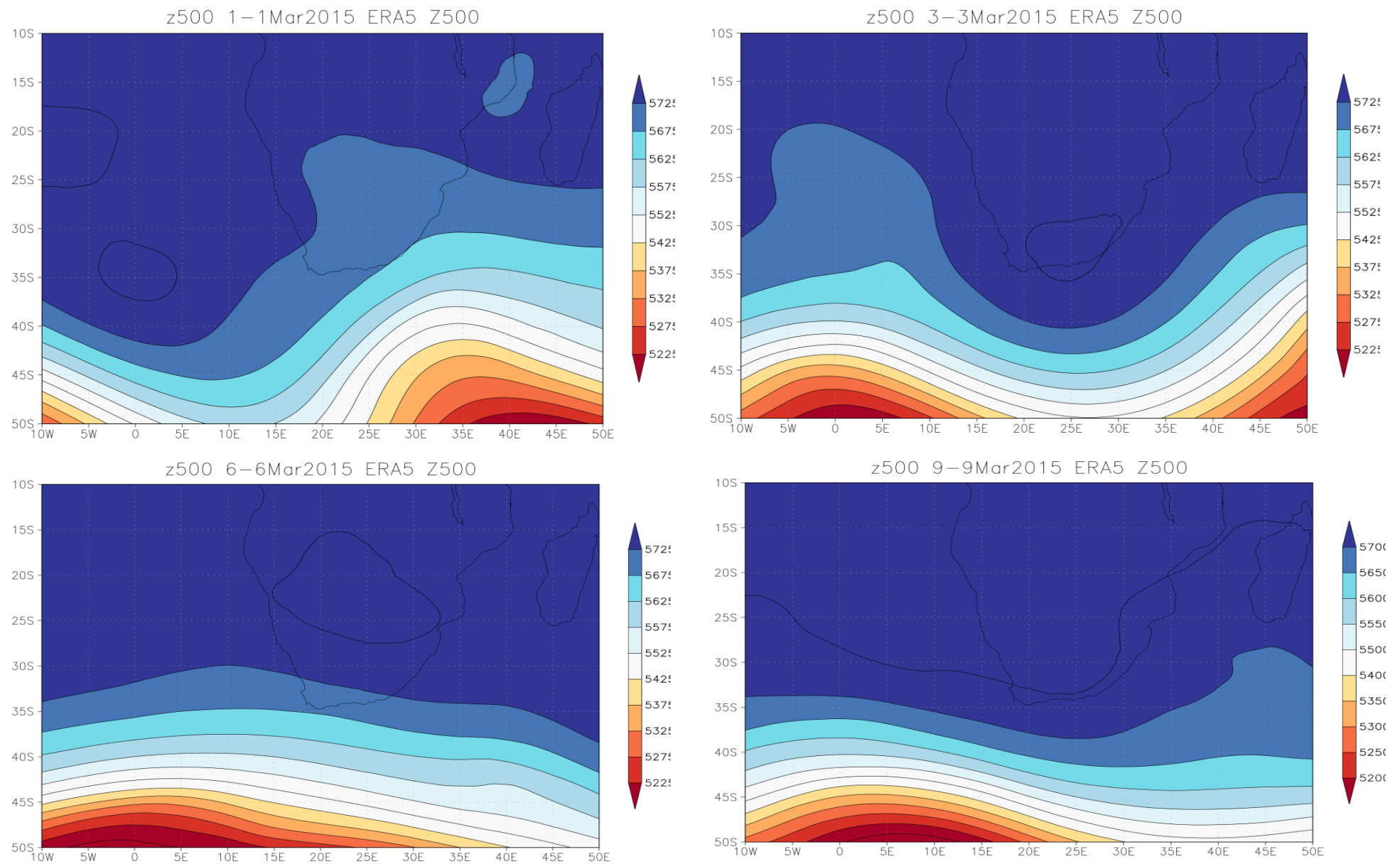


Figure 4.27: Geopotential Height over South Africa for selected days in March 2015

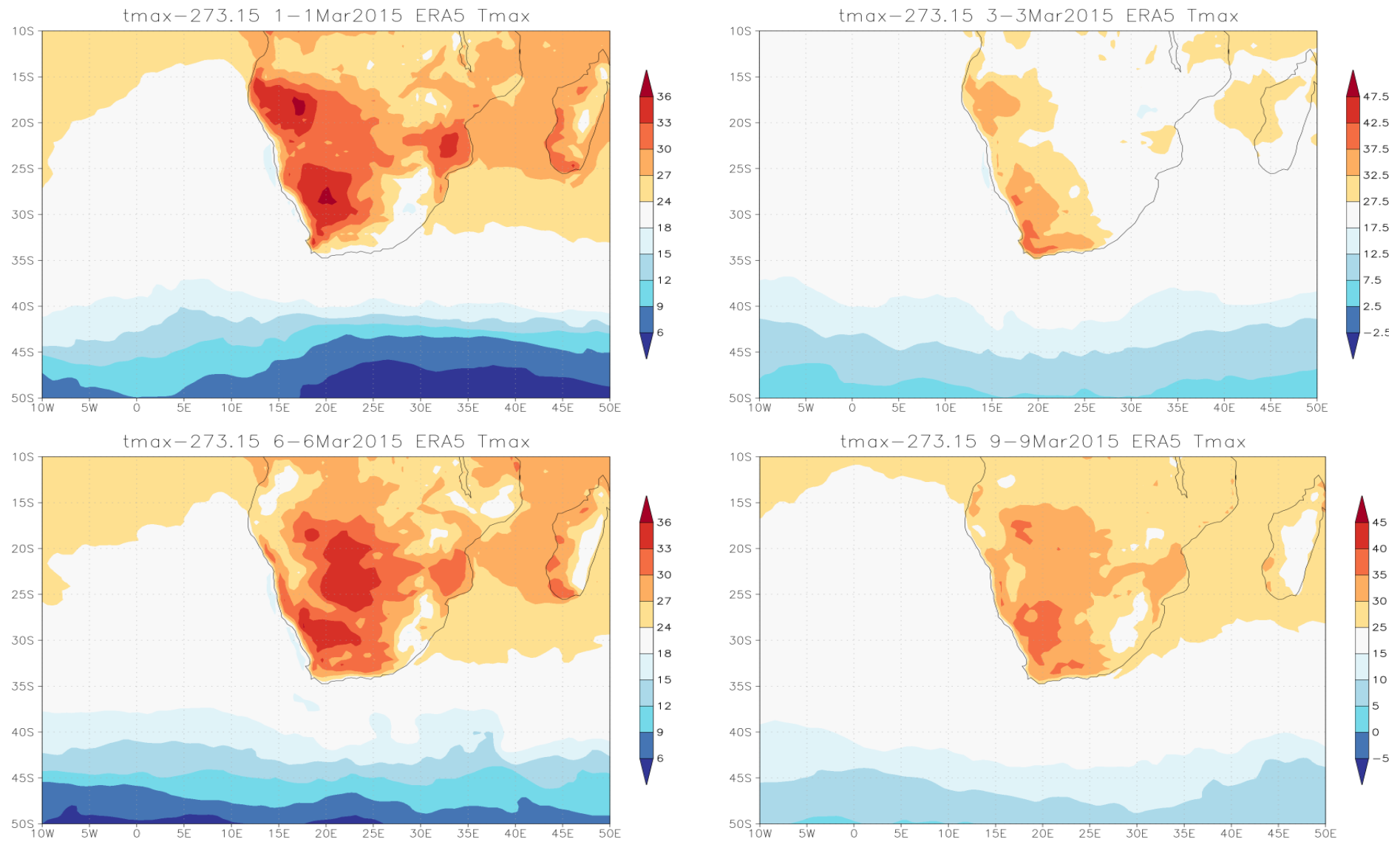


Figure 4.28: Maximum temperatures over South Africa for selected days in March 2015

Figure 4.29 show the meteorological data for the SA Astronomical Observatory for 28 February 1 March. While the temperature values remain relatively constant between 18 and 24°C on both days, it is interesting to note the temperature remains close to its peak value in the afternoon of the 1st of March. The previous day temperature values declined after 15:00. Windspeeds recorded at this station initially decreased on the 28th of February, before stabilising around 4.5 m/s (16.2 km/h) on the 1st of March. On both days, the wind came from a southerly direction. Relative humidity values dipped between 10:00 and 15:00 on the 28th of February, while it continued to decline from before 10:00 on the 1st of March. This showed a similar pattern to the temperature values for the hours after 15:00. Air pressure values remained constant over both days.

Meteograms of 8-9 March are depicted by Figure 4.30. A slight peak in temperature was recorded on 8 March, while the station recorded a more significant diurnal temperature range on the 9th of March with the temperature reaching more than 30°C. Relative humidity values tended to mirror the trends in temperature values with values below 40% coinciding with temperature values above 30°C. Over both days, a slight decrease in air pressure was recorded. On the 8th of March southerly winds swept across the area, starting at a speed of 1.4 m/s (5.04 km/h) and reaching a peak of 5,8 m/s (20.9 km/h) by 19:00. Thereafter, the windspeed decreased and on the 9th of March, no winds were recorded between 05:00 and 17:00.

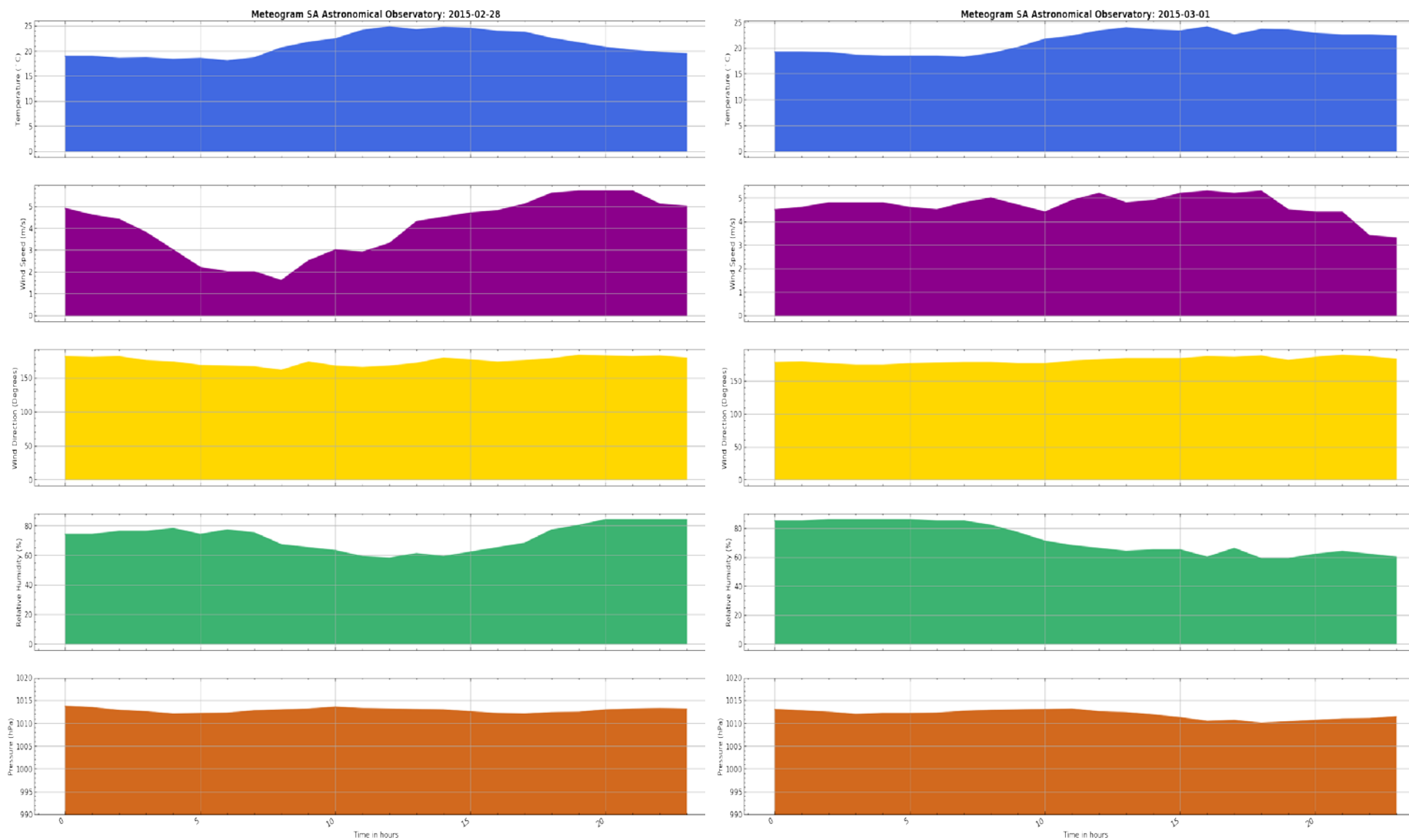


Figure 4.29: Meteorograms SA Astronomical Observatory for 28 February and 1 March 2015

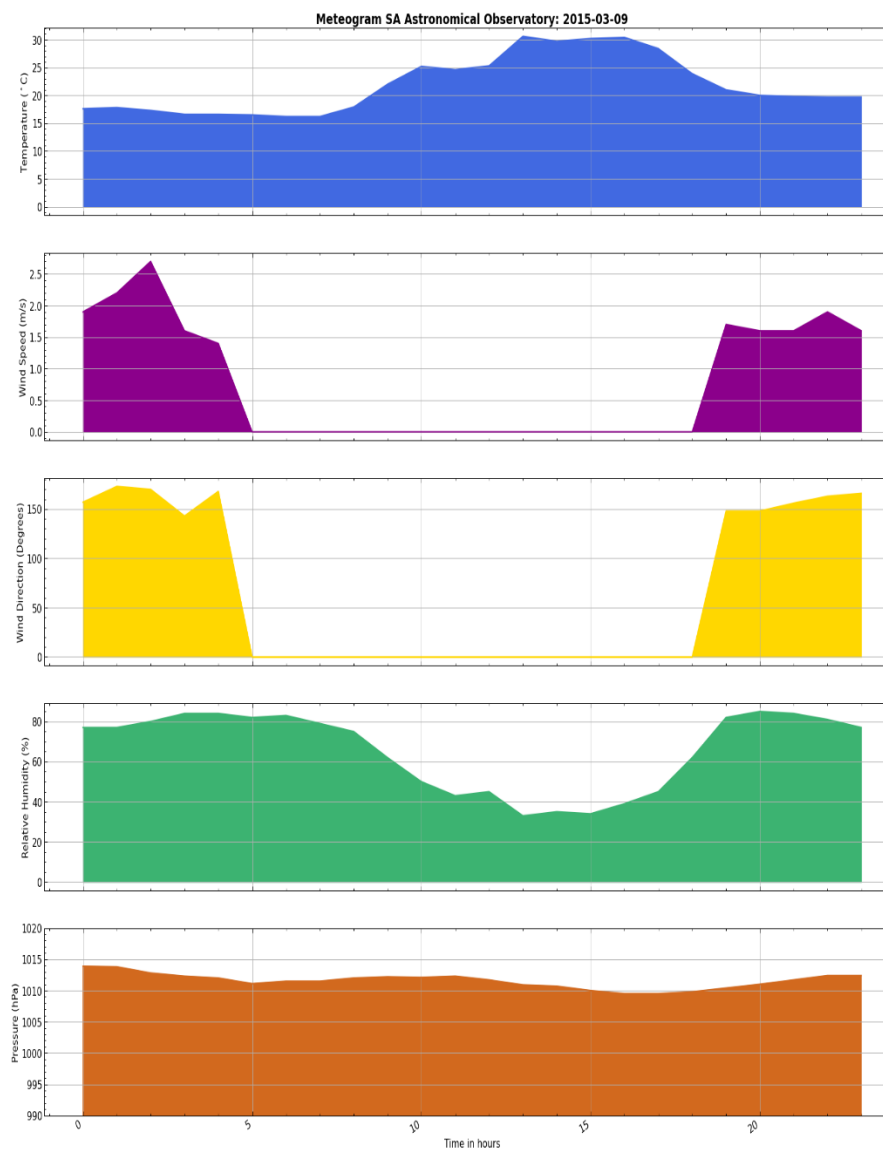
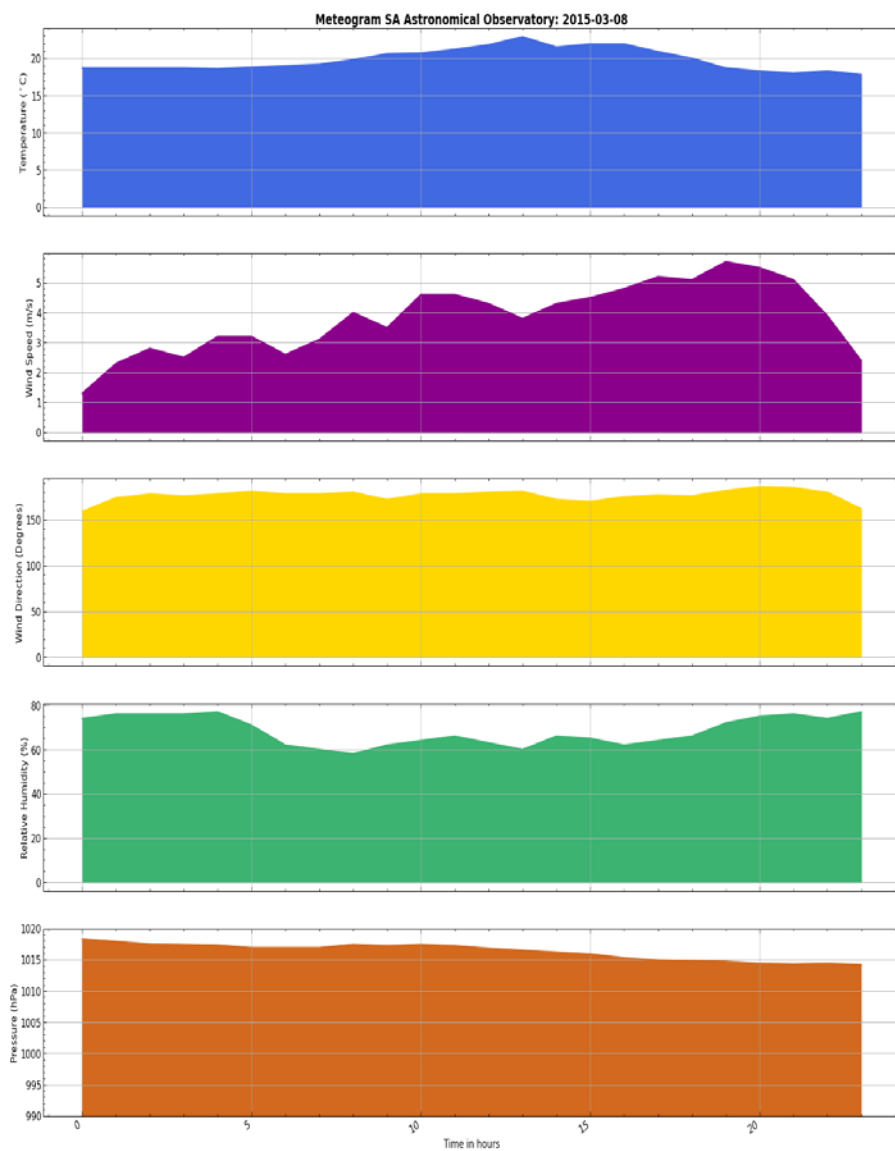


Figure 4.30: Meteograms SA Astronomical Observatory for 8-9 March 2015

Figure 4.31 depicts the average soil moisture in the top layer of soil (0-7 cm below the surface) over the South-Western Cape on the days leading up to the fire as well as the ignition day (26 February to 1 March 2015). The Garden Route area, located on the south-east of the map recorded the highest volumes of soil moisture ($0,2-0,35 \text{ m}^3$), while central and northern parts of the map had the lowest volumes of soil moisture ($<0,05 \text{ m}^3$). Over the Cape Peninsula region, the soil moisture volumes were between $0,15-0,2 \text{ m}^3$.

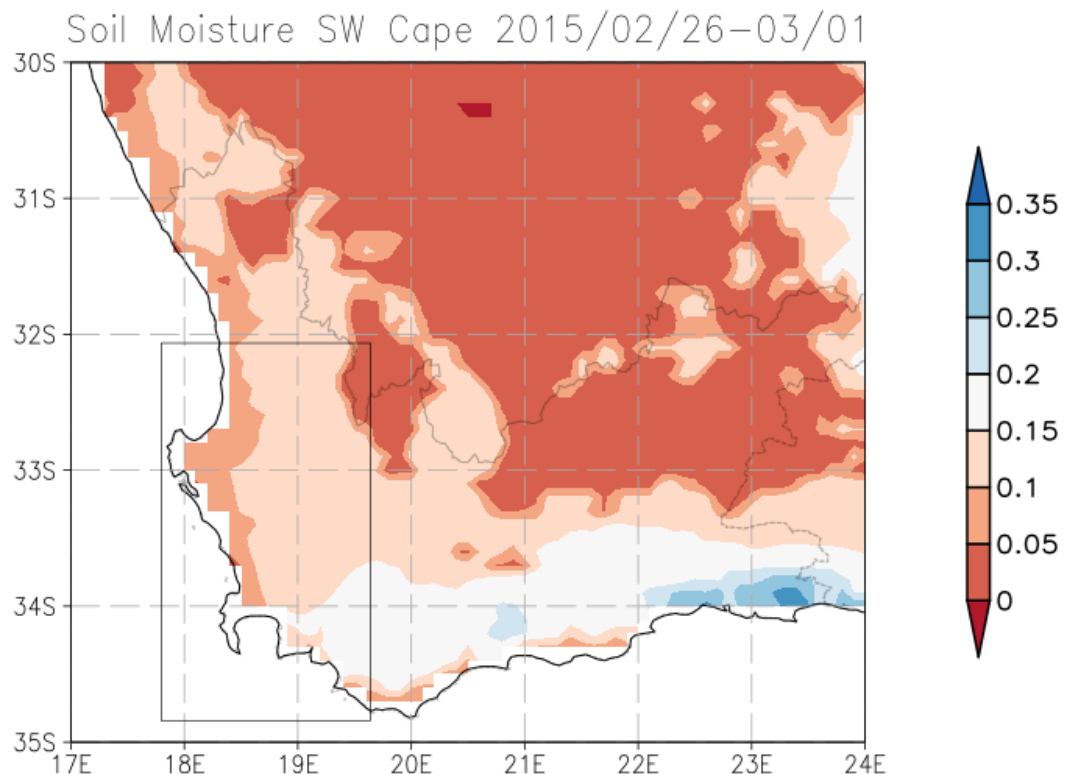


Figure 4.31: Average soil moisture over the South-Western Cape for 26 February to 1 March 2015

4.3.2 NDVI and NBR

Figure 4.32 shows the NDVI comparison between prior to and after the fire. Prior to the fire, the vegetation across the region were mostly under stress (values below 0,33) with a few areas with vegetation in moderately healthy conditions (0,33-0,66). After the fire, the dead vegetation (values below 0) and unhealthy vegetation are clearly distinguishable in the box showing the area where the fire occurred. Vegetation in this area recorded very low positive to mostly negative NDVI values. Vegetation along the Table Mountain area recorded higher positive NDVI values in both instances, with the exception of the burnt area on the northern section of the Cape Peninsula. NBR values are displayed in Figure 4.33 below. Prior to the fire, most of the region reflected positive values with some areas detecting some damage to vegetation (values below -0,0412).

After the fire, there is a clear indication of where fires occurred. In the region of interest, this can be seen by the rectangle covering the burnt area – where negative NBR values had been recorded, on the northern end of the Cape Peninsula. There were also some fire activities occurring on the southern section of the Peninsula and towards the east, close to the Jonkershoek Nature Reserve. However, this study focused on the northern parts of the Cape Peninsula.

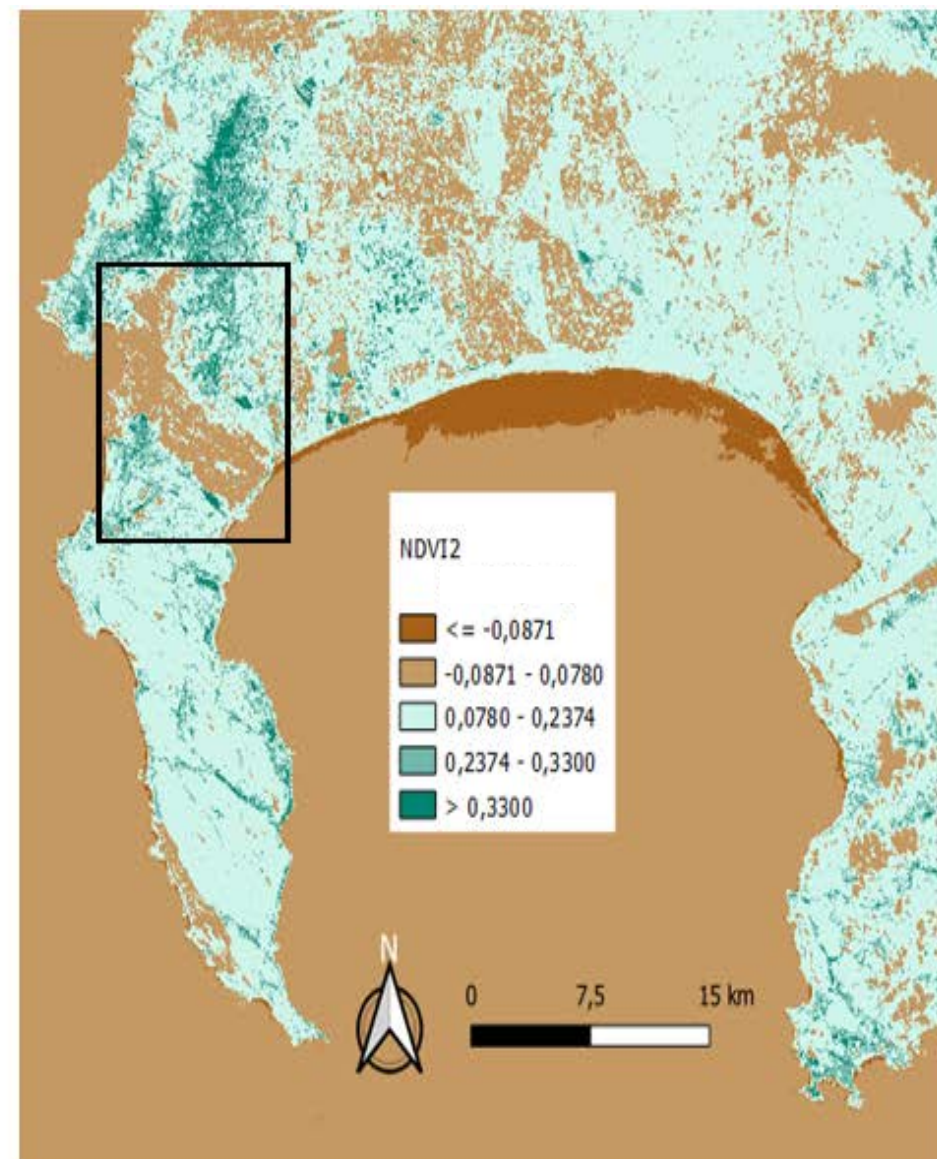
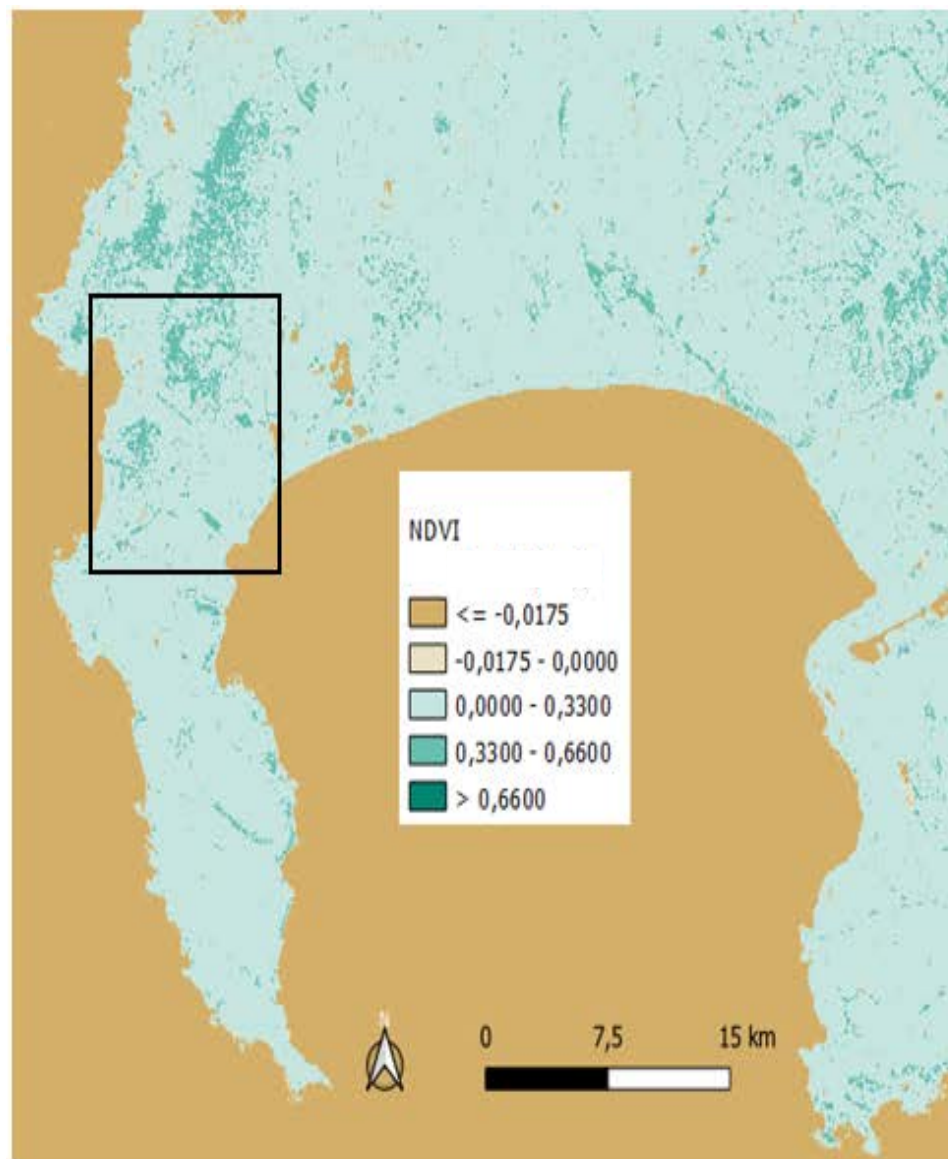


Figure 4.32: NDVI on 23 February vs 11 March 2015

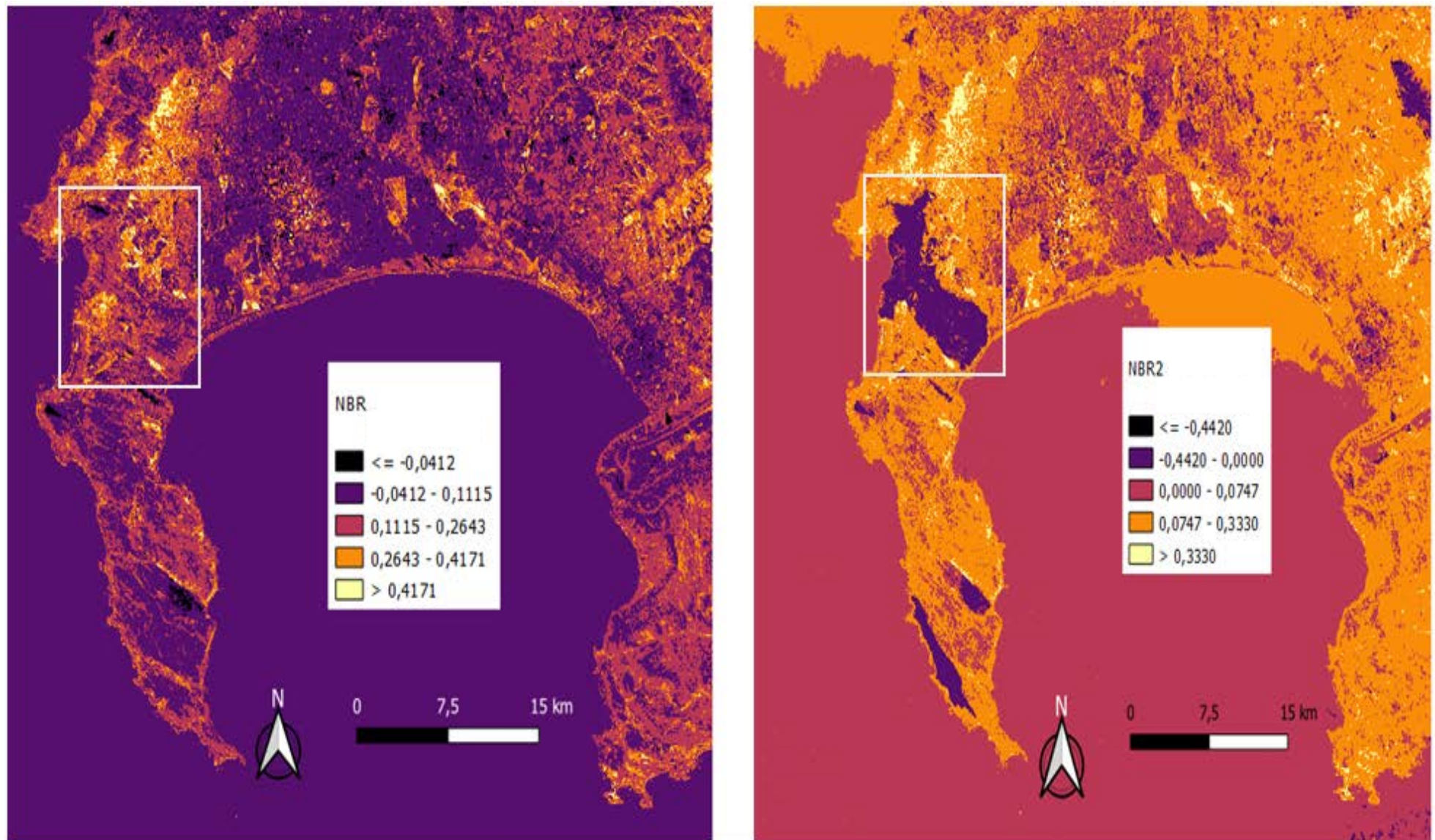


Figure 4.33: NBR on 23 February vs 11 March 2015

Figure 4.34 shows the fire severity of the burnt area identified in Figure 4.33 along the northern parts of the Cape Peninsula. This figure shows the dNBR. After reclassification and raster calculations were made, it revealed that the fire had burnt a total of 5114,25 hectares.

