GEF FYNBOSFIRE PROJECT

INFORMATION MANAGEMENT, FIRE RESEARCH & MODELLING AND FIRE RISK ASSESSMENT COMPONENT

Fynbos Fire Regimes, Fire Weather and Climate Change

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EXECUTIVE SUMMARY

The CSIR was contracted by the Forest Fire Association (Non-profit Company) to undertake a project entitled "information management, fire research and modelling, and fire risk assessment".

The CSIR work contributes to four specific outputs: (1) the collation and management of key fire management information; (2) improving wildland fire behaviour modelling and fire danger forecasting; (3) Assessing climate change and wildfire risk at a landscape scale in the Greater Cedarberg and Southern Cape Fire Protection associations (FPAs); and (4) Assessing risks to communities at the wildland-urban interface in the Gordon's Bay and Plettenberg Bay municipal areas.

We have finalised the requirements regarding information needed to support fire management. These data requirements can be broadly classified into (1) information needed on a daily basis during the fire season; (2) information required for planning purposes prior to a fire season including medium term fire related climate forecasts (6 months to a year in advance) similar to agricultural forecasts but customised for fire; and (3) baseline information. The analysis has demonstrated that such predictions are feasible and an application could be developed to provide this information through the Advanced Fire Information System (AFIS). The South African Weather Service would have to be consulted because we understand that they have the legal mandate to produce weather-related risk forecasts.

We have developed a model to map fire hazard at a landscape scale, which has been discussed with the Cedarberg and Southern Cape FPAs. The model uses vegetation types from the area which were then matched with a set of fuel-models to predict the post-fire age at which the predicted flame length would exceed 2 m, the threshold for a manageable fire. This fuel hazard information can be combined with data on the density of invasions by alien plants as a surrogate measure of fire hazard. The ideal would be to develop a system of tracking the vegetation age which could then be used to map and show the changes in fuel hazard. More refined fuel models, including ones for alien plant stands, would enable the managers to generate fire hazard maps for use in their annual planning and response strategies. The data and insights produced by this study were also incorporated into the analysis of risks in the wildland-urban interface (output 4) which is covered in a separate report.

We have identified a set of typical synoptic conditions that would be associated with large wildfires, based on historic data. The ability to predict this understanding can be incorporated into the AFIS system, so that fire managers can interpret weather forecasts in terms of whether or not they would be likely to include conditions that would lead to large fires. This would have to be done in consultation with the South African Weather Service because we understand that they have the legal mandate to produce weather-related risk forecasts.

We identified five real-time fire behaviour prediction models that are in a fairly advanced stage of development: Phoenix; FIRESCAPE; FARSITE; Prometheus; and Australis. Of these, three (Phoenix in Australia, FARSITE in the United States, and Prometheus in Canada) are in operational use. We have held discussions with Dr George Milne who works on the Australis model and he and his co-workers would be prepared to run their model if the necessary data (e.g. fuels, terrain, weather) can be provided. This is not as simple as it sounds because a key requirement is detailed and accurate fuel models and the models they can offer for the similar vegetation in Western Australia do not match the fynbos fuel characteristics well. We do not believe that simulation models like these would be suitable tools for real-time fire management but we do believe they could be used as teaching tools for people being trained as fire managers.

Projections of global climate change were down-scaled to the level of the fynbos biome, achieving a high level of spatial resolution for a global model (±50 km x 50 km). The results suggest the burning season will become longer over the Greater Cedarberg region, but with a significant reduction in risk during the late summer. For the Cape south coast region, increases in the number of days of high fire danger (0.5 to 3 days per month) are projected to occur, consistently across all seasons. These changes would be attributed to increases in temperature and decreases in rainfall that are projected for the region.

The Wildland-Urban Interface study has been presented in a separate report.

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1. BACKGROUND AND BRIEF

The CSIR was contracted by the Forest Fire Association (Non-profit Company) to undertake a project entitled "information management, fire research and modelling, and fire risk assessment". This project is a component of the GEF-funded Fynbos Fire Project, a three-year project to implement integrated fire management programmes in the Fynbos biome. The goal of the GEF project is to reduce the risk to life, the economy and the environment caused by unwanted wildland fires associated with climate change.

Our terms of reference are to contribute to specified outputs of the larger GEF project, namely:

- **Output 2.1** – Key fire management information collated and managed. Under this task, we will establish data requirements and gaps in current data available (this will be based on the results of existing surveys of needs, supplemented by additional interviews where necessary); identify sources that can supply the needed data; design formatting protocols that will allow for the data to be integrated into AFIS management support systems; develop metadata that will be useful to end-users, and that complies with recognised national standards; curate data for the duration of this agreement; propose a suitable organization that could act as ongoing custodian of the data after the finalization of this agreement, and draft a data sharing agreement; and prepare a report that summarises the outcomes of the work listed under Output 2.1 above.

- **Output 2.4** – Wildland fire behaviour modelling and fire danger forecasting. Under this task, we will obtain a list of large wildfires that occurred in the fynbos biome after 1978, and establish the synoptic weather conditions that characterise such fires; use these identified synoptic patterns, together with observed and predicted changes in the daily weather and seasonal climate, to develop scenarios of large wildfire occurrence in the short-term future; review available fire behaviour prediction models, and illustrate how these could be combined with information on fire weather, fuel distribution (based on vegetation types and post-fire age) and topography to produce spatially-explicit estimates of future fire risk; review available risk and decision support systems and propose ways in which to incorporate new understanding into these systems; and prepare a report that summarises the outcomes of the work listed under Output 2.4 above.

- **Output 2.5** – Climate change and wildfire risk at a landscape scale. Under this task, we will assess observed and simulated climate trends in terms of how they would affect weather in two broad areas (the Cedarberg and Southern Cape FPAs), and project changes in the frequency of occurrence of weather conducive to fires; use existing information, supplemented where necessary by additional information at an appropriate scale, to map current land use, infrastructure and settlements in the Cedarberg and Southern Cape FPAs; model fuel loads based on vegetation types and post-fire age in the Cedarberg and Southern Cape FPAs, and use this in conjunction with historical fire occurrence, and projected climate change to spatially depict fire risks; develop an interface that will allow risks to be viewed on desktop AFIS terminals; and prepare a report that summarises the outcomes of the work listed under Output 2.5 above, and that includes standardised procedures for estimating the risks associated with wildfires at a landscape level.

- **Output 2.6** – Risks to communities at the wildland-urban interface. Under this task, we will define the features of the wildland-urban interface in the Gordon's Bay and Plettenberg Bay municipal areas, based on information already collected during FireWise workshops with these communities, supplemented by additional information gathered during at least one additional FireWise workshop; characterise the populations and assets at risk from veldfires; develop a template for assessing risks and developing community wildfire plans; and prepare a report that summarises the outcomes of the work listed under Output 2.4 above.

2. INTRODUCTION

There is growing consensus that the global climate is changing and that human activities are responsible for a substantial component of this change. One of the key features of this change is a general increase in global temperatures, particularly during the second half of the 20th century, and continuing into the 21st century (IPCC 2013) and an increase in the variability of climates and the impacts of climate-related extremes such as floods (IPCC 2012, 2013, 2014). South Africa is no exception to this (Mason and Jury 1997, Rouault and Richard 2003, Jury and Mpeta 2005, DEA 2011, Philippon et al. 2012, Malherbe et al. 2014): (a) observed surface air temperatures over land have increased significantly since 1950, sometimes in excess of the mean global temperature rise; and (b) there has been high inter-annual, decadal, and multi-decadal variability in the climate closely linked to global weather phenomena (such as the El Niño). Rainfall trends have been more mixed with some decreases in the summer rainfall region and some increases in the winter rainfall region, with local scale variability complicated by topographic complexity (e.g. orographic and rain shadow effects) and inter- and intra-annual variability (New et al. 2006, Kruger 2006, DEA 2011, MacKellar et al. 2014). If there is a moderate to high rate of increase in greenhouse gas concentrations (IPCC 2000 A2 scenario), then by 2050 the coastal areas are likely to have warmed by around 1-2°C and the interior by around 2-3°C. If there is little mitigation (IPCC 2000 A2 family), the mean temperatures will increase by 3-4°C along the coast and 6-7°C in the interior (DEA 2011). Rainfall is likely to decrease in the western parts of the country, particularly the western coastal regions (Hewitson and Crane 2006). These changes are expected to have significant impacts on natural ecosystems, agricultural production and socio-economic systems (Jury 2002, Midgley et al. 2005, Holmgren and Öberg 2006, Blignaut et al. 2009, DEA 2011, Midgley and Thuiller 2011, Wintle et al. 2011, West et al. 2012, Huntley and Barnard 2012, Botts et al. 2013, Mead et al. 2013, Dallas and Rivers-Moore 2014, MacKellar et al. 2014).

The Fynbos Biome, which covers an area of about 56,200 km^2, extends from the western part Western Cape Province to the far western part of the Eastern Cape Province and has some outliers on mountain ranges in Namaqualand (Rebelo et al. 2006). It is situated in the part of South Africa which has been identified as particularly vulnerable to climate change, particularly because the temperate weather systems that bring the winter rainfall are projected to shift southwards, decreasing the winter rainfall (Midgley et al. 2005, DEA 2011, Philippon et al. 2012). This shift is also likely to increase the variability of the rainfall and decrease its predictability with potentially significant ecological impacts (Cowling et al. 2005). The shrubland vegetation of the Fynbos biome is fire dependant and requires fires to regenerate plant species and to maintain its high biodiversity (Kruger and Bigalke 1984, van Wilgen and Scholes 1997, Le Maitre et al. 2014b). Unlike moist grassland and savannah vegetation types where grasses provide the fuels and can produce enough fuel for fires in a single season, fuel accumulation in fynbos depends on the production of and accumulation of standing dead material and litter (Van Wilgen 1984a). Once sufficient fuel has accumulated, then the main driving factors for fires become sources of ignition and climatic conditions, particularly dry spell durations, relative humidity of the air, air temperature and wind speed (Van Wilgen 1982, 1984b, Van Wilgen et al. 2010).

These projected changes in climate will affect the likelihood of fires through: (a) decreased intensity of rainfall and moisture in the dry summer period; (b) increased air temperatures will evaporation rates and dry out fuels (but see Hoffman et al. 2011a, 2011b) who found decreasing wind speeds were leading to reduced evaporation); and (c) there may be an increased likelihood of lightning storms. One issue that could affect fire regimes is an increase in biomass, and thus fuel, production because increases in CO_2 concentrations increase plant water-use efficiency (Bond et al. 2003, Midgley et al. 2003, 2004). In combination, these drivers will have a significant influence on the number of days where the risks of a fire are high (Midgley et al. 2005). A key threat to fynbos is the ongoing invasion by a number of species which increase the fuel load (van Wilgen and Richardson 1985) and thus the fire hazard and fire risk, and may alter hydrological responses (Le Maitre et al. 2014a). These factors were an important consideration in identifying the Fynbos biome as the most vulnerable region in the country with respect to disaster risks from wildland fire due to patterns of urbanisation, agriculture and potential impacts upon water catchment areas of changes in fire regimes and alien plant invasions (DEAT 2003). They were also important in motivating for the GEF funded project on fire which commissioned the studies summarised in this report. The following sections present the findings of these studies.

3. OUTPUT 2.1 (KEY FIRE MANAGEMENT INFORMATION COLLATED AND MANAGED)

3.1 Data requirements

After consulting with a number of Fire Protection Associations (FPAs) including the Greater Cedarberg, Cape Peninsula and Southern Cape FPAs we have finalised the requirements regarding information needed to support fire management. These data requirements can be broadly classified into (1) information needed on a daily basis during the fire season; (2) information required for planning purposes prior to a fire season including medium term fire related climate forecasts (6 months to a year in advance) similar to agricultural forecasts but customised for fire; and (3) baseline information. These data are listed in Table 1 and the intention is to have these available (displayed) on the computers (AFIS terminals) of each FPA.

Much of the information is available in the public domain but in many cases there are conditions to its use such as the acknowledgement of its source. More detailed information such as the location of water points, the suitability of roads for vehicular fire-fighting equipment, the availability of fire-fighting equipment per property and the number of trained staff per property can only be compiled by each individual FPA over time. Such information can be linked to baseline information such as property boundaries and displayed via the AFIS terminal.

Table 1: Geospatial and other data needed to support fire management decision making within Fire Protection Associations listed by the frequency required and indicating current or potential suppliers.

DAILY INFORMATION		
Data	**Suppliers**	**Comments**
Real time weather	Vital Weather; Climate Systems Analysis Group (CSAG); SA Weather Service & Fire Protection Associations	
Fire danger rating forecasts	Vital Weather & SA Weather Service	At least twice per day
Active fires	Advanced Fire Information System (AFIS)	Derived from MODIS and MSG satellite imagery
Fire-fighting resources available		At 9h00 each day
Fire-fighting resources dispatched	Fire Protection Associations; Working on Fire & Local Municipalities	At any time during the day
PRE-FIRE SEASON PLANNING INFORMATION		
Data	**Supplier**	**Comments**
Area burnt during previous fire season	Fire Protection Associations & Advanced Fire Information System (AFIS)	Maps (hand drawn or digital) produced by FPAs AFIS burn scars to varying degrees of accuracy
Ignition points	Fire Protection Associations & AFIS "hotspots"	Not available for cloudy days
Causes of fire	Fire Protection Associations	
Veld Age (fuel) maps	Fire Protection Associations	Derived from area burnt during the previous fire season
Season of burn maps	Fire Protection Associations	Derived from area burnt during the previous fire season
Veldfire risk maps	Fire Protection Associations	Derived from veld age (fuel) and location of assets(e.g. buildings and crops)
Position of firebreaks	Fire Protection Associations	
Condition of firebreaks	Fire Protection Associations	
Condition of access roads	Fire Protection Associations	
Condition of water points and fire hydrants	Fire Protection Associations	
Medium term fire related climate forecasts	CSIR	From a month to a year in advance
Standing of FPA membership	Fire Protection Associations	
FPA Fire Management Unit (FMU) fire response plans	Fire Protection Associations	Who will do what where, when and how should a fire occur
BASELINE INFORMATION		
Data	**Supplier**	
Land cover	CSIR & Agricultural Research Council	National Land Cover (NLC) 2000, updated by SANBI 2009
Veld type	South Africa Bio-diversity Institute (SANBI)	Vegetation map of South Africa available from Biodiversity GIS

		(B_GIS)
Critical Biodiversity Areas	South Africa Bio-diversity Institute (SANBI)	(C.A.P.E. fine scale planning maps) available from Biodiversity GIS (B_GIS)
National Invasive Alien Plant Survey (NIAPS)	Agricultural Research Council	
Invasive alien plant control projects	Working for Water Programme	Water Information Management System (WIMS)
Agricultural Fields	Department of Agriculture, Forestry and Fisheries	
Geo-corrected 1: 10000 digital aerial photographs (2010)	Chief Directorate: National Geo-spatial information	
Contours	Chief Directorate: National Geo-spatial information	
Property boundaries	Surveyor-General	Rural cadastral
Land ownership	Deeds Office or FPA records	
Property use	Fire Protection Associations	E.g. residential, farming, forestry, conservation or tourism
Settlement types	Statistics South Africa	Census 2011 enumeration areas (EA)
Buildings (categorised by type)	Statistics South Africa	SA Dwelling Frame containing localities and types of buildings
Roads (Type and dimensions)	Chief Directorate: National Geo-spatial information and Fire Protection Associations	
Turning points on roads	Fire Protection Associations	
Rivers and dams	Chief Directorate: National Geo-spatial information	
Water points and hydrants	Fire Protection Associations	
Fences	Fire Protection Associations	Position and types (e.g. farm, game electric)
Contact details for all land owners and tenants	Completed and / or reviewed annually pre-fire season by FPA	
Fire-fighting equipment per property	Fire Protection Associations	
Level of training per for each property	Fire Protection Associations	
Water points and hydrants (Means of access, helicopters suitability , capacity, obstacles such as high trees)	Fire Protection Associations	
Air strips	Fire Protection Associations & Chief Directorate: National Geo-spatial information	
Helicopter refuelling sites	Fire Protection Associations	
Powerlines	Eskom	Transmission & distribution lines (450 KV, 66 KV, 22 KV & 11 KV)
Telephone lines	Telkom	
Cell phone infrastructure	Cell phone companies	
Cell phone coverage areas	Cell phone companies	
SABC infrastructure	SABC	
Radio coverage	Fire Protection Associations	High and mid-bands

Repeater stations	Fire Protection Associations & local municipalities	
Staging areas – forward control points	Fire Protection Associations	
Natural buffer zones – strategic safe zones	Fire Protection Associations	
Safe zones for evacuations	Fire Protection Associations	
Synoptic weather patterns associated with large veldfires	CSIR	
Wildland Urban Interface	Fire Protection Associations	
FIRE EXTINGUISHING COSTS		
Data	**Supplier**	**Comments**
Worker days used	Fire Protection Associations	
Type and class	Fire Protection Associations	As per Incident Command System
Fuel	Fire Protection Associations	Petrol, diesel or paraffin
Health and safety	Fire Protection Associations	Record of incidents
Total extinguishing costs	Fire Protection Associations	

Almost all the data required to support fire management are in the available free in the public domain, although in certain cases permission to use the data is required, or are specific that are generated by Fire Protection Associations. Data that are specific to individual Fire Protection Associations need to be collected as part of their fire management activities. Such data could then be locally uploaded to the AFIS system.

3.2Formatting protocols that will allow for the data to be integrated into AFIS

We are making use of open source platform-independent software for the distribution and direct use of various geospatial data the Advanced Fire Information System (AFIS) field terminal. This will allow for the importation of the different formats of the data listed in Table 1. The software is currently being modified to operate within AFIS thus allowing users to get the answers they need inside their preferred application or on their preferred device.

An interface or dashboard is currently also being developed that will allow a user to examine, query and analyse fire information presented as in tables, graphs and maps on the AFIS terminal (Figure 1). One of these tools will be fire risk tool and it will enable a user to view fire risk for a specific area in the short, medium and long term based on vegetation conditions, type, fuel loads and weather forecasts.

MHFT Dashboard Mockup

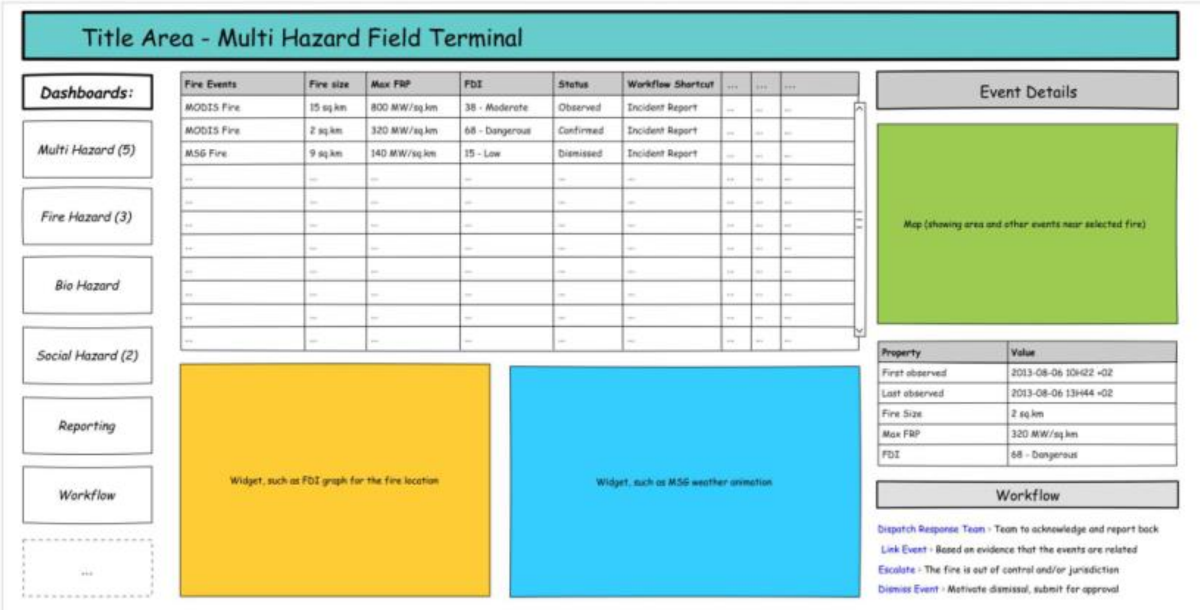


Figure 1: Multi Hazard Field Terminal (MHFT) interface to be developed to allow users to examine, query and analyse a variety of fire information accessed or stored on the Advance Fire Information Terminal.

3.3 Further development

Development of the multi hazard version of the AFIS terminal interface (Figure 1) is due to commence at the start of November and planned to be completed by July 2014. Development of the fire risk component will be undertaken between April and June 2014.

The data types listed in Table1 will used to inform the design of the fire risk component. We will hold further discussions with FPAs and Umbrella FPAs during the development phase to determine how they generate information specific to their areas and how they currently obtain baseline information needed for fire management planning.

During the next quarter we will also collate and / or compile metadata for each of the identified datasets so that these that these can also be accessed through the AFIS terminal and aid users in the interpretation of the information to be displayed.

Many of the data sets have been obtained by our team but FPA specific data still needs to be acquired. Once the formatting protocols have been finalised and the user interfaces developed copies of all data collected will made available to FPAs through AFIS terminals.

4. OUTPUT 2.4 WILDLAND FIRE BEHAVIOUR MODELLING AND FIRE DANGER FORECASTING

4.1 Developing models of vegetation-related fire hazard

4.1.1 Introduction

Fynbos vegetation is flammable and, thus, a fire hazard which hazard varies depending on the structure and characteristics of the vegetation, particularly the dead material that accumulates as fynbos ages (Van Wilgen et al. 1985, 2010). Fynbos can vary from being dominated by grass-like reeds (Restionaceae) to evergreen shrubs, and from low shrublands to tall shrublands (Kruger 1977, Rebelo et al. 2006). Each of these structural types varies again with the degree to which they have been invaded by alien trees and shrubs (van Wilgen and Richardson 1985, Jayiya et al. 2004). Fuel models, which describe how the fuel load varies with increasing post-fire age were used, in conjunction with typical summer fire conditions to develop fire hazard models for the Catchment Management System (Le Maitre et al. 1993, Richardson et al. 1994). These fuel models were then matched and adapted to that they could be used to predict the fire hazard for the vegetation types found in the Cedarberg and Southern Cape study areas.

An understanding of vegetation-related fire hazard is a key input to understanding the likelihood of fire in an environment where flammable natural vegetation and flammable invasive plant species occur (Forsyth et al. 2010, Le Maitre et al. 2014b). It is also important for determining the consequences of a fire in terms of the potential hazard to human lives, assets and livelihoods. This section outlines an approach to assessing vegetation-related fire hazard for the two case study areas. The vegetation-related components can be divided into two interlinked components namely the natural vegetation and the invading plants. In both cases these communities can be divided into two types from a fire perspective: (a) one that does not accumulate fuels that can be burnt in a fire and (b) one that does accumulate sufficient, continuous fuels to sustain fires (Forsyth et al. 2010, Le Maitre et al. 2014b). In the sections that follow we first relate each of the vegetation types in the study areas to a fire ecology-type based on the classification developed by Forsyth *et al*. (2010) and then relate the flammable ones to fuel models so that we can group them in terms of their fire hazard.

4.1.2 Fire-ecology type classification

4.1.2.1 Natural vegetation types

The vegetation types defined in the national vegetation map (Mucina and Rutherford 2006) provide an appropriate spatial resolution for the study areas and the boundaries can be considered sufficiently accurate for delineating fire hazard. The more detailed case studies (Gordon's Bay and Plettenberg Bay, see section 5) could use this map but should preferably use finer-scale vegetation mapping if available (e.g. Vlok et al. (2008) for the Garden Route).

The recent assessment of fire risks in South Africa used the national vegetation map's vegetation types and also reviewed of the fire-ecology of ecosystems throughout the country to relate them to specific fire ecology-types (Forsyth et al. 2010, Le Maitre et al. 2014b). The typical fire regime characteristics: recurrence interval, seasonal distribution, intensity, extent (Gill 1975, Falk et al. 2007, Gill and Allan 2008, Krebs et al. 2010) in each fire ecology-type were described. This review identified the following fire ecology types which occur in the two study areas (Table 2).

Table 2: Fire-ecology types found in the two study areas in the Cedarberg and the southern Cape (Outeniqua-Tsitsikamma region) Fire Protection Areas based on those defined by (Forsyth et al. 2010, Le Maitre et al. 2014b).

Fire ecology-type	Fire regime	Classification
Forest	Fire sensitive; fuel properties limit fires to exceptionally hot and dry conditions	No fires
Fynbos - renosterveld	Fire-dependent; mainly fine fuels (grasses, shrubs) able to burn at a young age, few fire recurrence interval dependant species	Regular fires
Fynbos - fynbos	Fire-dependent; variable structure and fuel accumulation dynamics; fires carried by fine fuels (reeds, sedges, shrubs); able to burn from about 4 years of age; many fire recurrence interval dependant species	Regular fires
Thicket	Fire-independent; Albany thicket and dune thicket (strandveld); Albany thicket has low fuel loads except for grassy (eastern) forms; dune thicket accumulates fuels but fires are rare except in mosaics with dune fynbos	Fires rare, no fires assumed
Succulent Karoo	Fire-independent; shrubland with high proportion of succulents; insufficient fuel so it rarely burns; some transitional vegetation types have more fuels and may burn occasionally	Fires rare, no fires assumed
Nama Karoo	Fire-independent; insufficient fuel to carry fires except the grassier (eastern) Karoo which can burn after exceptional rainfall years	Fires rare, no fires assumed

The fire ecology-type study was done at a national scale, and included the "azonal" vegetation types, which are not biome-linked (Mucina et al. 2006), within their respective biomes. At the more detailed level of this study it is appropriate to explicitly recognise these types. Although they only comprise a small proportion of the case study areas, they have distinctive fuel characteristics which place them into different fire ecology types (Table 3). The characteristics of these azonal types affect fire behaviour and fire regimes because some are flammable and others not. Where they are flammable they have been classified as such.

Table 3: Fire ecology-type classification of the azonal (not biome-linked) vegetation types in the two case study areas: Cedarberg = C and southern Cape (S). Vegetation descriptions based on information in (Mucina et al. 2006) and matched to fire-ecology types (Forsyth et al. 2010, Le Maitre et al. 2014b).

Vegetation type and study area	Description	Fire ecology-type
Cape Seashore Vegetation	Herbaceous dune pioneer vegetation with some shrubs, including succulents; insufficient fuel	No fires
Cape Coastal Lagoons (C,S)	A waterbody, no fire hazard	No fires (water)
Cape Vernal Pools (C,S)	A seasonal waterbody with low herbaceous vegetation; fire hazard negligible	No fires (water)
Cape Estuarine Salt Marshes (C,S)	A tidal marsh with semi-succulent and herbaceous vegetation; fire hazard low	Fires rare, no fires assumed
Cape Inland Salt Pans (C,S)	A seasonal wetland with sparse, herbaceous vegetation; insufficient fuel	No fires
Freshwater Lakes (C,S)	A waterbody with fringe vegetation including reeds, sedges and shrubs which accumulate high fuel loads	Fynbos
Cape Lowland Freshwater Wetlands (C,S)	Perennial to seasonal wetlands; highly variable vegetation structure dominated by reeds, sedges, palmiet or restios; high fuel loads	Fynbos
Cape Lowland Alluvial Vegetation	Variable structure, typically reed or bulrush dominated or with forest trees; high cover and fuel loads except in closed forest forms	Fynbos
Fynbos Riparian Vegetation (C)	Variable structure from forest tree to palmiet, shrub or restio dominated; high cover and fuel loads except in closed forest forms; closed tree forms rarely burn except under hot, wildfire conditions	Fynbos
Albany Alluvial Vegetation (S)	Variable structure, reed or grass dominated to tree dominated woodland on river floodplains; high cover and fuel loads	Fires rare, no fires assumed
Muscadel River & Southern Karoo River	*Vachellia* (*Acacia*) -dominated woodland on floodplains; can have high grass cover and fuel loads after high rainfall periods	Fires rare, no fires assumed

4.1.2.2 Invasive alien plants

A wide range of invasive alien plant species can be found in the two study areas but the focus here is mainly on those that increase the fire hazard in flammable natural vegetation types (van Wilgen and Richardson 1985, Jayiya et al. 2004). There are invasions by *Pennisetum setaceum* in the Succulent Karoo Biome which have the potential to introduce fire to these generally fire-free vegetation types (Rahlao et al. 2009). However, these invasions are very limited in extent and so will have little impact on the current fire hazard. The most widespread flammable invading species, and those which have the greatest impact on fuel loads, are the shrubs and trees that invade fynbos, renosterveld and forest (van Wilgen and Richardson 1985, Jayiya et al. 2004), particularly pines, wattles, hakeas and eucalypts (Table 4).

Biomass is directly related to age in stands of invasive *Acacia saligna, A. cyclops* and *A. longifolia,* ranging from 5 200 to 14 000 g/m^2 in mature stands, and reaching as much as 19 800 g/m^2 (Milton and Siegfried 1981). A fuel load of about 7 700 g/m^2 for was reported for mature *Acacia cyclops* (Van Wilgen and Holmes 1986) based on an equation relating biomass to stem diameter (Milton and Siegfried 1981). Further studies found a mean for an *A. cyclops* stand was 10 400 g/m^2 with roughly 3 800 g/m^2 being fine fuels with a stand height of 5-7 m which is within the range reported by (Jayiya et al. 2004). The biomass estimates for *A. cyclops* stands on the west coast lowlands, the Agulhas area and Eastern Cape had a similar range: 12 200-21 200 g/m^2 (Van Laar and Theron 2004). The biomass for *A. saligna* stands has decreased significantly from those reported by Milton and Siegfried (1981) following biological control (Wood and Morris 2007).

Table 4: Impacts of invasive alien plant species on fuel loads compared with the adjacent uninvaded vegetation. The matched natural vegetation for Van Wilgen and Richardson (1985) was fynbos and for the Jayiya *et al*. (2004) study *A. cyclops* was compared with strandveld and the *P. pinaster* with renosterveld.

Alien plant species	Impact on fuel loads	Source
Acacia saligna	Increase in height from 2.5-5.8 m; fine fuel 1.5 x higher (1 796 g/m^2); fuel moisture content 1.7 x higher	Van Wilgen and Richardson 1985
Acacia cyclops	Increase in height from 0.5-3.8 m; fine fuel 8.2 x higher (4 900 g/m^2); fuel moisture content similar	Jayiya *et al*. 2004
Hakea sericea	Increase in height from 2.5-3.2 m; fine fuel 1.6 x higher (1 951 g/m^2); fuel moisture content 0.7 x (lower)	Van Wilgen and Richardson 1985
Pinus pinaster	Increase in height from 0.5-20+ m; fine fuel 6.9 x higher (8 300 g/m^2); fuel moisture content similar	Jayiya *et al*. 2004

One of the major fynbos invaders, especially in the Southern Cape study area, is *Acacia mearnsii* (black wattle), which mainly invades water courses but can also spread into dryland situations (Richardson et al. 1992). No studies of the fuel loads in stands of *A. mearnsii* could be found but there are data on the biomass of plantations which can be used to estimate fuel loads excluding litter. The total biomass of *A. mearnsii* plantations in Kwa-Zulu ranges from 10 990 g/m^2 (poor site) to 14 820 g/m^2 (average site) with leaves comprising 530-700 g/m^2, dead branches 520-680 g/m^2 and live branches 1 670-2 000 g/m^2 (Dovey 2005, 2009). Only a small proportion of live branches is fine fuels, so the fuel load is probably no more than 10% of the total mass or about 1 100-1 500 g/m^2 in stands of this species. These plantations were assumed to have fuel characteristics similar to those of the other invasive *Acacia* species (Table 3), although they typically become much taller trees than *A. saligna* or *A. cyclops*. There are anecdotal reports that dense *A. mearnsii* stands in grasslands are fire-resistant but no such reports have been found for fynbos environments.

The biomass of mature *Pinus radiata* plantations on a good quality site ranged from 18 400-26 500 g/m^2, but only about 10% was branches and leaves (Van Laar 1983) so the fuel mass would be much less. Unmanaged stands have not been pruned or thinned so ground fires would carry up into the canopy under the right conditions (e.g. strong winds (Alexander and Cruz 2012)). For this analysis we have used the information on *P. pinaster* from (Jayiya et al. 2004). The combination of their fuel properties, different growth forms and typical spatial distribution patterns, suggest that five fire ecology-types are needed for the main alien invasive species (Table 5).

Table 5: Proposed fire ecology-types for invasive alien species known to substantially increase fuel loads and, thus, modify fire behaviour.

Dominant invasive alien plant species	Description	Fire ecology-type
Acacia cyclops, longifolia, pycnantha, saligna	Shrubs and small trees 3-5, sometimes up to 8 m tall; high proportions of dead canopy fuel in mature *A. cyclops* and *A. saligna* stands; mainly on the coastal lowlands	Cyclops
A. mearnsii, melanoxylon, dealbata, decurrens; Paraserianthes lophantha	Medium to tall trees with relatively low loads but can have high canopy fuel loads in mature stands; dense, continuous, mature stands can be relatively fire resistant, burning only around the edges; mainly along water courses and in lowlands	Mearnsii
Pinus pinaster, radiata, elliottii	Medium to tall trees up to 20-30 m tall; young and middle-aged pines can retain a canopy to near ground level, creating high fuel loads; older trees have raised canopies but moderate to dense stands can sustain canopy fires under hot and windy conditions; mainly on mountain slopes and in some lowland areas; flaring pines can cause spot fires	Pinus
Hakea sericea, drupaceae, gibbosa	Shrubs up to 4 m tall with a high fuel load; continuous, dense stands may be relatively fire resistant; mainly on mountain slopes and ridges	Hakea
Eucalyptus camaldulensis, diversicolor	Medium to tall trees up to 20-35 m tall; mainly found in riparian settings; moderate to dense stands can sustain canopy fires; flaring eucalyptus & burning bark strips (stringybark species) can cause spot fires	Eucalyptus

4.1.3 Fuel models for fynbos vegetation types

During the 1990s the CSIR developed a set of fuel models for the vegetation of the fynbos biome (Le Maitre et al. 1993, Le Maitre and Marais 1995). The fuel models were divided into two groups: non-fynbos types in which there are no fires because there is no fuel or because the fuel characteristics are such that they do not burn or rarely burn; and fynbos types which do burn (Table 6). The division into the non-fynbos (non-flammable) and fynbos (mostly flammable) types matches well with the fire-ecology types described earlier (Tables 2 and 3) (Forsyth et al. 2010, Le Maitre et al. 2014b). However, this study includes vegetation types which were not previously distinguished (e.g. sub-types of fynbos) because the fire-ecotype mapping was designed for use at a national level and this study is being conducted at a level where such detail is appropriate.

For the flammable (fynbos) types, regression models were developed to project the increase in biomass with increasing post-fire age (Le Maitre and Marais 1995). The biomass-age data for fuel models was derived from a synthesis of the available data on the biomass of different types of fynbos which was then matched with the structural groups developed by Campbell (1985) for the vegetation of the fynbos biome (Le Maitre and Marais 1995). The projected biomass for a set of post-fire ages was then used to develop fuel models based on the approach for fynbos developed by (Van Wilgen 1984a). The BEHAVE fire behaviour prediction system (Burgan and Rothermel 1984, Andrews 1986) was used to predict flame lengths for each post-fire age for each of the fynbos fuel model types.

Campbell (1985) distinguished between renosterveld and fynbos using their structure and floristics, but renosterveld also has different fuel properties as it is typically dominated by fast-growing, fine-leaved shrubs (Rebelo et al. 2006). Although there have not been any studies of fuel loads in renosterveld, the indications are that fuel accumulates rapidly so that renosterveld can burn more often than fynbos (Forsyth et al. 2010, Le Maitre et al. 2014b). The fynbos types were subdivided based on the dominant growth forms, whether the site was wet (high rainfall or wetland), moist or dry based on rainfall, and whether the soils were derived from nutrient-poor rock types (oligotrophic sandstones or quartzites) or relatively nutrient-rich (mesotrophic granites or shales) rock types (Boucher 1978, Campbell 1985, Cowling et al. 1988, Rebelo et al. 2006). This classification provides the basis for linking vegetation types in the case study areas with fuel models and using the predicted fire behaviour to define the fire hazard based on the predicted flame lengths at different post-fire ages.

Table 6: A summary of the fuel classification and fuel models developed for the fynbos biome by Le Maitre and Marais (1995).