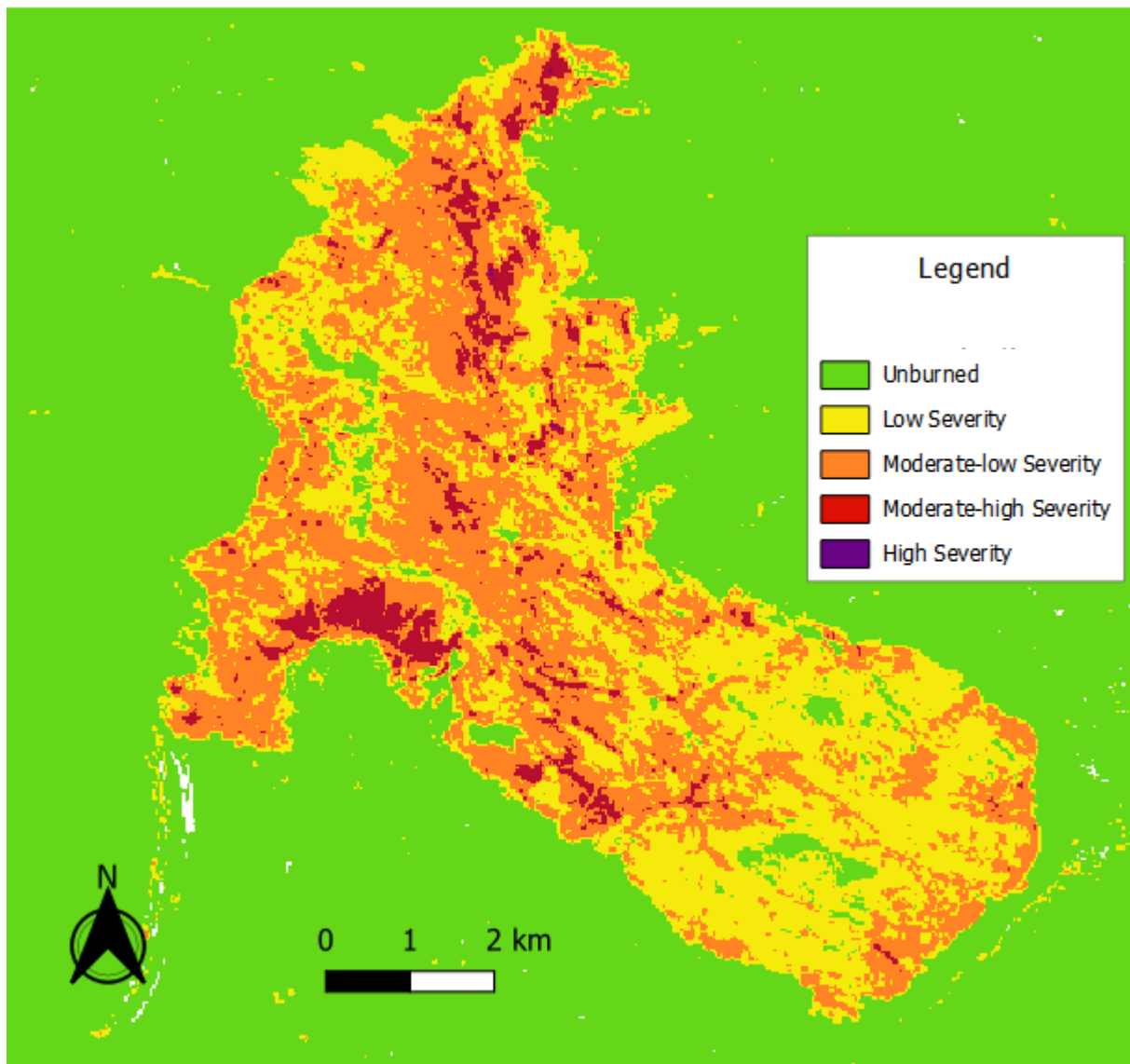


Figure 4.34: Burnt area map: Cape Town Peninsula 2015

The distribution of burnt area values are contained in Table 4.6 below. The biggest proportion of the burnt area was classified in the moderate-low severity class (2420,1 ha), while a slightly smaller area was classified as low severity (2382,84 ha). Small patches of the moderate-high severity class (310,41 ha) are scattered through the central to southern parts of the burnt area.

Table 4.6: Fire severity of the 2015 Cape Town fire

Severity	Area (hectares)
Unburned	12098,97
Low Severity	2420,1
Moderate-Low Severity	2382,84
Moderate-High Severity	310,41
High Severity	0,9
Burnt area total:	5114,25

4.4 FIRE EVENT 2: CAPE TOWN 2021

4.4.1 Weather

During the previous wet season, above normal precipitation anomalies were recorded over the south-western Cape as shown in Figure 4.35. A strong HP system was present over the eastern interior and south-western Indian Ocean on the day of ignition as shown in Figures 4.36 and 4.37. Over the next few days, the weather was still dominated by high pressure systems extending over the continent and ridging from the Atlantic Ocean. Figure 4.38 shows extremely high maximum temperatures occurred over the western interior and coastal regions of South Africa and Namibia. These conditions indicate the adiabatic heating of dry air moving from the interior plateau down the escarpment onto the coastal areas. It should be noted that the highest maximum temperatures appear close to the ignition date with slightly lower temperatures recorded on the day of extinction.

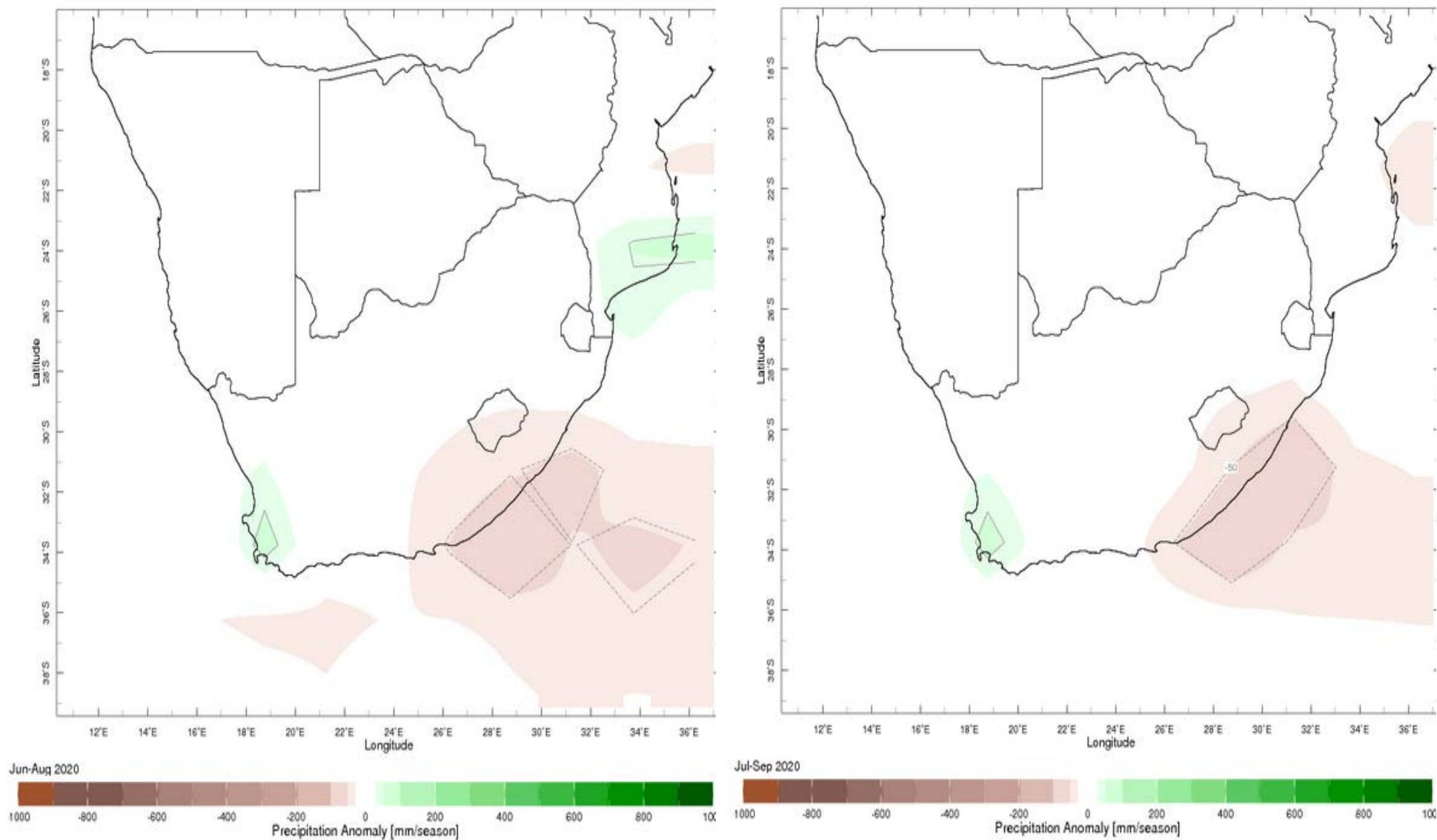


Figure 4.35: Seasonal precipitation anomalies recorded in June to September 2020

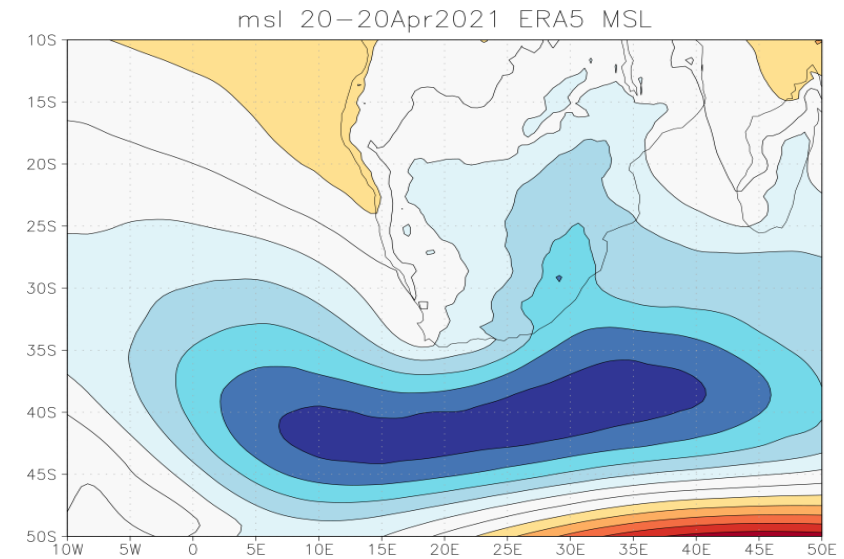
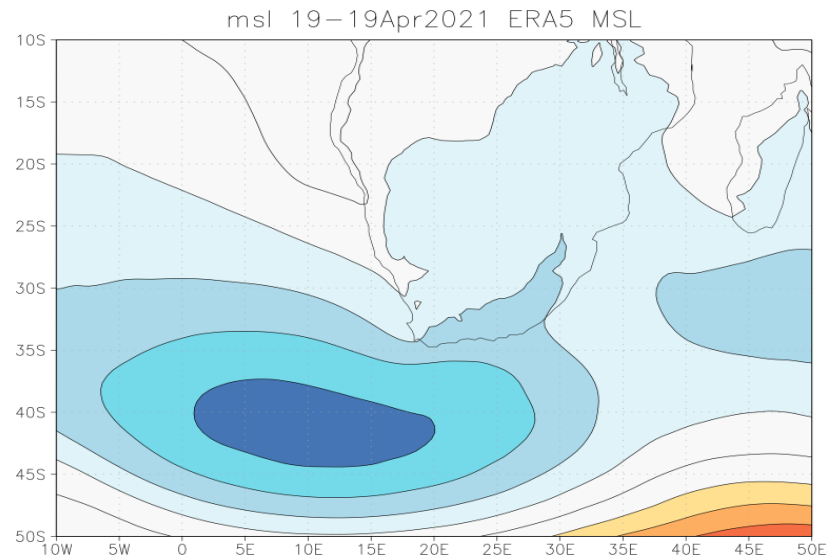
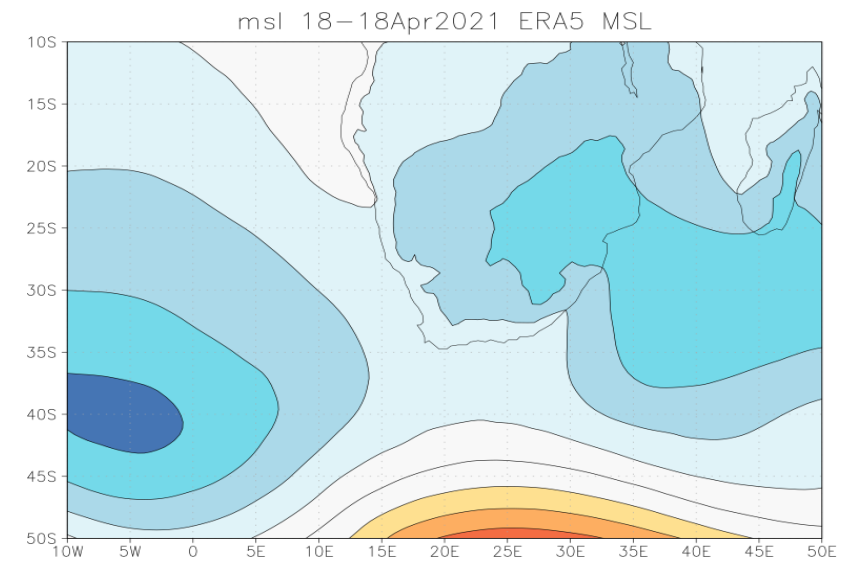
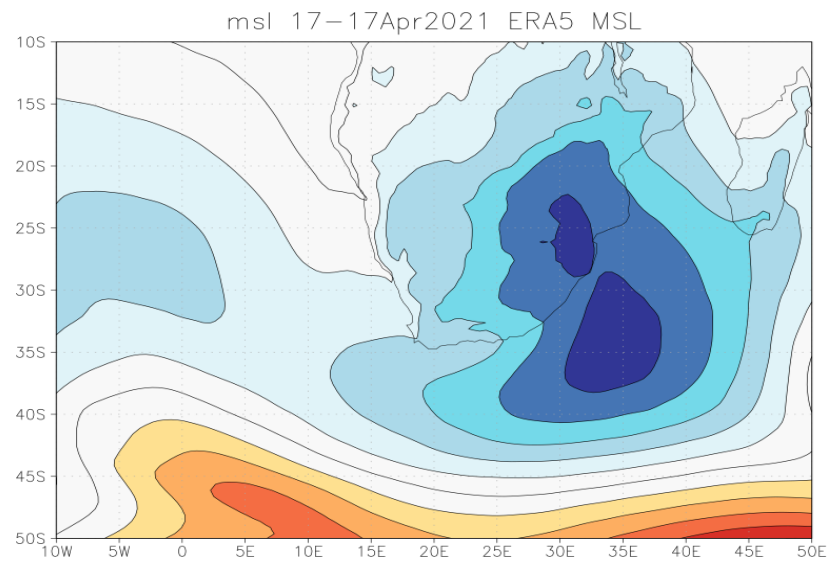


Figure 4.36: Mean-Sea-Level Pressure over South Africa for 17-20 April 2021

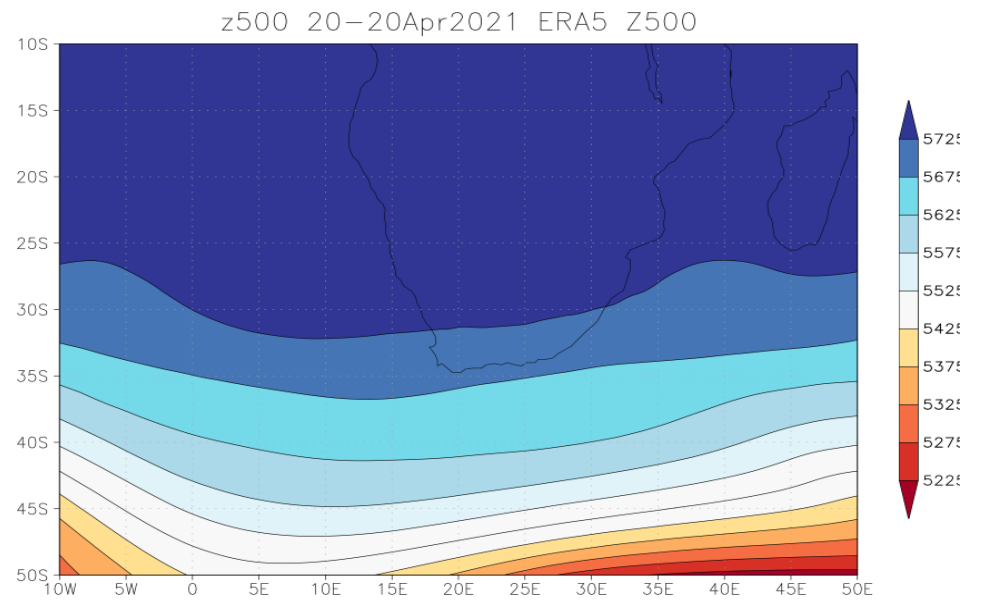
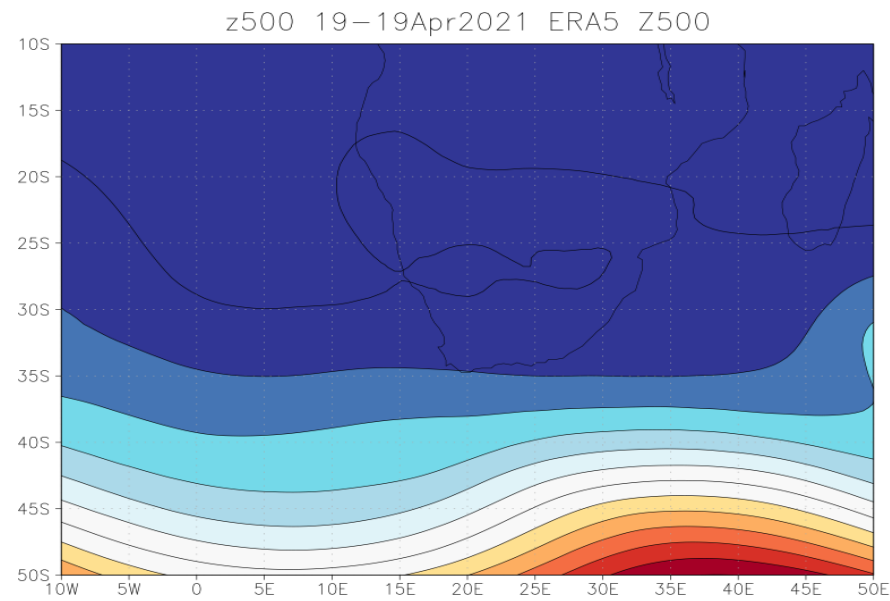
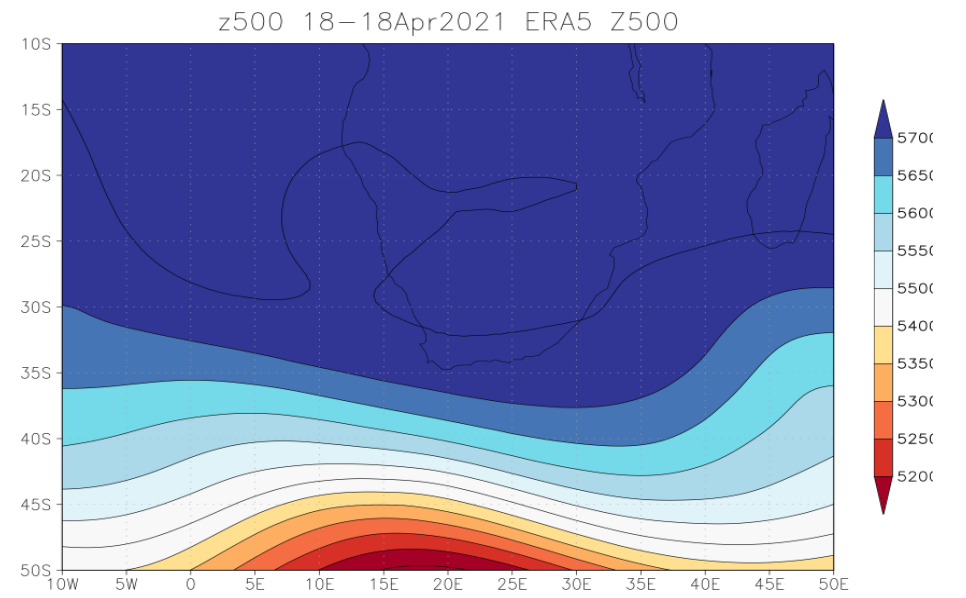
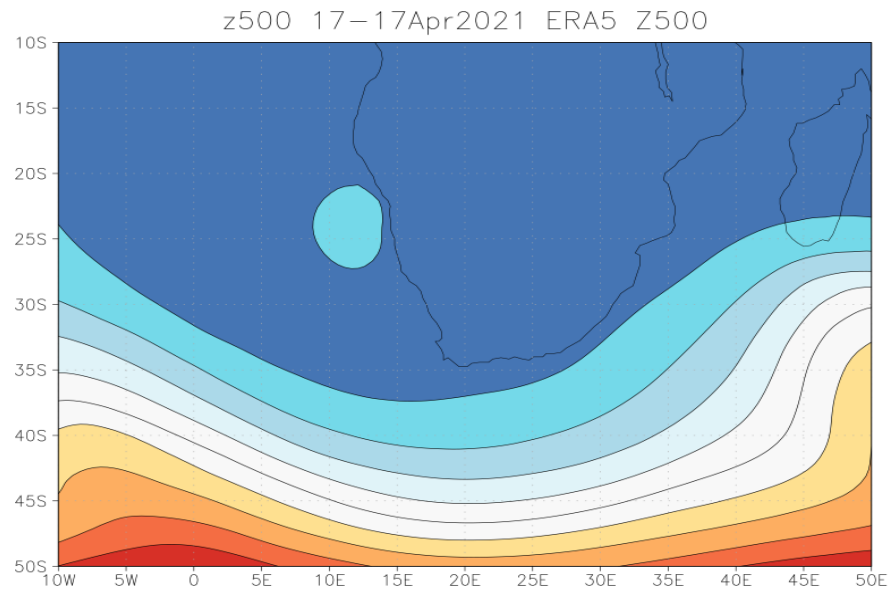


Figure 4.37: Geopotential Height over South Africa for 17-20 April 2021

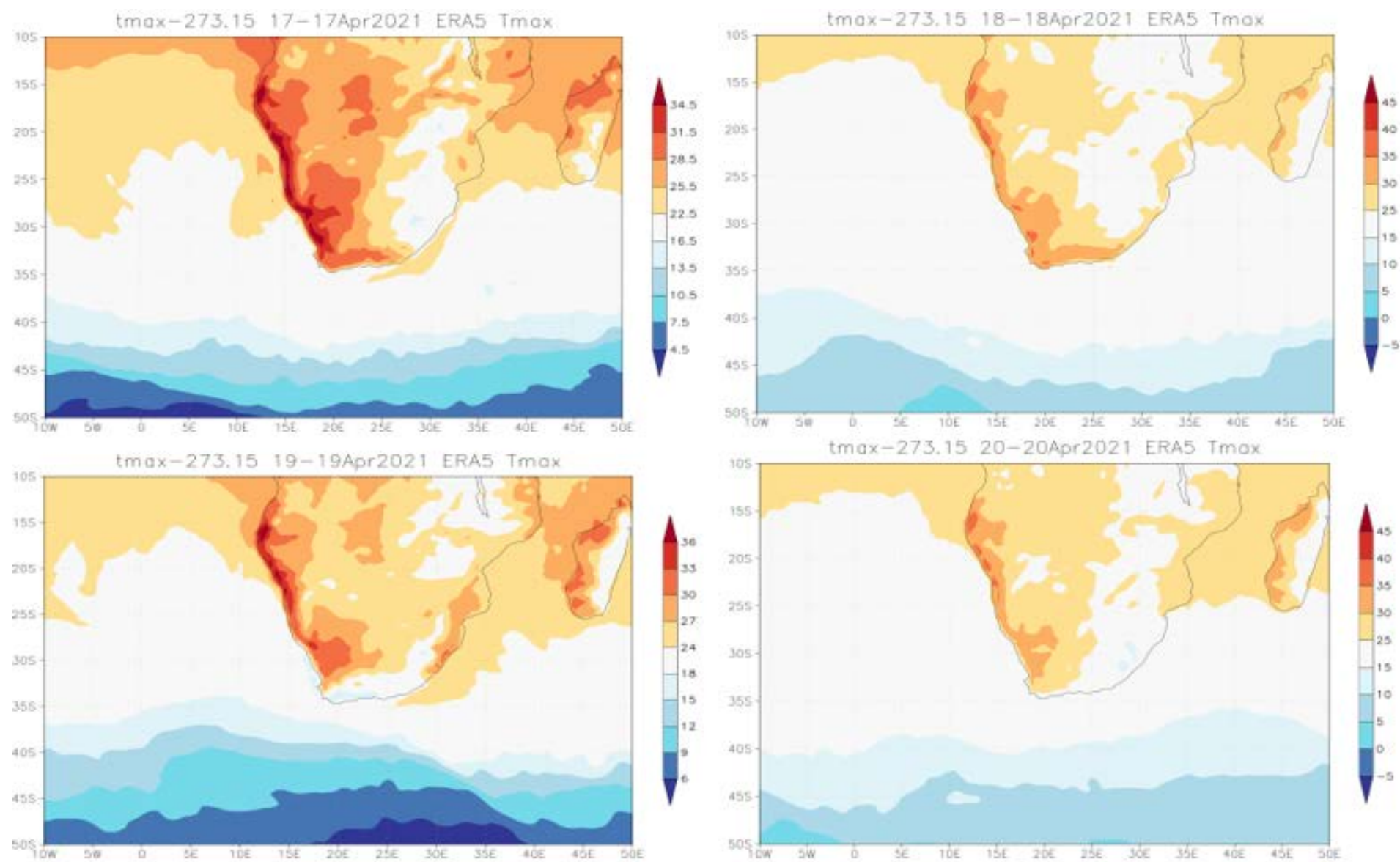


Figure 4.38: Maximum temperatures over South Africa for 17-20 April 2021

The meteograms of the Molteno Reservoir, displayed in Figure 4.39 below, indicate that the temperature values on the 17th and 18th of April exceeded 30°C. Interestingly, the temperature already reached 30°C at 09:00 on the 18th of April. Northerly winds, with wind speeds between 1,2 and 1,7 m/s (4,3-6,1 km/h) were recorded on the 17th. The Northerly winds continued to blow over the area on the 18th of April, with wind speeds reaching 5 m/s in the late afternoon. Relative humidity values were mostly below 50% on both days, with notable decreases between 10:00 and 15:00. Very low relative humidity values (<20%) persisted throughout the 18th of April. Air pressure values remained fairly constant over both days, within the range of 1003 and 1008 hPa documented for both days.

Figure 4.40 depicts the weather conditions recorded for the 19th and 20th of April. It should be noted that only the first six hours of the weather conditions were recorded for the station on the 20th of April. Temperature values were stable on both days, within the 18-22°C range. On the 19th of April, the wind speeds reached values between 4 and 6,1 m/s (14,4-22 km/h) with a decrease in speed from 15:00. These winds came from a south-easterly direction and shifted to a south-westerly direction in the early hours of the 20th of April. The wind speed had also decreased and were below 1,5 m/s (5,4 km/h) on the 20th of April. Over both days, relative humidity values were mostly above 50%, with a slight dip in values occurring between 15:00 and 23:00 on the 19th of April. Air pressure values were stable and within a range of 1006 to 1011hPa.

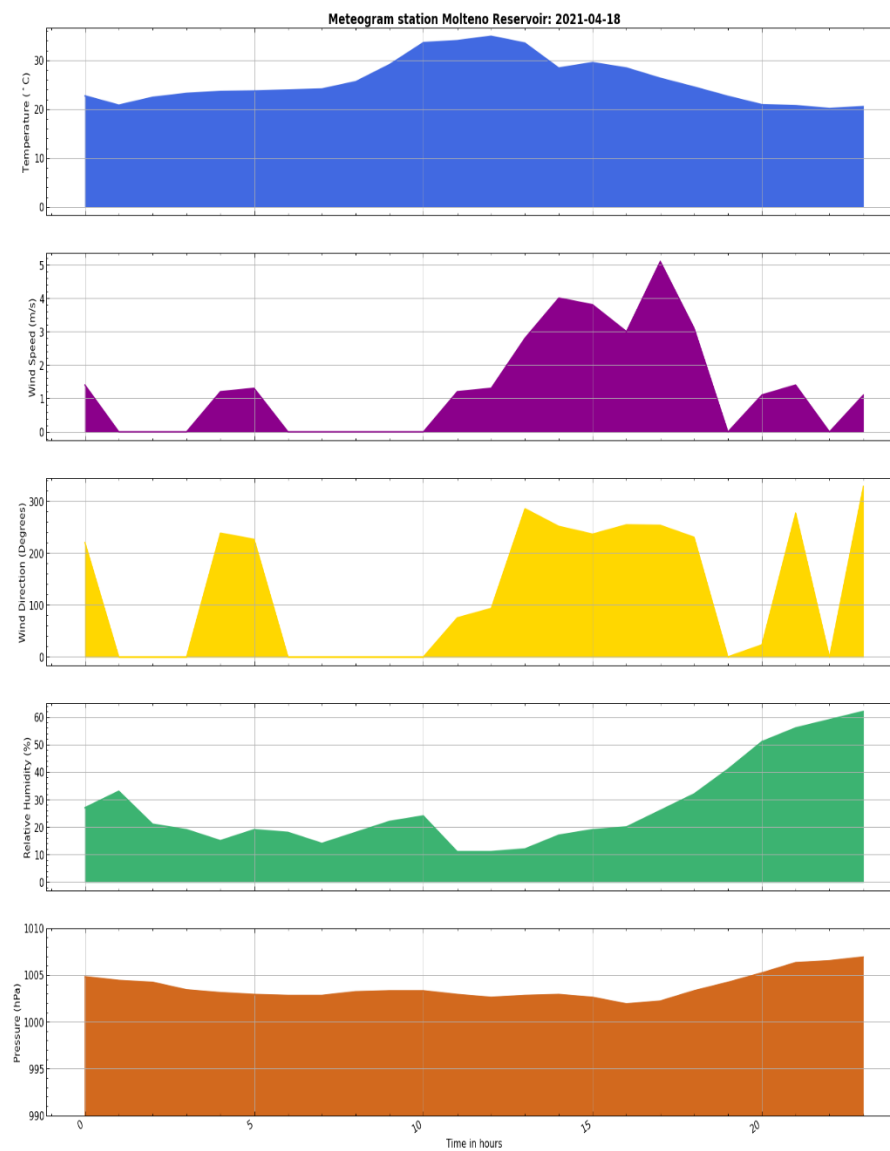
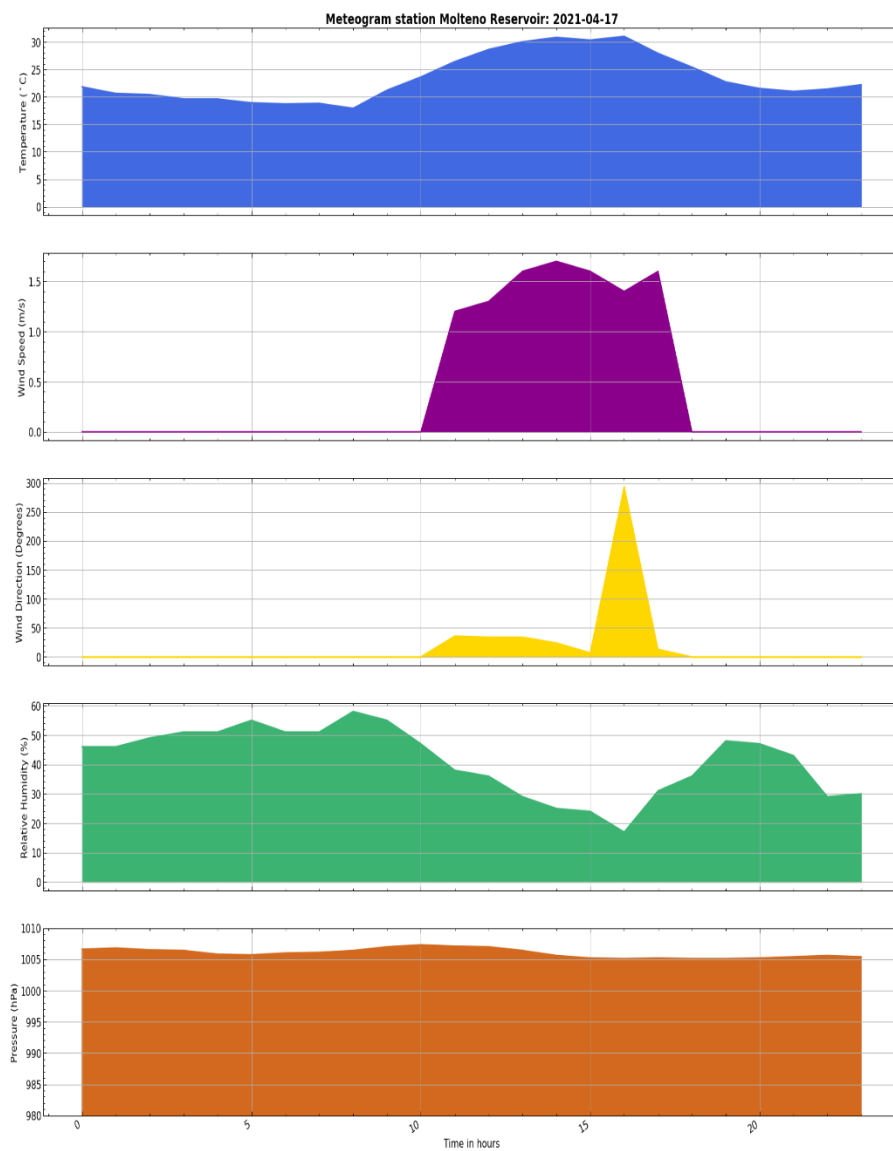