Group	Sub-group	Fuel class	Fuel model
Non-fynbos	Forest & thicket	Forest, Thicket	No fires
		Dune Thicket	Fires rare, no fires assumed
	Succulent Karoo	Karroo shrubland	Fires rare, no fires assumed
	Grass & Grassy Shrubland	Grassy shrubland	Grassland
		Grassland	Grassland
Fynbos	Renosterveld	Renoster Shrubland	Renosterveld
	Cape Fynbos	Grassy Fynbos	Moist ericoid
		Asteraceous fynbos	Asteraceous
		Restioid	Wet, Moist, Dry
		Ericoid	Wet, Moist, Dry
		Proteoid	Wet, Moist, Dry: Mesotrophic
			Wet, Moist, Dry: Oligotrophic
		Closed-scrub fynbos	No fires, or fires rare and no fires assumed

4.1.4 Matching fuel models to vegetation types

The first step was to divide the vegetation types in each of the study areas into those that matched non-fynbos fuel models: (a) those which do not accumulate sufficient fuels to burn, and (b) those whose structure makes them generally non-flammable so that they only burn rarely and under exceptional conditions. This was done by matching the broad, structural classification of fynbos vegetation types developed by Campbell (1985) to the more detailed descriptions of each of the national vegetation types in the case study areas from (Rebelo et al. 2006). Four main criteria were used in the matching for the fynbos types: dominant growth forms, soil types, rainfall and the topographic setting (lowland, montane [lower or upper slopes, alti-montane]).

The vegetation of part of the Southern Cape FPA was mapped for a regional conservation planning project funded by the Garden Route Initiative (Vlok et al. 2008). Vlok *et al.*'s (2008) classification, together with information on flammability and plant reproductive maturity for slow maturing, seed-regenerating species, was used to develop a wildfire risk assessment based on largely on expert inputs (Wessels et al. 2009). Information from this assessment was used to refine the assignment of fuel models to vegetation types in the Southern Cape study area.

4.1.5 Linking vegetation types to fire hazard

The result of this exercise is a classification is a division of the vegetation types in the case study area into non-fynbos types, which do not pose a hazard, and fynbos types, which do pose a hazard. The hazard in the fynbos types can be related to the flame length by classifying the predicted flame lengths according to the difficulties they are likely pose to fire fighters as well as the hazards to any assets in the study area (Table 7). Ideally, if there was sufficient information on post-fire ages for the remaining natural areas of all the fynbos types, a dynamic map could be produced which would show the fire-hazard changing from year to year. However, the CapeNature historical fire data only provide a patchy coverage of the remaining natural fynbos vegetation focused on the protected areas (see de Klerk et al. (2012) for more details), with the post-fire age of many areas, especially on the lowlands, being unknown. We could attempt to fill these gaps by assuming a default age but this could be misleading and lead to inappropriate allocation of resources. We have chosen, therefore, to rather classify the vegetation type using the post-fire age at which its predicted flame lengths are such that they would make it difficult to fight the fire and threaten fire-fighter lives. The younger the age at which it reaches that predicted flame-length, the greater the hazard it poses.

The most direct measure of the difficulty of fighting a fire is the amount of radiant energy it emits because the radiant energy is what heats skin, clothes and other materials (not directly in contact with the flames) to the point where they char and then ignite (Butler and Cohen 1998, Raj 2008). The energy output is directly related to the energy being emitted by the fire front, or Byram's fireline intensity, but research has found that fuel-bed structure also plays an important role (Alexander and Cruz 2012). Unfortunately, no data on the radiant heat flux exist for fynbos fuels although there are data on estimated fireline intensities and flame lengths (Van Wilgen et al. 1985). Although flame-length (and the related flame height) are not strongly related to radiant energy output, flame length still provides a direct measure as well as being something that fire-fighters can estimate reasonably accurately (Cheney et al. 2012). It also provides a useful measure of the hazard to fire fighters. For example, Butler and Cohen (1998) estimated that a fire-free safety zone of at least 4-times the flame height is needed to protect exposed fire fighters from harm. For this study we have used the threshold of a 2 m flame length as used for the Catchment Management System (Le Maitre et al. 1993, Le Maitre and Marais 1995).

Table 7: Predicted flame lengths (m) for each fynbos fuel model and age based on Le Maitre and Marais (1995). A non-fynbos model was included for completeness

Fuel model	Age class (years)										
	0-2	3-5	6-8	9-11	12-14	15-17	18-20	21-23	24-26	27-29	30-32	≥33
Moist Mesotrophic Proteoid	0.0	0.8	2.3	6.5	10.5	12.4	13.6	14.3	14.8	15.3	15.6	16.0
Moist Oligotrophic Proteoid	0.0	0.0	0.4	1.1	2.3	4.2	5.1	6.1	6.8	7.3	8.2	8.5
Dry Mesotrophic Proteoid	0.0	0.6	1.5	3.0	4.5	5.5	6.0	6.4	6.9	7.3	7.6	7.8
Dry Oligotrophic Proteoid	0.0	0.2	0.5	0.8	1.5	1.9	2.6	3.5	4.0	4.8	5.6	6.3
Wet Ericoid	0.0	1.1	3.2	4.9	13.3	15.8	17.1	18.0	18.8	19.2	19.5	19.7
Dry Ericoid	0.0	0.3	0.5	0.6	0.7	0.7	0.8	0.9	0.9	0.9	1.0	1.0
Wet Restioid	0.0	2.4	10.7	11.0	12.4	13.2	13.8	14.3	14.6	14.9	15.1	15.4
Moist Restioid	0.0	0.2	1.0	1.8	2.1	2.3	2.4	2.5	2.6	2.7	2.7	2.7
Dry Restioid	0.0	0.3	0.5	0.6	0.7	0.7	0.8	0.9	0.9	0.9	1.0	1.0
Asteraceous	0.0	0.0	0.1	0.7	1.9	3.5	3.6	3.7	3.7	3.8	3.8	3.8
Renosterveld	0.0	0.5	1.5	3.2	5.7	6.6	6.8	6.9	7.0	7.1	7.2	7.3
Non-fynbos	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Invasions by alien plant species which increase the fuel loads, and thus the fire hazard (Table 4), are a complicating factor. As is the case with the fynbos areas, there are many invaded areas where we do not have adequate data on the post-fire age to use this approach to predict the flame-lengths and thus the fire hazard. However, the impacts of such species on fuel loads will increase as their density increases, and may even decrease at high densities in continuous stands (Table 4). We have adopted a pragmatic approach which is to highlight the location and density of invasions so that managers are made aware of their presence by highlighting areas where stands of invading species pose an important fire hazard. The fire risk assessment for part of the Southern Cape FPA (Wessels et al. 2009) used a similar approach where less than 25% cover did not increase the "fuel hazard" but more dense invasions (25-50%, 50-75%, 75-100%) progressively increased the fuel hazard. A logical extension of the approach use in this assessment would be to use the dominant species, its age and its density class to determine a fire hazard class. Where the predicted fire hazard from the invading alien species is greater than that of the natural fynbos vegetation the hazard class for the invading species should be used. This would involve the development of models to predict biomass of different invading species for different post-fire ages so that the flame-length could be predicted.

At present, cultivated crops, whether dryland or irrigated, have not been included because they rarely, if ever, accumulate sufficient fuel to create a potential fire hazard (Kruger et al. 2000). One obvious exception to this is dryland cultivation of annual grain crops such as wheat. The wheat stubble is regularly burnt by farmers as is evident in satellite images of burnt areas, but much more so on the western coastal lowlands of the Swartland than in the Overberg (D C Le Maitre unpublished data). The stubble may also help to spread a fire from one natural patch to another. However, the stubble is rarely ignited by events such as lightning. The fire intensity is typically low although the rate of spread is high. One option for resolving this issue is to include dryland cultivation as a low fire hazard rather than excluding it from the fire hazard mapping. A similar approach was used by Wessels et al. (2009) where "grassy" forms of dryland agriculture (i.e. wheat, oats) were given a minimum age at which they could burn of two years.

Commercial tree plantations accumulate fuels and can have loads after clear-felling. They could be included as fire-hazard by assigning them to a fire hazard class but they are also considered an asset with a high risk of loss (Forsyth et al. 2010), because substantial financial losses can be incurred when they burn before they are mature enough to produce enough salvageable wood to offset the establishment and maintenance costs. As they are both a hazard and a valuable asset at risk, care needs to be taken to avoid over-weighting them in fire risk assessments.

4.1.6 Results

4.1.6.1 Greater Cedarberg FPA

The Greater Cedarberg FPA covers much of the west coast, extending from the northern boundary of the Cape Town Metropole to north of Vredendal, and from the west coast to the Tanqua Karoo (Figure 2a). The FPA covers about 21 485 km^2 and includes more than 50 different vegetation types based on the national vegetation map (Mucina and Rutherford 2006). About 18 598 km^2 falls within the fynbos biome and this includes 30 different types of fynbos and renosterveld, the main vegetation types which are flammable and also require fire. The forest only occupies about 0.5 km^2, most of which is located in the Groot Winterhoek Mountains. Most of the rest is Succulent Karoo and azonal riparian vegetation, the latter occurring mainly along the Doring River and the lower Olifants River where it has not been transformed by farming. Azonal salt marsh vegetation types are also found at Langebaan and around the Olifants estuary.

The fynbos vegetation can be divided into two broad groups: Sandstone fynbos found on the mountains ranges and on inselbergs and outcrops of the sandstone in the coastal plains; and Sand Plain fynbos found on the deep, sandy, acidic soils of the coastal plains. Much smaller areas of the fynbos occur on the more fertile granite and shale derived soils and on limestone-derived soils in the Saldanha region. Most of the renosterveld vegetation is the West Coast type of the Swartland with small areas of Karoo Renosterveld in the north and the Western Fynbos-Renosterveld mosaic. Large areas of the natural vegetation, particularly the renosterveld, have been transformed by cultivation so that only small remnants are left (Figure 2b). Almost all the fynbos has a fuel hazard of 11-15 years with the renosterveld and fynbos renosterveld mosaics from 7-10 years post-fire. The shale band vegetation in the mountains also stands out because its higher cover of grasses and sedges makes it a fuel hazard at a younger age. The West Strandveld is also known to burn under summer wildfire conditions but probably only at intervals >15 years. The Sand Plain fynbos in the northern regions (e.g. around Graafwater) gets much less rainfall than the south (e.g. around Hopefield) and is likely to burn less frequently but more fuel data need to be collected to confirm this interpretation.

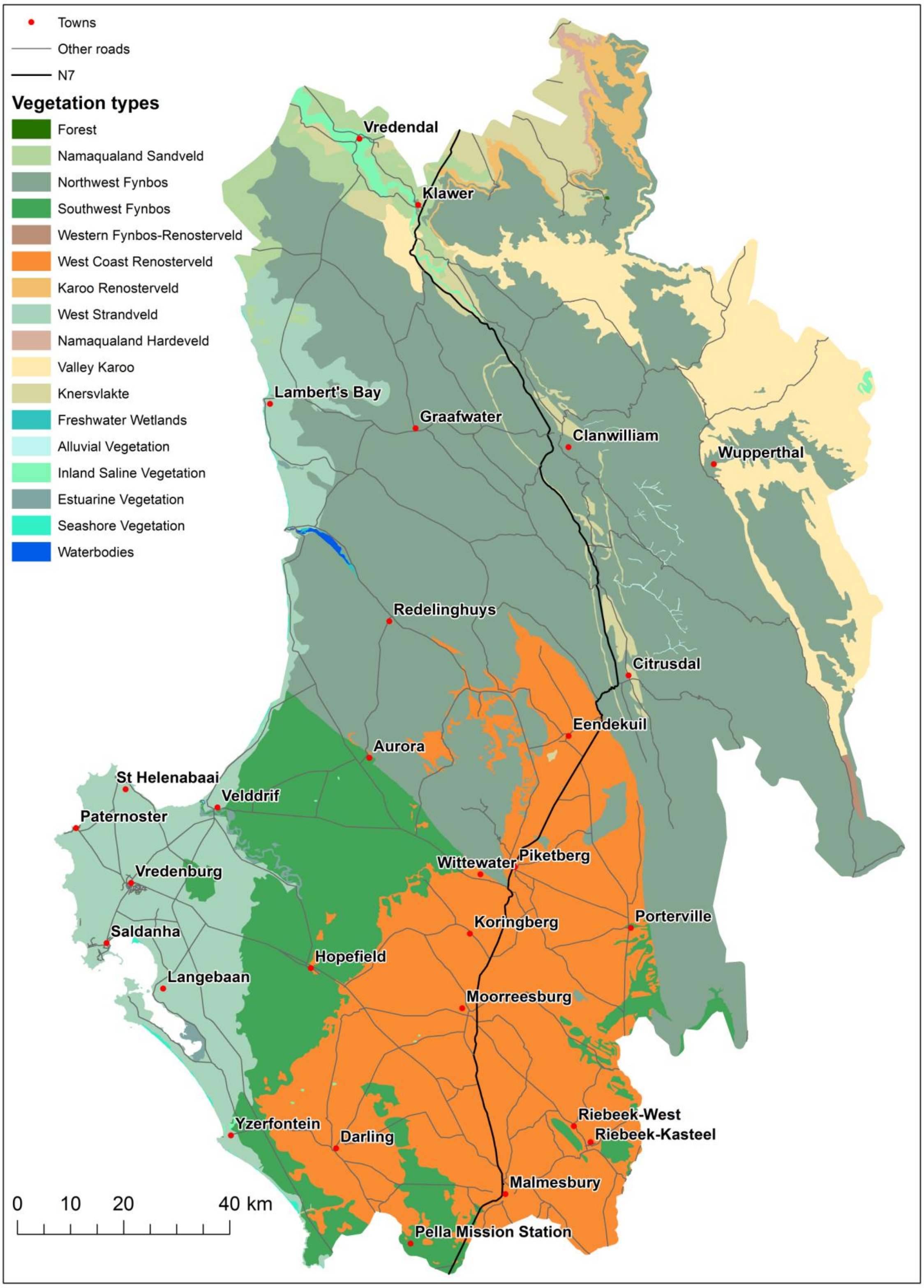


Figure 2a: The distribution of the original natural vegetation of the Greater Cedarberg FPA. It is shown at the bioregional level based on the national vegetation map (Mucina and Rutherford 2006, Rebelo et al. 2006) because there are too many vegetation types to show them all.

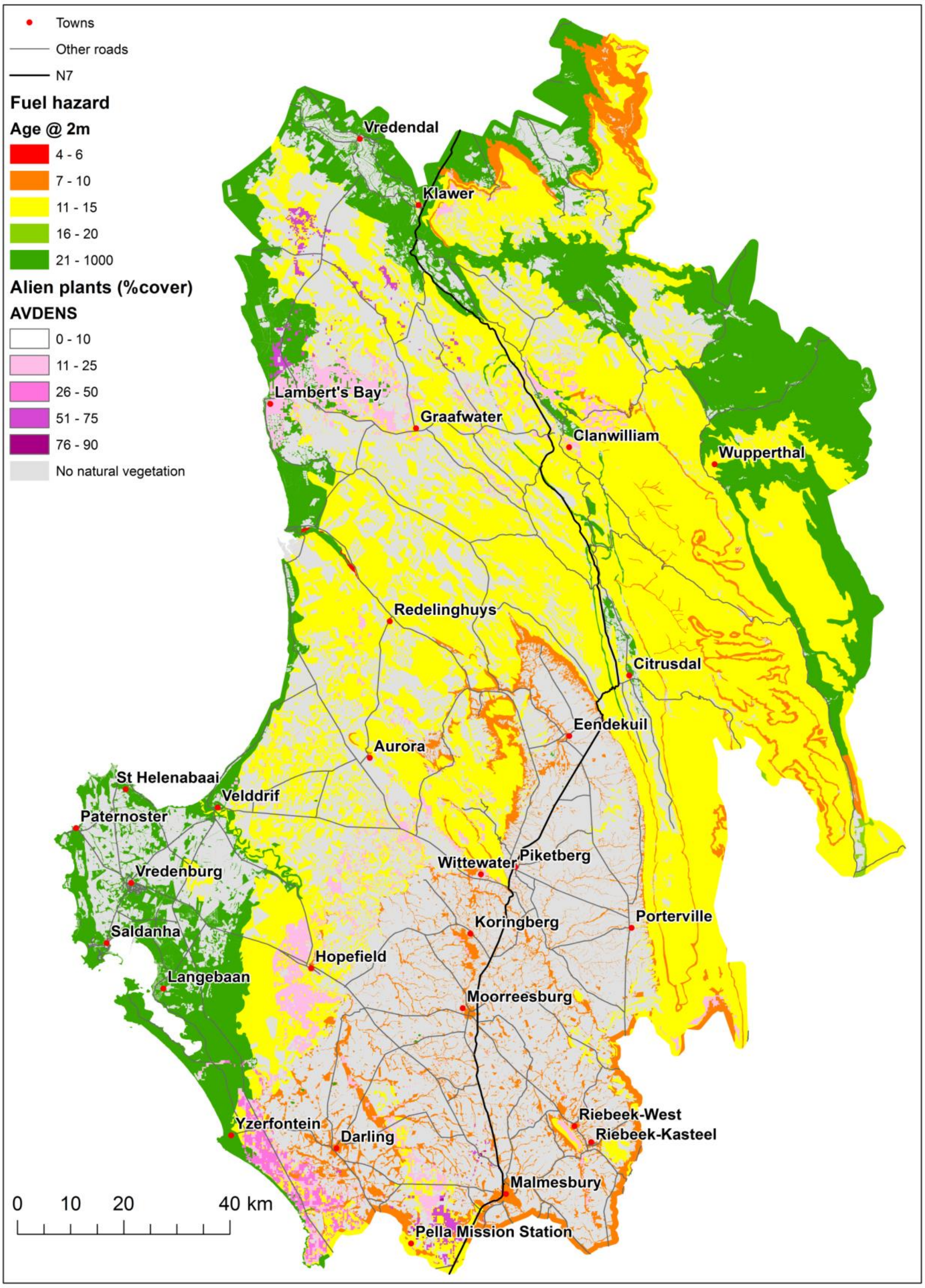


Figure 2b: The fuel hazard in the Greater Cedarberg FPA based on the post-fire age at which the flame length would reach 2 m under summer wildfire conditions. Also shown are the areas which no longer support natural vegetation and the main areas invaded by woody alien plants based on the National Invasive Alien Plant Survey (Kotzé et al. 2010). Moderate to dense invasions typically increase the fuel load and the hazard level.

4.1.6.2 Southern Cape FPA

The Southern Cape FPA also covers a very extensive area, extending almost from Swellendam, in the Western Cape, to Humansdorp in the Eastern Cape and from the southern coast into the Great Karoo north of the Swartberg (Figure 2c). It covers an areas of about 32 757 km^2, with most of this falling into the Fynbos biome (23 043 km^2) and the Succulent Karoo Biome (6 432 km^2). Albany Thicket occupies about 1 871 km^2 and the Forest Biome about 780 km^2. Then fynbos and fynbos-renosterveld mosaics include about 45 different vegetation types which are flammable and require fire. There are extensive areas of alluvial vegetation on the river floodplains in the Gouritz (mainly flammable reeds) and the river systems in the Little and Great Karoo (*Vachellia (Acacia) karoo* woodland) where they have not been converted to agricultural fields.