Figure 4.39: Meteograms Molteno Reservoir for 17-18 April 2021

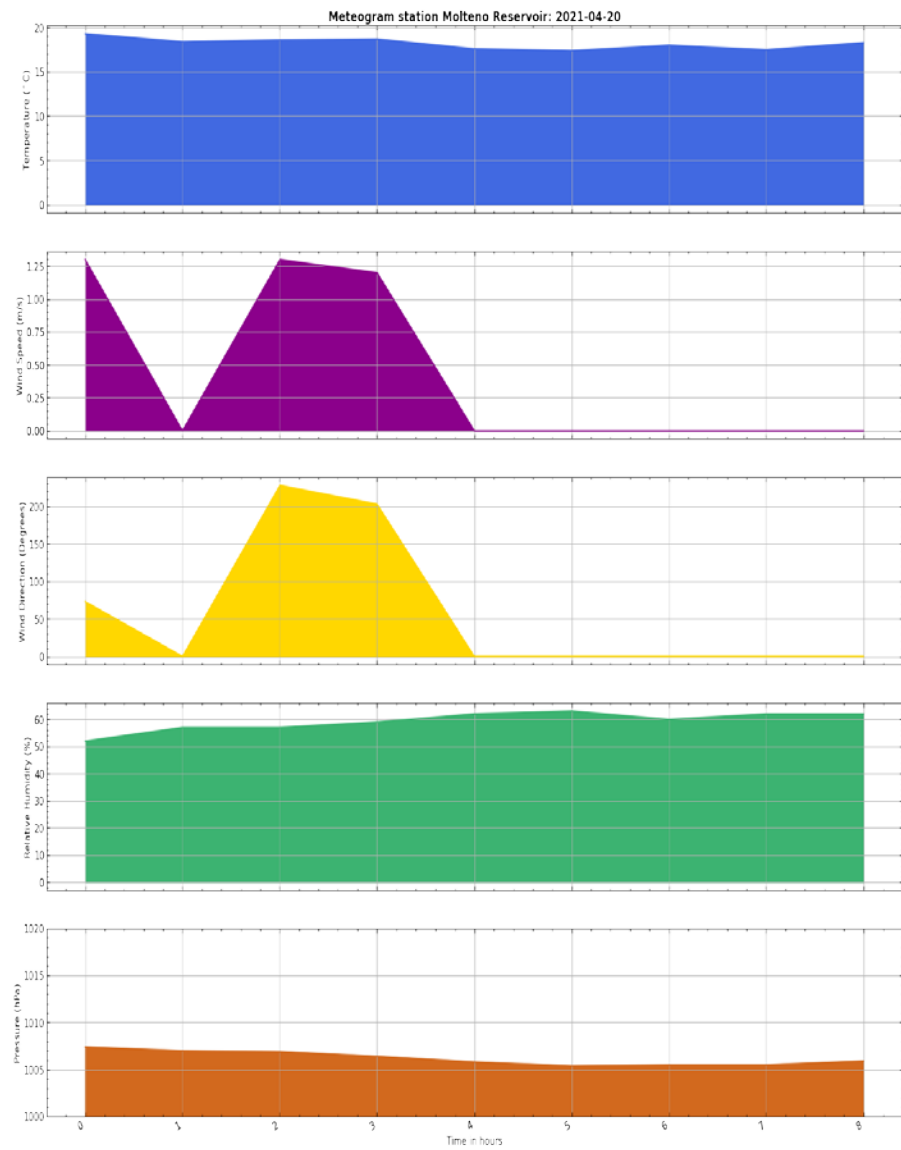
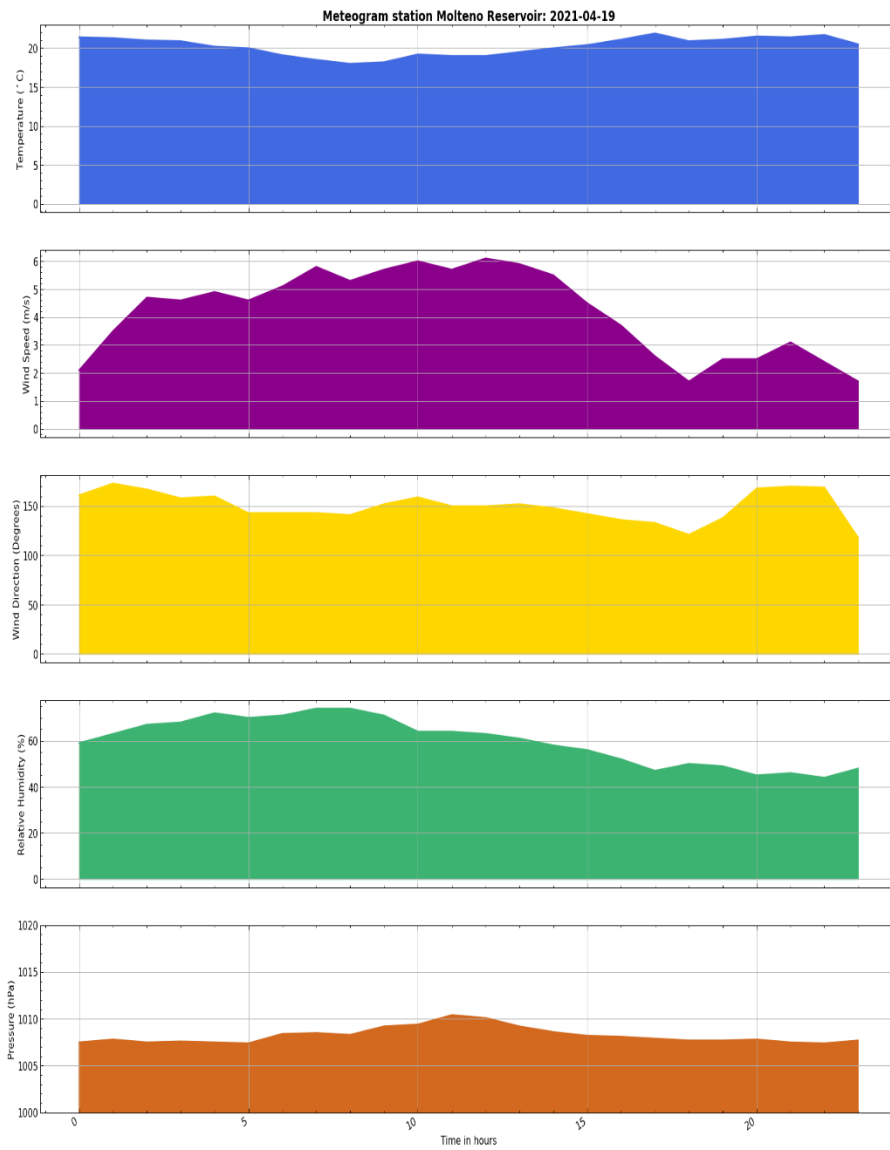


Figure 4.40: Meteograms Molteno Reservoir for 19-20 April 2021

4.4.2 Volumetric soil moisture

The days prior to the fire event and the ignition day show low volumes of soil moisture over the South-Western Cape ($<0,15 \text{ m}^3$) in Figure 4.41. The Garden Route area displayed the highest volume of soil moisture, with values within the $0,15\text{-}0,25 \text{ m}^3$ range. Over the Cape Peninsula, the soil moisture volumes were recorded in the $0,15\text{-}0,2 \text{ m}^3$ range.

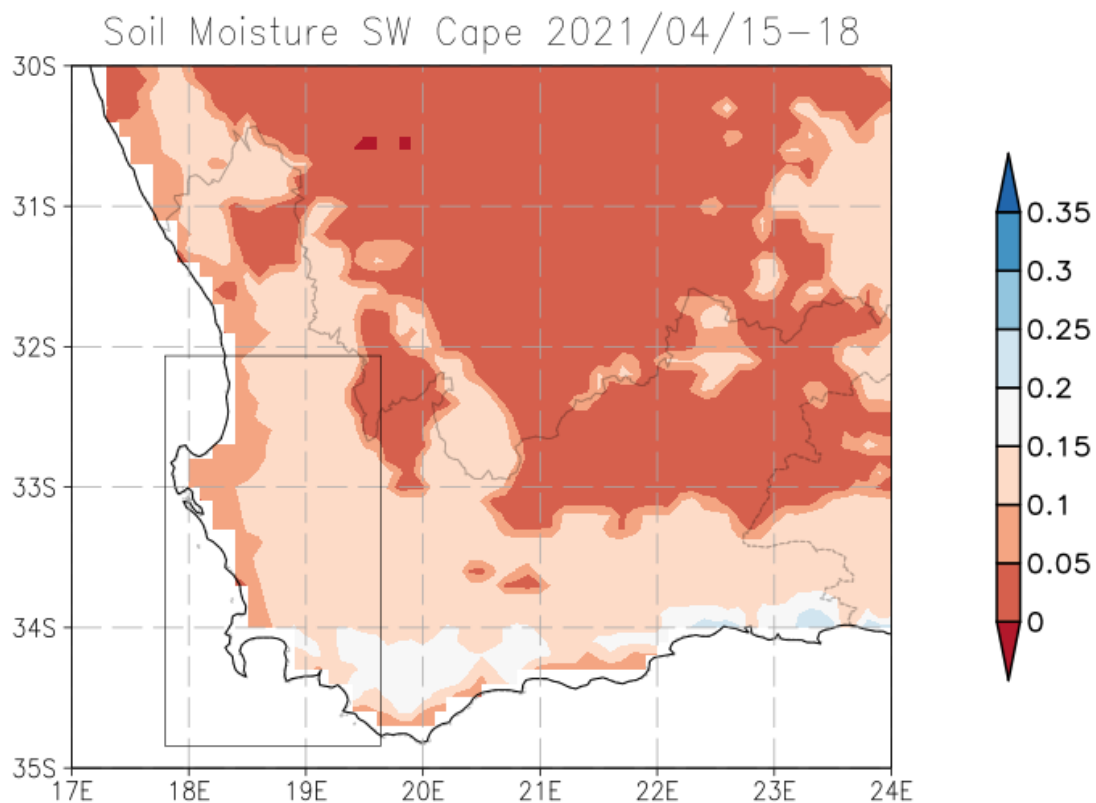


Figure 4.41: Average soil moisture over the South-Western Cape for 15-18 April 2021

4.4.3 Vegetation indices

Figure 4.42 shows the NDVI values recorded before and after the fire event. Prior to the fire event, NDVI values for vegetation were mostly within the $0,33\text{-}0,66$ category – indicating the vegetation had been considered to be moderately healthy. On the eastern slopes of Table Mountain vegetation appeared to be healthy, reflecting values $>0,66$. After the fire, a significant change in NDVI values can be seen. The region of interest displayed low positive values – indicating unhealthy vegetation with few patches recording negative values, associated with plant mortality. In Figure 4.43, the NBR values are displayed. Prior to the fire, the region of interest contained mostly low positive values. However, after the fire event, the extent of the fire is clearly visible as NBR values mostly fell into the $-0,4876$ to $-0,1157$ category.

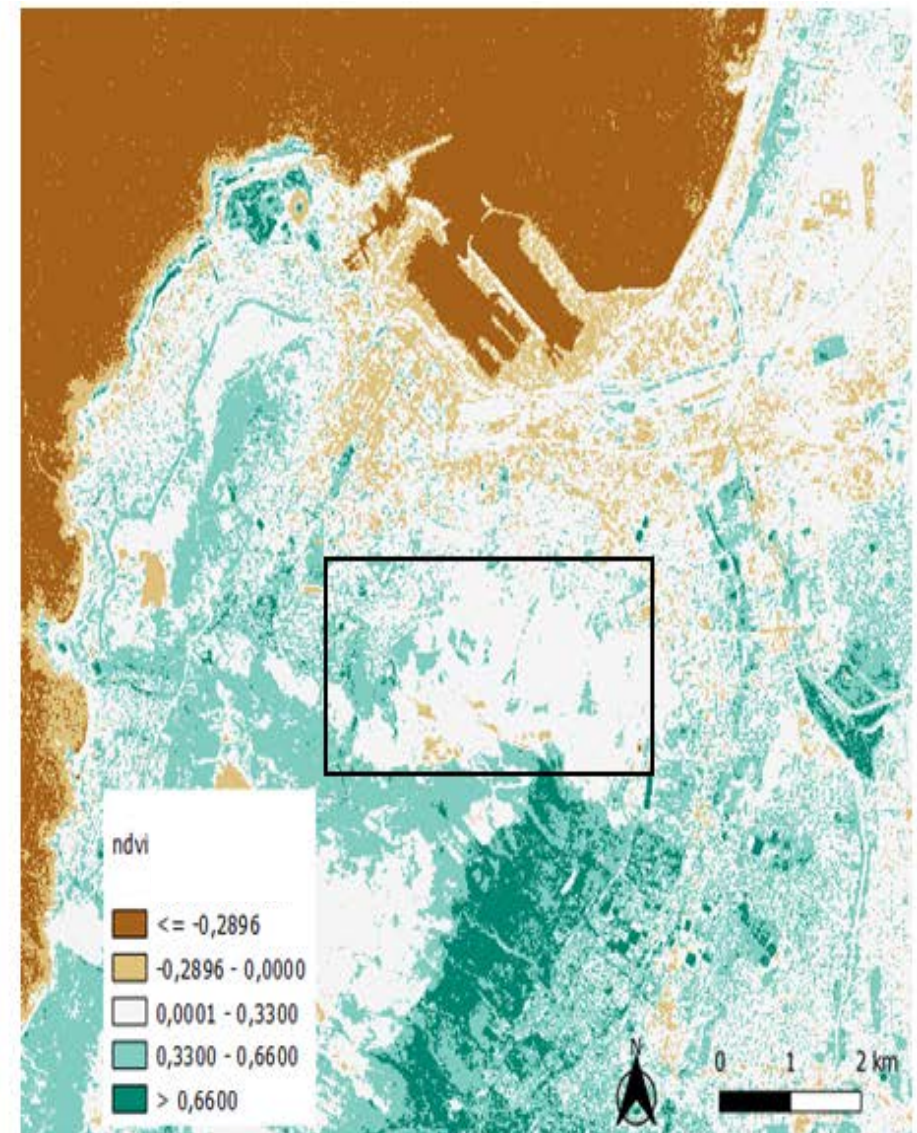
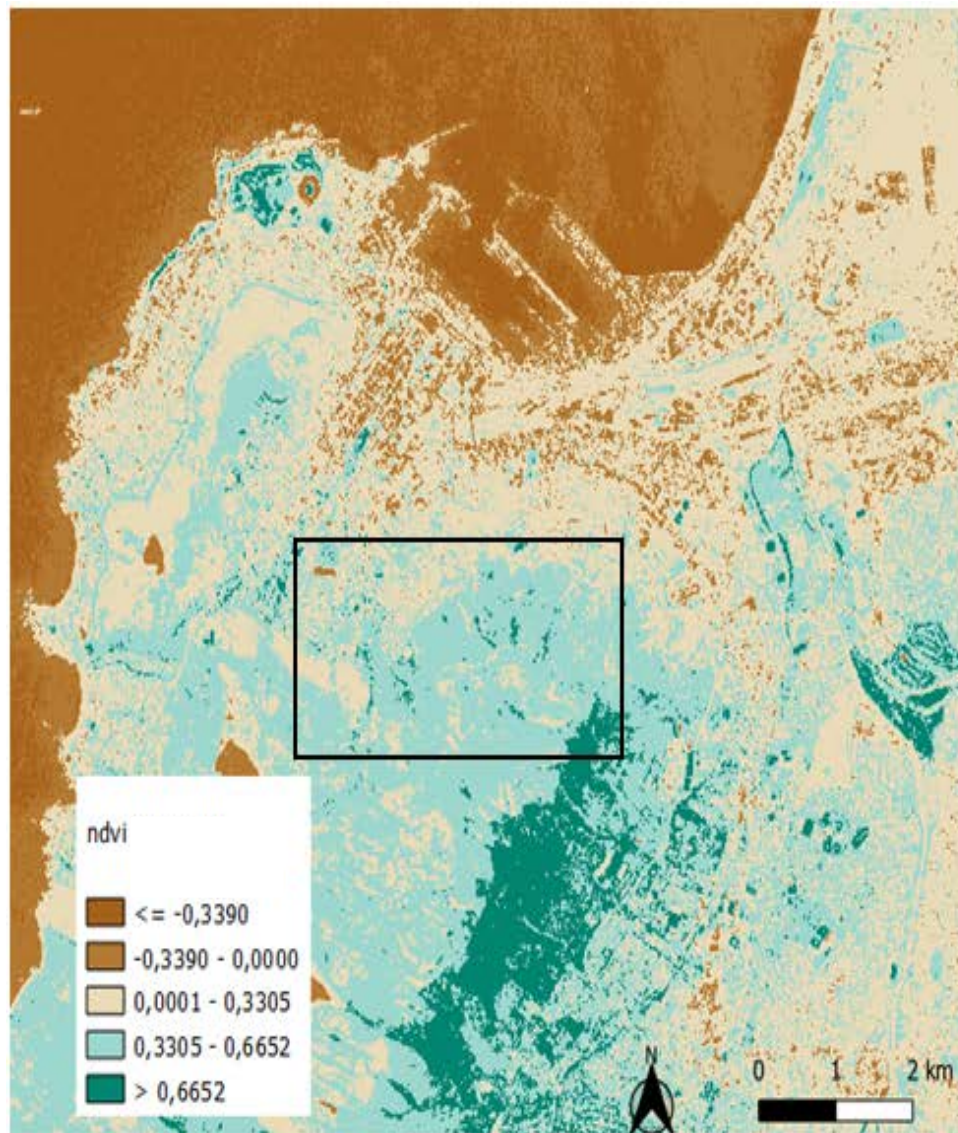


Figure 4.42: NDVI on 21 March vs 30 April 2021

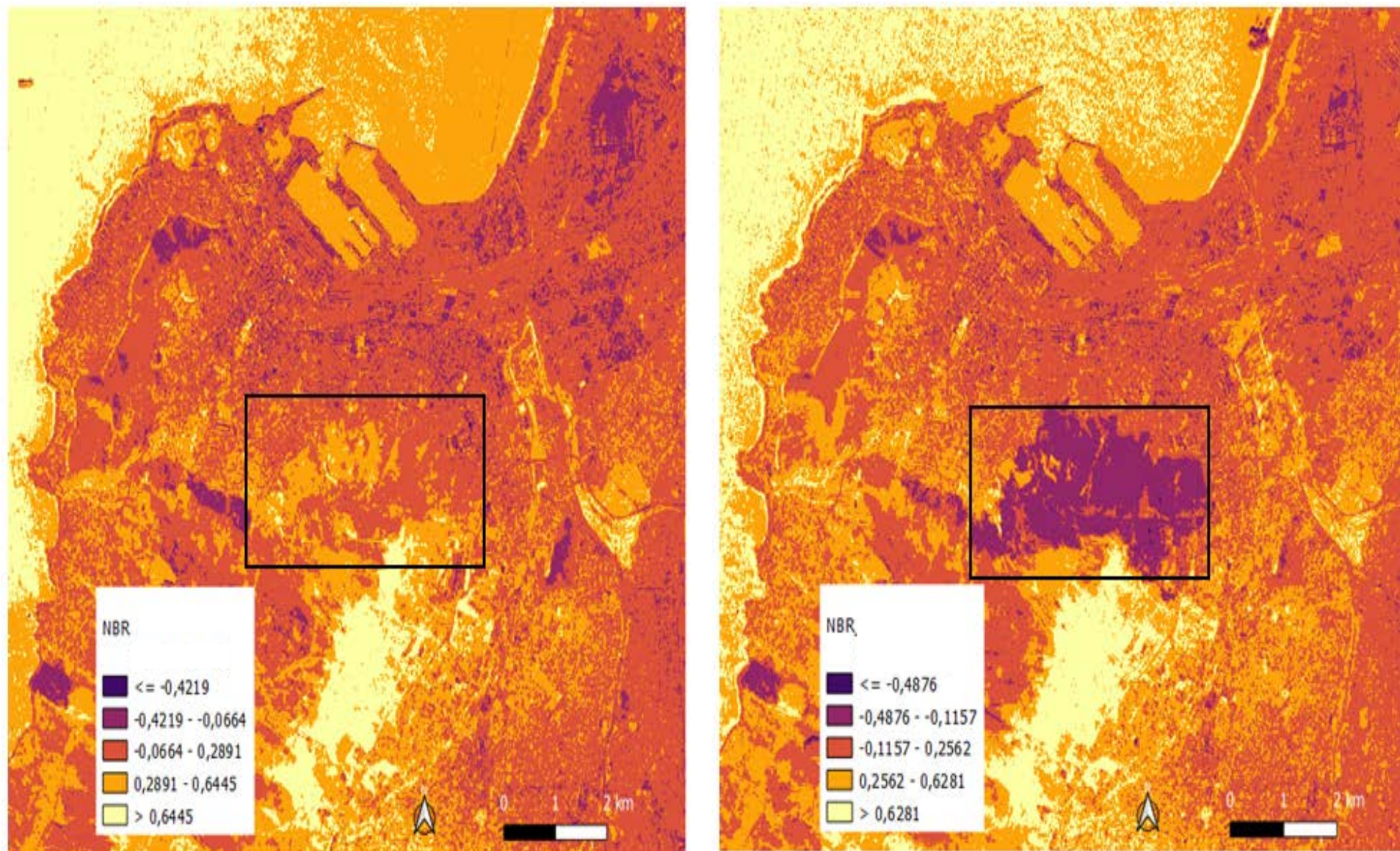


Figure 4.43: NBR on 21 March vs 30 April 2021

Figure 4.44 depicts the spatial distribution of burnt areas for the Cape Town fire in 2021.

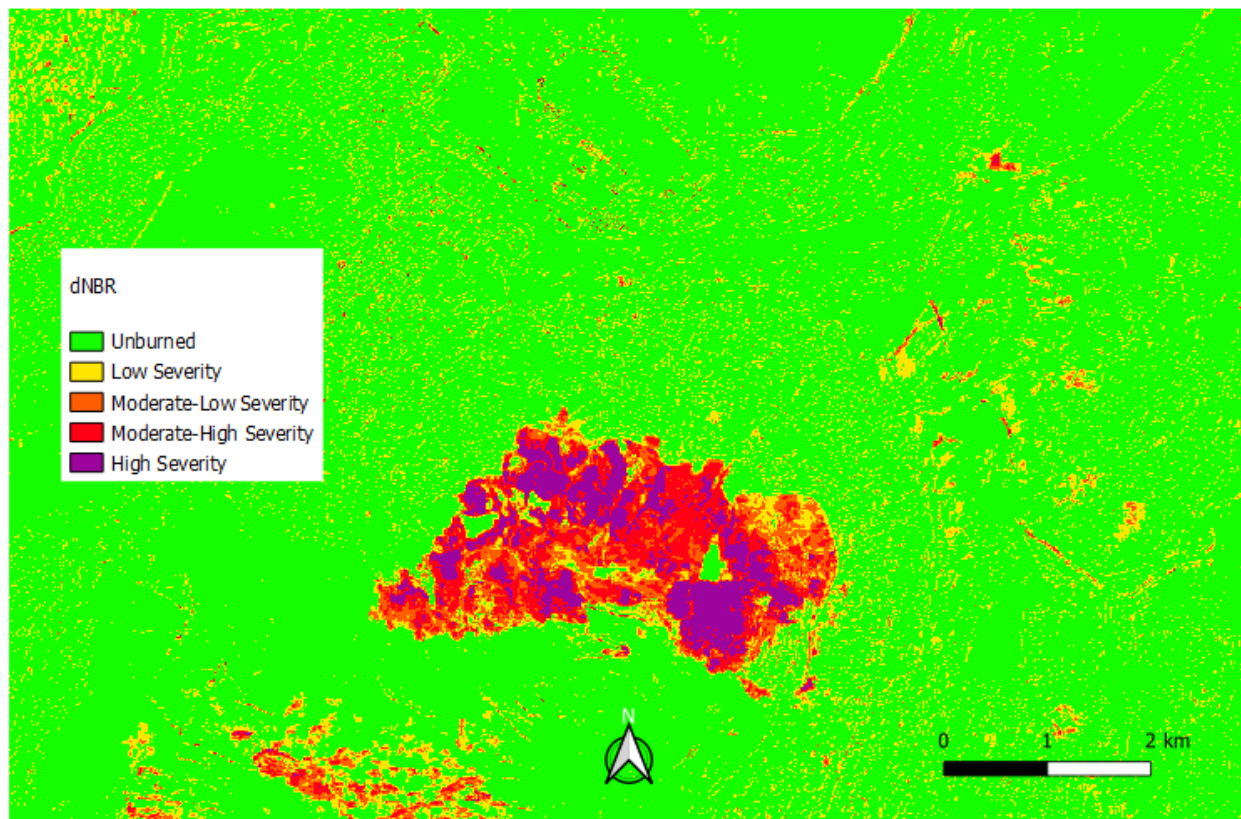


Figure 4.44: Burnt areas in Cape Town Peninsula in 2021

In total, 4822 hectares were classified as burnt areas. However, some cloud cover over the area may have led to an overestimation of values in the low to moderate-low severity classes. Importantly, the biggest proportion of burnt area values are found within the high severity class (2571 ha), followed by moderate-high severity (878 ha) and moderate-low severity (708 ha).

Table 4.7: Fire severity of the 2021 Cape Town fire

Severity	Area (hectares)
Unburned	4196
Low Severity	665
Moderate-Low Severity	708
Moderate-High Severity	878
High Severity	2571
Total burnt area	4822

4.5 FIRE EVENT 3: KNYSNA 2017

4.5.1 Weather

On the day of ignition, strong HP systems were located in the oceans east and west of the country. However, directly south – in the Indian Ocean, a strong LP system occurred as shown in Figures 4.45 and 4.46. Isobars in the figure show a strong pressure gradient existed on this day. Maximum temperatures over South Africa were mostly below 25°C, except for the east coast as indicated in Figure 4.47. On the 11th of June, a ridging high occurred over the continent with a LP system located further south of the continent. The maximum temperature over the southern interior declined while there were increases in temperature over Madagascar and the northern sections of the interior. By the 15th of June, a ridging HP system extended over the continent and maximum temperatures were similar to those recorded on the 11th of June. On the day of fire extinction, a HP system extended from the Indian Ocean over the continent, while a LP system was located far off to the south. These two systems brought higher temperatures to the coastal regions of the south coast. This indicates that berg wind conditions existed on this day.

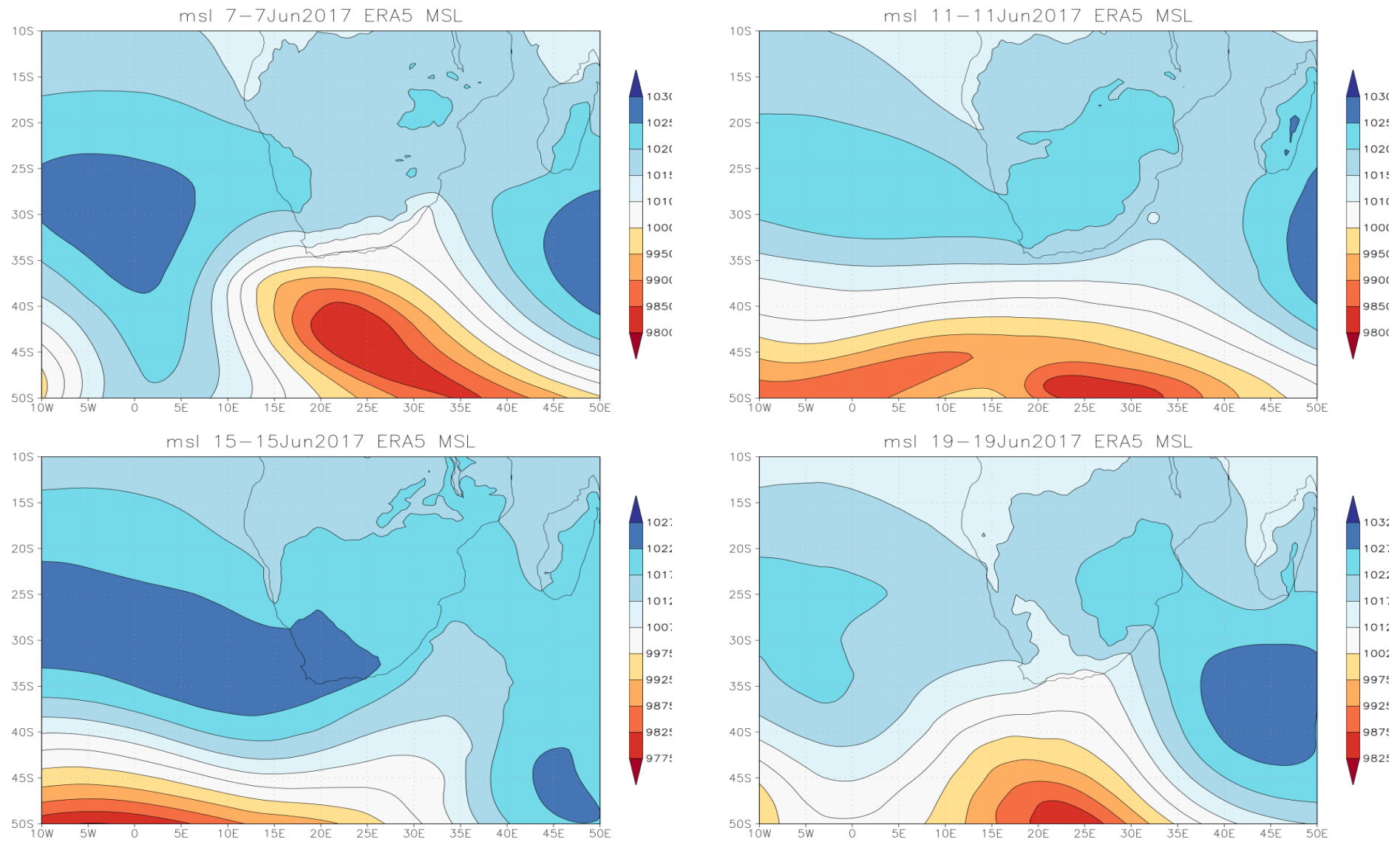


Figure 4.45: Mean-Sea-Level Pressure over South Africa for selected days in June 2017

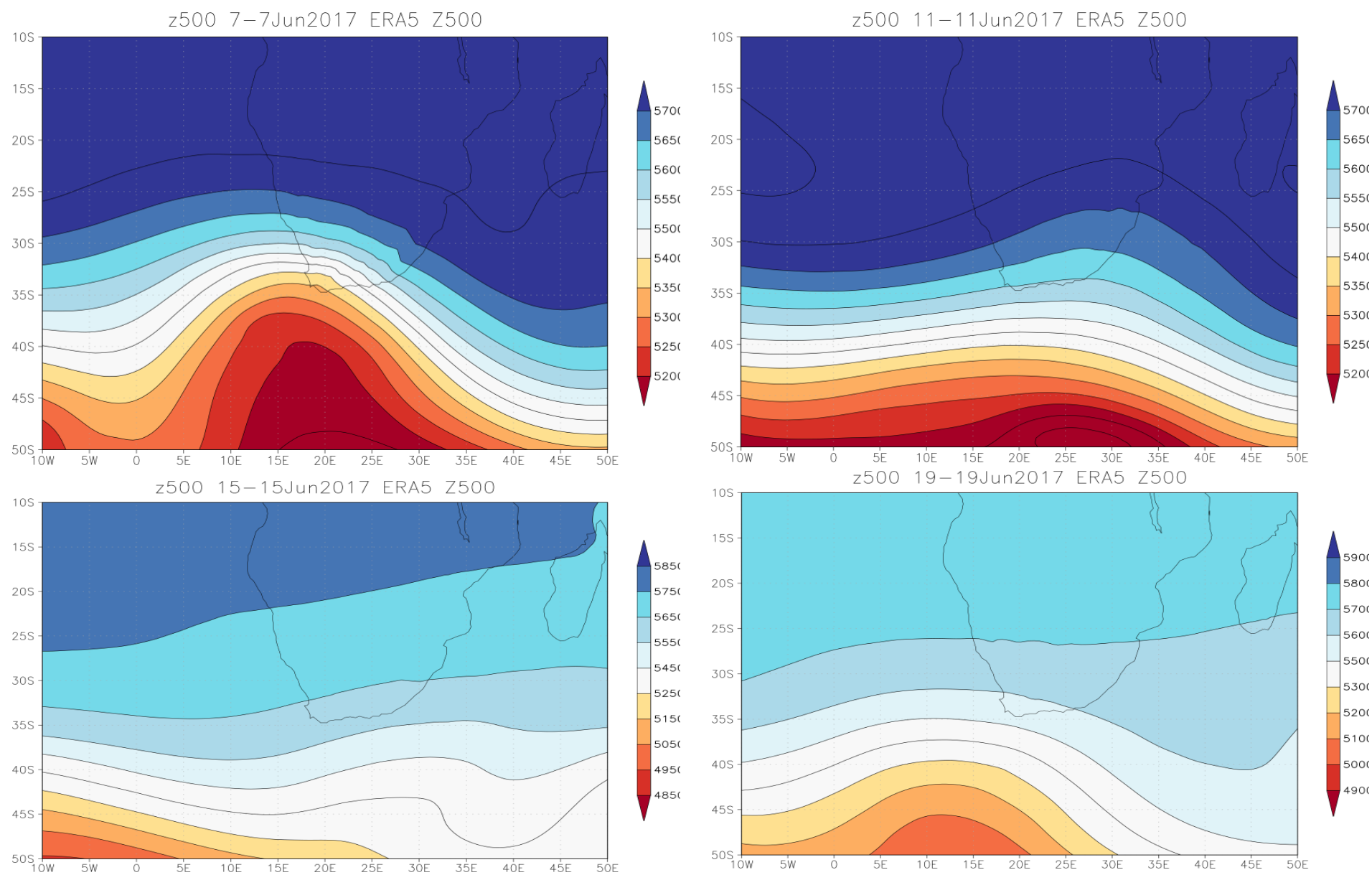


Figure 4.46: Geopotential Height over South Africa for selected days in June 2017

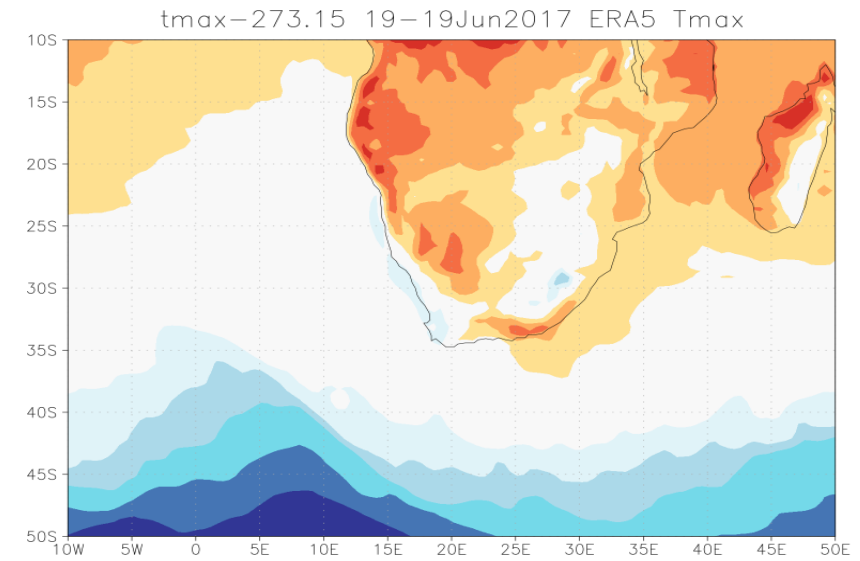
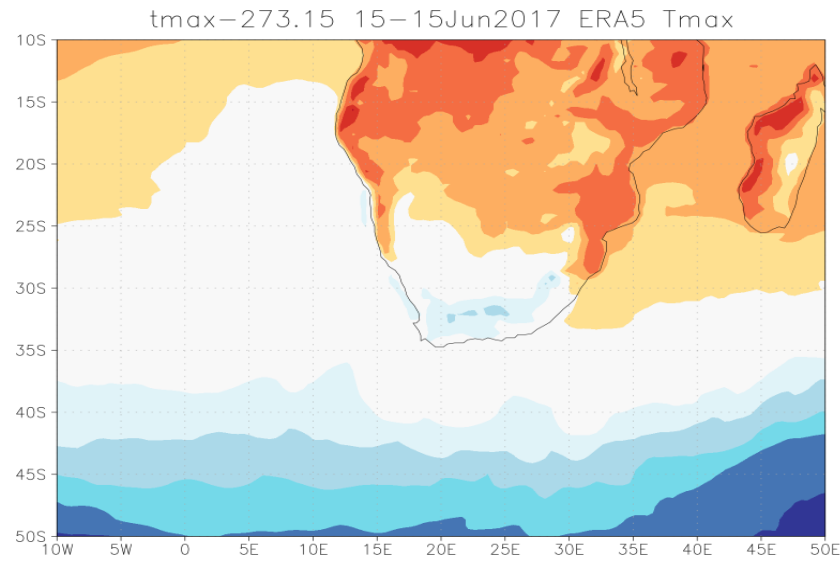
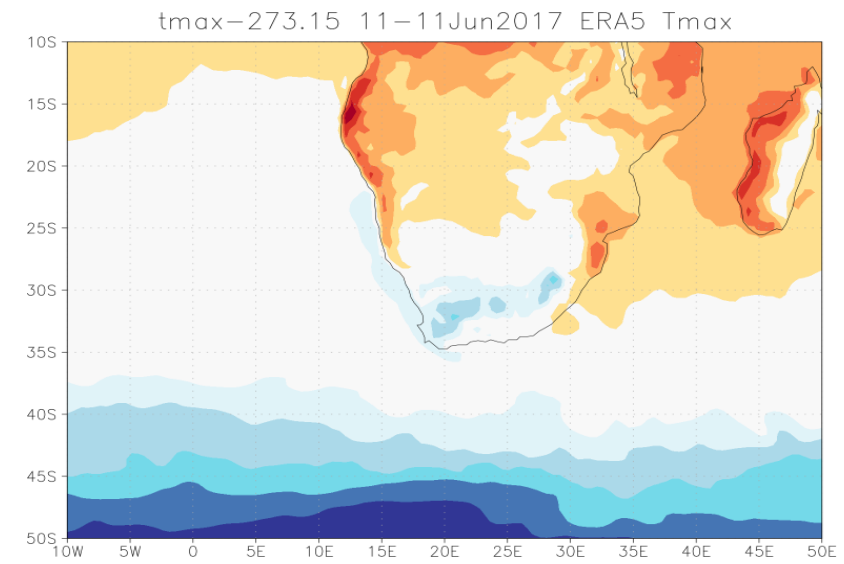
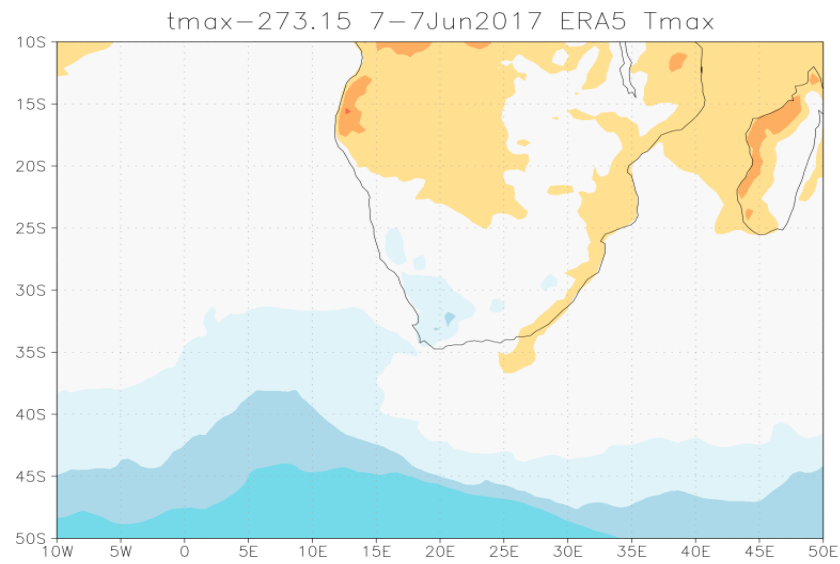


Figure 4.47: Maximum temperature over South Africa selected days in June 2017

Figure 4.48 depicts the weather station data for Knysna for 6-7 June 2017. Temperature values increased rapidly from 17,4°C at 07:00 to 30°C at 10:00 on the 6th of June. A peak temperature of 34°C was reached and while the temperature decreased after 22:00 on the 6th, the early morning hours of the 7th of June still recorded relatively high temperatures - 26°C at 04:00. On the 6th of June, north to north-westerly winds with speeds varying between 1,7 to 3,7 m/s (6,1-13,3 km/h) blew across the region. However, by the 7th of June the wind changed direction to westerly and exceeded 6 m/s (21,6 km/h) at 04:00. The wind speed reached a maximum speed of 10,8 m/s (38,9 km/h) by 18:00. A significant decrease in relative humidity values occurred on the 6th of June, with values over 80% at the start of the day, halving by 07:00 and declining further to below 20% by 09:00. Relative humidity values remained consistently low on the 6th of June and while it increased on the 7th of June, the values remained below 40% throughout the day. Interestingly, air pressure values decreased from 1007 hPa at 00:00 on the 6th of June to 992,5 hPa at 05:00 on the 7th of June. A slightly slower increase in air pressure values occurred after this time to reach 1004 hPa by the end of the day.

Figure 4.49 shows the weather variables for Knysna on 18 and 19 June 2017. Temperature values for both days show a diurnal pattern of low temperatures before 09:00 and peaking temperatures above 15°C for the hours between 10:00 and 15:00, with a maximum temperature of 22,8°C recorded at 13:00 on the 7th of June. Easterly to south-easterly winds occurred on the 18th of June during the hours of 10:00-19:00, with speeds fluctuating between 1,9 and 2,4 m/s (6,8-8,6 km/h) in the afternoon. On the 19th of June, winds from the south-west blew across the area between 11:00-20:00. The wind speed increased from 1,5 m/s (5,4 km/h) at 12:00 to 3,6 m/s at 17:00 after which it rapidly decreased. Relative humidity values on both days tended to exceed 60%, except on the 18th of June, when these values decreased to below 40% - coinciding with the wind blowing across the area. In addition, relative humidity values declined from 76% at 08:00 to 30% at 13:00 on the 19th of June, whereafter it increased and remained stable around 80% from 18:00. Air pressure stayed relatively high for the 18th, with values exceeding 1013 hPa until 13:00. After this hour, the air pressure decreased until the next day to reach 1002,3 hPa at 14:00. From 15:00 the air pressure values increased to reach a maximum of 1009,2 hPa at 23:00.

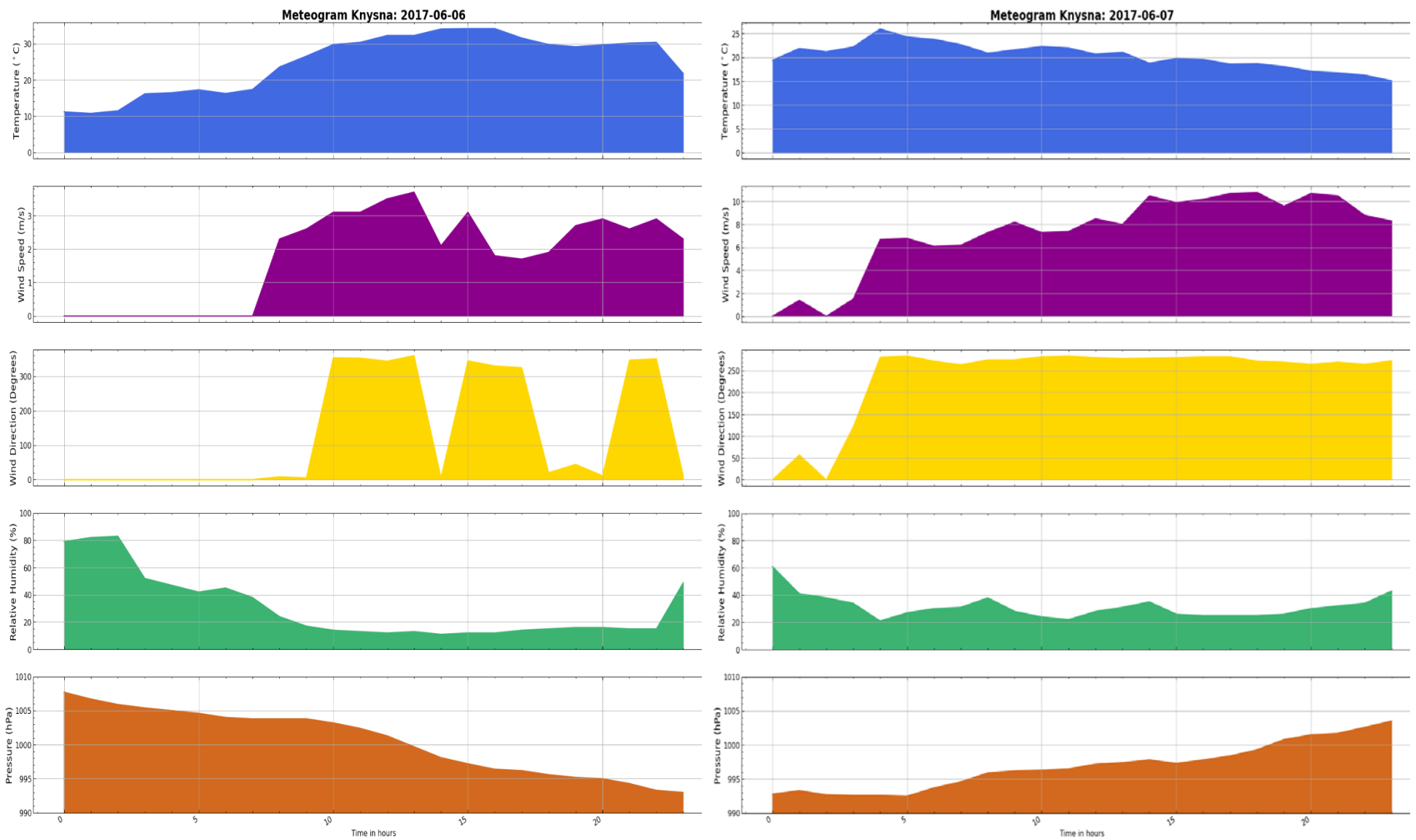


Figure 4.48: Meteograms: Knysna 6-7 June 2017

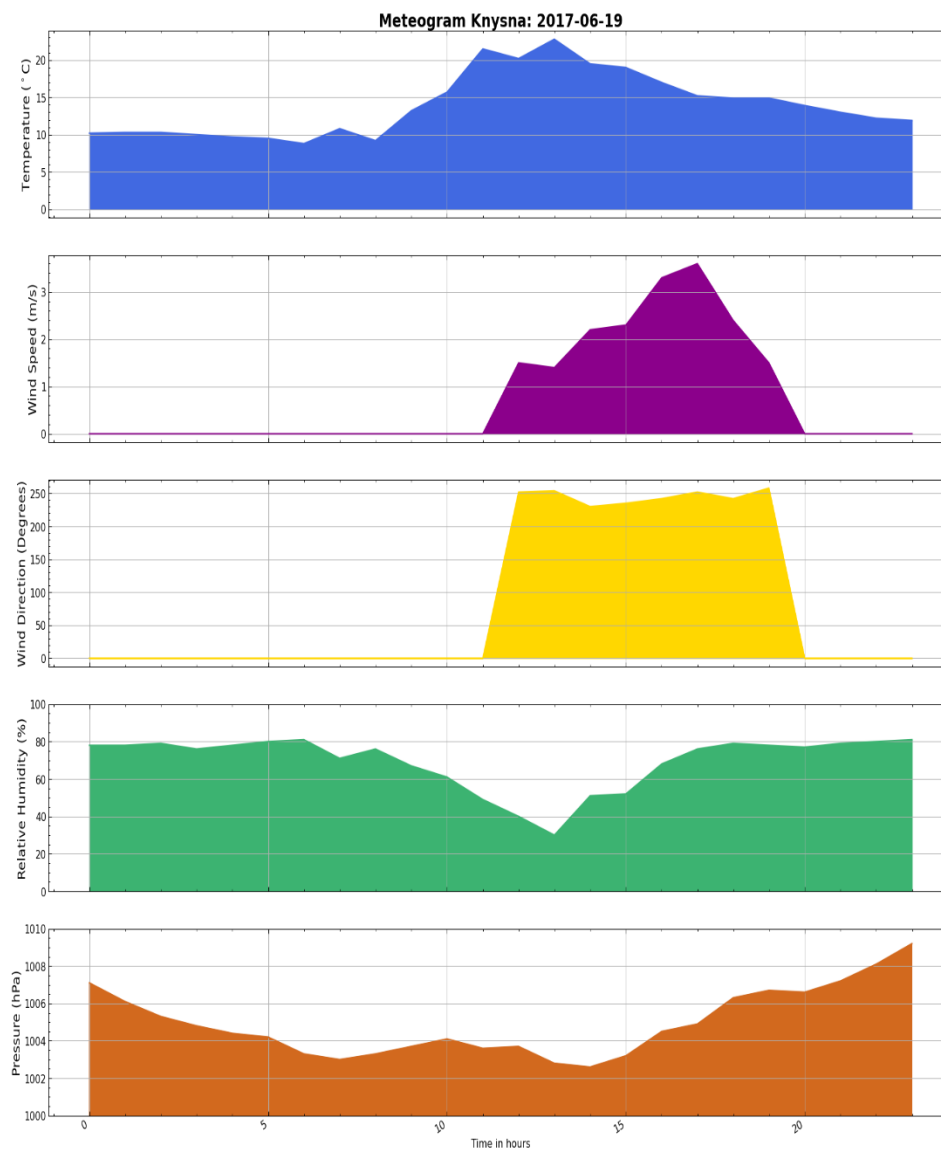
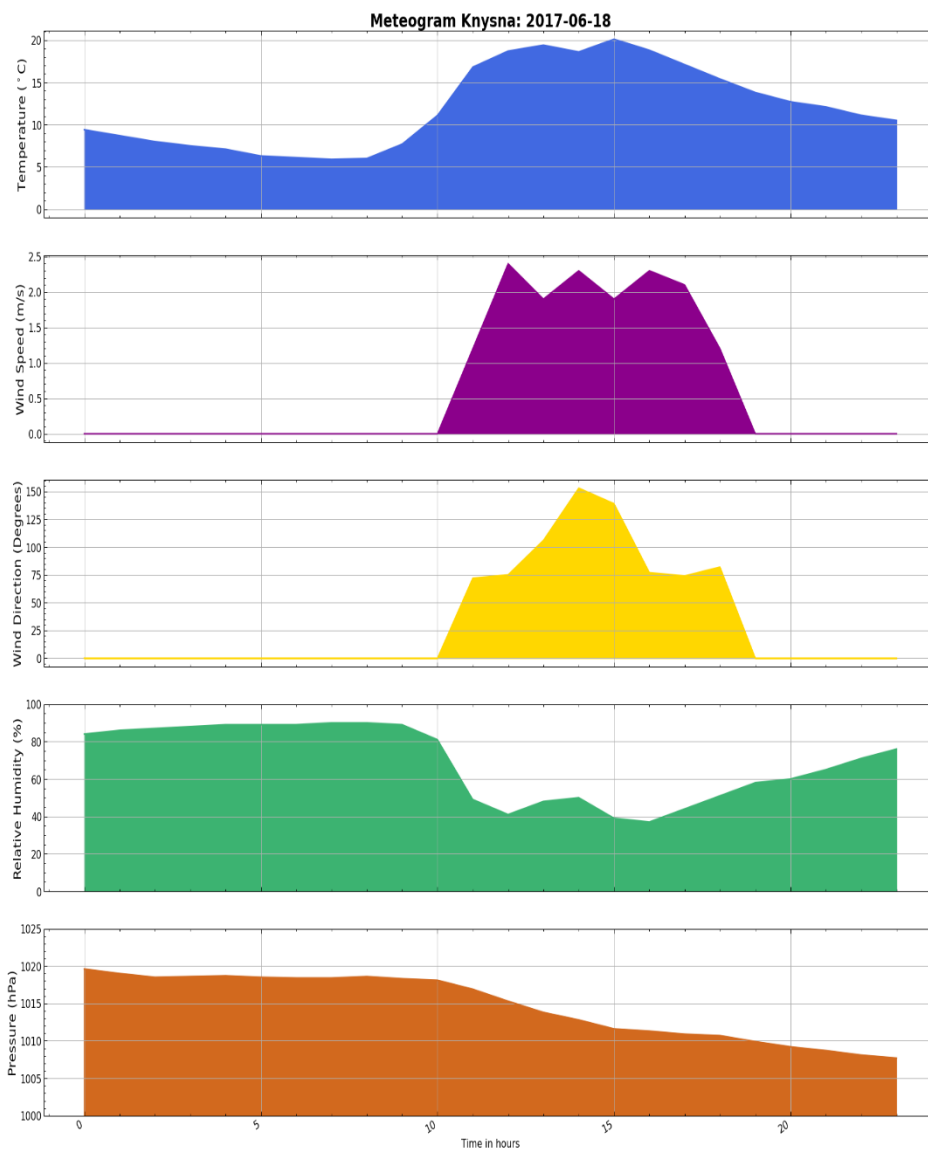


Figure 4.49: Meteograms: Knysna 18-19 June 2017

4.5.2 Volumetric soil moisture

Figure 4.50 show the low soil moisture volumes over the large parts of the Western, Eastern and Northern Cape Provinces, with the lowest volumes recorded over the north-eastern Western Cape and southern Northern Cape ($<0,2 \text{ m}^3$).

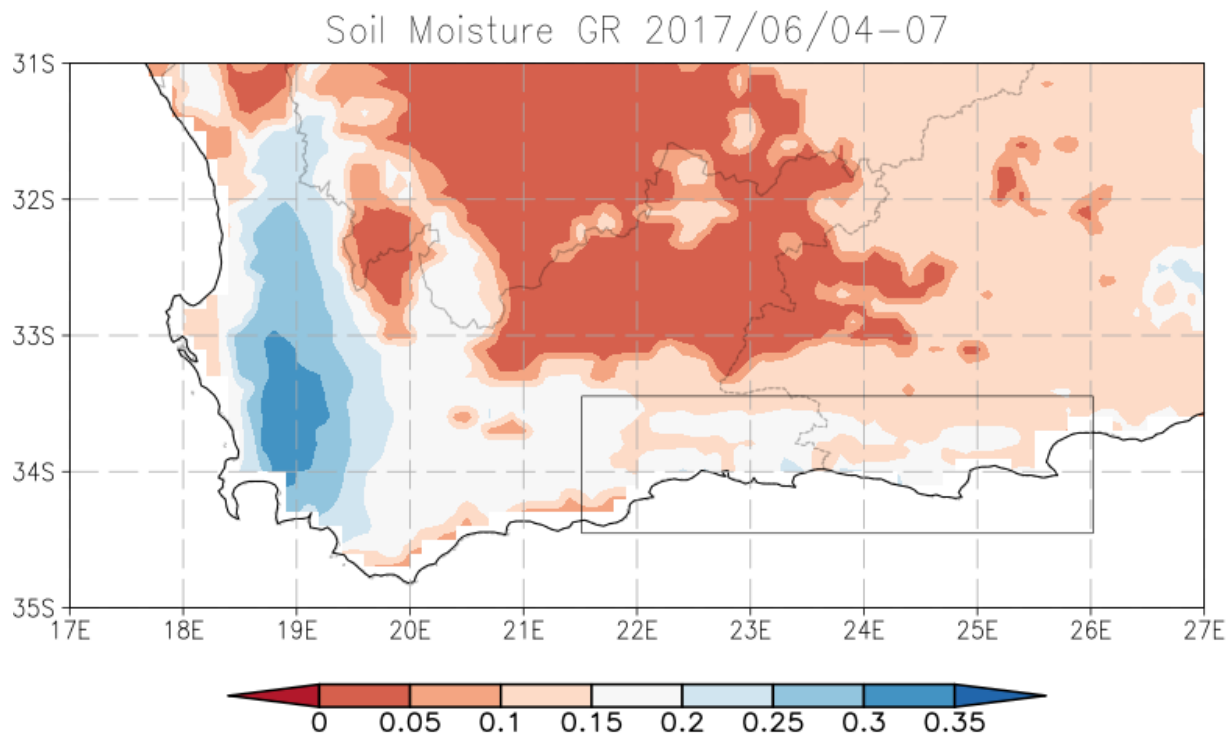


Figure 4.50: Average soil moisture over the Garden Route for 4-7 June 2017

The highest values of soil moisture occurred along the western escarpment and low-lying regions along the Western Cape with a range of $0,2-0,35 \text{ m}^3$. However, notably, the Garden Route region experienced low soil moisture volumes. This region recorded values mostly between $0,1-0,2 \text{ m}^3$, with a small area southeast to Knysna recording volumes in the range of $0,2-0,25 \text{ m}^3$ range.

4.5.3 Vegetation indices

NDVI values prior to and after the fire event are shown in Figure 4.51. Overall, vegetation appeared to be moderately healthy before and after the fire. A clear decline in vegetation health was detected among the southern sections of the region and within the regions of interest NDVI values decreased significantly. Within the region of interest, the vegetation values were mostly in the unhealthy vegetation class ($0-0,33$) after the fire, with some areas reflecting dead vegetation ($-0,2230$ to 0). Figure 4.52 shows the NBR prior to and after the fire. Areas along the coast and within the region of interest reflected values mostly $>0,3309$ before the fire. However, after the

fire, vegetation reflected low positive to negative values along the coast and the town of Knysna (values below 0,0394).

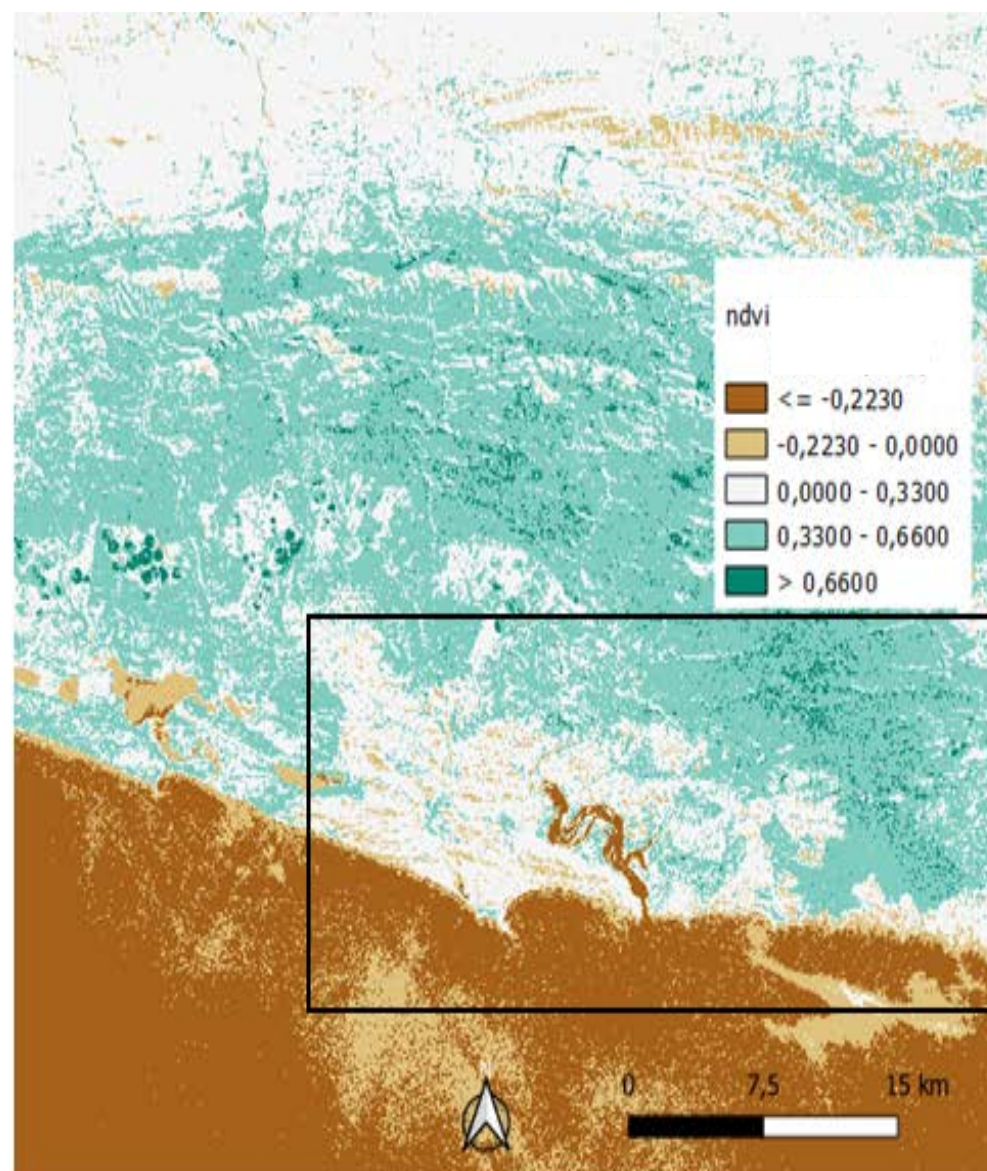
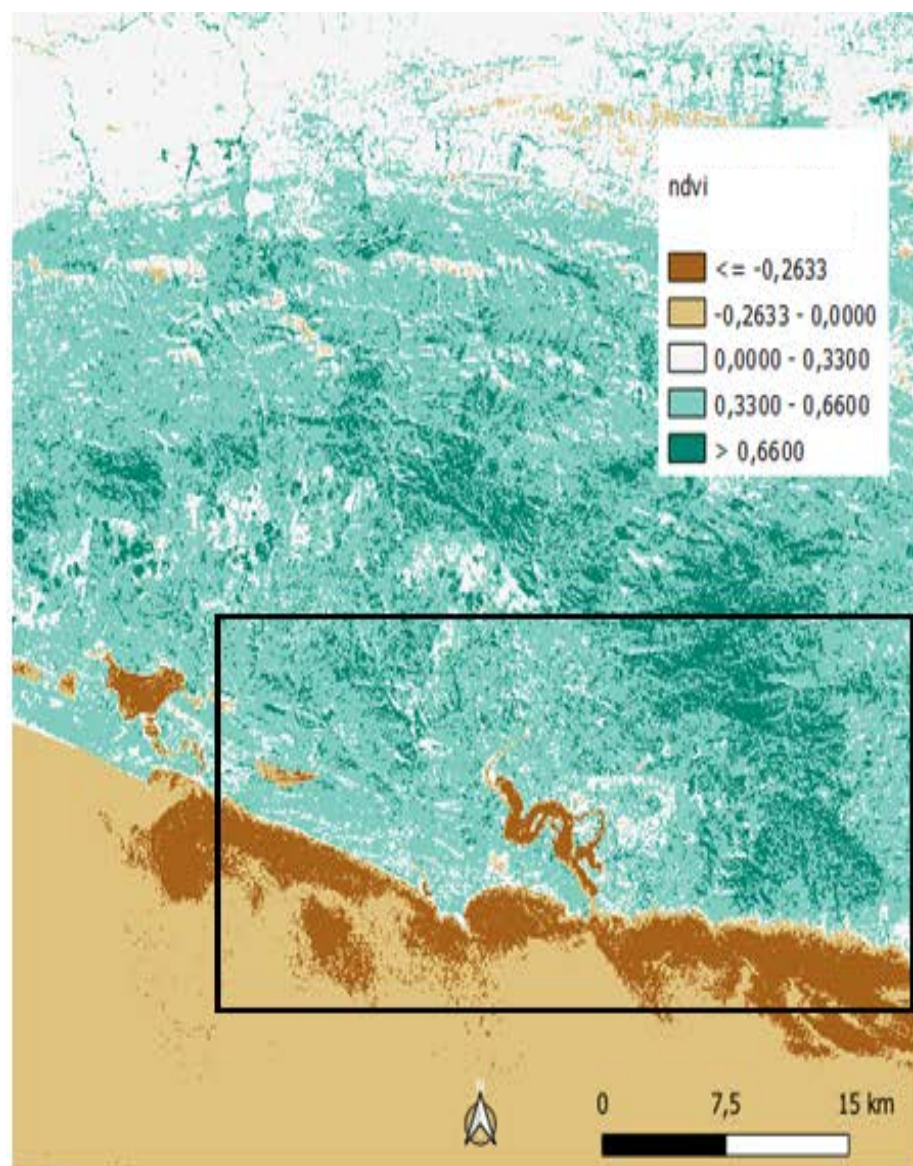