A large part of the renosterveld in the south-eastern part of the FPA has been converted to cultivated lands for annual crops of grain and in the Mossel Bay to Knysna are for intensive vegetable and dairy farming (Figure 2d). Plantations are mainly found in the area from Robinsons pass through to the Tsitsikamma. Most of the fynbos reaches the fuel hazard threshold between 11 and 15 years of age, but there are extensive areas of fynbos-renosterveld mosaics, grassy fynbos and renosterveld which reach the threshold between 6 and 10 years of age, especially on the inland mountains and in the Kouga and Baviaanskloof. There are extensive invasions by pines and hakea on the middle and upper slopes of the eastern Langeberg, Outeniqua and Tsitsikamma which could increase the fire hazard considerably, in addition to reducing river flows and other impacts (van Wilgen et al. 2008, Cowling et al. 2009, Le Maitre et al. 2014a). Many of the river valleys on the coastal plan are densely invaded by *Acacia mearnsii* which also increases the fire hazard although dense stands my reduce it. Portions of the coastal plains, especially dune areas are also densely invaded by *A. cyclops* and *A. saligna*. The combination of flammable plantations, invasions and fynbos poses a substantial fire risk. The invasions in the Southern Cape FPA are far more extensive than in the Greater Cedarberg, and ways need to be found to collaborate with the Working for Water programme and land owners to deal with this problem.

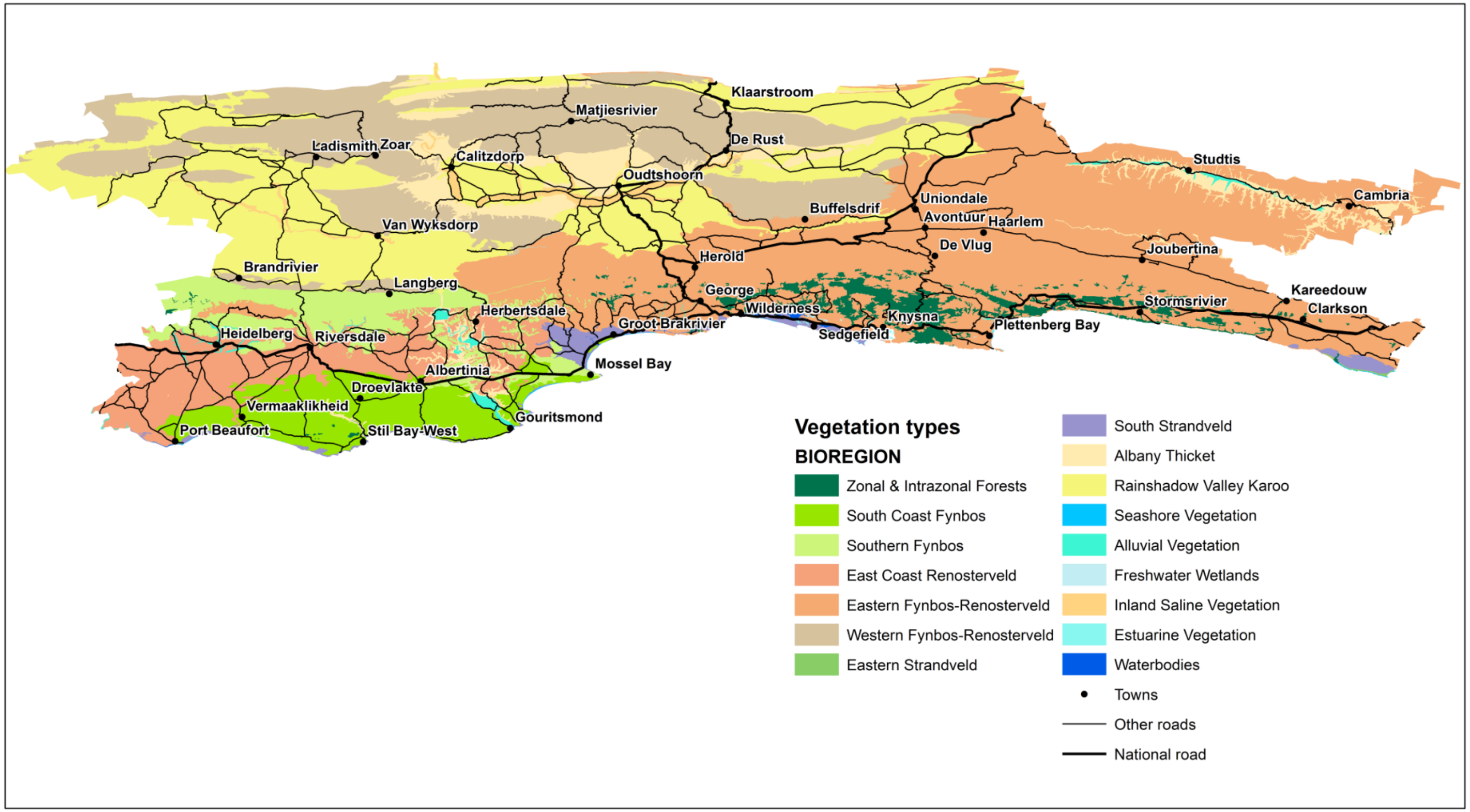


Figure 2c: The distribution of the original natural vegetation of the Southern Cape FPA. It is shown at the bioregional level based on the national vegetation map (Mucina and Rutherford 2006, Rebelo et al. 2006) because there are too many vegetation types to show them all.

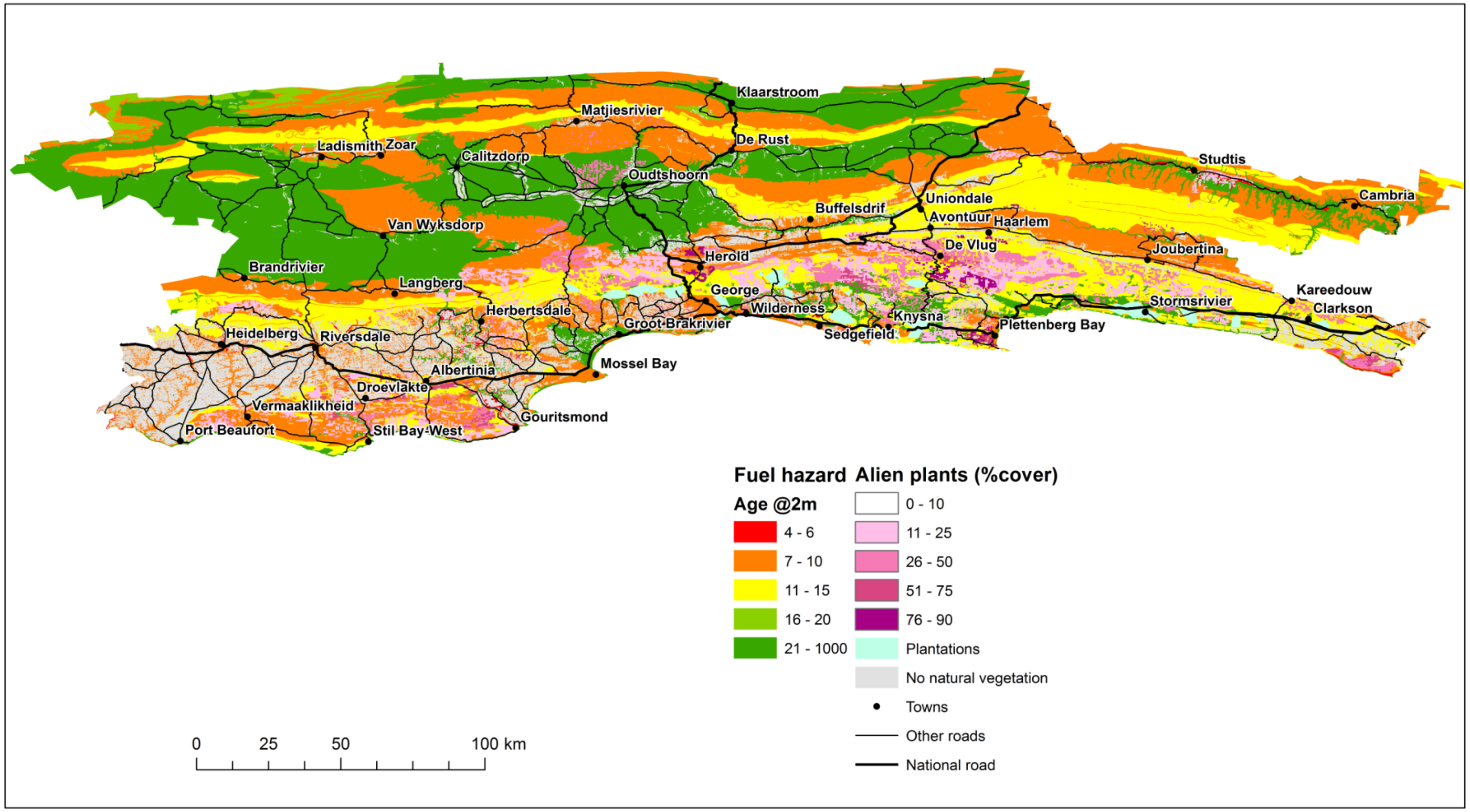


Figure 2d: The fuel hazard in the Southern Cape FPA based on the post-fire age at which the flame length would reach 2 m under summer wildfire conditions. Also shown are the areas which no longer support natural vegetation and the main areas invaded by woody alien plants based on the National Invasive Alien Plant Survey (Kotzé et al. 2010). Moderate to dense invasions typically increase the fuel load and the hazard level.

4.1.7 Conclusion

This study has shown that it is possible to spatially represent the fuel properties of the natural vegetation and highlight which areas within an FPA have a greater fuel hazard than others. This information can also be combined with data on invasions by alien woody plants and vulnerable human assets to highlight areas at risk from unmanaged fires. The fuel models that have been used to estimate the flame lengths were all derived from biomass and fuel data collected many decades ago in the Boland and Cedarberg mountains. There is an urgent need for further work on fuel classification and fuel-based fire hazard modelling, both to improve the prediction of areas with high and low hazards and to develop fuel handbooks which can be used by managers to determine their fuel hazard based on the algorithm used in this assessment (Figure 3). This would also allow for more nuanced mapping of the fuel hazard so that the variations within the large seemingly homogeneous areas would be evident, including the addition of information on the actual post-fire age.

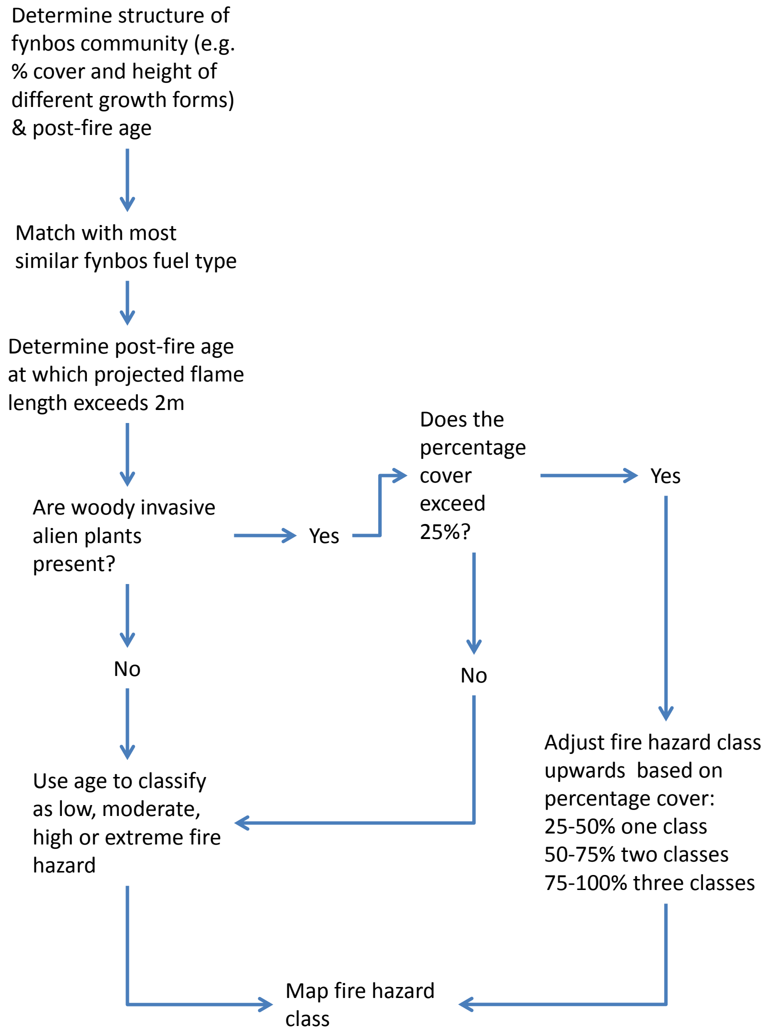


Figure 3: A flow diagram for the process of determining fuel-based fire hazard used in this assessment.

4.2Wildland fire behaviour modelling and fire danger forecasting

4.2.1 Introduction

Fire Protection Associations need to have access to projections of fire risks (likelihood of occurrence, and consequences) over a range of time scales so that they can plan their activities and interventions. Projections are needed for periods from 2-10 years into the future so that resources, infrastructure and mitigatory measures can be put into place. Seasonal forecasts are needed to plan the distribution of resources between FPAs and assess the general level of preparedness and resources that may be required. Daily weather-based fire danger estimates need to be supplemented with 5-10 day projections of potential fire danger based on the predicted synoptic conditions (i.e. weather system states) to determine levels of preparedness and arrange for inter-FPA co-operation and sharing of resources where necessary. This is already done to some degree, but the ability to predict these more reliably would enable managers to make better decisions about their fire preparedness.

The ability to project fire danger and fire risks over these different time-scales is based on an understanding of the relationships between synoptic weather patterns and fires. The short-term projections (days) are based on being able to relate particular synoptic patterns to the occurrence of fire. Longer projections (seasons or years) depend on understanding how large-scale climate-system dynamics alter the frequencies of these same synoptic patterns and where overall fire danger is likely to be higher or lower than normal. Even though the fire danger may be high, and the weather is hot and dry with strong, gusting winds, a fire will still need an ignition source. However, if weather that will be conducive to fires can be predicted, it would enable the managers to be ready to deal with them as and when they occur. It is also true that there are many fires, even large ones, which occur under conditions when the fire danger was low and ignitions should not easily have resulted in large fires (e.g. Kraai *et al*. 2013). This means that the unexpected can happen and potentially dangerous fires can occur under apparently unfavourable conditions.

We first provide some information on what is known about the occurrence of fires in fynbos and large-scale climate-system shifts and then on fire occurrence and synoptic conditions. Then we summarise the findings on relationships between large fires and synoptic conditions and, lastly, present the findings of the review of fire behaviour prediction systems. By assessing changes in the phases and strengths of large-scale circulation systems such as the Antarctic Ocean Oscillation, fire managers can get an understanding of typical climatic conditions (e.g. rainfall trends) over the next 5-10 years. An understanding of current changes in atmospheric circulation and synoptic patterns, and surface wind fields can be used to develop fire danger indices (current and future) which integrate wind speed and temperature can be used for seasonal forecasts. For short-term planning and preparedness the projected synoptic conditions for the next 5-10 days can be used in conjunction with fire danger indices to establish levels of preparedness.

4.2.2 Large-scale systems and circulation patterns

Inter-annual variation in the occurrence of fires in fynbos has been shown to be linked to warm, dry fire seasons, with more fires in such seasons than in cooler wetter ones (Wilson *et al*. 2010). These seasons, in turn, are linked to changes in circulation patterns typical of particular phases of the Antarctic Ocean Oscillation (AAO) which influence rainfall (Philippon et al. 2012). When the AAO is in a positive phase (toward the northern end of its range), the fynbos region (Cedarberg to Swartberg) experiences warmer than average conditions, often characterised by periods of hot weather, and slightly higher rainfall, interspersed with dry periods. Using this information, together with historical fire records, and outputs from a regional climate model for seasonal temperature and precipitation, Wilson *et al*. (2010) estimated that fires became more common, and there was a decrease of 4 years in mean fire return intervals from 1950-1975 compared to 1976-2000. They also found some evidence of an increase in fire probability the year after a high rainfall year (because higher rainfall drives faster fuel accumulation), confirming the findings of an analysis of the fire regimes in the Swartberg (Seydack *et al*. 2007).

4.2.3 Synoptic conditions and fires

The relationships between day-to-day weather patterns and fire danger are well known and are the basis for fire danger indexes such as the MacArthur Forest Fire Danger Index (Noble et al. 1980) and those of the United States National Fire Danger Rating System (e.g. Van Wilgen 1984b). These indexes typically use information on temperature, humidity, rainfall and days since the last rain to estimate fire danger. They show clear seasonal and day to day trends which show that fire danger is also linked, at time scales of a few days, to synoptic systems. However, they use historical data and cannot be used to predict what the conditions are likely to be for the next few days. A useful addition would be the ability to predict fire danger in advance. This possibility was investigated by (Southey 2009) who found that fire frequencies or occurrences in different regions of the biome were related to particular synoptic conditions, or sets of conditions, as identified using a pattern analysis technique (Self-Organising Maps) (Kohonen 2001). Fires in the eastern parts of the fynbos biome (Swartberg, Outeniqua) were associated with different synoptic states from those in the west (Cedarberg, Hottentots-Holland) and there were more subtle differences within these two regions. The differences were in line with more recent studies which have found markedly seasonal fire regimes in the western part of the biome and non-seasonal patterns in the south-eastern part of the biome (Van Wilgen et al. 2010, Kraaij et al. 2013a, 2013c). The eastern part of the biome is also characterised by fires in winter under berg wind conditions and extensive fires under low fire danger conditions (Kraaij et al. 2013b). The relationships found by (Southey 2009) indicate that periods of high fire danger can be predicted in advance using the anticipated synoptic patterns, and that these forecasts can differentiate between regions. They also suggest that changes in the frequencies of these synoptic conditions from simulated present to future climates can be assessed, providing additional insights into the impacts of climate change on fire regimes in the fynbos based on actual fire occurrence, an aspect not investigated by (Southey 2009).

4.2.4 Large fires, co-occurrences of fires

4.2.4.1 Single large fires

This component of the project is aimed at establishing the synoptic patterns that are typically associated with large wildfires in the fynbos biome, and then predicting their frequency on days to a season ahead. Once these patterns have been identified, the Weather Services must be consulted about the forecasting because we understand that they have the legal mandate to issue forecasts of weather-related risks. Once agreement has been reached, a module could be developed for the AFIS system which would alert managers when these conditions are forecast to occur.