Figure 4.51: NDVI on 18 May vs 7 July 2017

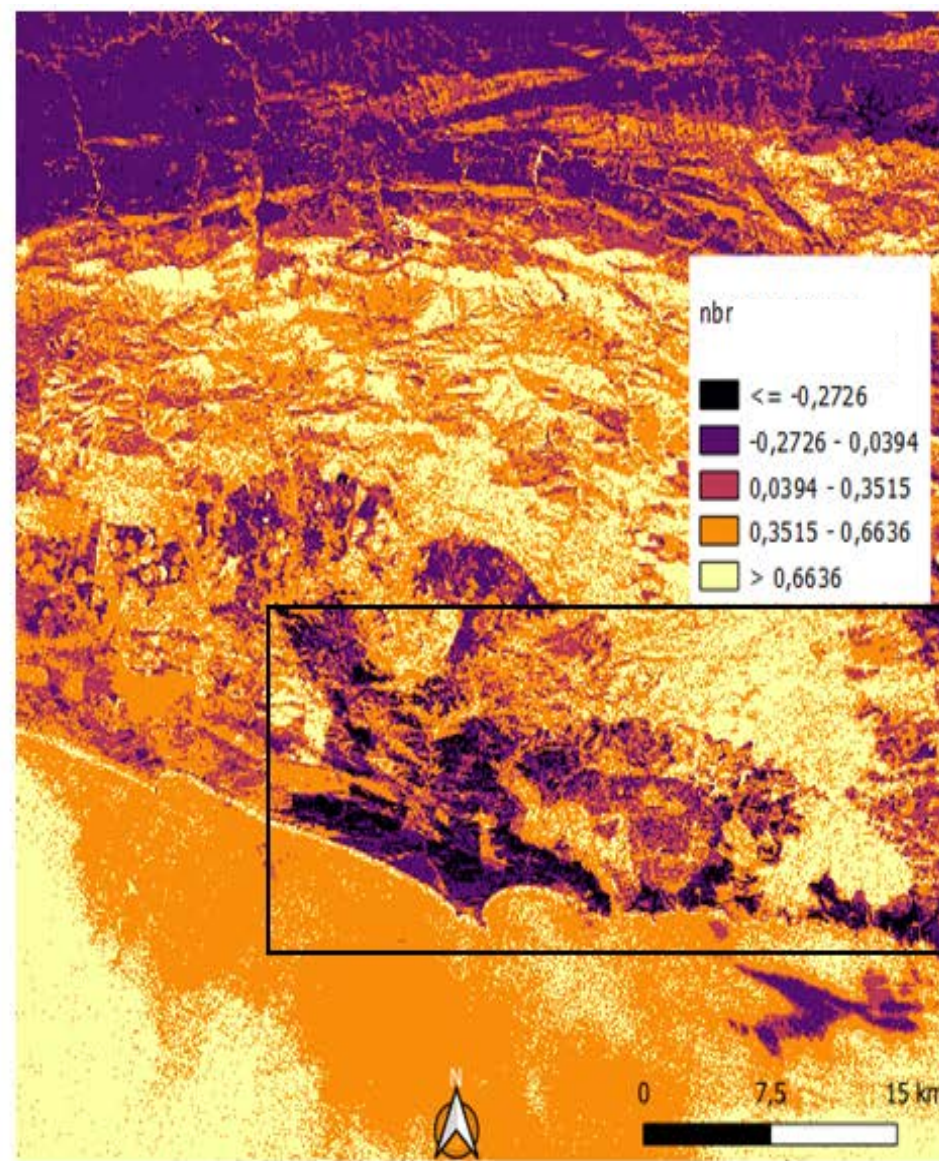
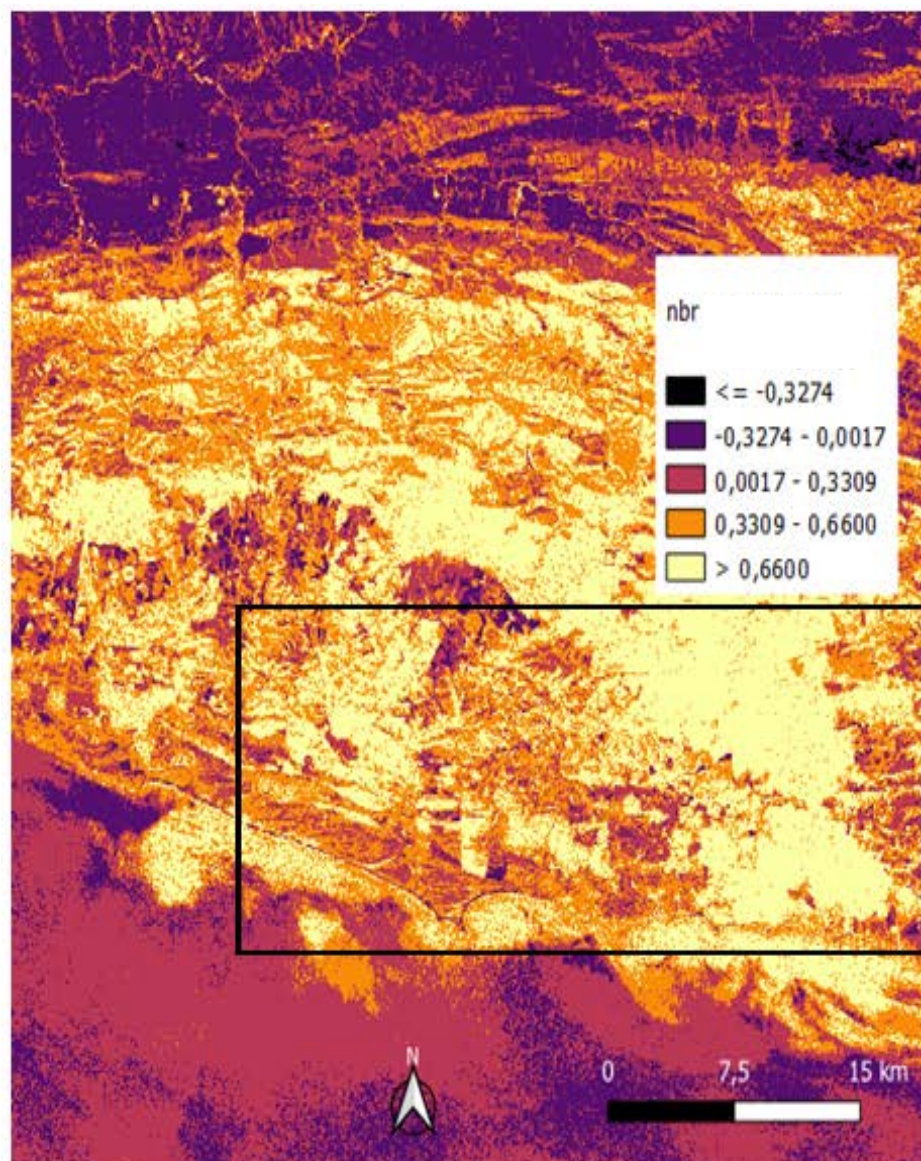


Figure 4.52: NBR on 18 May vs 7 July 2017

Figure 4.53 shows the burnt areas of the Knysna 2017 fire. The fire affected mostly areas along the coast. The fire consumed 34563,36 ha of land.

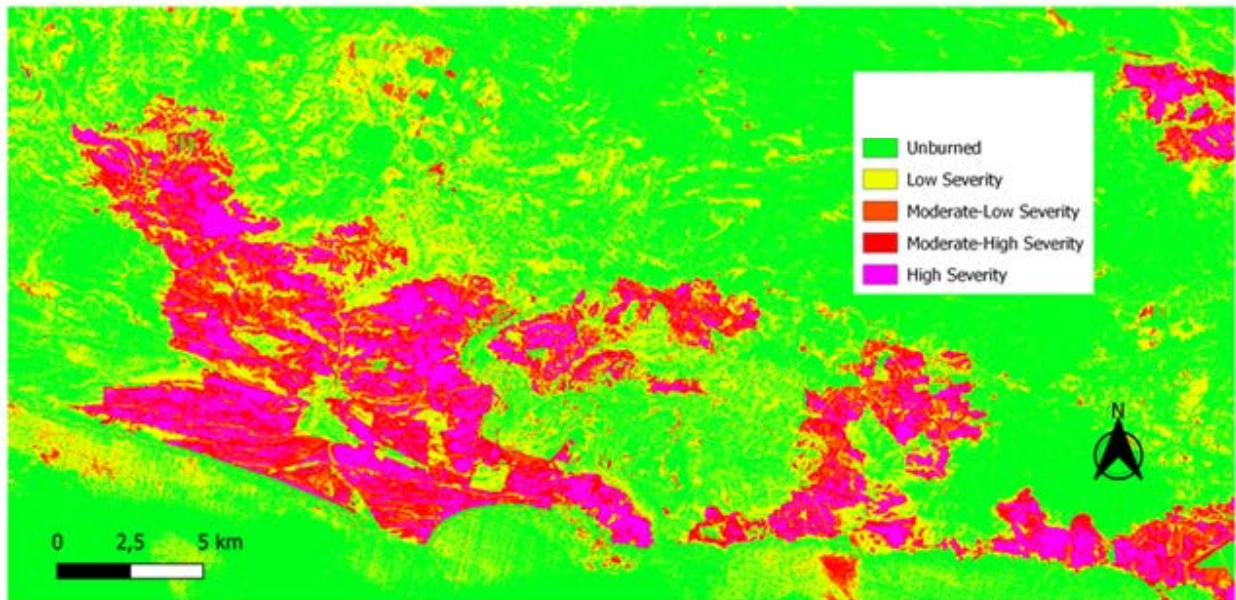


Figure 4.53: Burnt areas in the Knysna area in 2017

While the low-severity class recorded 174971,71 ha of burnt area, a significant proportion of the burnt areas fell in the moderate-high and high severity classes (6030,52 and 5934,30 ha respectively) as shown by Table 4.8.

Table 4.8: Fire severity of the 2017 Knysna fire

Severity	Area (hectares)
Unburned	50 006,22
Low Severity	17 497,71
Moderate-Low Severity	5 100,30
Moderate-High Severity	6 030,52
High Severity	5 934,83
Total burnt area	34563,36

4.6 FIRE EVENT 5: KNYSNA 2018

4.6.1 Weather

On the day of ignition, HP systems dominated the weather over southern Africa as indicated in Figures 4.54 and 4.55. Interestingly, some of the highest maximum temperatures ($>31^{\circ}\text{C}$) were recorded along the western coasts of South Africa and Namibia as well as the Garden Route area of South Africa as shown in Figure 4.56. On the 28th of October, a LP system extended over the western interior of the continent while a HP system occurred over the Indian Ocean, south east of the country. These systems resulted in high maximum temperatures over most of the interior ($>32^{\circ}\text{C}$). A ridging HP system occurred south of the continent on the 2nd of November, which brought lower maximum temperatures over South Africa. A LP cold front system extended across the continent on the day of extinction. A strong HP system developed on the same day, towards the south-west of the continent. The combination of these pressure systems brought cooler air over the region, especially over the Western Cape Province.

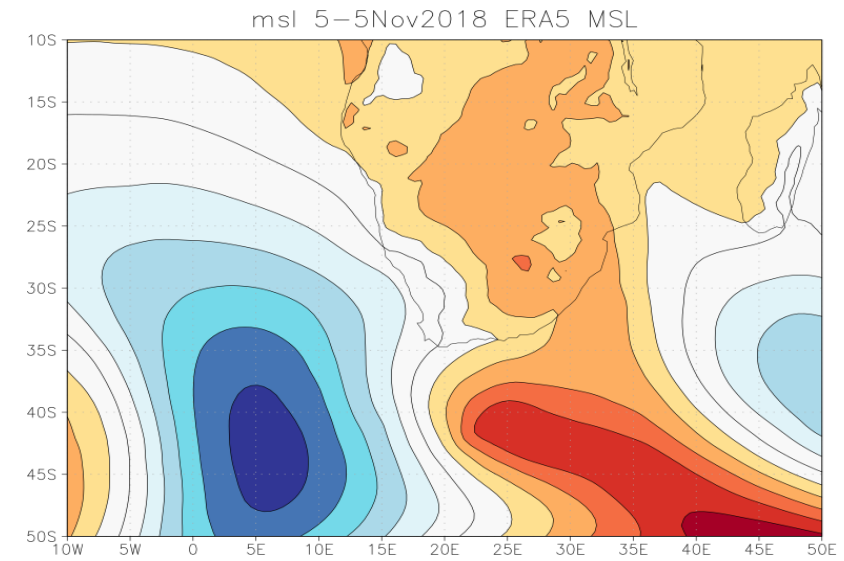
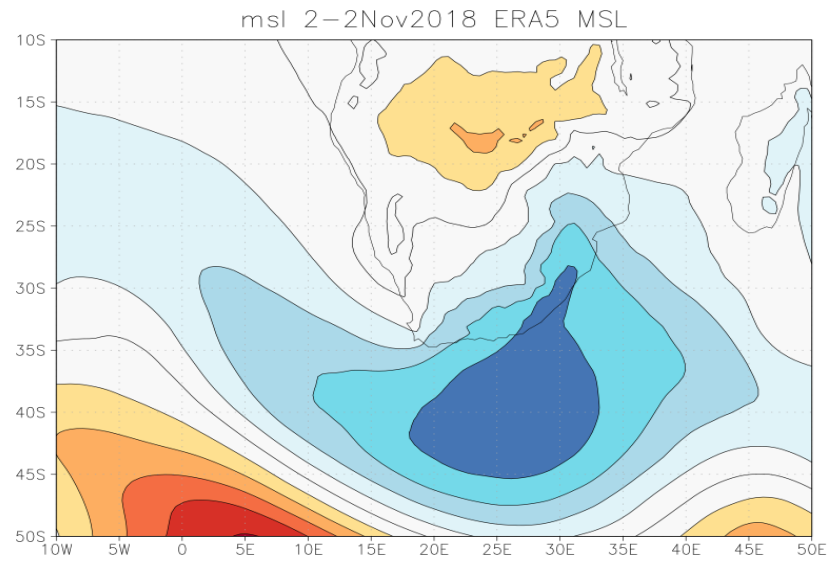
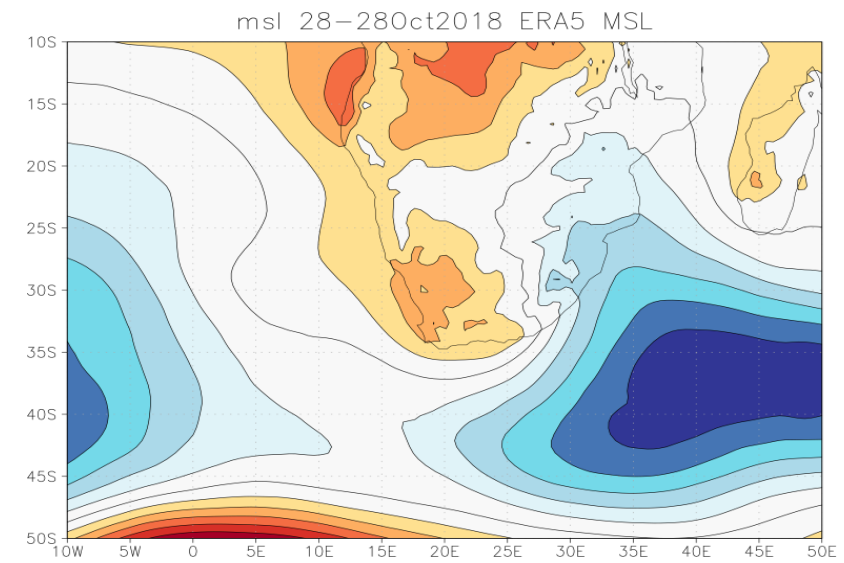
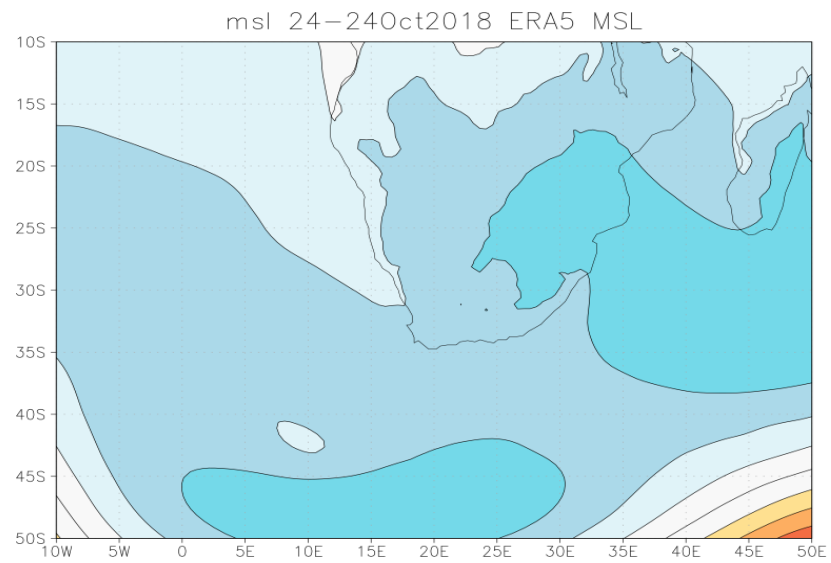


Figure 4.54: Mean-Sea-Level Pressure over South Africa for selected days in October and November 2018

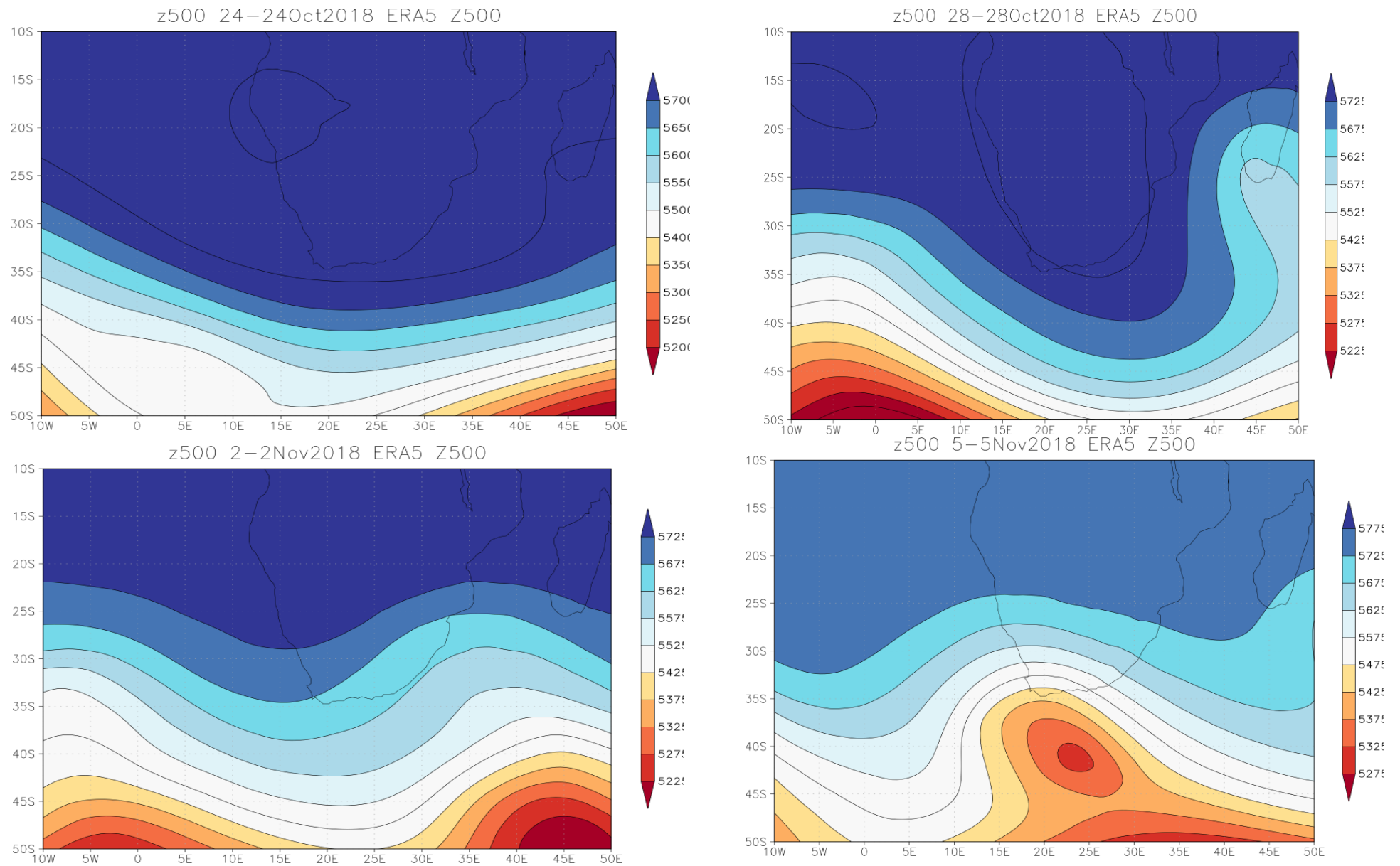


Figure 4.55: Geopotential Height over South Africa for selected days in October and November 2018

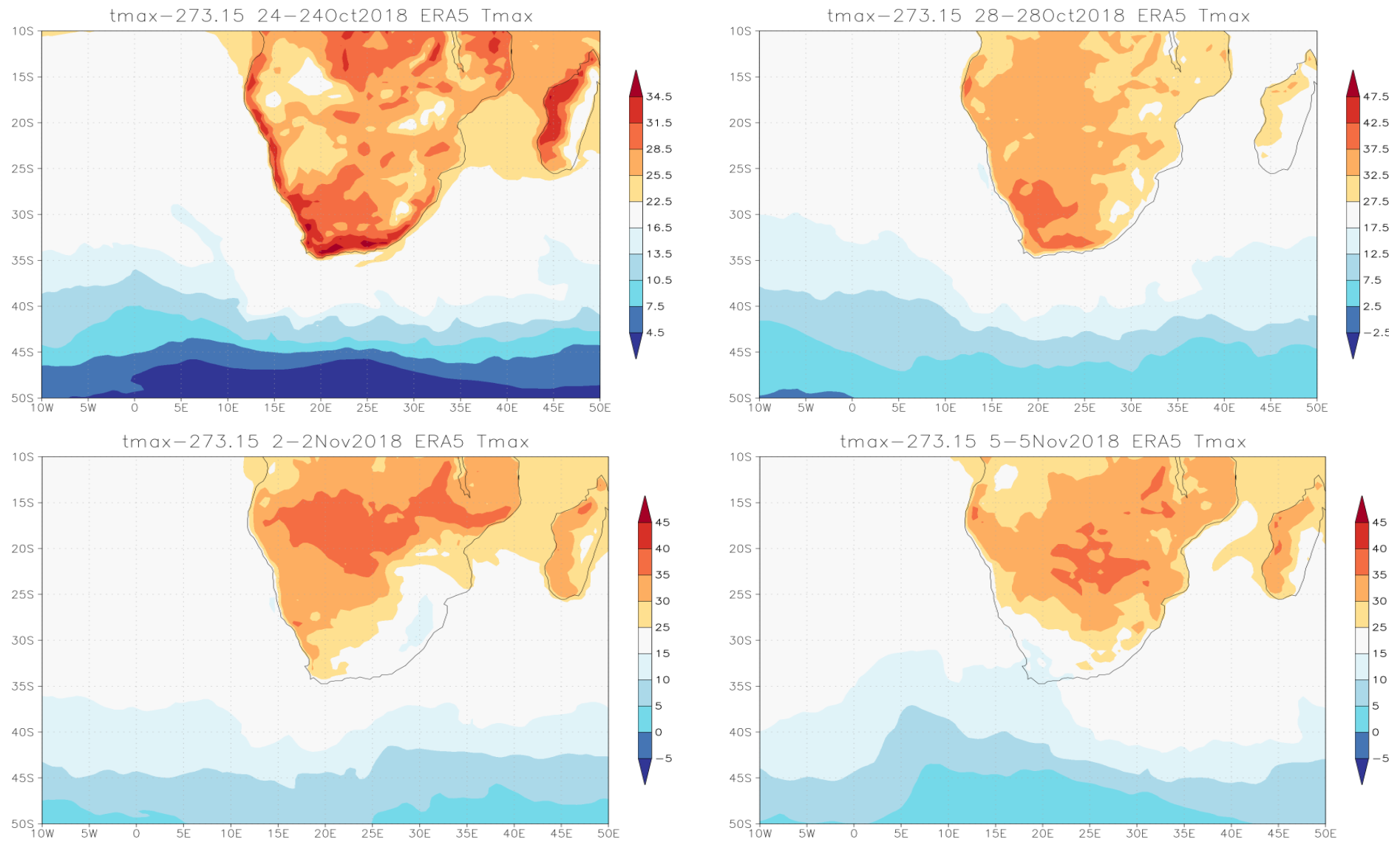


Figure 4.56: Maximum temperature over South Africa for selected days in October and November 2018

Figure 4.57 below shows the changes in weather variables over the Knysna area on the 23rd and 24th of October 2018. The temperature increased significantly on the 23rd of October, with values exceeding 30°C from 09:00 to 18:00 and a maximum of 38,7°C at 13:00. On the 24th of October, temperature values were slightly lower, however, 30°C was reached by 10:00 and a maximum of 34°C recorded at 11:00. North-westerly winds, with wind speeds varying between 1,2-5 m/s (4,3-18 km/h), occurred between 08:00 and 14:00 on the 23rd of October. By 15:00, winds were blowing from the south-east with speeds below 3 m/s (10,8 km/h). A southerly wind started blowing across the region at 11:00 on the 24th of October, however its direction shifted eastward, and its speed increased from 1,3 m/s to 2,5 m/s (4,7-9 km/h) by 17:00. A rapid decline in relative humidity occurred on the 23rd of October. At 00:00 the relative humidity was recorded as 69%, while it fell to 15% at 04:00. The values remained below 20% for most of the day, while increasing after 20:00. On the 24th of October, the relative humidity values were mostly below 60%, with a decrease in values starting from 59% at 04:00 to 16% at 15:00. Relative humidity values increased thereafter to reach 62% at 23:00. Air pressure values tended to fluctuate on both days in the 1009-1014 hPa range, with peaks reached around 08:00 and lows at 15:00 and 16:00. on the 23rd of October, it fluctuated between 1010-1014 hPa.

Figure 4.58 shows the meteograms generated for Knysna station for 4-5 November 2018. Temperature values tended to remain above 15°C on the 4th of November, it declined significantly on the 5th of November and fell to 7,8°C by 23:00. Westerly winds blew across the area on both days and wind speeds were mostly above 2 m/s (7,2 km/h), with peaks of 5 m/s (18 km/h) at 10:00 on the 4th and 4,7 m/s (16,9 km/h) on the 5th of November. Relative humidity values fluctuated on the 4th of November between 35 and 77%. However, on the 5th of November, relative humidity values mostly remained above 80%, with a peak of 91% reached at 09:00. Interestingly, rainfall occurred on this day, varying between 0,2 mm at 06:00 and 2 mm at 19:00 and reaching a total of 15,2 mm. Air pressure values increased gradually from 995 hPa on the 4th of November to 1011,9 hPa on the 5th of November.

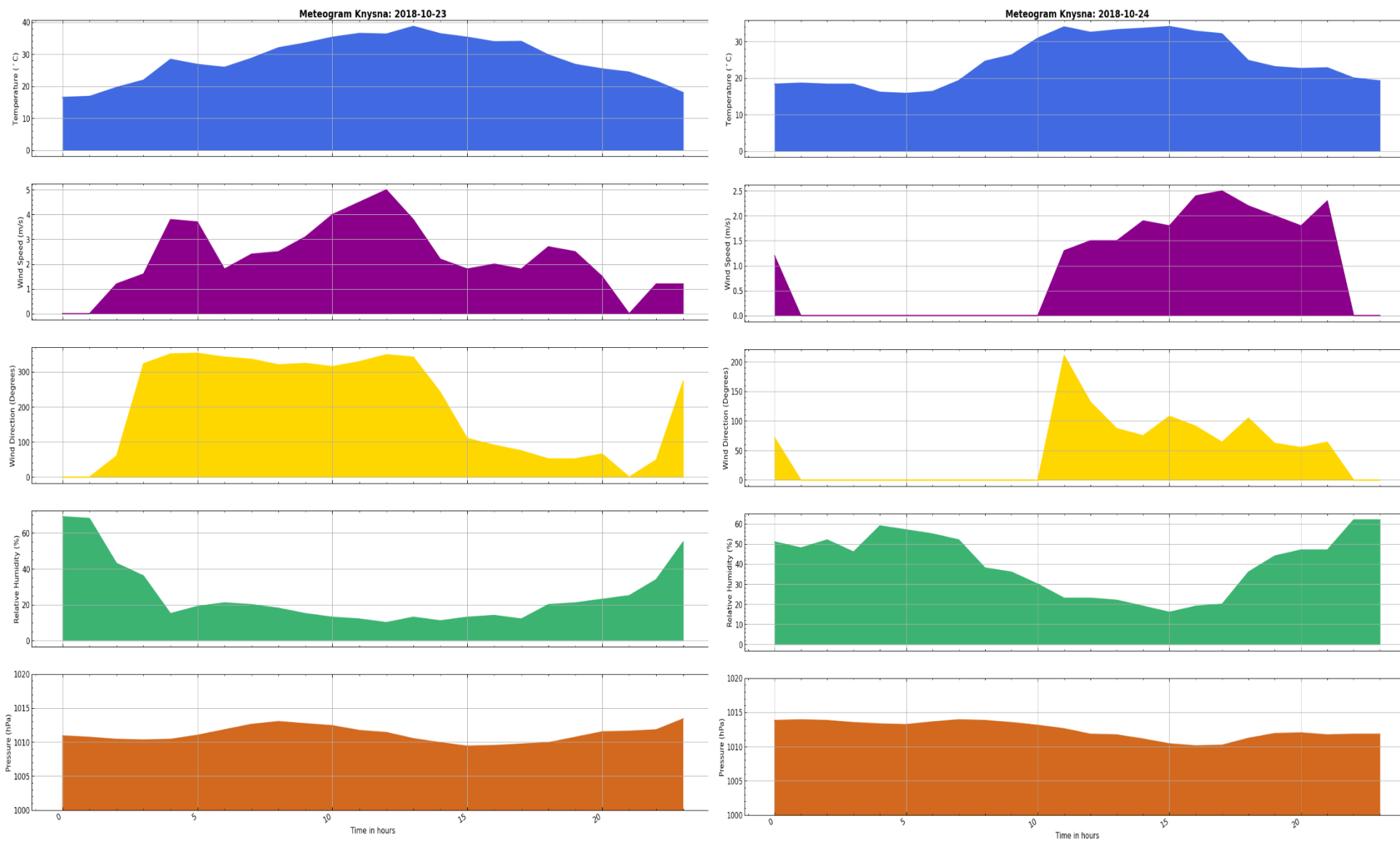


Figure 4.57: Meteograms: Knysna 23-24 October 2018

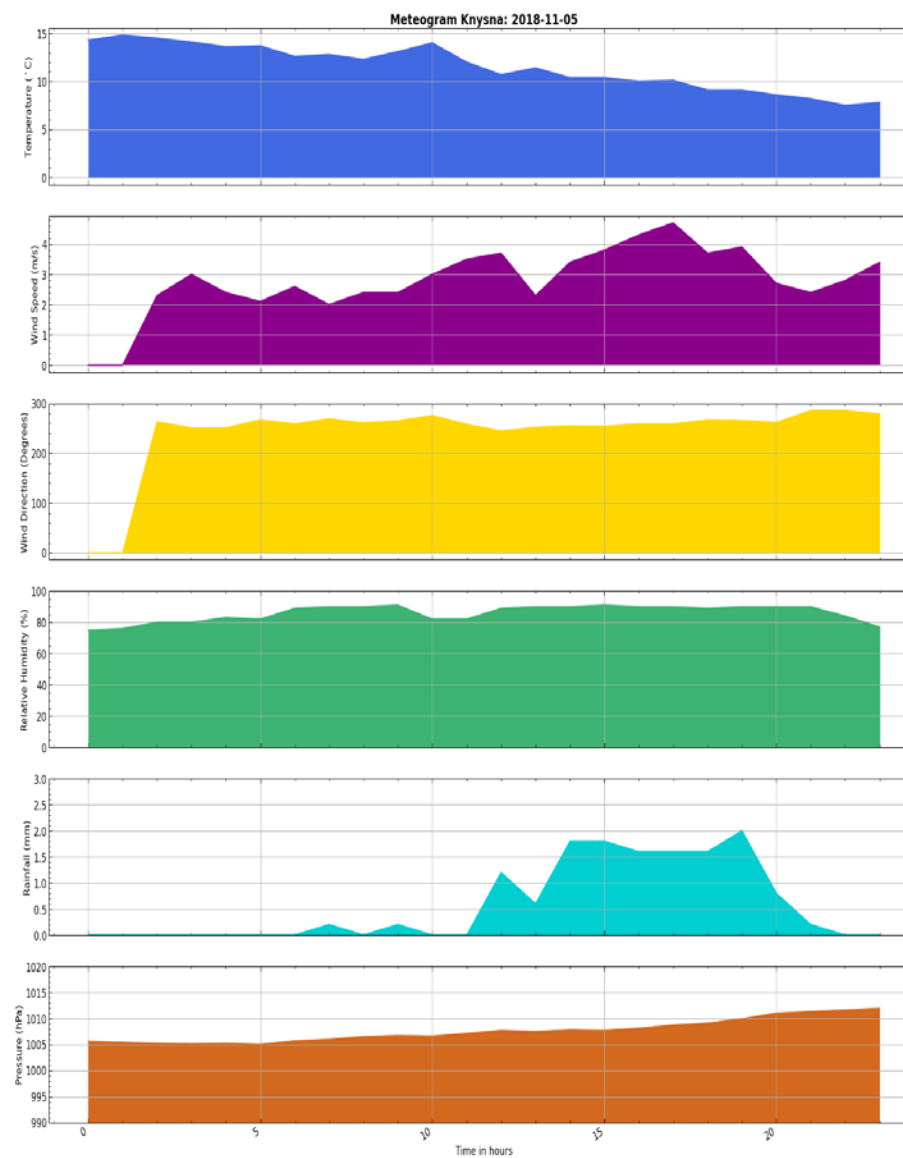
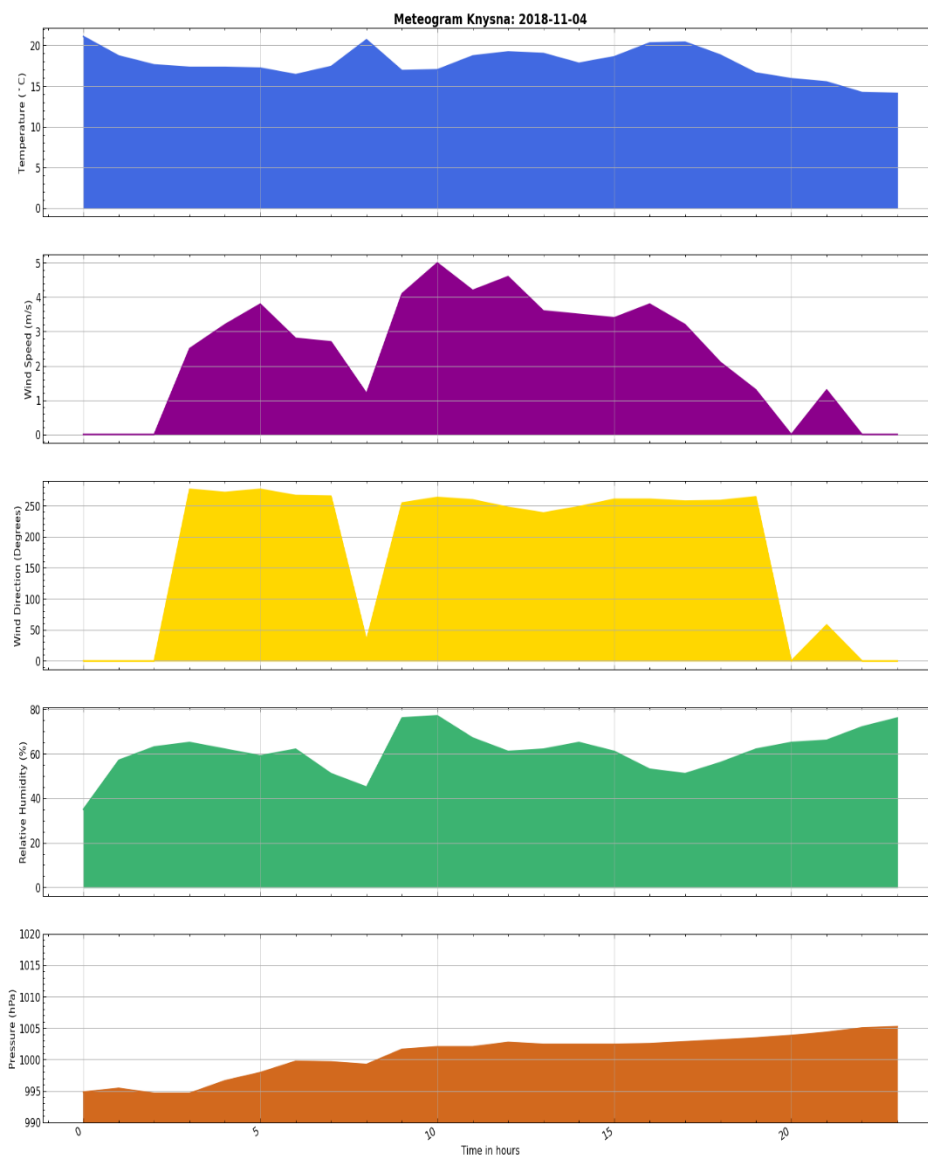


Figure 4.58: Meteograms: Knysna 4-5 November 2018

4.6.2 Volumetric soil moisture

Days leading up to the fire event, saw low volumes of soil moisture occurring at a regional level, with particularly low values overlapping with the Succulent Karoo biome ($<0,05 \text{ m}^3$) as shown in Figure 4.59. Elsewhere, soil moisture volumes were mostly below $0,2 \text{ m}^3$, with the Garden Route and an area in the Eastern Cape recording volumes in the $0,2\text{-}0,3 \text{ m}^3$ range.

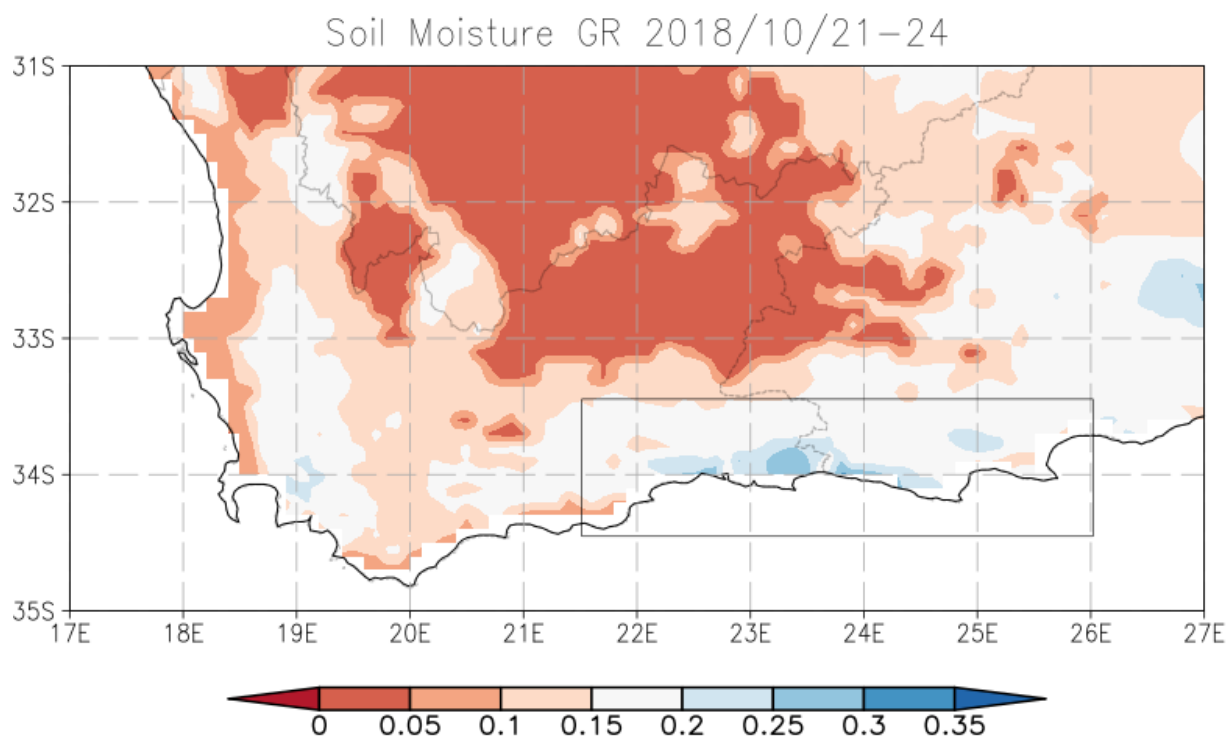


Figure 4.59: Average soil moisture over the Garden Route for 21-24 October 2018

4.6.3 Vegetation indices

NDVI values for the region prior to and after the fire are depicted by Figure 4.60. Prior to the fire, the majority of the vegetation in the region of interest fell into the moderately healthy ($0,33\text{-}0,66$) class, with unhealthy vegetation towards the north-west ($0\text{-}0,33$ class) and patches of healthy vegetation ($>0,66$ class) occurring towards the south and south-east. After the fire event, the vegetation in the region of interest fell mostly in the unhealthy vegetation class ($0\text{-}0,33$) with some of the vegetation mortality being visible through a negative value class ($-0,3890$ to 0). Moderately healthy vegetation ($0,33\text{-}0,66$) occurred along the fringes of the unhealthy and dead vegetation areas with healthy vegetation occurring to the south and south-eastern sections of the region of interest.

The NBR values prior to and after the fire event are depicted in Figure 4.61 below. While most of the area reflected positive values prior to the fire, some low negative values were recorded for

the mountainous regions toward the north and isolated patches along the coast. After the fire event, a significant proportion of the region of interest displayed negative values, with certain areas recording values below -0,4189. These values indicate where the fire had occurred as the immediate surroundings reflect mostly positive values towards the south, east and west of the burnt area. Toward the north, the mountainous slopes recorded low negative values with some positive values recorded in the north-east.

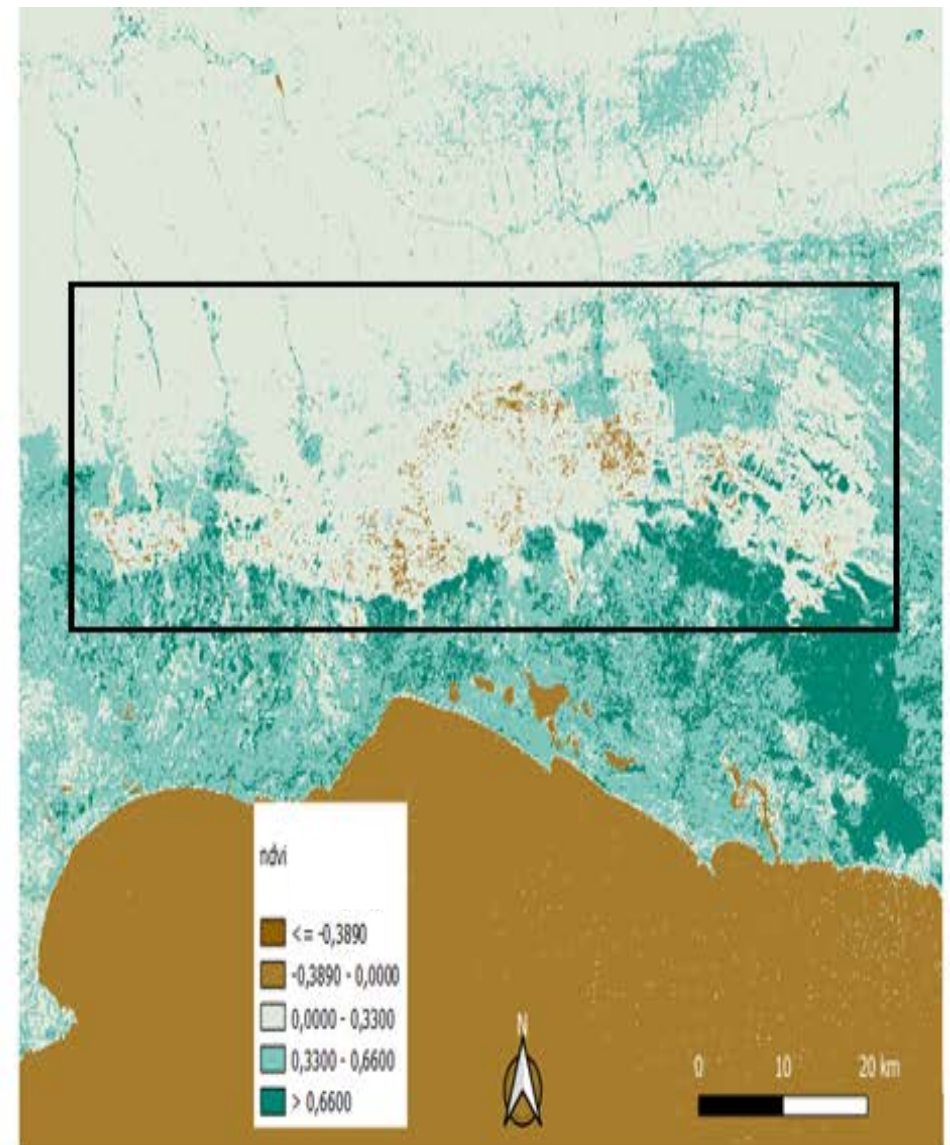
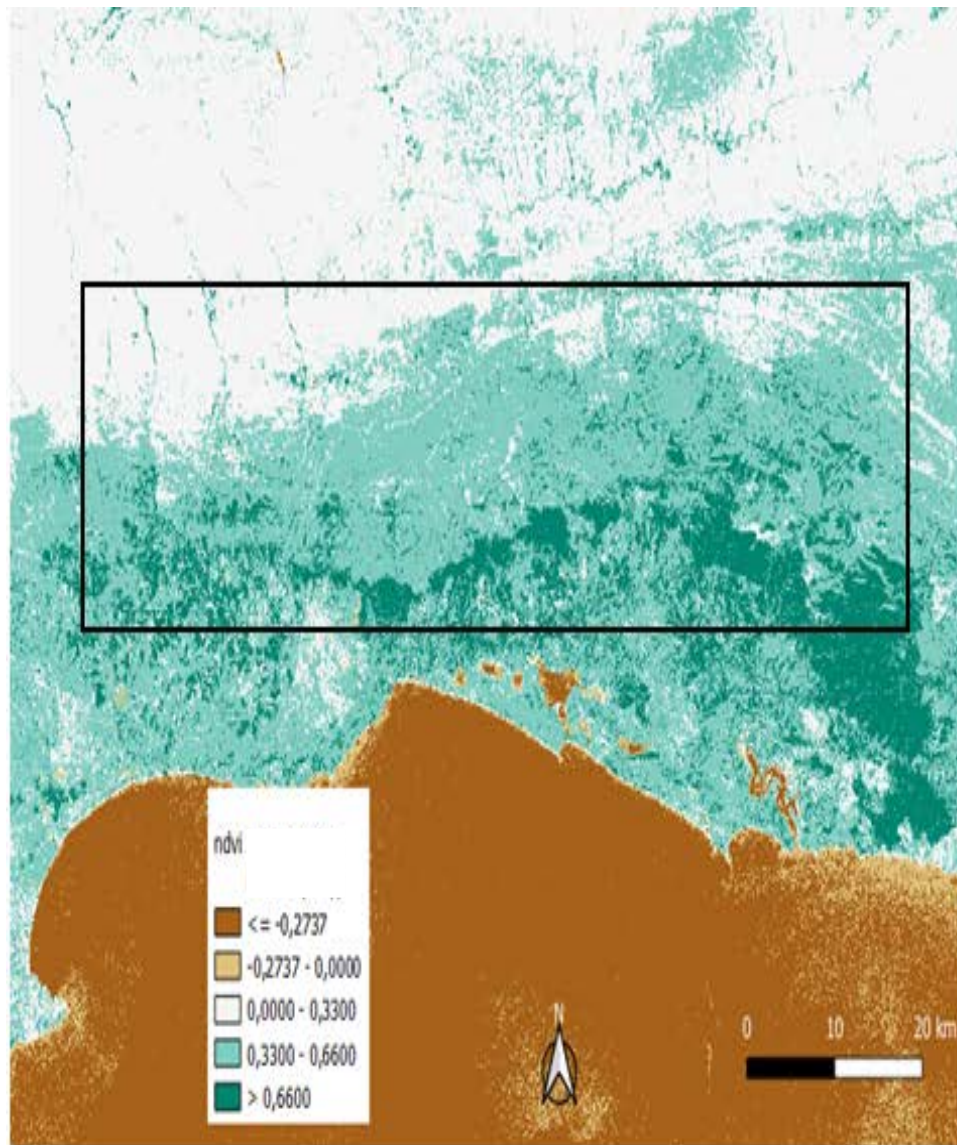


Figure 4.60: NDVI on 30 September vs 11 November 2018

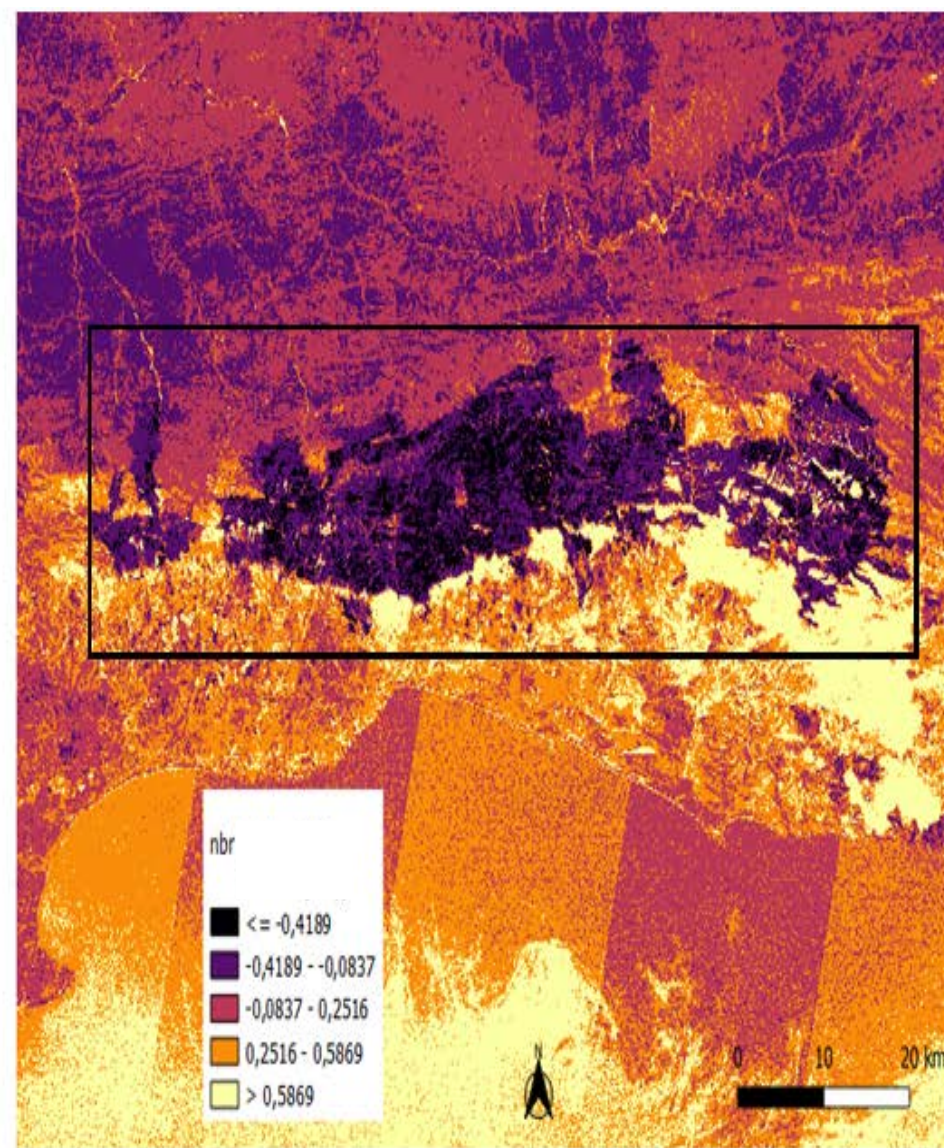
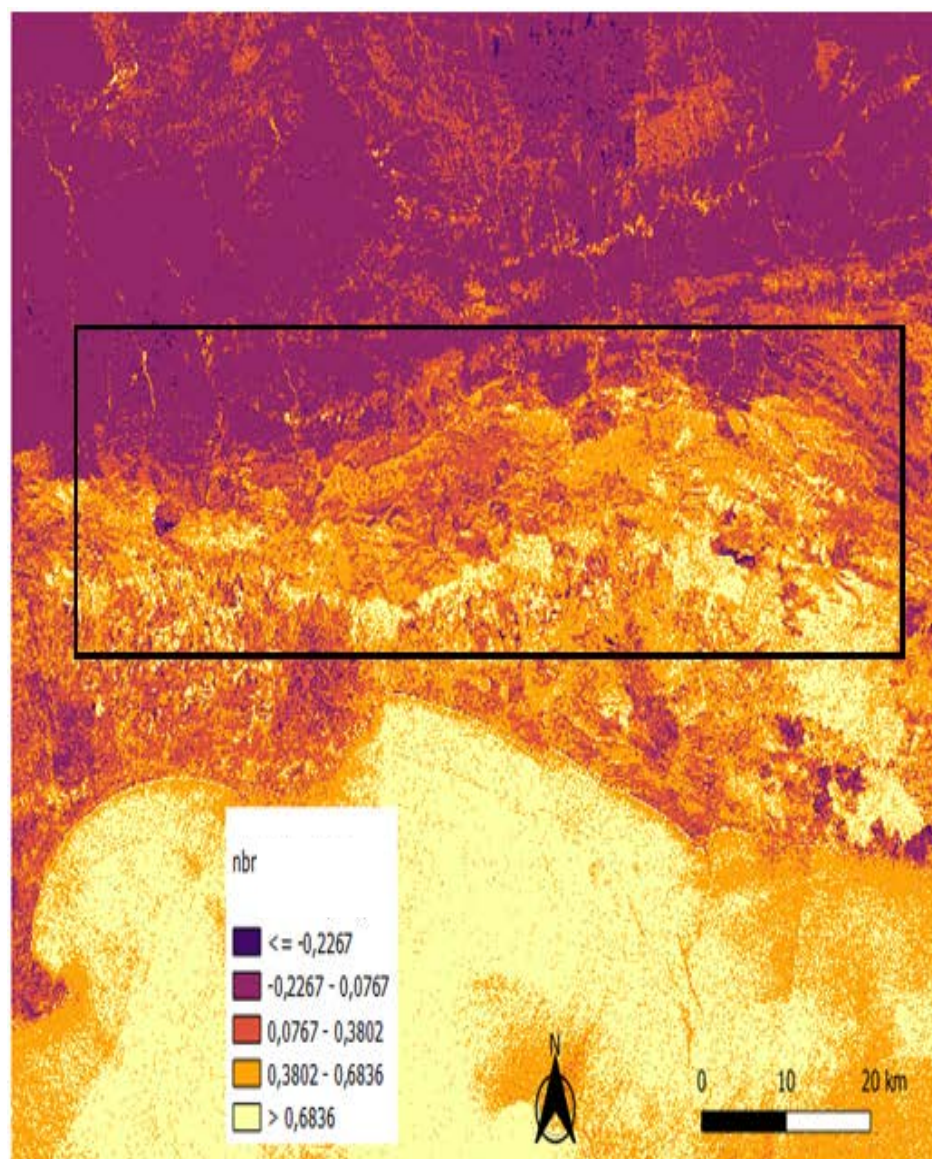


Figure 4.61: NBR on 30 September vs 11 November 2018

Figure 4.62 shows the burn severity of the Knysna fire in 2018.

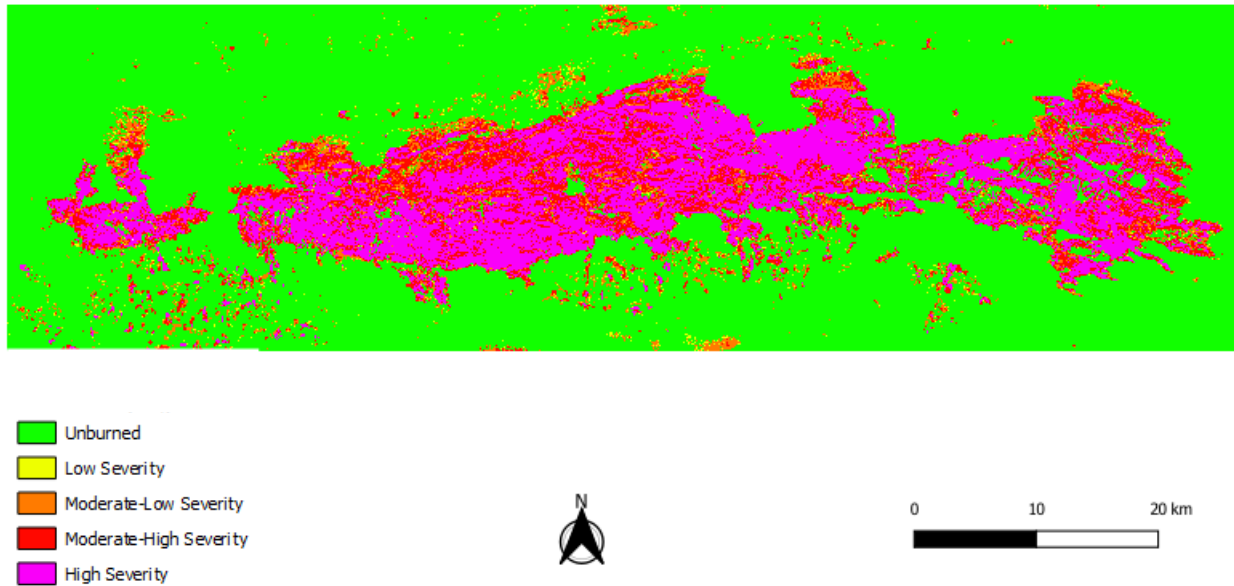


Figure 4.62: Burnt areas in Knysna in 2018

The total burnt area from this fire event amounted to 100714,22 ha as indicated in Table 4.9. From this table it can be seen that largest section of burnt area pixels were classified in the high severity (46171,90 ha) and moderate-high severity (26989,47 ha) classes.

Table 4.9: Fire severity of the 2018 Knysna fire

Severity	Area (hectares)
Unburned	118 130,86
Low Severity	14 599,55
Moderate-Low Severity	12 653,30
Moderate-High Severity	26 989,47
High Severity	46 471,90
Total burnt area	100 714,22

4.7 Fire Event 5: SE Kalahari

4.7.1 Weather

The SE Kalahari region, western and central parts of the Free State province recorded above normal precipitation in the wet season prior to the fire event as depicted by Figure 4.63 below. On the 16th of October, a ridging HP system with its core over the Indian Ocean dominated the weather over the continent as shown in Figures 4.64 and 4.65. This resulted in high maximum temperatures over the continent – a large proportion of the continent experienced temperatures of more than 32°C, as depicted in Figure 4.66. By the 18th of October, the HP system had weakened slightly, leading to a slight decline in maximum temperatures over the region. The 21st of October witnessed the formation of a strong ridging highpressure system over the continent which returned high maximum temperatures over the central and western interior. A LP trough extended over the continent from the north, slightly altering the maximum temperature patterns over the region.

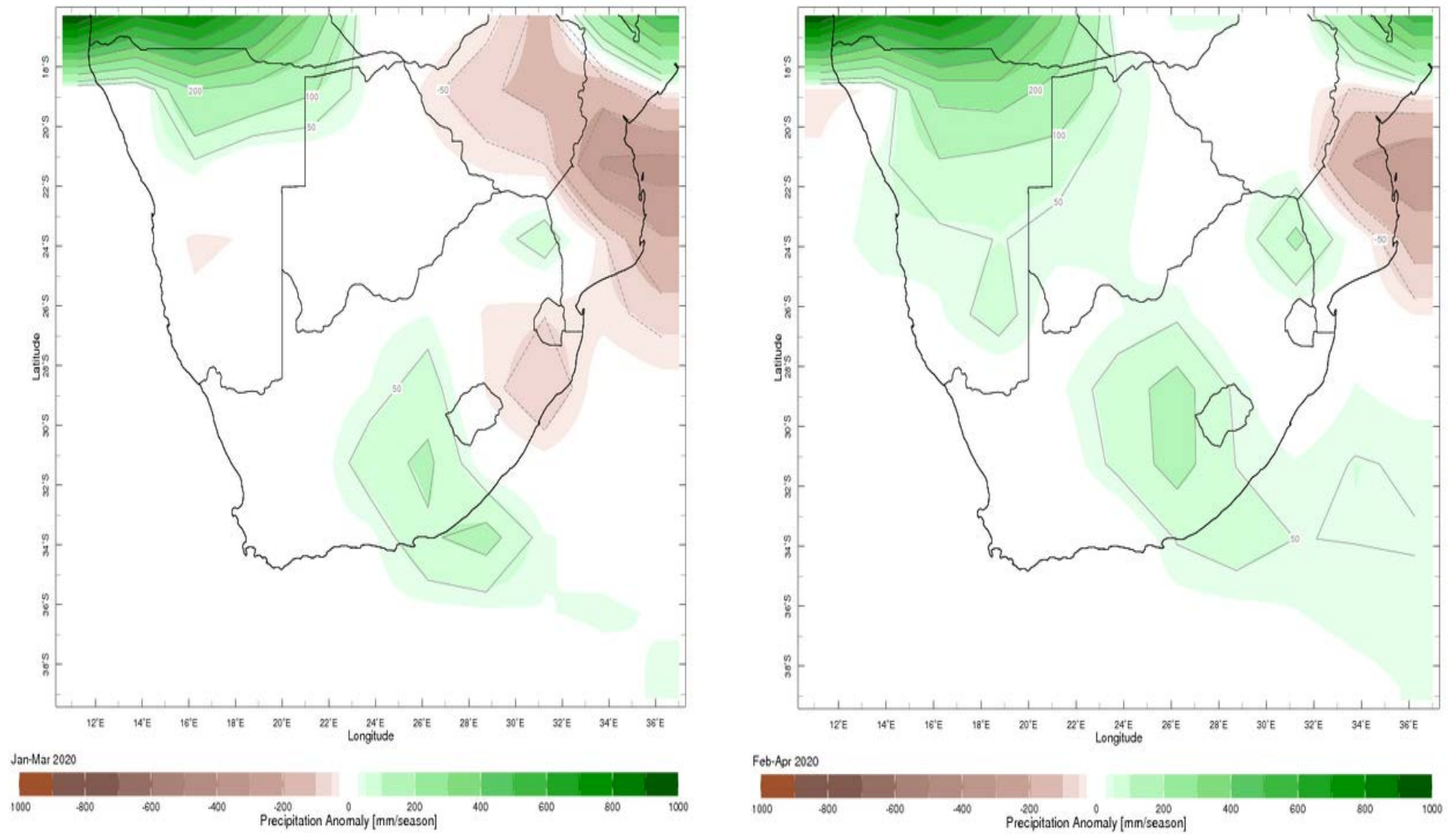


Figure 4.63: Seasonal precipitation anomalies recorded in January-April 2020

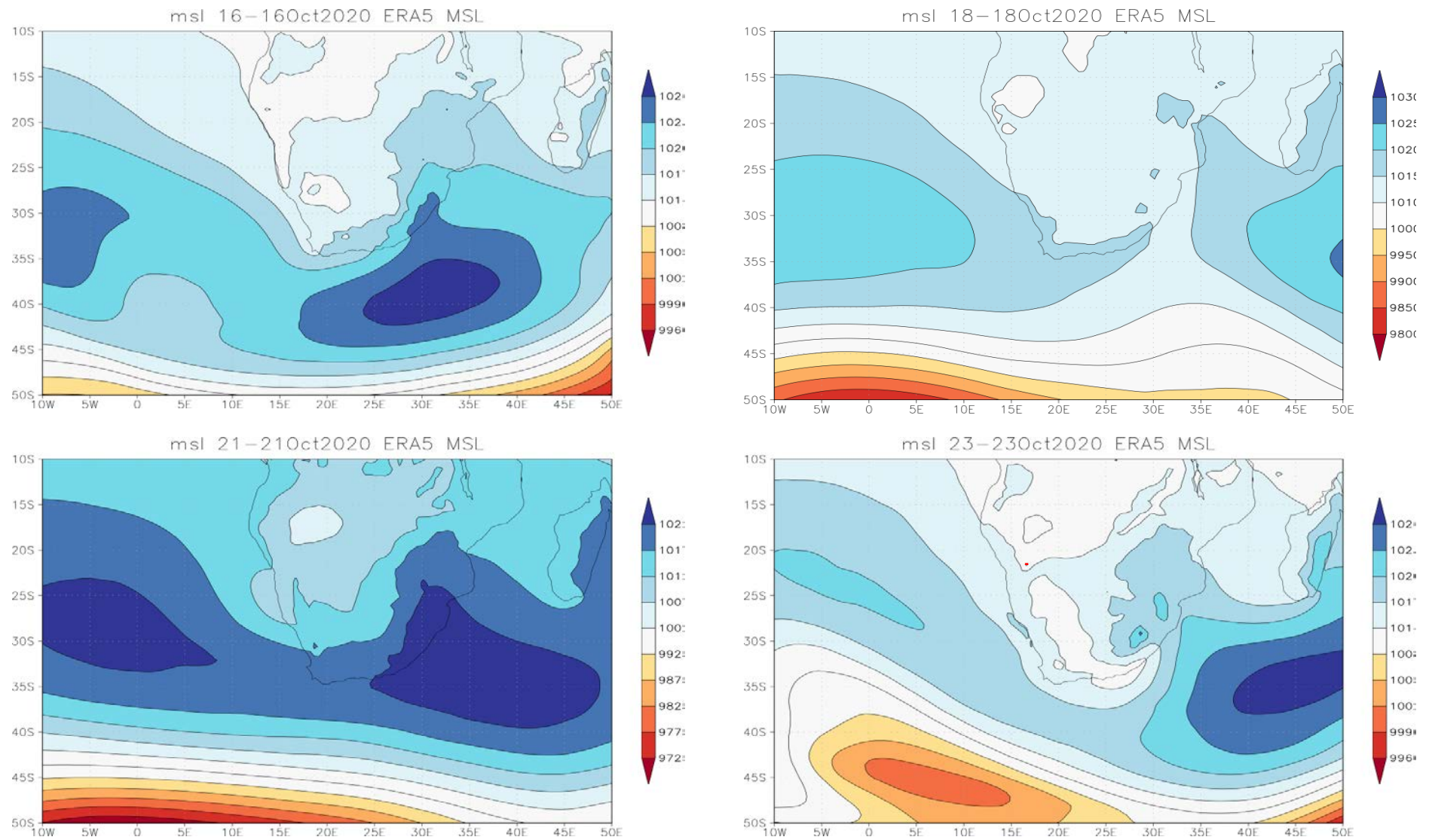


Figure 4.64: Mean-Sea-Level Pressure over South Africa over selected days in October 2020