A preliminary list of large fires have occurred in the biome since 1978 was compiled based on spatial and non-spatial fire data obtained from CapeNature (for the Western Cape province) and from Dr Tineke Kraaij (SA National Parks) for the Tsitsikamma and Outeniqua regions. Fires prior to 1978 were removed because the detailed climate records that will underpin further modelling of the climate are only available from 1978. These data are limited to protected areas, including national and provincial nature reserves as well as designated mountain catchments under the Mountain Catchment Areas Act, but the data also cover a large part of the area under pine plantations.

The two databases were merged and duplicate fires in the Outeniqua region were removed. This left records for 3 261 fires that burnt a total of 2 885 991 ha between January 1978 and December 2012. Analysis of the data showed that most of the area burnt in a few large fires, with 52 fires (1.6% of all fires) accounting for 33% of the area burnt. These fires were all >10 000 ha, and we used this as a threshold for selecting fires for further investigation (Table 8). Most large fires occurred between December and March, with December having the highest incidence of large fires. The winter months have almost no large fires, with only one being recorded in June and none between July and September. The single large fire recorded in June was in the Southern Cape which is subject to berg winds during winter.

Large fires often also occur in the more isolated protected areas where there is sufficient space and fuel for them to spread, and where fire mangers often only actively contain these fires when they approach the wildland-urban interface. The duration of the large fires is known for 45 of the 52 fires, and on average these large fires burn for ca 12 days. Besides the large individual fires that we have identified there are other occasions, when clusters of smaller fires occur over a short time period. Although they may be widely separated, these fires collectively burn considerable areas and we believe they are often also associated with particular weather conditions. This list of large fires has been given to our climate experts and they have undertaken their investigations.

Table 8: The location, dates and size of the 52 largest fires between 1978 and 2012 on record in the fynbos biome based on data supplied by CapeNature and South African National Parks.

Location	Date	Area (ha)			
Cedarberg WA	January 1979	11090.1	Groot Swartberg NR	December 1999	19512.4
Matroosberg MCA	February 1982	11324.9	Doringrivier WA	December 1999	10840.5
Goudveld	November 1984	13124.1	Stormsrivier	June 1999	17687.6
Cedarberg WA	November 1985	18504.3	Koue Bokkeveld MCA	May 2000	11107.2
Kammanassie NR	February 1988	14692.3	Riviersonderend	December 2000	13917.5
Boosmansbos WA	February 1988	13755.6	Riviersonderend MCA	December 2000	11082.1
Matroosberg MCA	October 1988	12939.7	Cedarberg WA	December 2002	11618.0
Cedarberg MCA	December 1988	58485.3	Garcia NR	January 2003	11717.2
Haweqwa NR	February 1990	32315.2	Kammanassie NR	December 2003	12382.1
Kogelberg NR	March 1991	10258.2	Cedarberg MCA	December 2004	15615.5
Langeberg -Oos/East MCA	May 1991	11761.7	Hawequas MCA	December 2005	12774.8
Matroosberg MCA	January 1992	15624.5	Haweqwa NR	December 2005	12362.8
Riviersonderend MCA	December 1992	16829.2	Lottering	October 2005	29854.6
Grootwinterhoek WA	March 1995	16736.2	Walker Bay NR	January 2006	32260.1
Towerkop NR	December 1997	14568.3	Bergplaas / Karatara	November 2007	13170.6
Cedarberg MCA	March 1998	26491.9	Kogelberg NR	December 2008	11736.2
Keurboomsrivier	April 1998	41901.7	Groot Swartberg NR	January 2009	13004.4
Haweqwa NR	February 1999	35503.3	Cedarberg WA	February 2009	10075.9
Jonkershoek NR	March 1999	27099.6	Grootwinterhoek WA	March 2009	34323.5
Grootwinterhoek WA	March 1999	16153.0	Riviersonderend	December 2009	16010.7
Matroosberg MCA	April 1999	16396.2	Buelilliesbush	March 2009	23934.6
Riviersonderend MCA	November 1999	13579.4	Swartberg East NR	January 2010	13743.8
Kogelberg NR	November 1999	12732.0	Swartberg East NR	January 2010	10938.6
Boosmansbos WA	December 1999	25380.3	Hawequas MCA	March 2011	35494.7
Langeberg -Wes MCA	December 1999	22112.8	Kogelberg NR	March 2011	13291.1
			Waterval NR	January 2012	13839.2
			Kammanassie NR	February 2012	15636.6

4.2.4.2 Co-occurrences of fires

The analysis of the fire history also identified that there were particular years when clusters of fires, sometimes including the large fires identified above, occurred over a short time (days to weeks). Although not contiguous and often spread across the biome, these fires collectively burnt considerable areas. We believe these occasions with many fires are also associated with particular weather conditions. Temporal sequences of fires were selected so that the gaps between successive reports of fire ignitions were not more than one day and large fires were included. In most cases the fires during the selected periods were also widespread. Spatial data for the Tsitsikamma fires were not available so they cannot be shown in the maps. They were, however, taken into account in selecting periods for more detailed analysis. The first step was to examine the area burnt by fire each "fire year", where a fire year begins in November and ends in October. In each case the "year" was shifted to give totals from November to October (i.e. 1980 extends from 11/1979 to 10/1980).

The area burnt in each fire year varies very widely from about 19 000 ha in 1978 to 210 000 ha in 1999 with relatively small areas per fire year from 1978-1987, 1991-1997, 2001-2004 and 2007-2008 (Figure 4). Some of the variation, particularly the limited areas burnt from 1978-1987, may be due to less complete reporting of fires, especially prescribed fires. The 75th percentile for the area burnt in a fire year is about 100 000 ha and the 90th percentile about 150 000 ha. Thus, fire years such as 1988, 1989, 1998-2000, 2005, 2006, 2009, 2010 and 2011 are clearly exceptional. The fact that they are followed by years with a lower total are burnt is probably to be expected because they would have left large areas which would have been too young to burn for at least 3-5 years.

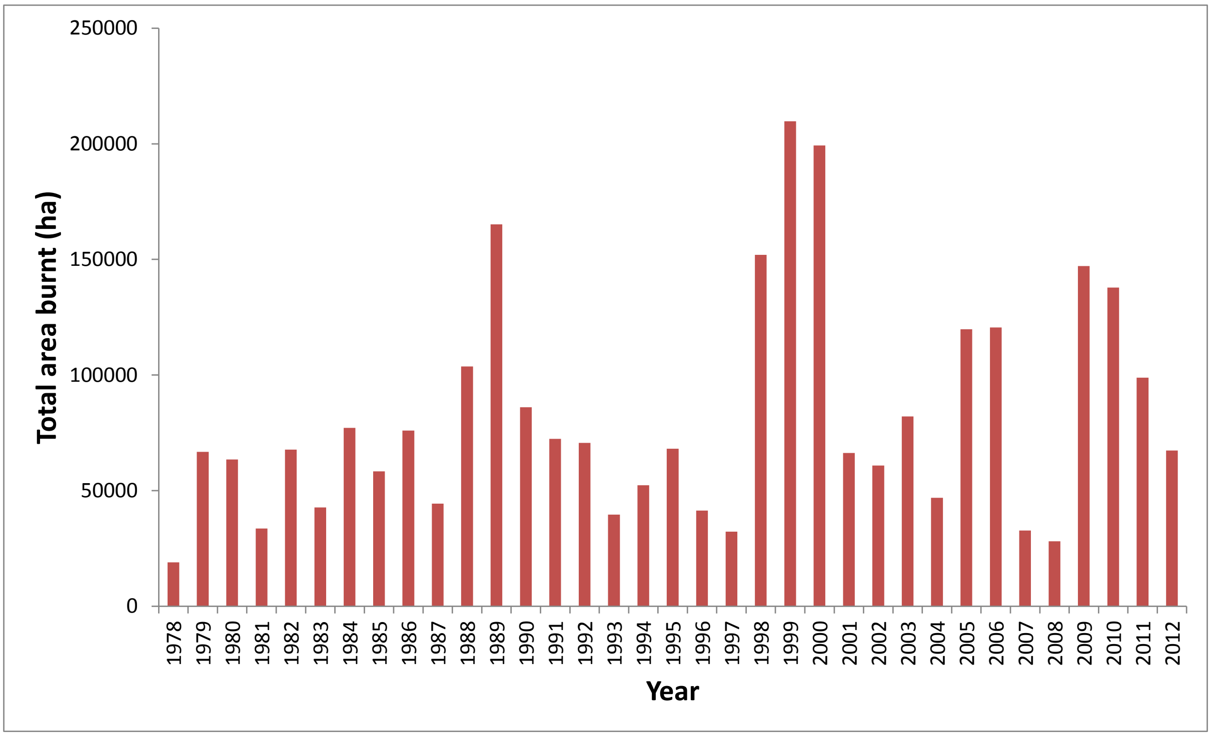


Figure 4: Areas burnt by fire year where the year extends from November in one year to October the next year and all fires are counted as falling in the second year (thus 1978 runs from November 1977 to October 1978).

The effects of the variation in the area burnt are also evident in the cumulative area burnt (Figure 5). When the cumulative area burnt is compared with the cumulative mean annual area burnt (about 81 450 ha per year), the cumulative actual area remains consistently below the cumulative mean until 1998, 1999 and 2000 when it rapidly approaches the mean. From 2001 onwards the area burnt each year has remained much closer to the mean, but at no point did the cumulative area curve cross the mean curve though they met in 2011. At least part of the limited area burnt per year in the early years is due to under-reporting but it does seem that less area may have burnt in those years than is the case from 2000 onwards which is in line with the findings of Wilson et al. (2010). Even though there have been several years since 2000 when very large areas burnt, none of these seem have been exceptional compared with the others over this period.

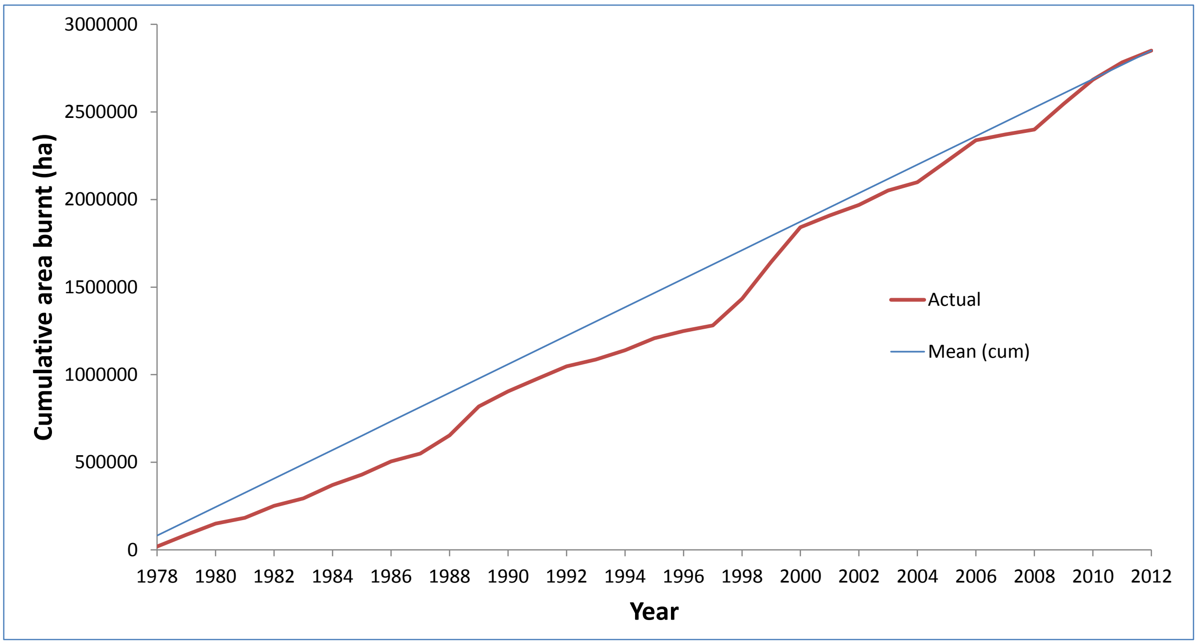


Figure 5: A comparison of the actual cumulative area burnt with the cumulative annual mean area burnt (81 450 ha per year) from 1978-2012.

Separating the fire-year into its summer (November-April) and winter (May-October) periods shows up some different patterns (Figure 6). This analysis shows that in some years a large area was burnt but essentially only in the summer months (e.g. 1989, 2009) whereas in other fires during the winter made a substantial contribution.

In the winter of 1999 there were a number of large fires in the southern part of the biome where the rainfall is bimodal and fires often occur in association with berg winds. The large area burnt followed after a summer fire season when very large areas were burnt as well. In contrast, the extensive fires in the 2000 fire year occurred primarily in the summer. The 2005 fire year is unusual as it is the only one in the record where the area burnt in fires in the winter exceeded the area burnt in the summer months.

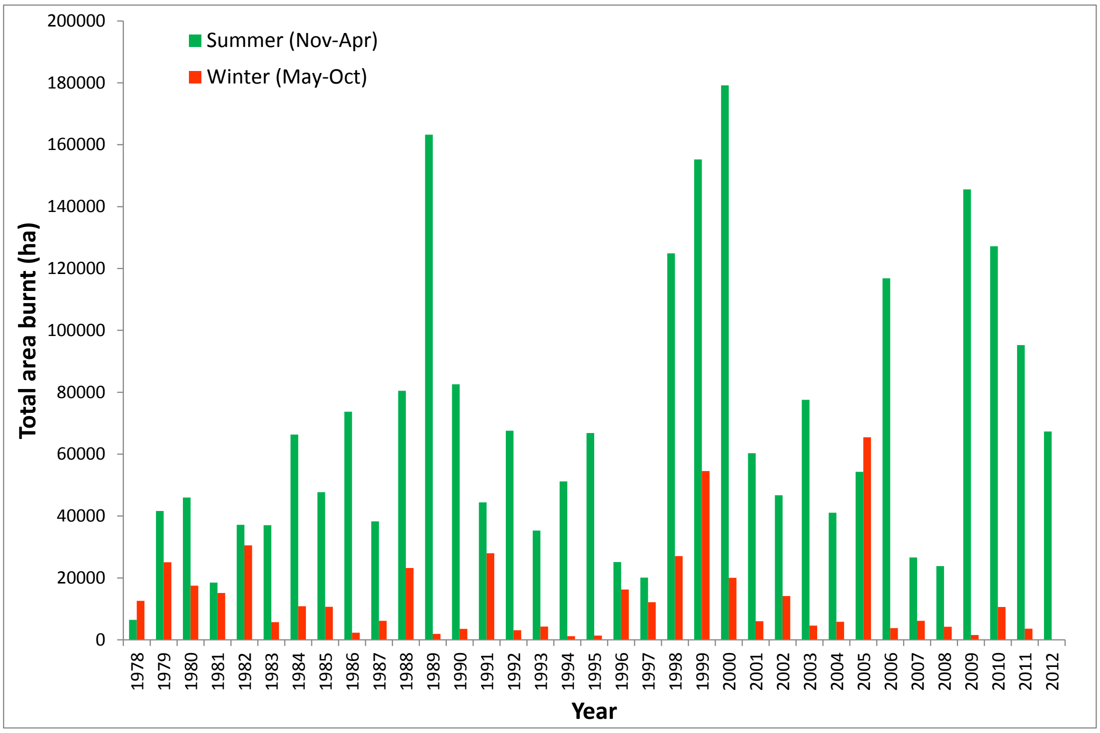


Figure 6: Area burnt per fire-year and season where the fire-year was split into its summer and winter periods (for an explanation of the fire-year see Figure 4).

When this analysis is refined by identifying exceptionally large areas burnt by year and months (i.e. those where the area burnt per year and month exceeded the 90th percentile), there are a number of periods of 2-3 months when exceptionally large areas were burnt (Table 9). For example January and February of both 1989 and 1990 were characterised by large areas burnt but there was only one exceptionally large individual fire in those four months. The period from February 1999 to January 2000 was exceptional in both the number of (consecutive) months when very large areas were burnt as well as the number of exceptionally large individual fires (10). The total area burnt in the selected years and months (Table 9) comes to 52% of the total area burnt in the full record.

A few of the large individual fires (>10 000 ha) did not coincide with years and months when an exceptionally large total area was burnt (Table 10). In each year and month there was only one of these fires and they were smaller than the mean for all fires >10 000 ha (18409 ha). Only in January 2003 and January 2009 did they precede or follow months in which very large areas were burnt. This suggests that exceptionally large individual fires do not always coincide with years and months when large areas were burnt overall, and some may be large simply due to unusual circumstances. This is probably to be expected given that such large fires require the right combinations of dry fuels and an ignition source, spatial continuity of fuels, and weather conditions favouring spread.

Table 9: Months and years when total area burnt in fires exceeded the 90th percentile of the area burnt by year and month for the entire record. The number of large fires (individually > 10 000 ha) in that year and month is also shown.

Year	Month	Area (ha)	Large fires
1984	4	25805	0
1985	11	41290	1
1988	2	44258	2
1988	12	96767	1
1989	1	21953	0
1989	2	19338	0
1990	1	19626	0
1990	2	45790	1
1991	5	26451	1
1992	1	28109	1
1992	12	19299	1
1995	3	35995	1
1997	12	31929	1
1998	3	27903	1
1998	4	42803	1
1999	2	51549	1
1999	3	62754	2
1999	4	23286	1
1999	6	21675	0
1999	11	30617	2
1999	12	109015	4
2000	1	20727	0
2000	12	33927	3
2002	3	26012	0
2002	12	40870	1
2003	12	21133	1
2004	12	25444	1
2005	3	19561	0
2005	10	57343	0
2005	12	38340	2
2006	1	49181	1
2009	2	44879	1
2009	3	63600	2
2009	12	32488	1
2010	1	48349	2
2010	2	25839	0
2011	3	63130	2
2012	1	44923	1
2012	2	20935	1

Table 10: Exceptionally large fires (>10 000 ha) which did not coincide with periods when large areas were burnt (Table 9).

Year	Month	Number of fires	Area burnt (ha)
1979	1	1	11 090
1982	2	1	11 325
1984	11	1	13 124
1988	10	1	12 940
1991	3	1	10 258
2000	5	1	11 107
2003	1	1	11 717
2007	11	1	13 170
2008	12	1	11 736
2009	1	1	13 004

4.2.4.3 Selected periods with co-occurring fires indicating unusual conditions

The years and months where the total area burnt exceeded the 90^{th} percentile (Table 9) were individually examined to see whether there was evidence of spatial of temporal co-occurrence across the biome or with portions of the biome. The periods of late December 1988 and late January 1999 are good examples (Figure 7). On 28 December 1988 a set fires was ignited by lightning in the Cedarberg, Matroosberg, Jonkershoek, Hottentots-Holland and western Riviersonderend. Lightning fires were also reported on 8-9 and 18 December 1988.