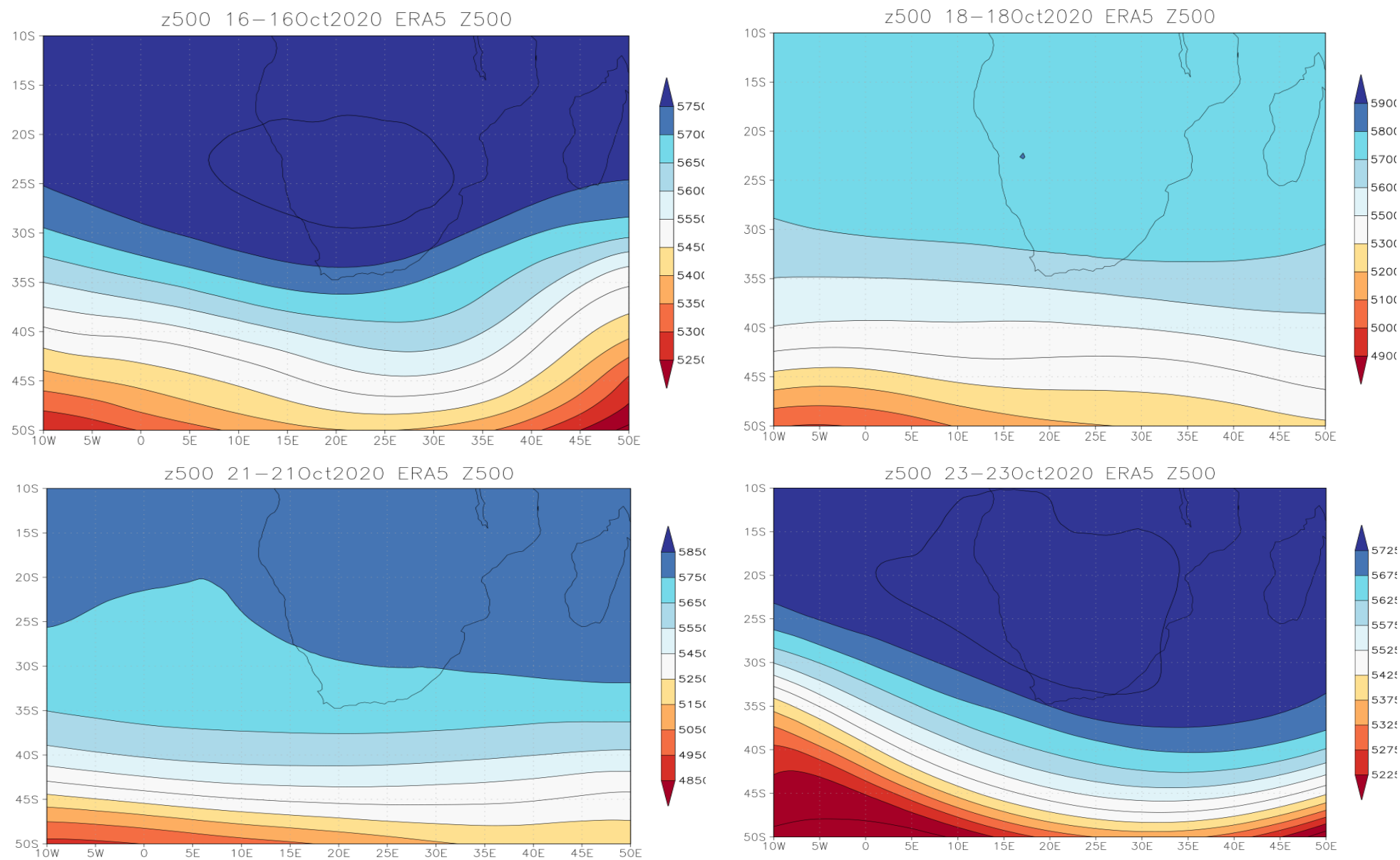


Figure 4.65: Geopotential Height over South Africa over selected days in October 2020

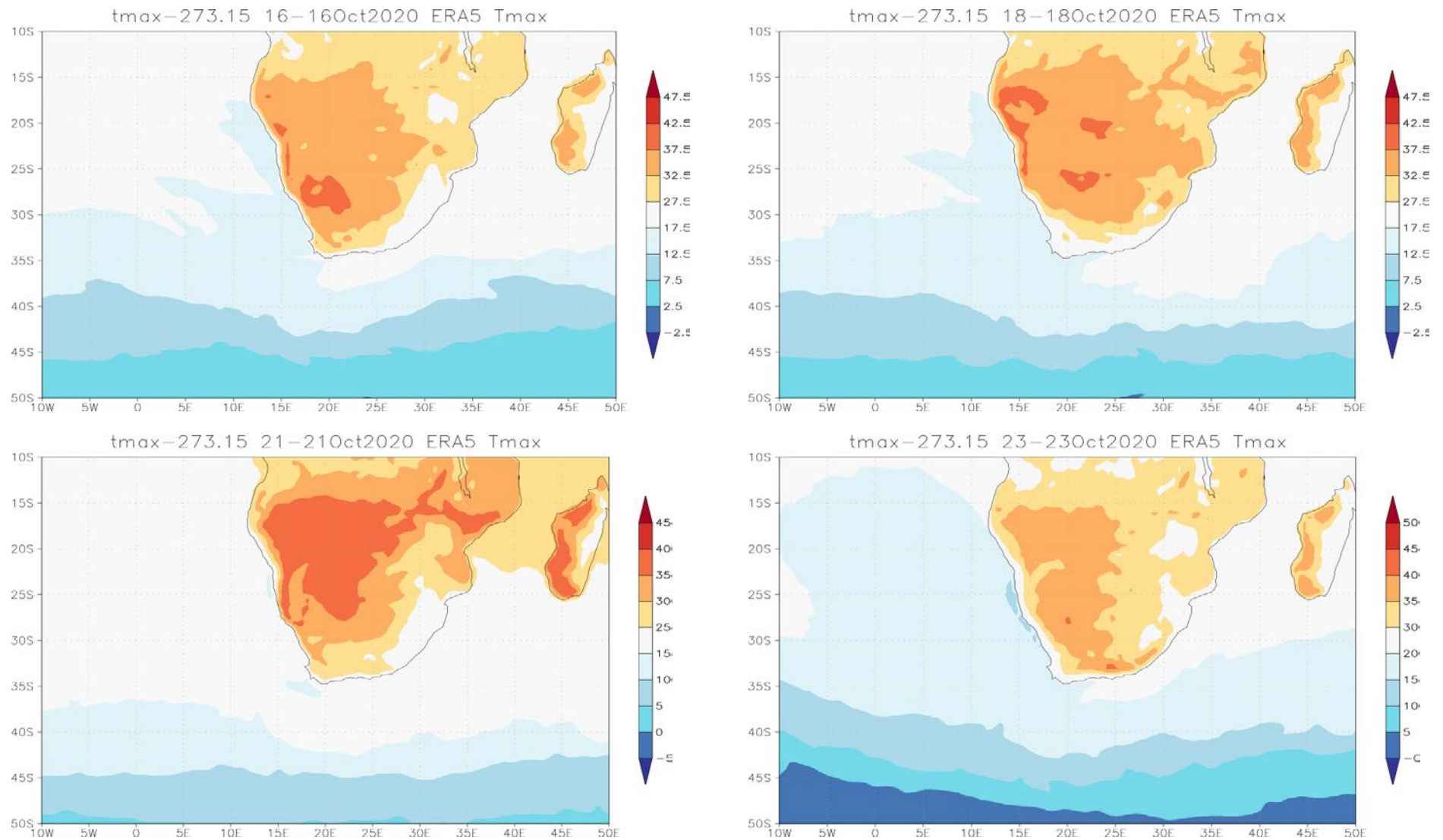


Figure 4.66: Maximum temperature over South Africa over selected days in October 2020

Figure 4.67 shows the meteograms for the Kimberley station for 15-16 October 2020. Temperature values show a large diurnal range with minimum values recorded at 05:00 and 06:00 and maximum values recorded at 15:00 on both days. The maximum temperature on the 15th of October was 38°C while it reached 39°C on the 16th of October. Mild north-easterly winds blew across the station in the early morning hours of the 15th, however, the wind changed direction by 08:00 to the west and reached a peak of 7,7 m/s (27,7 km/h) at 10:00. Subsequently, the wind speed decreased. On the 16th, wind speed and direction tended to fluctuate in the morning (northerly, southerly, and easterly) and varied between the range of 0-2,4 m/s (0-8,6 km/h). By 10:00 the wind direction tended to be northerly and changed to westerly towards the end of the day. A maximum windspeed of 6,9 m/s (24,8 km/h) was reached at 17:00. Relative humidity values were below 50% on the 15th of October and the change in wind direction brought about a decline in relative humidity values to a minimum of 8% at 18:00. On the 16th of October, relative humidity values were below 40% and reached a minimum of 8% by 14:00. A slight increase in the relative humidity values occurred in the evening, where it reached 24% by 23:00. Air pressure values for both days tended to peak at 10:00 on 887 hPa, whereas it reached its minimum at 16:00 on 884 and 882 hPa respectively.

Figure 4.68 depicts the weather station data for Kimberley on 22-23 October. The temperature values reached their peaks in the late afternoon, with highs of 37,5°C recorded at 16:00 on the 22nd and 38,6°C recorded at 17:00 on the 23rd. On 22 October, northerly winds with speeds varying between 2,4-7,2 m/s (8,6-25,9 km/h) swept across the area. The following day experienced similar winds – northerly and varying speeds between a 2,6-9,4 m/s (9,4-33,8 km/h) range. Relative humidity values peaked in the early hours on both days – 62% at 05:00 on the 22nd and 45% at 05:00 on the 23rd. On both days the relative humidity values peaked when temperature values were low and reached low values when temperatures peaked. Air pressure values on both days remained within a range of 883-887 hPa.

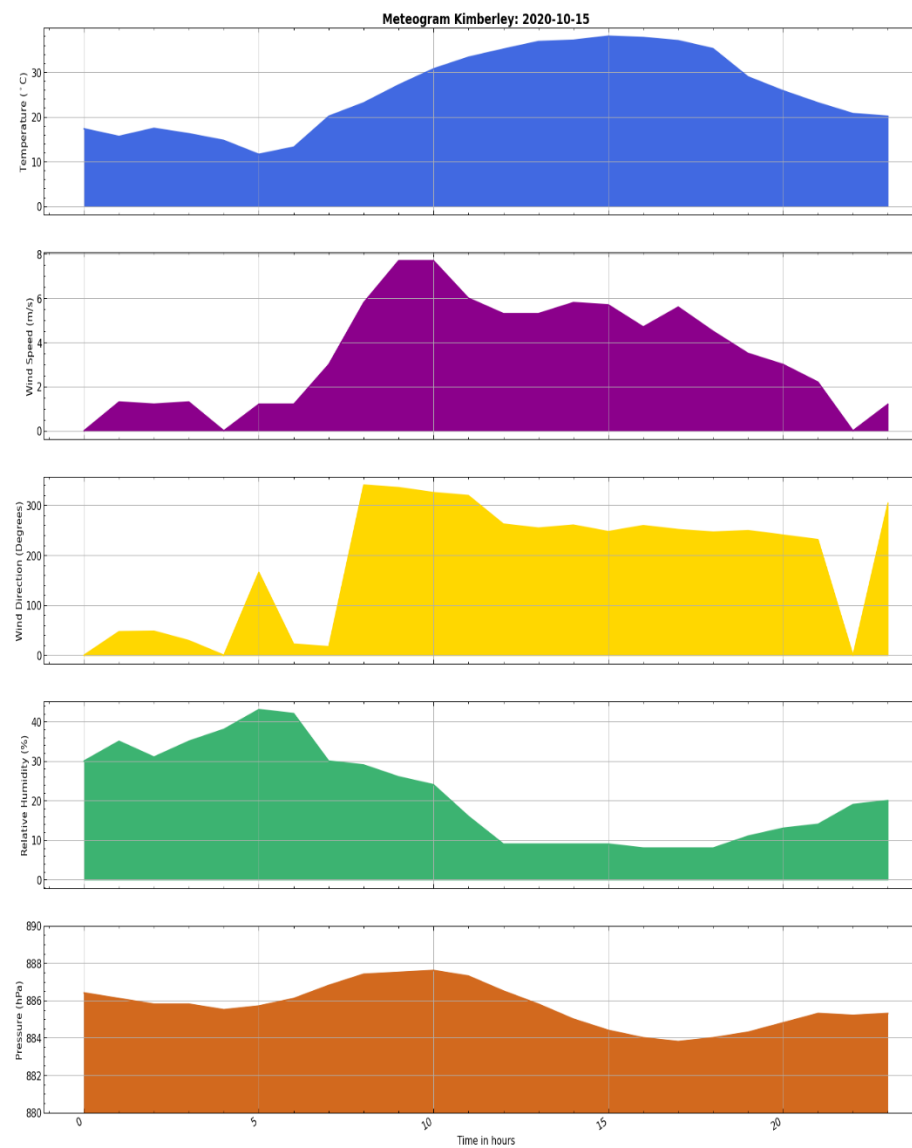
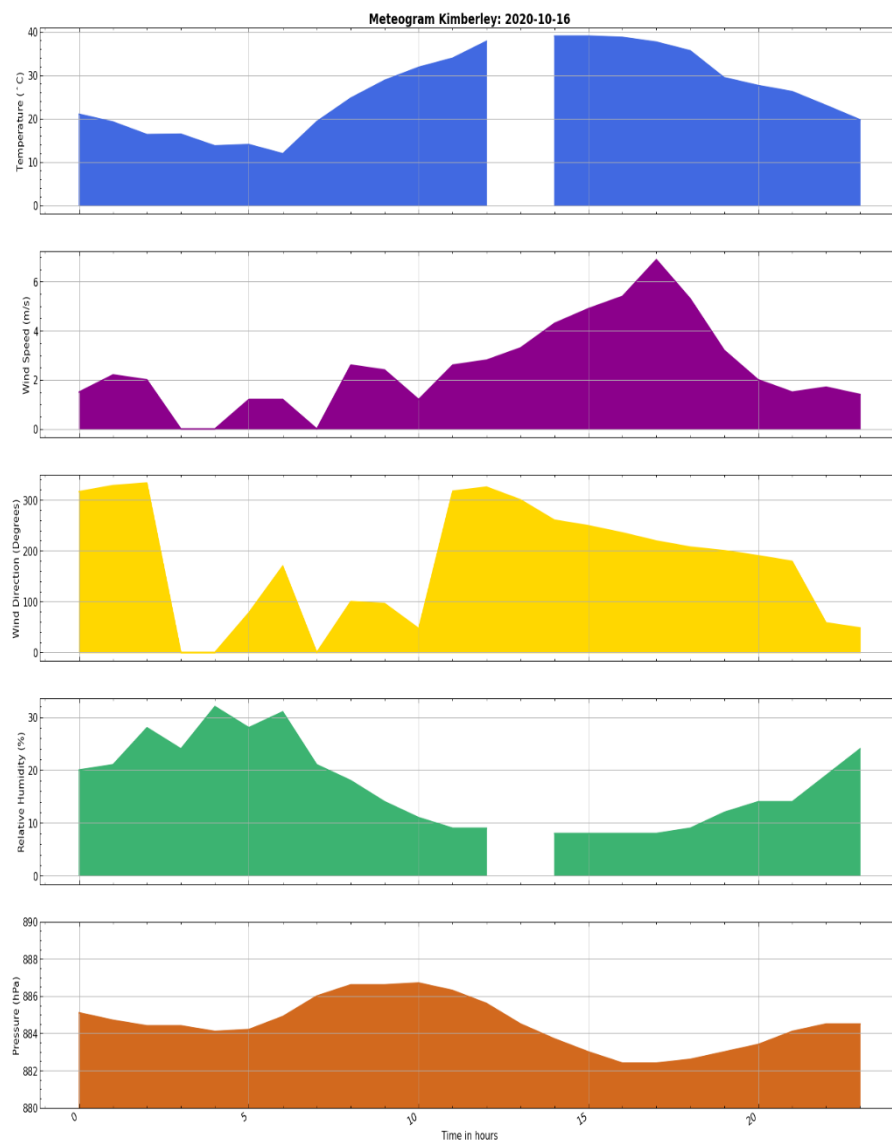


Figure 4.67: Meteograms: Kimberley 15-16 October 2020

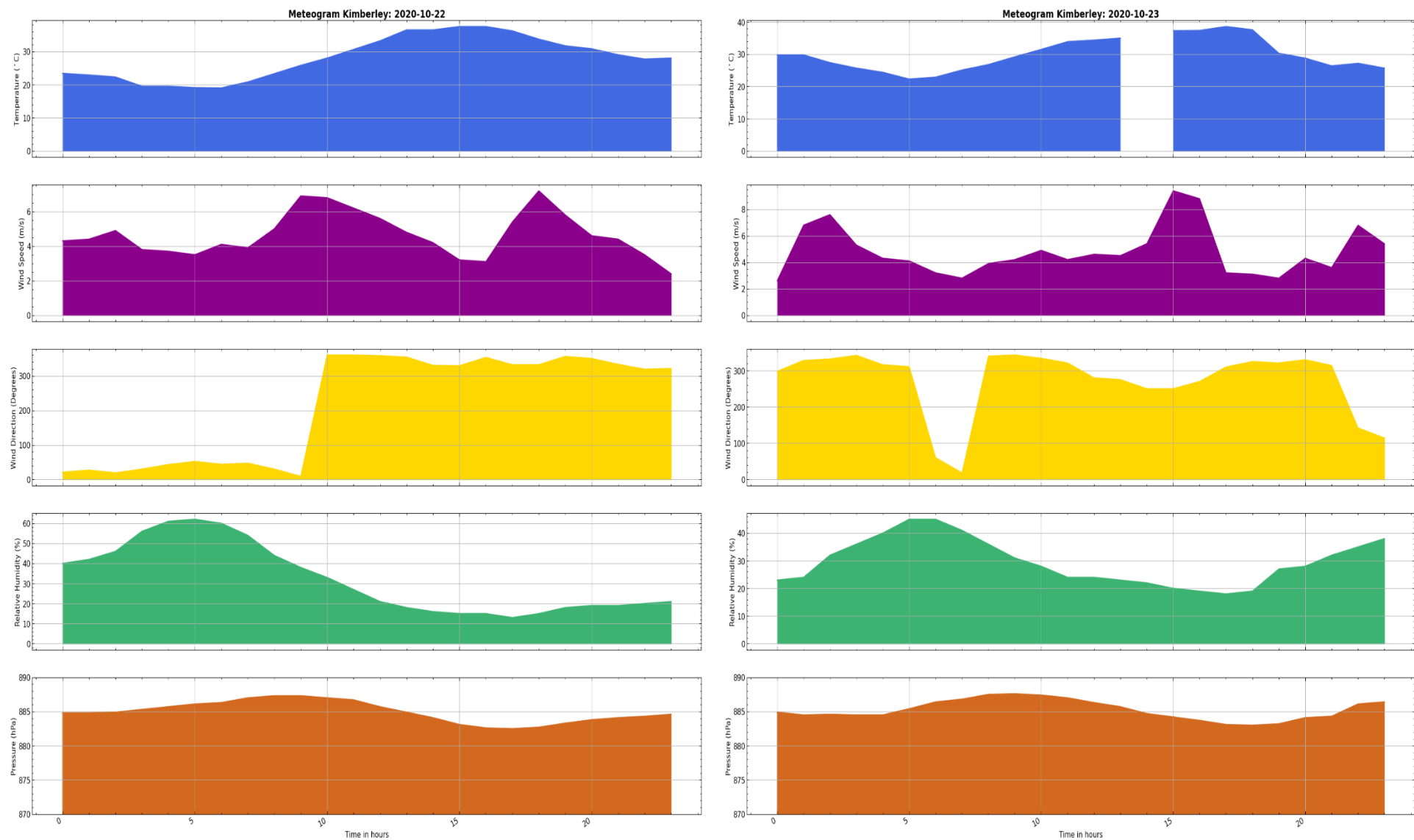


Figure 4.68: Meteograms: Kimberley 22-23 October 2020

4.7.2 Volumetric soil moisture

Figure 4.69 shows the average soil moisture volumes over the South-Eastern Kalahari region. Values in the 0,05-0,15 m³ range were recorded in the central region with lower values recorded to the north and west (<0,05 m³) and higher values occurring to the north-east (>0,15 m³).

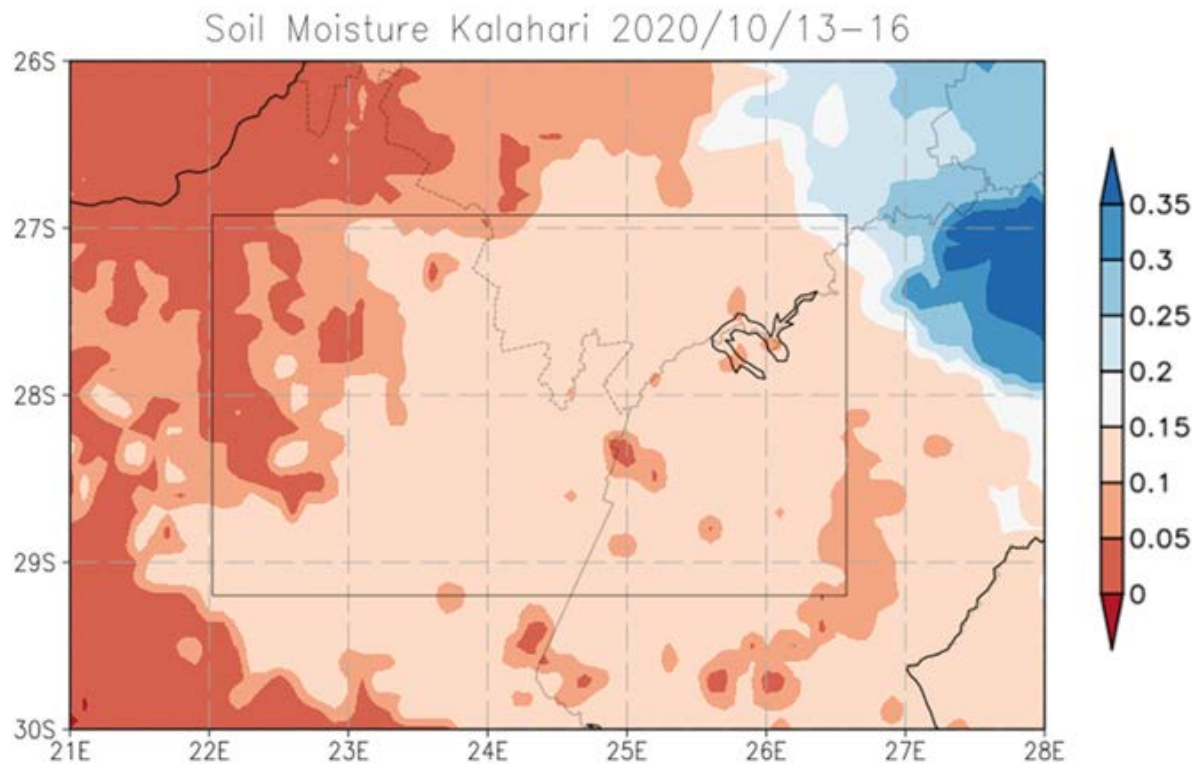


Figure 4.69: Average soil moisture over the SE Kalahari region for 13-16 October 2020

4.7.3 Vegetation indices

Figure 4.70 shows the NDVI values prior to and after the fire in the SE Kalahari region. Prior to the fire, the vegetation had been mostly in an unhealthy condition (<0,33), with isolated spots of moderately healthy vegetation (0,33-0,66) and healthy vegetation (>0,66). After the fire event, very few areas contained vegetation in a moderate-healthy range (>0,33) and unhealthy vegetation occurred (<0,33) over a large area. Within the regions of interest, vegetation in very poor conditions (<0,16) and some mortality of plants (<0) are visible. NBR values prior to and after the fire are depicted in Figure 4.71. Prior to the fire, the region reflected mostly low positive and slightly negative values in the range of -02,522 to 0,3137. After the fire, clear fire scars can be seen in the regions of interest with values below -0,3058 in black and the surrounding environments falling into the -0,3058 to -0,0784 range.

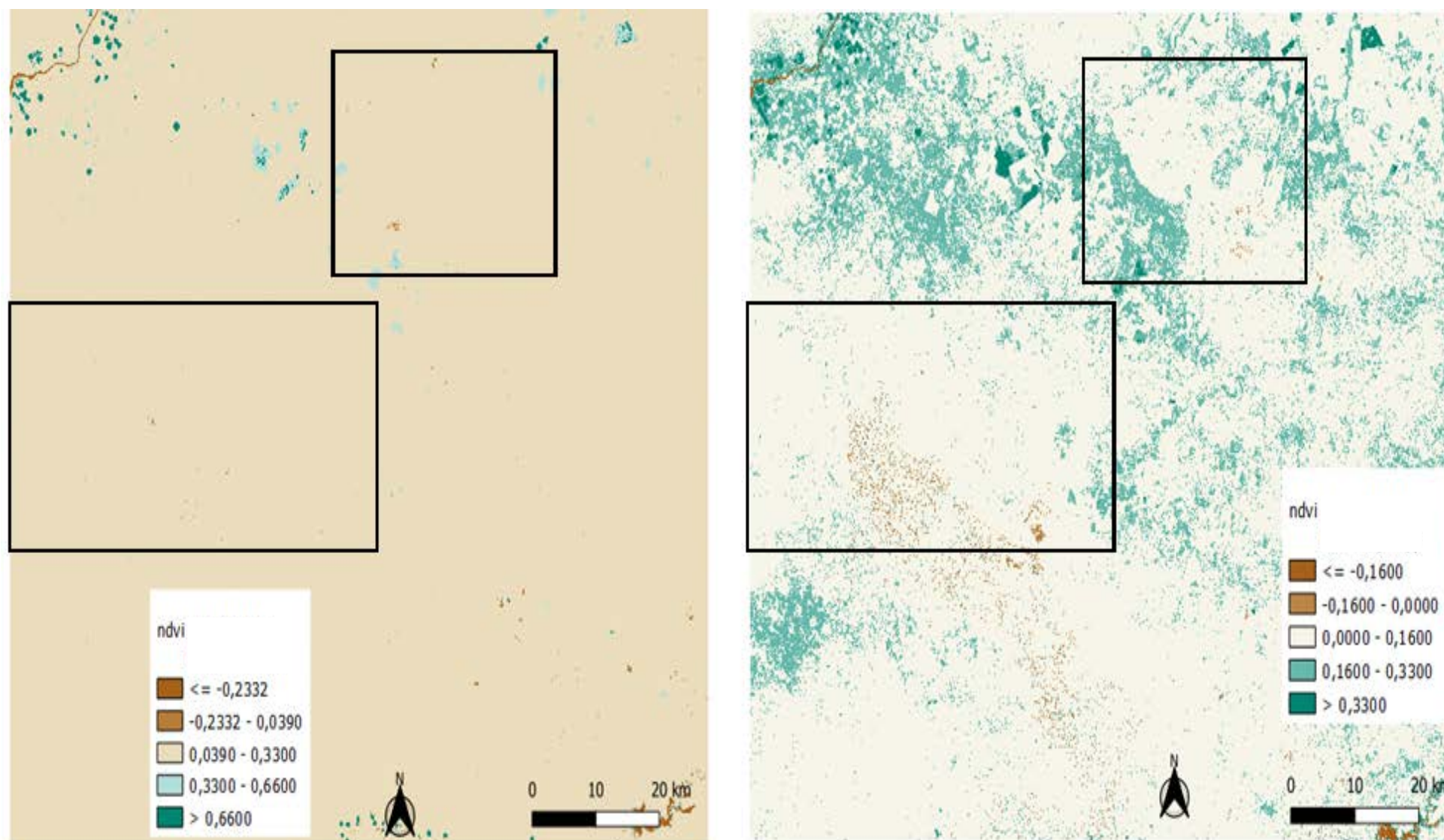


Figure 4.70: NDVI on 16 October vs 26 October 2020

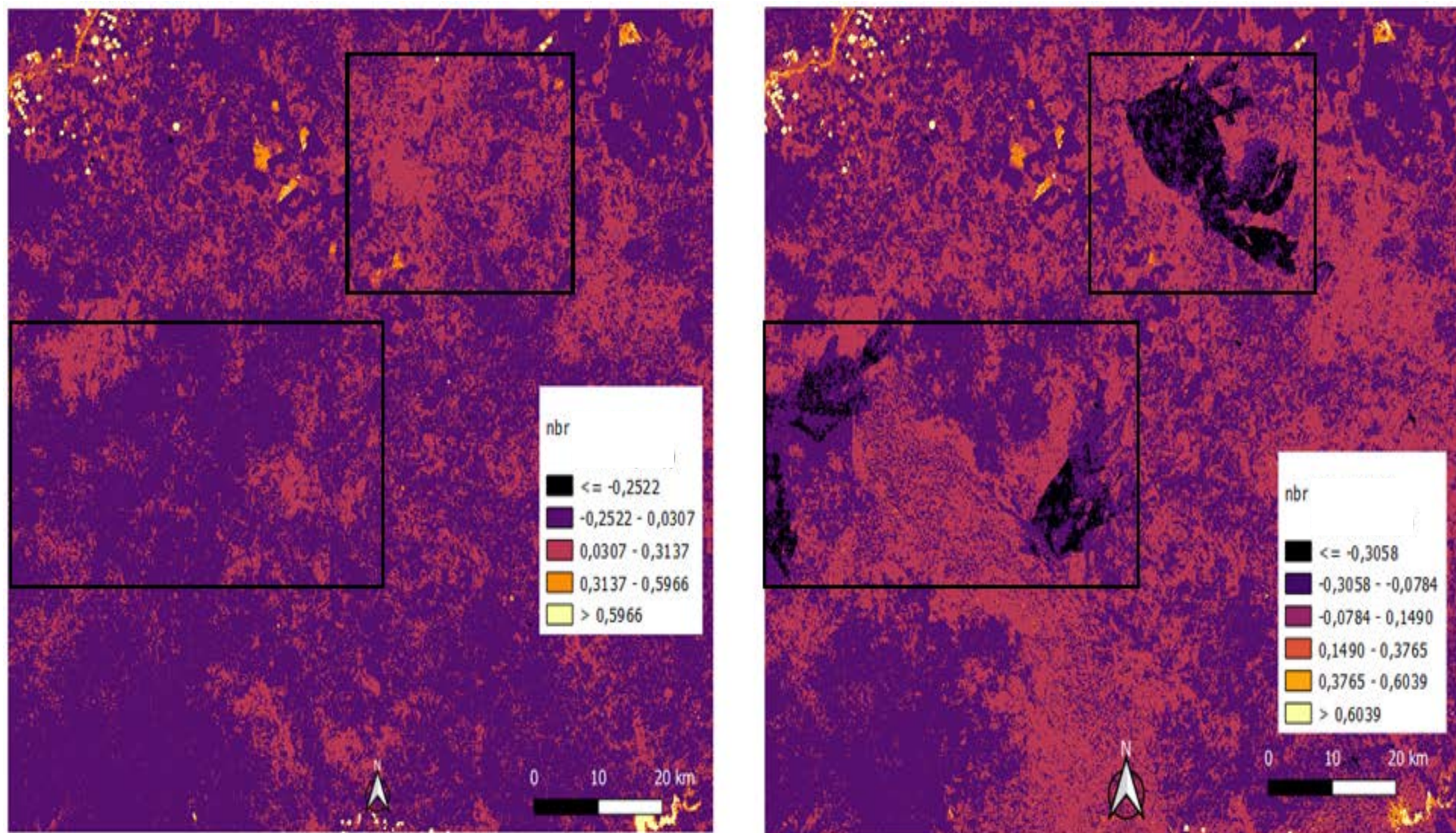


Figure 4.71: NBR on 16 October vs 26 October 2020

Figure 4.72 shows the burnt areas during the SE Kalahari fire of 2020. Three separate areas were burnt in this event.

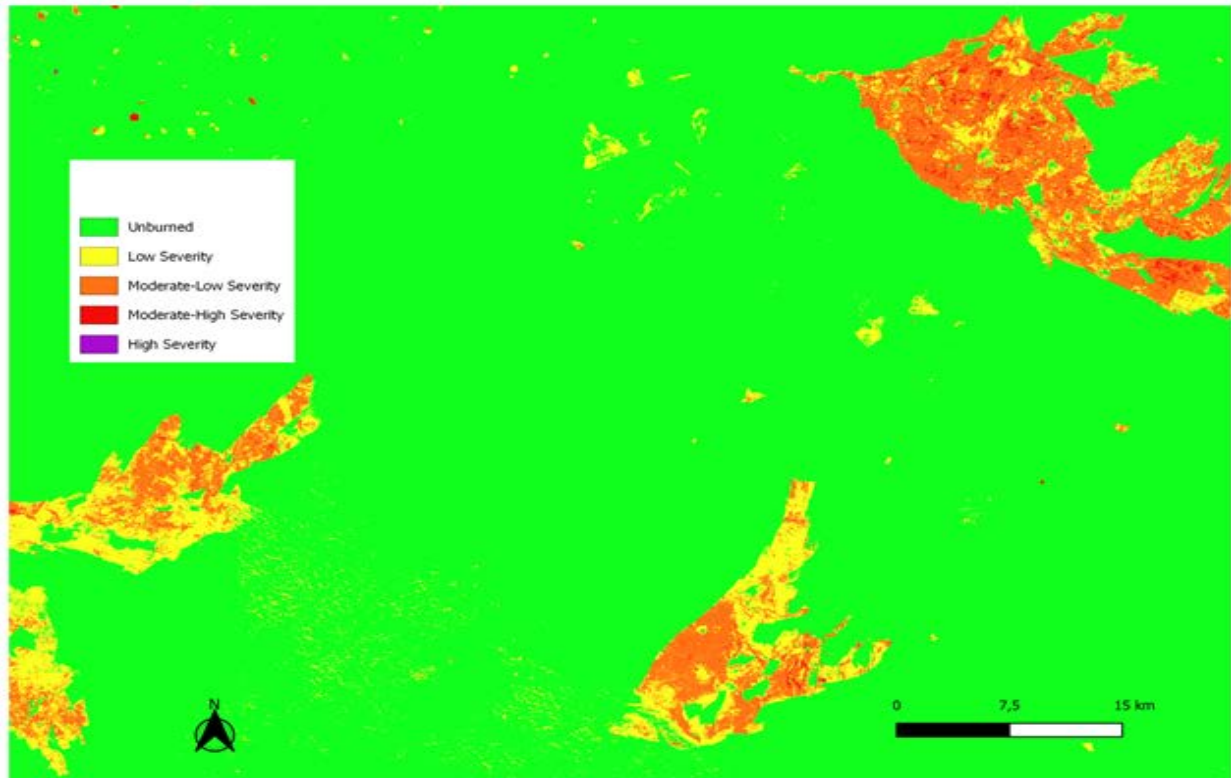


Figure 4.72: Burnt areas over the SE Kalahari in 2020

Table 4.10 shows the breakdown of the burnt area classes for the SE Kalahari fire in 2020. According to this table, a total of 59 655,65 ha of land was burnt during this event. The majority of the burnt areas fell into the low and moderate-low severity classes (31446,30 and 26518,04 ha respectively). Small patches recorded moderate-high severity (1686,89 ha) with a very small area recording high severity (4,42 ha).

Table 4.10: Fire severity of the SE Kalahari fire

Severity	Area (hectares)
Unburned	480 599,50
Low Severity	26 518,04
Moderate-Low Severity	31 446,30
Moderate-High Severity	1 686,89
High Severity	4,42
Burnt areas total	59 655,65

4.8 SYNTHESIS AND SUMMARY

The remotely sensed data revealed trends and seasonality of NDVI and NBR as well as seasonal fluctuations in fire pixel counts across the three points within the study areas. For the Knysna point, a gradual increase in NDVI with dip in mid-2000s was detected, while NBR remained stable with high values recorded by Landsat 7 data. Fire pixel counts remained relatively stable over long-term, with peaks in 2017 and 2018. The highest fire pixel counts were documented across two years: from December 2016 to November 2018. Additionally, fire pixel counts were higher during the austral summer with the most fire pixel counts in October 2018 (15158) and November 2018 (10701). The Cape Town point detected an irregular trend in NDVI and NBR values. High NBR values were detected between the mid-1990s to mid-2000s and after the year 2012. Overall, high fire pixel counts were recorded in the early 2000s and late 2010s. A seasonal pattern of high fire pixel counts was detected with the months of January to March recording the most of these pixel counts. In addition, December 2005 (3989) and March 2015 (3467) were the months with the highest fire pixel counts. A gradual increase in trend NDVI and NBR values with high fluctuation from mid-2000s was detected at the SE Kalahari point. Fire pixel counts increased in recent years, with numbers peaking in 2020 and 2021. Fire pixel counts were the highest during the austral winter and early spring with the highest pixel counts recorded during October 2020 (11638) and June 2021 (8709).

While an irregular trend of NDVI values were detected at the Cape Town point, gradual increases in NDVI and NBR values were detected at both of the other locations as well as in the NBR values in Cape Town. Additionally, a trend of higher fire pixel counts towards the latter part of the 2010s and early 2020s was detected. This trend may be an indication of either an increase in fire activity or the repeated detection of the same pixels after large fire events in a specific region. The remotely sensed data identified the seasonality of fires across the three sites as:

- Knysna: Austral summer
- Cape Town: Austral summer and early autumn
- SE Kalahari: Austral winter and early spring

The seasonal occurrences of fires correspond with the literature on the dry seasons across the Fynbos, Savanna and Grassland Biomes (Cape Town and SE Kalahari), while the fire season for the Forest biome (Knysna) has not yet been documented elsewhere (Mucina *et al.* 2011, Rebelo *et al.* 2011). This might be due to the small frequency of fire events in this biome (Rutherford 2011). The correspondence of the seasonal fires in the Forest biome to the Fynbos fire season might be due to the Forest in the Knysna area being surrounded by Fynbos vegetation, which

tends to be drier during the austral summer. When considering the officially recorded data, December to March (Austral summer and autumn) are identified as the months with the highest fire frequency. This period mostly corresponds with the late dry season over the winter rainfall area in South Africa and within the Fynbos biome. The officially recorded data and remotely sensed data therefore corresponds in terms of seasonality of fire events – with the exception of the SE Kalahari point, which was not included in the official records. Overall, the distinct seasonality recorded by the data used in this study corresponds with the literature with regards to the clear seasonal patterns of fires within Mediterranean (Fynbos) and savanna biomes (Prichard *et al.* 2017).

In terms of Fire Return Interval (FRI), the analysis of official records found that the two largest two fire events consumed more than 50000ha – the 1988 fire in the Cederberg Wilderness Area (58203,287 ha) and the 2018 fire in the Witfontein Nature Reserve (84402.069 ha). The time lapse between these two events was 30 years. It should, however, be pointed out that these two fires occurred in different biomes with the Cederberg Wilderness Area located in the Fynbos biome and the Witfontein Nature Reserve in the Forest biome. Fires recorded in the Citrusdal area (Cederberg Wilderness Area and Matjiesrivier Nature Reserve) showed an irregular time interval: 10 years, 15 years and then 3 years. In the Haweqwa Nature Reserve fires occurred with a 21-year gap between them, while the 7-year and 1-year intervals in large fire events occurred in the Grootwinterhoek Wilderness Area. While irregular FRIs were detected in the official records, the FRIs still correspond with the literature indicating a 2-10 year and 5–50-year FRI in the Fynbos biome (Rebelo *et al.* , 2011).

Earlier in this chapter, it was revealed that the majority (53%) of the largest fire events in the Western Cape occurred in the years following the El Niño phase of ENSO, positive phase of SAM (66%) and below normal seasonal precipitation anomalies (66%). Furthermore, the simultaneous occurrence of these teleconnections and precipitation anomalies were documented for six (40%) of the fire events, with four (27%) of the events took place after La Niña phases of ENSO, negative phases of SAM and below normal seasonal precipitation anomalies as indicated in Table 4.11 below. From this table, a clear pattern emerged between the seasonal climatology and fire events in specific locations. For example, all of the fire events in the Cederberg area occurred after El Niño phases of ENSO, negative phases of SAM, and below normal precipitation anomalies. When considering the six fire events in the Haweqwa and Grootwinterhoek areas, five occurred after positive phases of SAM, three after El Niño phases of ENSO and four after below normal precipitation anomalies.

Table 4.11: Climatological events prior to large fires in the Western Cape

Date of fire ignition	Area burnt (ha)	Location	Preceding ENSO cycle	Preceding SAM phase	Precipitation anomaly
1988/12/28	58203,287	Cederberg Wilderness Area - NE of Citrusdal	El Niño	Negative	Below normal
1990/02/10	31230,015	Haweqwa Nature Reserve - SE of Paarl	La Niña	Positive	No anomaly
1998/03/05	25097,914	Cederberg MCA Southern Cederberg	El Niño	Weak Negative	Below normal
1999/02/25	35330,392	Theewaters Nature Reserve - SE of Franschhoek	La Niña	Positive	Below normal
1999/03/24	26503,559	Jonkershoek Nature Reserve - E of Stellenbosch	La Niña	Positive	Below normal
1999/12/10	25424,957	Boosmansbos Wilderness Area - E of Barrydale	La Niña	Positive	No anomaly
2006/01/30	32260,132	Walker Bay Nature Reserve - N of Gansbaai	El Niño	Strong Negative	Above normal
2009/03/05	32215,875	Grootwinterhoek Wilderness Area - N of Tulbagh	La Niña	Positive	Above normal
2011/03/03	35494,661	Haweqwa MCA SE of Paarl	El Niño	Positive	Below normal
2013/02/16	32088,187	Matjiesrivier Nature Reserve - NE of Citrusdal	Neutral	Weak Positive	No anomaly
2016/01/10	34750,522	Grootwinterhoek Wilderness Area - N of Tulbagh	El Niño	Strong Positive	Below normal
2016/02/24	21911,115	Groot Swartberg Nature Reserve - NE of Oudtshoorn	El Niño	Strong Positive	Below normal
2016/12/15	24138,376	Cederberg Wilderness Area - NE of Citrusdal	El Niño	Negative	Below normal
2017/01/15	25722,941	Grootwinterhoek Wilderness Area - N of Tulbagh	La Niña	Negative	Below normal
2018/10/24	88402,069	Witfontein Nature Reserve N of George	El Niño	Positive	Below normal

Table 4.12 below summarizes, among other findings, the seasonal climatological patterns for the five selected case studies. While there is only one instance of the simultaneous occurrence of El Niño phases of ENSO, positive phases of SAM and below normal seasonal precipitation anomalies (Knysna 2018 fire) in the selected case studies, 60% of the events occurred after these seasonal climatological phenomena occurred. Therefore, fire events in the western parts of southern Africa are most likely to occur in years following El Niño phases of ENSO, positive phases of SAM and below normal seasonal precipitation anomalies. This finding agrees with

studies in Australia and South America (Holz and Veblen 2011, Mariani *et al.* 2018). Furthermore, Burton *et al.* (2020) found that globally fires increased significantly after the strong El Niño phases of ENSO of the years 1997/1998 and 2015/2016. At a regional scale, below normal precipitation conditions brought about by the 1997/1998 El Niño resulted in increased fire events occurring in Mexico, Brazil, and the US state of Florida (Trenberth 2019). In their study of the relationship between fire events and ENSO in Central Mexico, Farfán *et al.* (2021) found that more fires occurred after El Niño phases of ENSO when compared to the neutral and La Niña phases. Fires also increased significantly during and after El Niño phases of ENSO in Indonesia (Edwards *et al.* 2020). However, it is important to note that vegetation types and biomes may respond differently to ENSO. For example, while Trenberth (2019) mentions an increase in fire events in Brazil after strong El Niño phases of ENSO, Barbosa *et al.* (2021) found that La Niña phases of ENSO resulted in more fire activity in the Amazon rainforest region of the country.

With regards to the case studies in South Africa, three of the events occurred during or after the strong 2015/2016 El Niño phase of ENSO. It is also important to note that two of these events occurred in the Forest biome – where fires are not common. In fact, the biggest fire event according to the official records, had occurred in this region in the 2018 fire event. Therefore, one can link the fire activity in the Forest biome to the El Niño phase of ENSO. The case studies focused on fires in Cape Town did not show a clear link to a specific phase of ENSO, however this may be due to the small timeframe of the study. Nevertheless, in both instances there had been above normal precipitation anomalies in the previous wet season. This indicates that for this area – within the Cape Peninsula, wetter than normal conditions can lead to increased vegetation cover and therefore more fire-prone vegetation that can be consumed in the following dry season. Yet these two case studies were based on relatively small fire events in terms of total burnt area and when comparing it to the conditions outlined in Table 4.12, one can see that only two of the largest fire events occurred after above normal precipitation anomalies (Walkerbay 2006 and Grootwinterhoek 2009). This finding may indicate that local topographical factors – for example slope and aspect – could have played a role in these two fire events. Overall, it appears that fires in the Western Cape region tend to occur after El Niño phases of ENSO, positive SAM phases and below normal precipitation anomalies. Thus, the drier than usual conditions in both fire-prone (Fynbos) and fire resistant (Forest) biomes result in the increased susceptibility to fires and flammability of the landscape. The SE Kalahari fire occurred after a La Niña phase of ENSO, a negative SAM phase and above normal precipitation anomaly. This finding indicates that the increased precipitation from the climatological events might have resulted in an increase of grasses and flammable vegetation. An increase in grasses could occur due to the location of this study area within a transition zone between the Savanna, Grassland and Nama-Karoo biomes.

Despite this event occurring after a period of above normal precipitation, one also needs to consider other events in this biome and investigating these events across a larger timeframe within the same region. For example, further north in the savanna biome, Pricope and Binford (2012) recorded a large number of fires occurring in seasons succeeding extremely dry conditions induced by El Niño phases of ENSO.

In terms of synoptic weather conditions, the synoptic weather on the ignition day is crucial in understanding the SWTs associated with fire events in a particular area. A summary of the fire weather conditions is contained in Table 4.12 Below. Strong HP systems were present on the day of ignition across southern Africa for all five of the case studies, and in the 2017 Knysna fire case a strong frontal LP system had also been present. These SWTs brought about not only dry air, but also high maximum temperatures across the selected sites. While local weather stations recorded temperatures between 18-24°C and 30°C for both Cape Town fires, the temperatures exceeded 31°C for the other three fire events. Strong winds were recorded for all the case studies, with wind speeds reaching between 4.5 m/s (16.2 km/h) to 6,9m/s (24,8km/h) either on the day before the ignition or the ignition day. The wind blew from northerly or north-westerly directions for four of the cases, with a southerly wind documented for 2015 fire in Cape Town. Overall, relative humidity values showed a rapid decline prior to or on fire ignition day – with a substantial decrease in values recorded for the 2018 Knysna (decline to 15%) and SE Kalahari (decline to 8%). These results correspond to the finding of Hayasaka *et al.* (2019) linking the presence of HP systems to fire ignition in Alaska. The weather conditions occurring in June 2017 at Knysna – where the temperature rose to 34°C on day before ignition due to the development of bergwind conditions – relates to findings of Rodrigues *et al.* (2020) over Mediterranean Europe. They found a strong relationship between SWTs associated with unusually warm and dry conditions and fire ignitions.

Table 4.12: Fire weather in relation to teleconnections and precipitation anomalies

Case Study	Preceding ENSO cycle	Preceding SAM phase	Precipitation anomaly	Weather (ignition)	Weather (extinction)
Cape Town 2015/01	El Niño	Positive	Above normal	Synoptic weather: Continental LP with ridging South Atlantic HP High maximum temperature over western parts of South Africa Local weather: Temperature: Stable between 18-24°C Wind: Southerly, reaching 4.5 m/s (16.2 km/h) Relative humidity: Declined to 60% Air pressure: Stable between 1010-1013hPa	Synoptic weather: LP through extends over western South Africa Lower maximum temperatures than ignition day over western parts of South Africa Local weather: Temperature: Unstable, reached 31°C maximum Wind: Day prior to extinction southerly winds reaching 5,8m/s (20.9 km/h). Very little wind on day of extinction. Relative humidity: Declined to below 40% Air pressure: Stable between 1010-1013hPa
Cape Town 2021/04	La Niña	Positive	Above normal	Synoptic weather: Strong Ridging HP over SW Indian Ocean Extremely high maximum temperature over western parts of South Africa and Namibia Local weather: Temperature: Exceeds 30°C Wind: Northerly, reaching 5 m/s (18 km/h) Relative humidity: Declined to below 50% Air pressure: Stable between 1003-1008hPa	Synoptic weather: Strong Ridging HP from Atlantic Ocean High maximum temperature over western parts of South Africa and Namibia Local weather: Temperature: Stable, between 18-24°C Wind: South-easterly and south-westerly, reaching 6,1 m/s (22km/h) on day prior to extinction. Relative humidity: Mostly above 50% Air pressure: Stable between 1006-1011hPa

Case Study	Preceding ENSO cycle	Preceding SAM phase	Precipitation anomaly	Weather (ignition)	Weather (extinction)
Knysna 2017/06	El Niño / La Niña	Negative	Below normal	Synoptic weather: Strong HP in Atlantic and Indian Oceans with strong LP (frontal system) south of South Africa Maximum temperatures over South Africa were mostly below 25°C Local weather: Temperature: Rapid increase to maximum of 34°C on day before ignition Wind: North to North-westerly, changing to westerly, reaching 10,8 m/s (21,6 km/h) Relative humidity: Declined to below 40% Air pressure: Fluctuated between 992,5-1007hPa	Synoptic weather: HP over Indian Ocean extending over the continent, LP (frontal system) south of South Africa Maximum temperatures over southern Cape coast and east coast were mostly above 21°C Local weather: Temperature: Fairly stable, reaching maximum of 22,8°C on day of extinction. Wind: Short period of south-westerly winds, reaching 1,5 m/s (5,4km/h) on day of extinction. Relative humidity: Mostly above 60%, brief dip to below 40% on day prior to extinction and extinction day Air pressure: Decreased from 1020hPa on day prior to extinction to 1002,3hPa on day of extinction

Case Study	Preceding ENSO cycle	Preceding SAM phase	Precipitation anomaly	Weather (ignition)	Weather (extinction)
Knysna 2018/10/24	El Niño	Positive	Below normal	Synoptic weather: Strong HP over southern Africa High maximum temperatures (>31°C) over South African and Namibian west-coasts as well as Garden Route of South Africa Local weather: Temperature: Rapid increase to maximum of 38,7°C on day before ignition Wind: North-westerly, reaching 5 m/s (18 km/h) on the day prior to ignition, with south to south-easterlies, reaching 2,5m/s (9km/h) Relative humidity: Rapid decline to 15% on day prior to ignition, values were mostly above 30% on day of ignition Air pressure: Fluctuated between 1009-1014hPa	Synoptic weather: LP system extending over the continent, strong HP over Atlantic Ocean Cooler maximum temperatures over Western Cape Local weather: Temperature: Above 15°C on day prior to extinction, declined on day of extinction to 7,8°C. Wind: Westerly winds, reaching 4,7 m/s (16,9km/h) on day of extinction. Relative humidity: Fluctuated between 35-77% on day prior to extinction and remained above 80% on extinction day Air pressure: Increased from 995hPa on day prior to extinction to 1011,9hPa on day of extinction Rainfall: 15mm of rain were recorded on the day of extinction

Case Study	Preceding ENSO cycle	Preceding SAM phase	Precipitation anomaly	Weather (ignition)	Weather (extinction)
SE Kalahari 2020/10	La Niña	Negative	Above normal	Synoptic weather: HP over southern Africa High maximum temperatures (>32°C) over interior plateau Local weather: Temperature: Maximum of 39°C on day of ignition Wind: North-easterly to westerly, reaching 7,7 m/s (27,7 km/h) on the day prior to ignition, with northerly to westerly winds on ignition day, reaching 6,9m/s (24,8km/h) Relative humidity: Rapid decline to 8% on day prior to ignition, values were mostly below 30% on day of ignition Air pressure: Slight fluctuation between 882-887hPa	Synoptic weather: Slightly weaker HP system over the area, with LP from Angola extending southward across Namibia and western parts of South Africa High maximum temperatures (>35°C) over western parts of interior plateau Local weather: Temperature: High maximum temperature of 38,6°C on extinction day. Wind: Northerly winds, reaching 7,2 and 9,4 m/s (25,9 and 33,8km/h) on day prior to extinction and day of extinction. Relative humidity: Slight fluctuation, however mostly below 40% Air pressure: Slight fluctuation between 883-887hPa

In terms of fire extinction, all the fire events, with the exception of the 2021 Cape Town fire, were affected by the presence of a LP system over the region. A strong ridging HP system from the Atlantic Ocean occurred on the extinction day of the 2021 Cape Town fire. While the HP system brought about stronger winds (6,1 m/s or 22 km/h) than on ignition day (5 m/s or 18 km/h) – the mostly southerly winds may have brought in more moisture over the region as the relative humidity values were higher (above 50%) than the day of ignition (below 50%). Additionally, the temperature values were markedly lower on extinction day (18-24°C) than ignition day (>30°C).

On extinction day of the 2017 Knysna fire a LP (frontal) system occurred together with a HP from the Indian Ocean that extended over the continent. The combination of these systems brought about lower temperatures on extinction day (maximum of 22,8°C) than the day before ignition (34°C) along with decreased wind speeds and changes in wind direction. On ignition day, north to north-westerly and westerly winds reached 10,8 m/s (21,6 km/h) whereas south-westerly winds reached 1,5 m/s (5,4 km/h) on extinction day. The change in wind speed and direction also resulted in the relative humidity values being higher on extinction day (mostly above 60%) than on ignition day (below 40%).

A distinct difference between the regional and local weather occurred between the ignition and extinction days of the 2018 Knysna fire. The strong HP system across southern Africa, which brought high maximum temperatures over coastal regions of Namibia and South Africa on ignition day, was replaced with the simultaneous occurrence of an extended LP system (extending from the tropics into the ocean) and a strong HP system in the Atlantic Ocean on extinction day. In terms of temperature, a rapid increase to maximum of 38,7°C on day before ignition was recorded, while a temperature of above 15°C recorded on day prior to extinction, declined on day of extinction to 7,8°C. While north-westerly winds, reaching 5 m/s (18 km/h) on the day prior to ignition was recorded, the wind direction changed to westerly on the day of extinction and the wind speed reached 4,7 m/s (16,9 km/h). Evidently, the SWTs on extinction day brought more moisture over the study area. Not only did the relative humidity values increase substantially (decline to 15% recorded on day prior to ignition with above 80% recorded on day of extinction) but the local weather station recorded rainfall totalling 15mm on the extinction day.

The three cases discussed above, show a correlation to the literature in terms of fire extinction occurring once the overall weather conditions conducive of fire ignition and spread, changes (San-Miguel-Ayanz *et al.* 2013). Additionally, the hot and dry air descending from HP systems have also been linked to fire ignition days in Portugal (Ferreira-Leite *et al.* 2017). Paschalidou and Kassomenos (2020) also found a link between HP SWTs and fire ignition in Greece.

Interestingly, the 2015 Cape Town and SE Kalahari cases recorded almost the similar weather conditions prior to or on ignition and extinction days.

A ridging HP from the Atlantic Ocean along with a continental LP system occurred on the ignition day of the 2015 Cape Town fire. These SWTs were replaced with a continental LP system, which extended over the western parts of South Africa on the day of extinction. Even though the SWTs on ignition day brought higher maximum temperatures across the region than the one on extinction day, the local weather station recorded higher temperatures on extinction day (31°C maximum) than on ignition day (24°C). In addition, stronger southerly winds swept across the area on the day before extinction (reaching 5,8 m/s or 20.9 km/h) than on ignition day (reaching 4.5 m/s or 16.2 km/h). Moreover, lower relative humidity values were recorded on the extinction day (below 40%) than on ignition day (below 60%).

Both the ignition and extinction days of the SE Kalahari fire experienced the presence of a HP system across the region. Despite a slightly weaker HP system together with a LP from Angola extending southward across Namibia and western parts of South Africa on extinction day, higher maximum temperatures were (>35°C) over western parts of interior plateau than on ignition day (>32°C). The Kimberley weather station recorded similar maximum temperatures on both ignition (39°C) and extinction days (38,6°C). Moreover, strong winds were also detected - northerly to westerly winds reaching between 7,7 m/s (27,7 km/h) on the day prior to ignition and reaching 6,9 m/s (24,8 km/h) on ignition day. The day prior to extinction and day of extinction received northerly winds reaching speeds of 7,2 and 9,4 m/s (25,9 and 33,8 km/h). However, a slight difference occurred in terms of moisture moving across the area with relative humidity values being higher on extinction day (mostly below 40%) than ignition day and the day prior to ignition (decline to 8% on day prior to ignition, values were mostly below 30% on day of ignition).

The anomalous occurrence of dry, warm conditions with strong winds occurring close to and on the extinction days of the 2015 Cape Town and SE Kalahari fires may indicate that human efforts to extinguish the fires were successful in contrast to the argument of San-Miguel-Ayanz *et al.* (2013). They contend that fires in Greece, Spain and Portugal were only contained once the fire danger conditions diminished (San-Miguel-Ayanz *et al.* 2013).

Table 4.13 below presents the comparison of vegetation characteristics of each case study. Soil moisture volumes were mostly low prior to fire ignition, with the exception of the 2018 Knysna fire where soil moisture volumes were slightly higher (0,2-0,3 m³). The SE Kalahari fire had the lowest soil moisture value (0,05-0,15 m³) prior to fire ignition. Vegetation was determined to be moderately healthy (values between 0,33-0,66) prior to the Knysna fires and the 2021 Cape Town

fire. In contrast, vegetation was under stress (values below 0,33) prior to the 2015 Cape Town and SE Kalahari fires. The 2021 Cape Town and 2018 Knysna fire events recorded high burn severity, with the latter also classified as the largest fire in terms of burnt area (100714, 22 ha). A moderate-low burn severity was documented for the 2015 Cape Town fire, while the 2017 Knysna and SE Kalahari fires were classified as low severity fires. The low severity fires consumed more hectares than the two Cape Town fires.

Table 4.13: Vegetation characteristics of fire events

Case Study	Soil moisture (pre-fire)	Vegetation health (NDVI pre-fire)	Burnt area (ha)	Burn Severity
Cape Town 2015/01	Low (0,15-0,2 m ³)	Under stress (values below 0,33)	5114, 25	Moderate-Low
Cape Town 2021/04	Low (0,15-0,2 m ³)	Moderately healthy (values between 0,33-0,66)	4822	High
Knysna 2017/06	Low (0,1-0,2 m ³)	Moderately healthy (values between 0,33-0,66)	34563, 36	Low
Knysna 2018/10/24	Moderate-low (0,2-0,3 m ³)	Moderately healthy (values between 0,33-0,66)	100714, 22	High
SE Kalahari 2020/10	Very low (0,05-0,15 m ³)	Under stress (values below 0,33)	59655, 65	Low

This thesis contributes to the body of knowledge in the discipline of geography by highlighting the interconnected factors that contribute to fire events, including their occurrence over various spatial and temporal scales. The literature review chapter provides a new, geographical, perspective to understand and study fire events. Additionally, the climatological and biogeographical aspects of fire events along the southwestern parts of southern Africa evaluated in this study showed distinct patterns and variability of fires across this region. While previous work on fires in South Africa has emphasized – and sometimes overemphasized – the role of vegetation with regards to fire events, this work has shown the crucial role that climate and weather play in fire occurrence. Understanding the climatic and meteorological factors involved in fire events can improve disaster risk management and mitigation of impacts from fire events.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

Fires are multifaceted phenomena, with equally multifaceted causes and consequences. While attention is drawn to fires mostly by the events that lead to economic and social impacts on humans – including the loss of lives and livelihoods – it is important to examine both natural and anthropogenic influences on fires. The research aim of this thesis was to establish the fire regime characteristics for the biomes in southwestern Africa. This chapter provides the synthesis of the findings of the thesis as well as recommendations for future research, management, and policy frameworks.

5.2 SYNOPTIC WEATHER TYPES

SWTs associated with fire ignition for all five case studies were identified as strong HP systems. These systems included the South Atlantic HP, continental HP and South Atlantic HP. In addition, a strong offshore frontal LP system had also been present for the 2017 Knysna fire. These SWTs brought about not only dry air, but also high maximum temperatures across the selected sites. It should also be noted that the 2017 Knysna fire experienced berg-wind conditions – i.e. the descent and adiabatic movement of air from the interior plateau to the coast, leading to unusually high temperatures. These conditions occurred due to the simultaneous occurrence of a HP over the continent and LP system close to the coast. Due to its location in the subtropics, it is no surprise that HP systems played a significant role in fire ignitions across South Africa. HP systems were also linked to fire events elsewhere in the world. The extinction of fire events is theoretically linked to a lowering of fire danger conditions – i.e., lower temperatures, an increase in relative humidity (moist air), weak or no winds and no subsiding dry air. Interestingly, four of the five case studies reflected this change in terms of SWTs. Fire extinctions of these four case studies were affected by the presence of a LP system over the region. These systems include continental LPs and frontal LPs. For the 2021 Cape Town fire a strong ridging HP system from the Atlantic Ocean occurred on the day of extinction. It is, however, imperative to also consider the local fire weather conditions at each site as topographical features and local winds can play a significant role in both the fire propagation and extinction.

5.3 MAIN DRIVERS OF FIRE

The main drivers of fire in the study area were linked to teleconnections, seasonal precipitation anomalies, SWTs discussed in the previous paragraph, local weather conditions, soil moisture and vegetation health conditions.

In the Western Cape, more than half of the largest fire events occurred in the years following the El Niño phase of ENSO, positive phase of SAM (66%) and below normal seasonal precipitation anomalies (66%). Additionally, these climatological phenomena acted in concert for six (40%) of the fire events. In contrast, only 27% of the large fire events occurred after La Niña phases of ENSO, negative phases of SAM and below normal seasonal precipitation anomalies. With regards to the five selected case studies, a majority (60%) of the fires occurred in seasons following El Niño phases of ENSO, positive phases of SAM and below normal seasonal precipitation anomalies. Interestingly, the largest fire in the study area – the 2018 Knysna fire – occurred in a season after all three of these climatological phenomena occurred simultaneously.

From the five case studies examined, local weather parameters influencing fire events were identified as temperature, wind speed, wind direction and relative humidity. Although air pressure values were also extracted, no clear indication came as to whether it played a significant role in these events. Fire ignition days of all five case studies recorded high temperatures, strong north to north-westerly winds (except for one instance of southerly winds) and rapidly declining relative humidity values (dry air). In three of the cases temperature values decreased and southerly to westerly winds (moving slower than previously) brought higher relative humidity over the area on extinction day. In one case, rainfall had been recorded. However, two of the case studies experienced similar local weather on ignition and extinction day. This finding may indicate that human efforts to contain the fires were successful in overcoming the weather conditions conducive of fire propagation.

5.4 SPATIAL VARIABILITY AND TEMPORAL DYNAMICS ACROSS BIOMES

Fires varied across the biomes in the western part of southern Africa. This is not only due to the different rainfall zones, but also due to differences in vegetation composition and topography. Two (Cape Town and Knysna) of the case study areas lie below the Great Escarpment, while the SE Kalahari is located on the central plateau. From the data the differences in the climate and vegetation structure becomes clear. Remotely sensed data for a point located in the Cape Town study area recorded an irregular trend of NDVI values over a large timeframe. Gradual increases in NDVI and NBR values were detected at both of the other locations (Knysna and SE Kalahari)

as well as in the NBR values in Cape Town. The seasonality of fire events were determined to be:

- Knysna: Austral summer
- Cape Town: Austral summer and early autumn
- SE Kalahari: Austral winter and early spring

Historically records confirmed the seasonality of fires across the Western Cape and overall seasonality of fire events included in this study corresponds to the existing literature. In terms of Fire Return Interval (FRI), a timelapse of 30 years occurred between the two largest fires in the Western Cape, according to the official records. When the official records were broken down into specific localities, an irregular FRI emerged with the Citrusdal area documenting 10, 15 and 3 year gaps. In the Grootwinterhoek Wilderness Area, 7 and 10 year timelapses were recorded in between large fires with a 21-year gap recorded between the large fires in the Haweqwa Nature Reserve. These FRIs were found to correspond to the recorded 2-10 year and 5-50 year FRI of the Fynbos biome.

Soil moisture volumes were mostly low prior to fire ignition, The SE Kalahari fire had the lowest soil moisture value prior to fire ignition. Vegetation was determined to be moderately healthy (prior to the Knysna fires and the 2021 Cape Town fire. In contrast, vegetation was under prior to the 2015 Cape Town and SE Kalahari fires. The 2021 Cape Town and 2018 Knysna fire events recorded high burn severity. Overall, the 2018 fire in Knysna recorded the largest burnt area as well as the highest burn severity. This may be due to the confluence of the preceding climatic phenomena and to the fact that crown fires (typically in a forested area) may have contributed to the propagation and severity of the fire.

5.5 FIRE REGIME FRAMEWORK

Even though this work did not set about to development of conceptual framework to evaluate and understand fire regimes, a framework was developed, presented and discussed in the Literature Review Chapter of this thesis. The framework sought to incorporate factors which had been underplayed by the literature.

5.6 RECOMMENDATIONS

From the results, it is evident that the fire history of the Fynbos biome is better documented than the histories of other biomes in the western part of southern Africa. This may be due, in part, to the vegetation structure and composition. However, the savannas and grassland biomes also

contain flammable materials and therefore needs further examination. In the section below, a number of recommendations are presented.

5.6.1 Future Research

With the changing climate, and specifically, the projected warming for the western parts of southern Africa, research into future temperature rises and shifts in rainfall patterns are required. These shifts not only relate to localized events – where rainfall events may become less frequent – but also in terms of the broader regional climatology. For example, as researchers detect a more positive polarity of SAM phases, models can provide insights into how this can affect precipitation – especially for the winter rainfall region. A southward shift in the LPs associated with rainfall over this region may not only lead to an increase in the flammability of vegetation but might also play a role in the extinction of future fire events. If the influence of HPs over southern Africa is amplified by positive SAM phases, this can possibly lead to a prolonging of fire danger conditions along the western and southern coasts.

While this work has emphasized the role of climatological factors in fire regimes, future work should incorporate topographical variables such as slope, aspect, and mountain ranges along with the role of fluvial systems on fire propagation. Additionally, models tracking and assessing fire progression may be useful in the form of a digital elevation model (DEM).

The human dimension of fire regimes is relatively poorly understood in the context of fires in the biomes excluding the savannas. There is a need to incorporate the human aspects with the physical aspects of the fire events, especially in fire-prone areas such as the Fynbos biome. These human aspects are not only limited to prescribed burning, LULCC and the WUI, but also to the distance of roads to large fire events and the possible ignitions of fires during school holiday periods.

The increasing capability of cloud computing systems in processing and analysing data related to fire events should further be harnessed and explored in future studies. These tools have potential to incorporate the factors described in the above paragraphs and to reduce the timely pre-processing and downloading of remotely sensed products.

5.6.2 Fire Management and Disaster Risk Reduction

The main aim of fire management is to mitigate the impacts of fire events on humans and their livelihoods. In South Africa, regulations to manage fire events exist in the form of various laws. These laws have specific emphasis on prescribed burning through firebreaks (National Veld and

Forest Fire Act 101 of 1998) and the extinguishing of fires (the Disaster Management Act 57 of 2002 and the Municipal Structures Act 117 of 1998) (South Africa 1998a; South Africa 1998b; South Africa 2002). At a national level, the Department of Forestry, Fisheries and the Environment launched and manages the Working on Fire programme. This programme not only seeks to reduce the number of IAS – which are highly flammable in the Western Cape, in particular – but also to provide resources to respond to large fires across the country. This initiative attempts to try to establish an integrated fire management approach to address fire occurrence and impacts. While these laws and initiatives are important to reduce disaster risk, they do not clearly address the implications of LULCC, the long-term natural fire regimes and how it has been altered by humans, or the impact of climate change on both the water availability as well as the vegetation in fire-prone areas. Moreover, the penalty for committing arson – fines of up to ZAR 100000 – is not effective in reducing human-caused fire ignitions. This might be attributable to difficulties in proving the malicious damage to property in court (Hector 2019). Therefore, landowners and the broader public should be vigilant on high fire danger days to alert authorities to ignitions and minimize the flammability of the landscape by limiting fuel continuity (removing dead organic materials) and assisting with the removal of IAS. Policy-makers should also reconsider the location of commercial forestry activities in fire-prone areas as these activities are almost exclusively using IAS, which increases the flammability of the landscape.

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