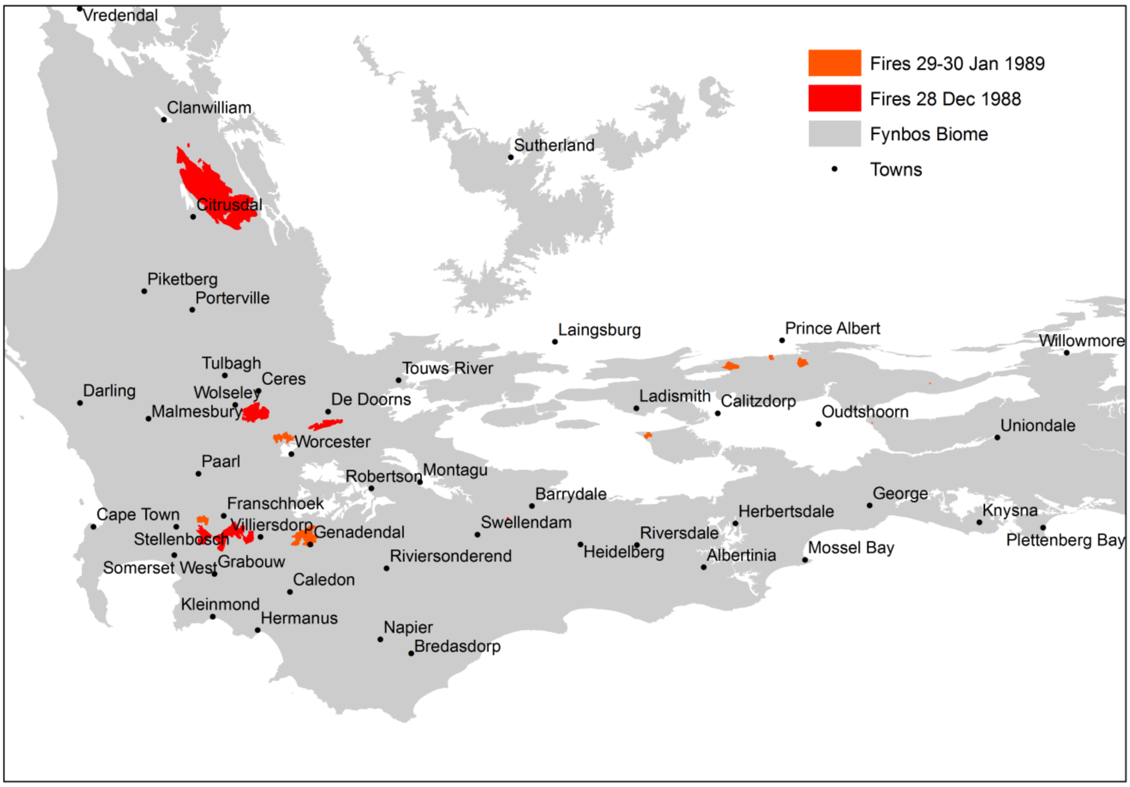


Figure 7: The location of fires which were reported to have started on 28 December and 29-30 January 1989. There were additional small fires which are not visible at this scale (e.g. east of Oudtshoorn).

In January 1989 the geographic spread of the fires was much wider, extending from the Jonkershoek Mountains in the west to the Groot Swartberg in the east with a small, naturally caused fire reported at Lottering[1] in the Tsitsikamma Mountains. The fires in the eastern part of the biome were all caused by lightning and there were additional lightning-caused fires on 1-2 January in the Koue Bokkeveld Mountain Catchment Area (MCA) and the Hottentots-Holland.

The fire year 1999 stands out as having the greatest total area burnt in the entire record, nearly 210 000 ha. Many fires, many of them large, occurred throughout the biome from the west to the east. They included large areas burnt in the winter months (especially June) in the Tsitsikamma region. There were particularly extensive fires in late November to early December and again from mid- to late-December (Figure 8). A number were ignited by lightning on 1, 9, 10, 12, 13, 16, 19 and 23 December. The lighting fires on the 1st occurred in the western Langeberg and Groot Swartberg but those between the 9th and 23rd were all confined to the western part of the biome.

[1] Many of the fires in the Tsitsikamma cannot be shown as there are no spatial data for these fires.

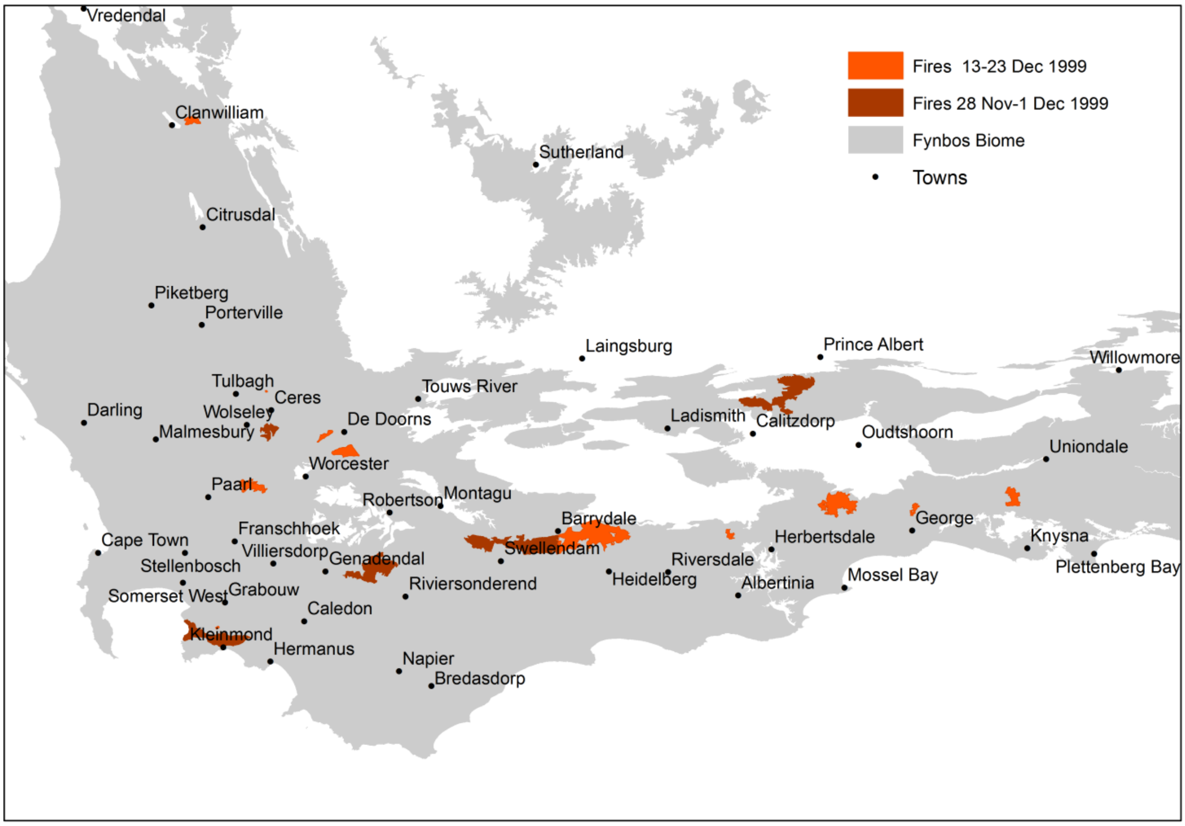


Figure 8: The location of fires which were reported to have started between 28 November and 1 December and 13-23 December 1989. There were additional small fires which are not visible at this scale.

The period from December 2009 to February 2010 was also characterised by a large number of fires. For example, from 2-24 January there were 35 reported fires across the biome from Hawequas MCA in the west to Blueliliesbush in the Tsitsikamma and the eastern Swartberg (Figure 9). Lightning-caused fires were reported on 2, 5, 14 and 22 January 2010, all in the eastern part of the biome. On the 10th of February 2010 there were four reports of lightning ignited fires, two in the west (Cedarberg MCA, Hawequas Nature Reserve (x2)) and one in the east (Kammanassie MCA). On the 21st of February and additional fire caused by lightning was reported in the Cedarberg. None of these fires exceeded 10 000 ha although the one ignited on the 10th of February burnt 9 544 ha.

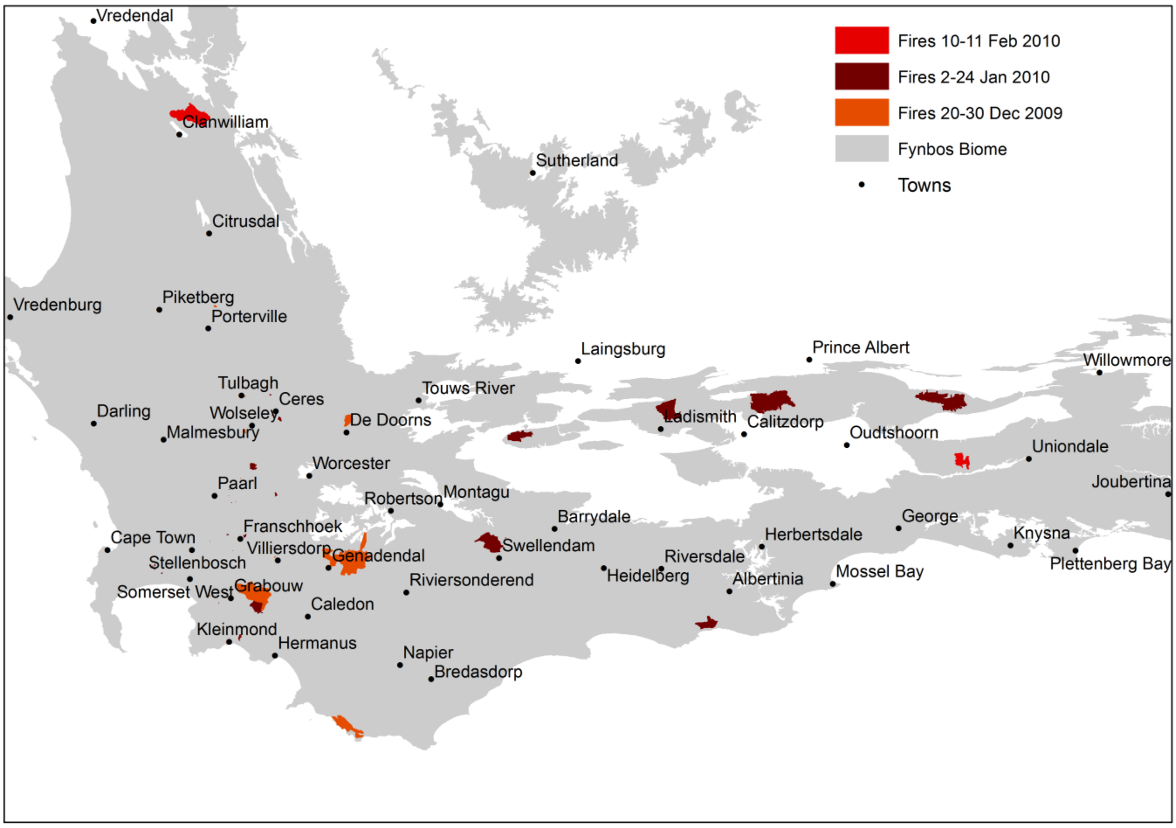


Figure 9: The location of fires which were reported to have started from 20-30 December 2009, 2-24 January 2010 and 10-11 February 2010. The gaps between successive fires from 2-24 January were no more than a day. There were additional small fires which are not visible at this scale.

The fire-year 2005 had an exceptionally large area burnt in the winter period (Figure 6), with nearly 6 500 ha burnt in May and more than 57 000 ha in October, almost all in the Tsitsikamma area. Nearly 5 300 ha was burnt in a single fire in the Outeniqua mountains which began on 20 May and was caused by people making a fire to warm themselves. Additional, small fires occurred on 21, 22, 29 and 31 May, all either of unknown causes or accidental. In October 2005 there were 14 fires reported, mostly between the 27th and 31st with two lightning-caused ones on 27 and 30 October in the Groot Swartberg. The largest fire was 29 855 ha and began at Lottering, apparently due to natural causes, followed by ones of 8 612 ha (16th, Witelsbos, natural), 7 432 ha (27th, Witelsbos/Kromrivier, accidental) and 5952 ha (30th, Groot Swartberg, lightning).

In 1999, June was characterised by an exceptionally large area burnt (21 657 ha, Table 1) but large areas were also burnt in July, August and October (11 139, 9 539 and 8 899 ha respectively). Again, nearly all these fires were in the south-east (Tsitsikamma) or eastern interior (Groot Swartberg) with most being in the Tsitsikamma. The exception was a fire in DuToitskloof (Hawequas MCA) which began on 13 June and burnt about 2 177 ha; its cause was unknown. The largest fire was 17 688 ha which began in the Langkloof on 13 June and burnt across to the Storms River area. The next largest was 8 279 ha in the Groot Swartberg; it began on 12 July and its cause is not known. On 28 August a lightning storm started five lighting fires in the western and eastern Langeberg (east and west of Barrydale) but only one was larger than 100 ha. On the same day a fire began at Ruitersbos (near Mosselbay) and burnt 7 209 ha; it was apparently of human origin. In October 1999 there were two large fires: 4 296 ha in the Kammanassie MCA (cause unknown) and 3 753 ha in the Witsenberg (Winterhoek MCA) attributed to a falling rock. These records confirm that when exceptionally large areas have been burnt in fires in the winter months, these are generally confined to the south-easternmost part of the biome.

The analysis of the historical records indicates that there have been particular years when exceptionally large single fires and clusters of fires (often including large single fires) occurred and years when limited areas were burnt. Fire years with exceptionally large areas burnt include 1989, 1998-2000, 2005, 2006, 2009 and 2010 and those with limited areas burnt include 1987, 1993, 1996, 1997, 2007 and 2008. The analysis of the relationship between winter rainfall and atmospheric systems found that wet spells during May-June-July are more frequent, last longer and are wetter during El Niño years than during La Niña years as found by Philippon et al. (2012). The fire years with extensive fires tend to coincide with La Niña years and those with less extensive fires with El Niño, although the fire year 2000 (with the most area burnt on record) was characterised as an El Niño year. However, the possible relationships between wet (and dry) spell characteristics need to be assessed more rigorously in the light of other factors before any firm conclusions can be drawn.

4.3 Short-term prediction of fire danger conditions using synoptic states

This section reports on an analysis which extended the initial investigations done by Southey (2009) using the data on the single large fires reported in section 4.2.

4.3.1 Methods

During the period from 1978-2012 there were 51 large fires distributed over the Fynbos biome in South Africa. The observed duration of these fires ranged from 4-40 days. The exiting date of 7 fires is unknown. For the purpose of the synoptic pattern classification, these fires are treated as active for 1 day only. Therefore, in total 560 large fire days occurred during 1978-2012.

The non-linear statistical procedure known as Self-Organising Maps (Kohonen 2001) was used to characterise and classify the low-level and atmospheric circulation patterns (850 hPa geopotential height fields) which occurred during the 560 large fire days into synoptic conditions or nodes. The atmospheric circulation data was obtained from the National Centres for Environmental Prediction (NCEP) (Kalnay et al. 1996) and has a 2.5° longitude by 2.5° latitude resolution. The SOM was developed on anomaly fields, as the circulation (and therefore the wind) is more dependent on the gradient than the magnitude of the geopotential heights. The daily 1200Z anomaly fields were calculated relative to the 1200Z domain average of that day. The domain considered for the statistical analysis is bounded by 27.5° S to 35° S and 15° E to 27.5° E (Figure 10). The low-level circulation over this domain is known to be instrumental in the potential occurrence of fires over the Fynbos regions (e.g. Southey 2009). The 850 hPa pressure level was chosen to accommodate the elevation of the interior plateau (~1.5 km) over the interior because certain synoptic patterns favour air flows from the plateau seawards and the resulting berg winds can generate conditions conducive to fires (Van Wilgen 1984b, Geldenhuys 1994).

The analysis was set up to identify 12 (3 rows x 4 columns) synoptic nodes based on their frequency of occurrence in the seven fynbos fire climate zones (Van Wilgen 1984b, Van Wilgen et al. 2010): Southwestern Interior, Boland, Overberg, Klein Karoo, Langeberg, Garden Route and Tsitsikamma. Comparison with a 5x4 and a 7x5 node SOM showed that the main synoptic patterns associated with fire days in each region were consistent so the 12-node configuration was chosen. It also improves interpretation of the results and is consistent with Southey (2009) who also found 12 nodes to work best. Composite maps of the average daily 850 hPa and 500 hPa geopotential height fields for each of the 12 nodes were subsequently derived (Figure 10). The benefit of composite maps for each node is that the synoptic circulation over a larger domain is obtained, even though the classification of the synoptic patterns is based on the smaller domain relevant to the occurrence of fires.

4.3.2 Results

The Self-Organising Map (SOM) of the geopotential height anomalies shows the synoptic states associated with the occurrence of large fires with states 3, 11 and 12 having the strongest associations with fires (Figure 10). The same patterns are shown in the geopotential height fields for each of the 12 nodes (Figure 11).

The regional association of large fires with synoptic patterns is best illustrated by comparing large fires occurring over the Southwestern Interior to large fires occurring over the Garden Route and Tsitsikamma (Figure 12). Large fires over the Southwestern Interior are favoured by synoptic patterns which are associated with low-level winds with an easterly wind component, in particular with synoptic patterns resulting in strong low-level winds (Figure 10: nodes 4, 8 and 12). This synoptic configuration typically occurs with a high pressure belt south of the country, extending a ridge from the east over the country with a trough over the western interior. Favourable conditions for the occurrence of fires are enhanced when the surface trough is located in the extreme west or along the west coast. On the other hand, large fires over the Garden Route and Tsitsikamma are mostly associated with north-westerly winds as troughs near the country (Figures 10 and 11: nodes 1, 2 and 5). Troughs accompanied by a tight gradient that result in strong north-westerly flow, is in particular favourable for the occurrence of fires over these regions (Figures 10 and 11: node 1).

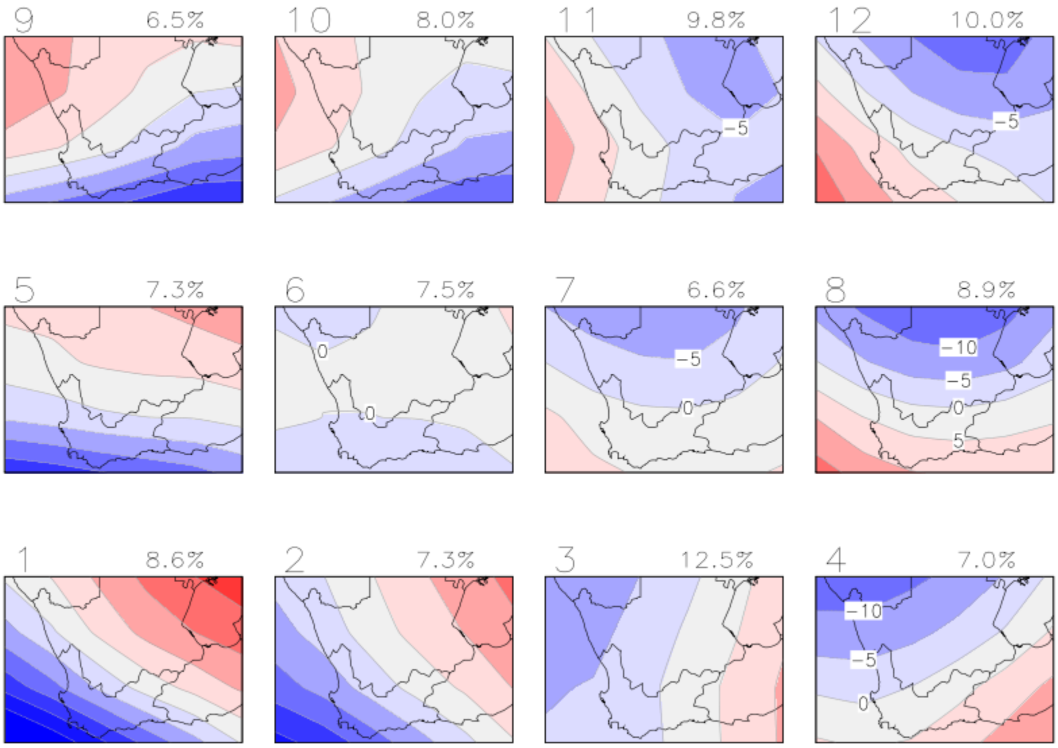


Figure 10: Self-Organising Map of 850 hPa geopotential height anomalies based on the 1200Z instantaneous NCEP reanalysis data for the days of large fire occurrences. The node numbers and node frequencies (%) are indicated for each node.

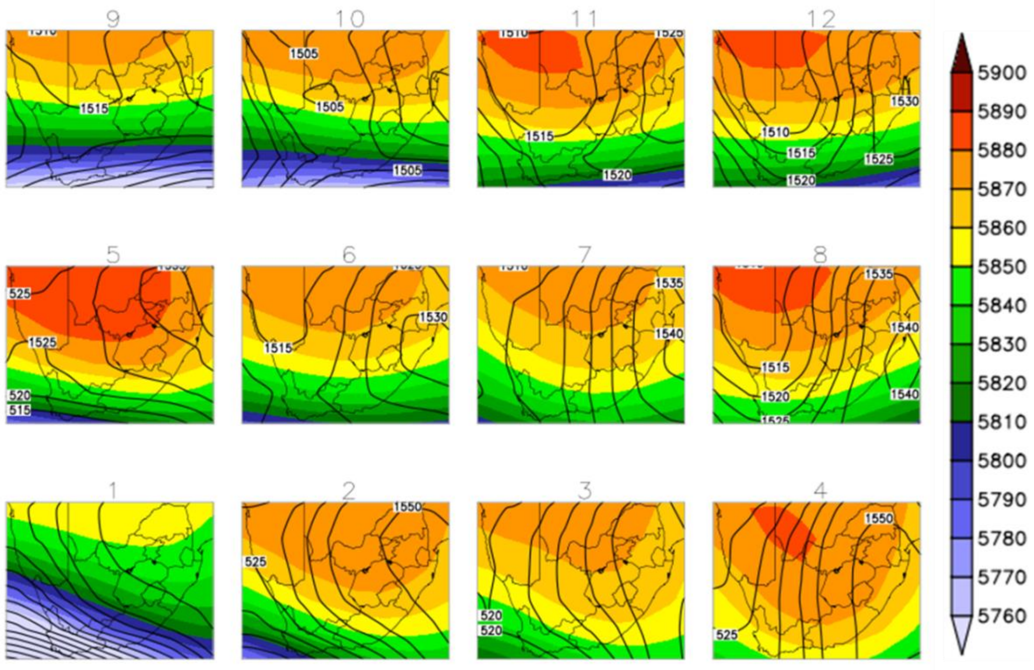


Figure 11: Composite maps of the 850 hPa (contour) and 500 hPa (shaded) geopotential height fields for each of the 12 nodes as seen in Figure 10.

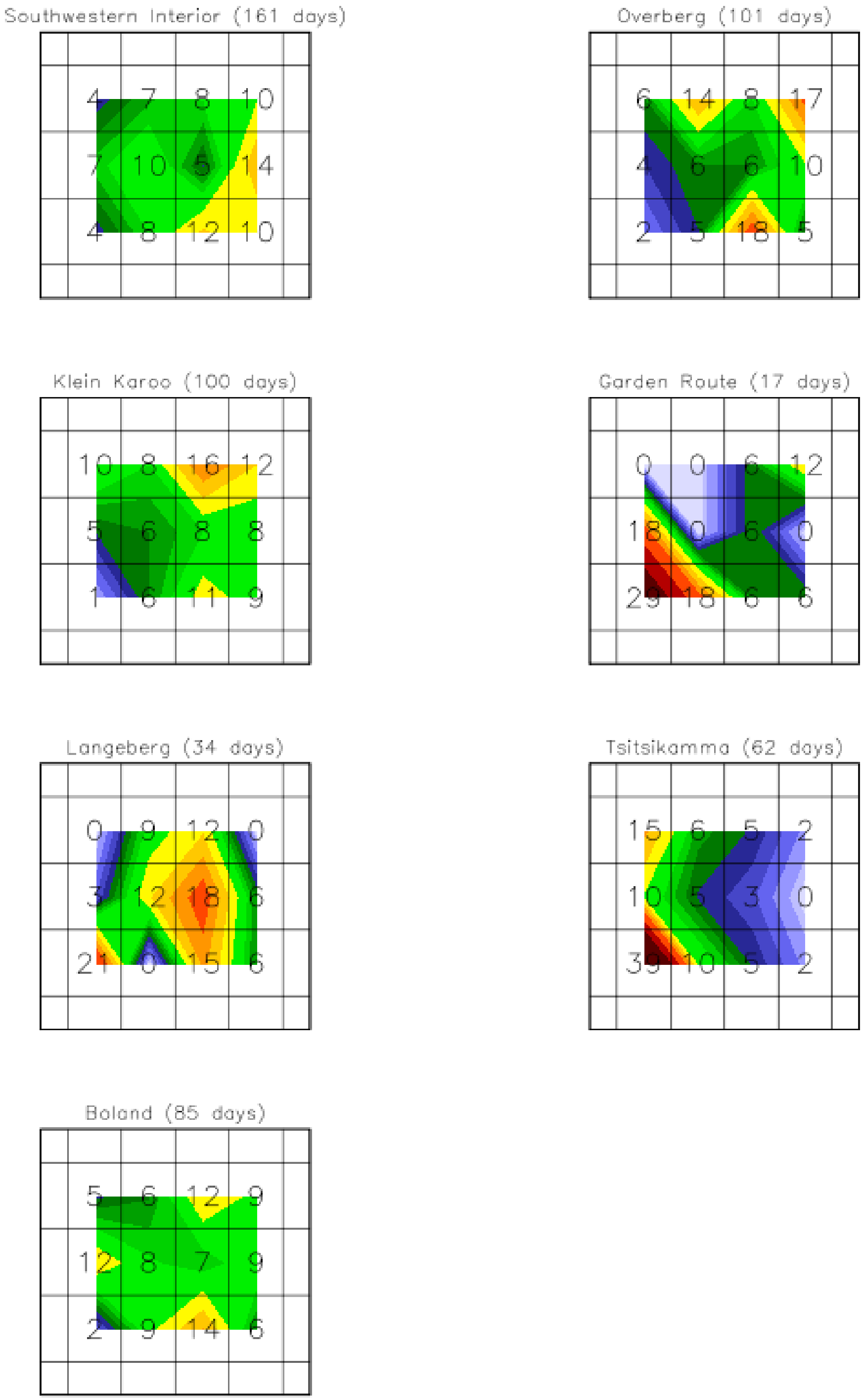


Figure 12: The regional occurrence of large fires for each SOM node. The node frequency is expressed as the percentage of the number of days that a large fire was reported over a region. The duration of large fires is indicated in brackets.

Whereas large fires over the Southwestern Interior, the Garden Route and the Tsitsikamma are favoured by synoptic patterns represented by nodes that are clustered together, large fires over the Klein Karoo, Langeberg, Boland and Overberg are associated with a larger variety of synoptic patterns. This is especially true for the Langeberg (e.g. node 1 vs node 12). The Klein Karoo, the Overberg and the Boland (to a lesser extent), are generally not associated with the occurrence of fires during the presence of frontal systems (north-westerly flow, node 1).

These findings concur with Southey (2009) who found that the frequency fire events in the western part of the biome was correlated with synoptic states characteristic of the southernmost extent of a tropical easterly wave low. In contrast, fires in the eastern part of the biome were correlated with a synoptic state characteristic of a tropical temperate trough. Easterly wave lows were coupled with strong atmospheric convection whilst tropical temperate troughs were associated with pre-frontal conditions and strong, hot and dry winds.

Strong convection systems are associated with lightning which is a known cause of fires in the Fynbos biome (Kruger and Bigalke 1984, Van Wilgen et al. 2010). The latter state corresponds with the well-known connection between large fires in the southern and eastern parts of the biome and berg wind conditions (Horne 1981, Van Wilgen 1984b, Geldenhuys 1994, Seydack et al. 2007, Kraaij et al. 2013a). The results are also consistent with recent research which has found a clear shift in the ecologically desirable season for fires between the western and eastern parts of the biome. In the eastern part, winter fires result in good recruitment of Proteaceae (Heelemann et al. 2008, Kraaij et al. 2013d) unlike recruitment in the western region which is poor after winter fires and best after summer or autumn fires (Jordaan 1982, Bond et al. 1990, Van Wilgen and Viviers 1990).

4.4Seasonal fire danger prediction using synoptic typing

This section reports on an assessment of the potential for predicting the seasonal fire hazard based on the expected climatic conditions, and is similar to the forecasting used for crop yields. The case study area selected was Garden Route and Tsitsikamma regions where fires are expected during autumn and winter in berg wind conditions (Geldenhuys 1994). Thus the period selected for the predictions was June, July and August 2014. A number of studies around the world have shown that there are relationships between large-scale atmospheric and ocean circulation systems and the occurrence of fires. There is an ongoing debate about the relative importance of the roles fuels and climate in driving exception fire seasons and events (Schoennagel et al. 2004, Westerling et al. 2006, Meyn et al. 2007, Koutsias et al. 2012), especially in North America where decades of fire suppression resulted in high fuel loads and massive fires. Both factors appear to be involved.

In South America, fire activity at an annual and seasonal timescale is linked to large-scale climate systems and their interactions, with droughts and high temperatures driving fire activity particularly in the Mediterranean and temperate forest regions of Chile (Veblen et al. 2008) but also in the Amazon (Chen et al. 2011) and in Australia (Harris et al. 2014). These interactions are complex, and typically involve certain coincidences of states which result in conditions conducive to fire activity and other coincidences which are not conducive to fire activity. For example, the states of the southern annual mode appear to determine the effects of systems such as El Niño and La Niña (Holz and Veblen 2012), interactions which also influence climatic conditions over southern Africa (Philippon et al. 2012) and fires in fynbos (Wilson et al. 2010). Very large fires account for the majority of the area burnt (see section 4.2) and also affect human well-being, air quality and stretch fire suppression resources to their limits (Meyn et al. 2007, Barbero et al. 2014). Wetter rain seasons than normal in grass-dominated fuels increase the potential for very large fires in the succeeding fire season (Barbero et al. 2014) and sometimes the one after as well (Govender et al. 2006, Archibald et al. 2009). In systems where litter and woody biomass is important for fires, such as forests, the occurrence of extended droughts enhances the probability of very large fires (Barbero et al. 2014).

The general increase in air temperatures is making conditions more favourable for the occurrence of massive fires (Flannigan et al. 2009, Keane et al. 2013). Although South Africa has never experienced fires on the scales of the very large ones experienced elsewhere (100s of km^2 (Haynes et al. 2010)), the potential for large fires is likely to be increasing. The fynbos is a particularly vulnerable vegetation type because it is able to carry fires at a much younger age than is ecologically desirable (Heelemann et al. 2010, Van Wilgen et al. 2010, Kraaij and Wilgen 2011, van Wilgen 2013). Current indications are that fire recurrence intervals in the Boland (Kogelberg to Winterhoek) are too short and populations of some rare Proteaceae with long reproductive maturation periods have already become extinct (A. Schutte-Vlok pers. comm. 2015). Those fires are sustained largely by the fine fuels produced by the Restionaceae and grassy components (sedges, grasses) and by high temperatures because the fuel loads still include high proportions of live fuels. This means that it is important to understand the potential for large fires, and fires in young fynbos, so that the occurrence and extent of ecologically and economically damaging fires can be minimised through fire preparedness and through social interventions such as Fire Wise communities and educational outreaches.

4.4.1 Methods

The forecast system was developed in two phases: (a) characterising the relationship between synoptic patterns and high fire danger days for the season and region of interest using Self-Organizing Maps (SOMs); and (b) mapping the synoptic patterns identified by the SOMs to outputs from the Conformal-Cubic Atmospheric Model (CCAM) global climate model.

The first relationship was characterised by utilizing daily atmospheric circulation reanalysis data from the National Center for Environmental Prediction (NCEP) (Kalnay et al. 1996) in order to classify the seasonal synoptic patterns by employing a non-linear clustering technique, the self-organizing map (SOM) (Kohonen 2001). The daily instantaneous 12Z 850 hPa geopotential height fields for the period 1979-2010 were used for the classification of twelve synoptic patterns (Figure 11) for 3-month rolling seasons. In order to determine which specific synoptic patterns are linked to a high likelihood of fires, the daily McArthur forest fire danger index (FFDI) was used. It may be noted that the daily FFDI's need to be calculated for each region (e.g. Southwestern Interior, Tsitsikamma) separately, as the synoptic patterns associated with fire-weather are dependent on the region where the fire occurs. Station data were employed for calculation of the FFDI.

For identification of the subset of synoptic patterns associated with fire-weather for a specific region, daily FFDI's that correspond to the 90th percentile or higher (for the period 1979-2010) were mapped to the twelve synoptic patterns identified by the SOM (Table 11). The JJA fire-weather synoptic patterns for the Garden Route and Tsitsikamma regions are represented by nodes 4, 8 and 12 (Figure 11). Before producing a fire-risk outlook of a probabilistic nature, the climatological terciles for each of the synoptic patterns for the 3-month rolling seasons were determined.

Table 11: Percentage occurrence of days during JJA for the period 1979-2010 when the 90th percentile of the FFDI is exceeded relative to the average occurrence for each of the synoptic patterns as shown in Figure 4.

Node 9 0.2%	Node 10 0.0%	Node 11 2.1%	Node 12 20.6%
Node 5 0.9%	Node 6 1.5%	Node 7 16.7%	Node 8 43.9%
Node 1 0.0%	Node 2 2.0%	Node 3 6.9%	Node 4 26.7%

The second phase in the fire-risk forecast system involved mapping of a 12-member ensemble forecast of the 850 hPa geopotential height fields produced by the Conformal-Cubic Atmospheric Model (CCAM) to the synoptic patterns identified by the SOM (Figure 11). The CCAM is run operationally every month at the CSIR. The probability of the frequency of each synoptic pattern occurring at below-normal, near-normal and above-normal rates, relative to the climatological terciles, is determined for each ensemble member. The forecast probabilistic occurrence of each synoptic pattern for each tercile, as determined by the ensemble members, is expressed as a percentage.

4.4.2 Results

An outlook of above-normal (*below-normal*) occurrence of synoptic patterns 4, 8 and 12 indicates an elevated (*decreased*) risk of fires relative to the climatological occurrence of fires. The fire risk outlook valid for June, July and August (JJA) 2014 was then forecast based on the initial conditions in February 2014 (Figure 12). The forecast was that there will be a normal to greater than normal risk of high fire conditions from June-August 2014 which was consistent with the dryer than normal conditions in the Outeniqua and Tsitsikamma region during this period.

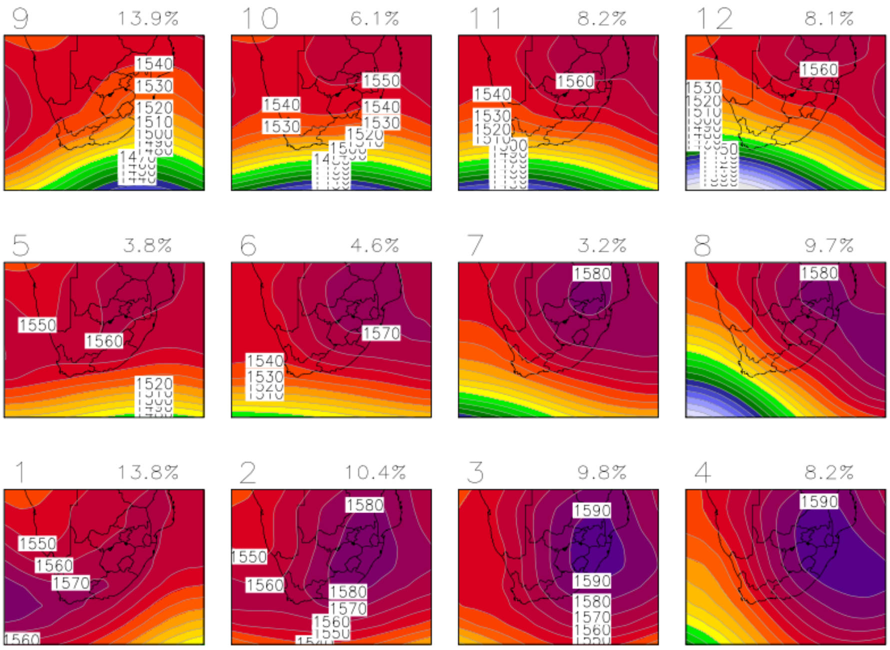


Figure 13: SOM classification of JJA daily NCEP reanalysis 850 hPa geopotential height fields for the period 1979-2010.

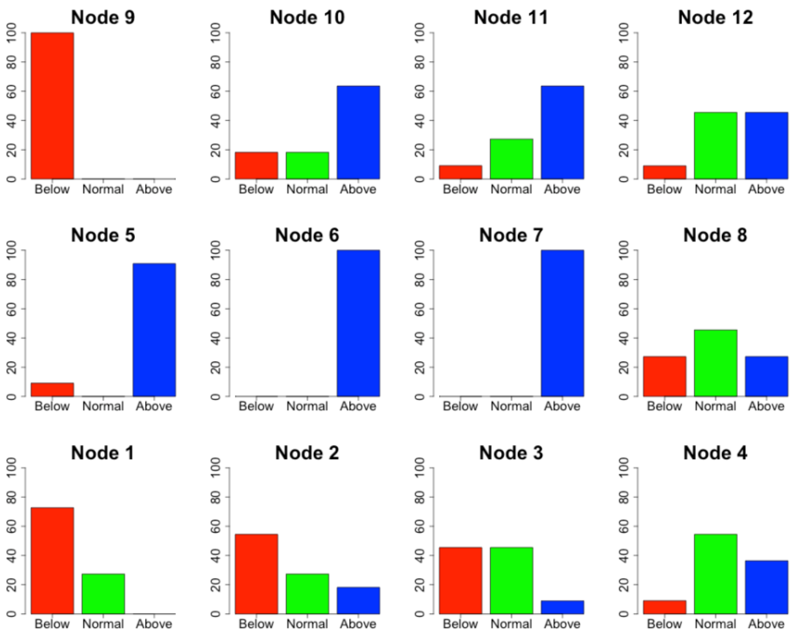


Figure 14: The forecast probabilistic occurrence of different synoptic patterns for June, July and August 2014, based on the CCAM forecast initialized in February 2014. The Y-axis gives the probability in percent.

Although this approach needs further testing and development it clearly indicates that seasonal forecasts which indicate whether there are likely to be more than the normal numbers of high fire danger days can be predicted. Since the climate models are run on a regular basis and the seasonal prediction algorithm can be automated, a forecast of this kind could be distributed via the AFIS system. The prediction model also needs to be tested to sure that it is sufficiently reliable for operational use and for seasonal planning of fire preparedness. The possibilities of implementing such a prediction system need to be investigated in more depth in collaboration with the CSIR climate modelling group, the AFIS team and the Weather Services who, we understand, have the legal mandate to issue such forecasts.

4.5Fire behaviour prediction models

4.5.1 Introduction

This component was introduced during the final stage of the proposal development because the Working on Fire management felt strongly that the ability to model 'real-time" fire behaviour would be very useful. The researchers were, however, concerned about the known limitations on the ability of these systems to simulate 'real-time" fire behaviour sufficiently reliably and accurately. In the end it was included and the original terms of reference for this study called for the following:

- Develop (or modify an existing) software tool for predicting fire behaviour in Fynbos; and
- Develop spatially explicit wildland fire behaviour models using weather conditions to predict spread and other key parameters.

This task proved to be considerably more complex than it seems on the surface because of: (a) limitations in the available models, (b) the sensitivity of fire behaviour models to key inputs, notably acceptable information on the weather and on fuels (see McCaw et al. 2012, Cruz et al. 2013), (c) the inability of models to adequately simulate fire behaviour under extreme conditions (see Cheney et al. 2012); and (d) the generally mountainous and rugged terrain where many wildfires in fynbos occur (which results in complex fine-scale wind patterns, spatially heterogeneous fuels and differences in fuel moisture and temperature).

In their proposal for this study the CSIR clearly indicated the limitations of these models and stated: "*We would however warn against unrealistic expectations regarding site-specific fire behaviour predictions. Our understanding is that the ability to accurately model fire behaviour in highly variable landscapes is at best very limited, and examples of successful operational applications are not common. We propose to investigate the state of the science, to identify and evaluate potentially useful approaches that could be integrated into decision-support systems, and would assist fire managers in meeting their needs. We plan to get inputs from international leaders in this field in Australia and the United States in our investigations*". Following negotiations with the Forest Fire Association on the scope of this study, and given the limited funds available for this study, there was agreement the terms of reference would be changed to:

- Perform a "*review of available fire behaviour prediction models, and illustrate how these can be combined with information on fire weather, fuel distribution (based on vegetation types and post-fire age) and topography to produce spatially-explicit estimates of future fire risk*".

4.5.2 Summary of the review

The CSIR then made contact with several international experts in this field, collated and reviewed the literature, and established the following:

- Fire spread models can be divided into three broad types (Keane et al. 2004, Sullivan 2009a, 2009b, 2009c): Physical and quasi-physical models are based on the fundamental chemistry and physics, or physics alone, of combustion and fire spread; empirical and quasi-empirical models are based on the statistical analysis of data obtained from observations in fire experiments (i.e. actual measurements), with or without some physical framework for the basis of the relations; and simulation and mathematical analogue models are those that are based on some mathematical concept (rather than a physical representation of fire spread) that co-incidentally represents the spread of fire. Of these three types, empirical and quasi-empirical models provide the basis for all current operational fire spread prediction systems used around the world.
- The ability of operational models to produce reasonably accurate predictions of fire spread is highly dependent on the quality of the spatial input data, such as wind speed and fuel moisture content. It is often the cost of collecting and maintaining accurate input data that constitutes the largest limitation to using these models.
- Five models that are in a fairly advanced stage of development were identified: Phoenix (Tolhurst et al. 2008); FIRESCAPE (King et al. 2011, Bradstock et al. 2012); FARSITE (Finney 1998, Scott and Burgan 2005); Prometheus (Tymstra et al. 2010); and Australis (http://smr.csse.uwa.edu.au/australis.html). Three of these - Phoenix in Australia, FARSITE in the United States, and Prometheus in Canada - are in operational use. The Australis model is being used in the development of Aurora – a prediction, detection, simulation and early warning system (http://smr.csse.uwa.edu.au/aurora.html) which is being supported by the Western Australian Land Information Authority and Fire and Emergency Services Authority. Aurora combines features of AFIS with a fire spread simulator.
- The use of these models requires dedicated teams of trained operators.

4.5.3 An overview of the available systems

Brief descriptions of the systems are provided below.

Phoenix: This system was developed in Australia, and uses modified versions of the McArthur Forest and Grassland spread models, and also incorporates a heathland spread model (Tolhurst et al. 2008). Like most of the Australian models, these were derived empirically from observations of the behaviour of fires. The input data require the landscape to be divided into uniform-sized square cells (size specified by user, usually 100 x 100 m). Data required include weather (temperature, relative humidity, wind speed, drought factor, grass curing and cloud cover) and fuel (from a menu with a choice vegetation types). Phoenix is now widely used but not yet widely exposed in the literature, though there are apparently some manuscripts in preparation. It has been tested on a fire in Cavaillon in France and was able to predict the fire perimeter at a specific time, but more testing is needed (Pugnet et al. 2013).

FIRESCAPE: This system was developed in Australia and is a process-based landscape fire regime simulation model that has been applied to a range of ecological, management and climate-related research questions for a variety of Australian landscapes (King et al. 2011, Bradstock et al. 2012). *FIRESCAPE* is essentially a research tool aimed at long-term regime simulation (Cary et al. 2006, 2009) rather than rate of spread and fire foot-print prediction (R.A. Bradstock, pers. comm. 2013). The model employs fire spread algorithms to simulate landscape-scale fire regimes incorporating spatially-explicit effects of terrain, weather and fuel dynamics. The effects of fuel accumulation and weather across daily, yearly and decadal time scales are represented in the model.

FARSITE: This system was developed in the United States, and uses the Rothermel fire spread model (the basis for the United States Fire Danger Rating System, and the BEHAVE fire behaviour prediction system) (Finney 1998, Scott and Burgan 2005). It relies on a wave-front expansion technique called Huygens' principle to achieve two-dimensional elliptical fire growth from the one-dimensional Rothermel outputs. The system generates vector and raster maps of fire growth and behaviour (time of arrival, fireline intensity, rate of spread, flame length, heat per unit area and fire type). The input data include fuel and topography provided as GIS raster-based data (choice of 40 fuel types), as well as crown data for trees (canopy cover, height, base height and bulk density). Weather data include temperature and relative humidity, rainfall. Rainfall assumed to be spatially constant; temperature and RH adjusted using relationships with elevation. Dead fuel moisture is simulated. Wind direction is assumed to be parallel to the terrain. The FARSITE model is robust and been in operational use for 10 years or more (Jim Gould, pers. comm.). The Rothermel-based model requires an array of fuel parameters, and local data will be lacking in South Africa, but they appear reasonably easy to understand and use and historical experience indicates that they are reasonably valid - at least in local conditions. A proteoid fynbos fuel model was developed for use with the BEHAVE fire prediction system by van Wilgen (1984) and performed well in predicting the rate of spread of small experimental fires (Van Wilgen et al. 1985). It has never been tested on large fire fires with heterogeneous fuels. Additional fuel models were developed for different types of fynbos by Le Maitre and Marais (1995) and these are described in more detail in sections 4.1 – 4.5.

Prometheus: Prometheus is a deterministic fire growth simulation model that was developed in Canada to help fire managers to understand the probable consequences of their decisions about the tactics to adopt in managing a fire (Tymstra et al. 2010). Fire growth is simulated by applying Huygens' principle of wave propagation to the rate-of-spread predictions from the Canadian Forest Fire Behaviour Prediction System of the Canadian Forest Fire Danger Rating System. This approach produces detailed fire perimeters at user-specified display time step intervals. Each active vertex along the perimeter has corresponding fire behaviour output and the fire perimeters can be exported in a format compatible with geographic information systems. Additionally, three interpolation techniques are available to produce optional raster fire behaviour outputs. The system requires spatial data (variable-sized grid) on topography (slope, aspect, and elevation), and fuel types. Available fuel types are for coniferous forests. Hourly weather data (at least one weather station required), including temperature, relative humidity, wind direction and speed, precipitation and outputs from the Canadian Fire Danger Rating System (fine fuel and duff moisture codes, spread index, fire weather index).

Australis: This Australian system is new and still under development. It is an interactive wildfire simulator that forecasts the progression of wildfire across a landscape and projects it as a series of fire perimeters, called isochrons, onto a map. At the core of Australis is a discrete event simulator in which the landscape is partitioned into cells (Johnston et al. 2008). Each cell contains information about fuel and topography. Simulations start with the ignition of a cell (or several cells), and fires spread to adjacent cells. When a neighbouring cell catches alight, it does so after a delay that represents the time taken for the fire to travel the distance between the two cells (Johnston et al. 2006). Each ignition is treated as an "event", and can trigger other ignition events after a suitable propagation delay. The simulator uses empirically-derived predictive fire spread rate models to estimate the propagation delay.

4.5.4 Implementing a fire behaviour model

The original intention was to invite one or more experts from one of these modelling groups to visit the Western Cape and assess the applicability of their models and what would be needed to be able to apply their model to fires in fynbos. As a result of the budget cuts this was no longer possible, but Dr George Milne, the lead programmer of the *Australis* system, happened to visit Cape Town to attend a symposium on modelling the spread of contagious diseases. He had discussions with the CSIR team who took him out to see the kinds of vegetation and the terrain the model would have to operate in. He agreed that it would be very challenging to apply the *Australis* model given the terrain and the detailed data that would be required. Nevertheless he offered to test the model on a fynbos case study providing that he could be supplied with the necessary terrain and fuel datasets, and appropriate weather data. There would also need to be a record of the location of the origin of the fire and the fire-front (head, back and side fires) at different times after ignition.

Dr Milne returned to Western Australia and put the CSIR into contact with the fire behaviour and fuel modelling experts on the Australis team. The CSIR was supplied with a set of fuel-type manuals with written descriptions and photographic depictions of the various fuel models developed for Western Australia. The aim was that the CSIR would source the necessary data for a case study and match the Australian fuel models as closely as possible to the Australian ones to avoid the need to create new fuel models. Accurate matching is important because fire behaviour in Australis depends on empirical relationships between fuels, terrain and weather to predict behaviour (Johnston et al. 2006, 2008), unlike the BEHAVE models where the relationships are built on a fundamental understanding of combustion and flame propagation in various fuel configurations (Burgan and Rothermel 1984, Andrews 1986). The CSIR conducted an assessment recent fire reports to assess whether there was information on the location of the fire-front but found that such data were rarely recorded or were incomplete and that the available weather station data typically were from sites that were not representative of those where the fires occurred.

4.5.5 Recommendations

These models do have potential for use in fynbos environments but they will need to be supported by appropriate data on terrains and fuels if they are to be used as real-time fire-behaviour prediction systems. Vegetation classes such as the national vegetation map's fynbos vegetation types (Rebelo et al. 2006) or the finer-scale Garden Route data (Vlok et al. 2008) are simply not homogeneous enough for these kinds of models, especially when it comes to vegetation structure and fuel characteristics. This is a real problem because the spread model apparently is very sensitive to the fuel characteristics. Sampling of fynbos to obtain suitable fuel data is very time-consuming but one option would be to provide one or bursaries to suitable students to start the process of fuel sampling and development of manuals to describe and depict the different fuel types. The topographic data requirements could probably be solved with data from existing high resolution digital elevation datasets DEMS, but modelling wind behaviour in these terrains would still be problematic.

However, these fire behaviour modelling systems could still be set up with a simulated terrain, fuels and weather conditions and used to test fire management scenarios such as abrupt changes in the weather. They could be used as an interactive teaching tool to help fire managers to develop a better understanding of likely fire behaviours and hazards (e.g. intensity, energy outputs) under different conditions. Over time and as they become more robust, they could be used to assess actual wildfires and in wildfire investigations.

The CSIR was subsequently approached by Zane Erasmus and gave inputs on what would be needed to be able to run the model using a case study as there apparently are suitable fire-front location and weather data for a recent fire in fynbos. Philip Frost of Meraka (CSIR) has also approached the *Australis* group to assess the potential for developing a real-time fire spread predictor for the AFIS system, based on the Aurora system. This task is being planned for 2015.

Dr Milne's original offer of running the *Australis* model for a fynbos case study still stands and would not involve substantial costs for Working on Fire as the developers regard it as an opportunity to test *Australis* in a new and different environment.

5. OUTPUT 2.5 (CLIMATE CHANGE AND WILDFIRE RISK AT A LANDSCAPE SCALE)

5.1 Simulating and projecting climate trends in the southern Cape and Cedarberg

5.1.1 Introduction

Temperatures are rising rapidly over the southern African region in response to the enhanced greenhouse effect, and as a regional manifestation of global warming and global climate change (Engelbrecht and Bopape 2011). The rate of increase in temperature over the region is projected to strengthen further during the 21st century, in response to the continued increase in greenhouse gas concentrations in the atmosphere. The regions of South Africa that receive winter rainfall (the southwestern Cape and Cape south coast) are no exceptions in this regard, and have experienced a warming trend over recent decades (Kruger and Shongwe 2004). Moreover, these regions have experienced decreasing trends in rainfall totals in recent decades, and significant drying is projected for these regions under the enhanced greenhouse effect (Christensen et al. 2007, Engelbrecht et al. 2009, 2011). These changes are projected to occur in response to the strengthening of the subtropical high pressure belt over the southern African region and the southward displacement of the westerly wind regime (and cold fronts). Over the Cape south coast and Cedarberg regions, annual average temperatures have been increasing at a rate of more than 2°C per century, over the last five decades (Engelbrecht et al. 2015).

Generally drier and warmer conditions over the Fynbos biome region are likely to be associated with increased fire risks. This section of the research aims to objectively project changes in the risk of occurrence of fynbos fires, as quantified by different fire indices. The findings of the report are based on projecting changes in Fynbos fire risk according to the McArthur Forest Fire Danger Index (FFDI) and the Lowveld Fire Danger Index (LFDI). The FFDI has been used to study fire risk over the southwestern Cape and Cape south coast regions (e.g. Midgley et al. 2005, Van Wilgen et al. 2010).

The climate projections used to calculate the fire indices under climate change have been performed at the CSIR using a dynamic regional climate model. The projections of a number of coupled global climate models (CGCMs) of Assessment Report Four (AR4) of the Intergovernmental Panel on Climate Change (IPCC) were downscaled to high resolution over southern Africa, and are analysed here over the southwestern Cape and Cape south coast regions.

5.1.2 The conformal-cubic atmospheric model and experimental design

The projections of climate change applied in the project have been obtained using a regional climate model, the conformal-cubic atmospheric model (CCAM). This is a variable-resolution global atmospheric model, developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) (McGregor 1996, 2005a, 2005b, McGregor and Dix 2001, 2008) (Figures 15 and 16). It employs a semi-implicit semi-Lagrangian method to solve the hydrostatic primitive equations. The model includes a fairly comprehensive set of physical parameterizations. The

GFDL parameterizations for long-wave and short-wave radiation are employed, with interactive cloud distributions determined by the liquid and ice-water scheme of (Rotstayn 1997). A stability-dependent boundary layer scheme based on Monin Obukhov similarity theory is employed (McGregor et al. 1993), together with the non-local treatment of Holtslag and Boville (1993). A canopy scheme is included, as described by (Kowalczyk et al. 2006), having six layers for soil temperatures, six layers for soil moisture (solving Richard's equation) and three layers for snow. The cumulus convection scheme uses a mass-flux closure, as described by (McGregor 2003), and includes downdrafts, entrainment and detrainment.

The model was forced with the bias-corrected sea-surface temperature (SST) and sea-ice concentrations of six different CGCMs used in AR4 of the IPCC, for the period 1961-2100 to obtain an ensemble of regional projections of climate change. The required boundary forcing data was obtained from the CSIRO in Australia. This included surface topography, vegetation, albedo and roughness fields required to force the model at its lower boundary. All six of the projections performed are for the A2 emission scenario of the Special Report on Emission Scenarios (SRES) (Nakicenovic et al. 2000). The A2 scenario describes the continued strong growth in emissions during the 21st century (low mitigation). The associated CO_2, sulphate, ozone and aerosol fields were all obtained from the CSIRO.

A multiple-nudging strategy was followed, by first integrating CCAM globally at quasi-uniform C48 resolution (about 200 km in the horizontal, that is, about 2° in latitude and longitude - Figure 15), forcing the model with the SSTs and sea-ice of each host model, and with CO_2, sulphate and ozone forcing consistent with the A2 scenario. In a second phase of the downscaling, CCAM was integrated in stretched-grid mode over southern Africa and the southwestern Indian Ocean, at C64 resolution (about 0.5° in latitude and longitude, or 50 km, over the area of interest). The high-resolution grid is centred at 28° E and 25° S (Figure 16). The higher resolution simulations were nudged within the quasi-uniform C48 simulations, through the application of a digital filter using a 4000 km length scale. The filter was applied at six-hourly intervals and from 900 hPa upwards.

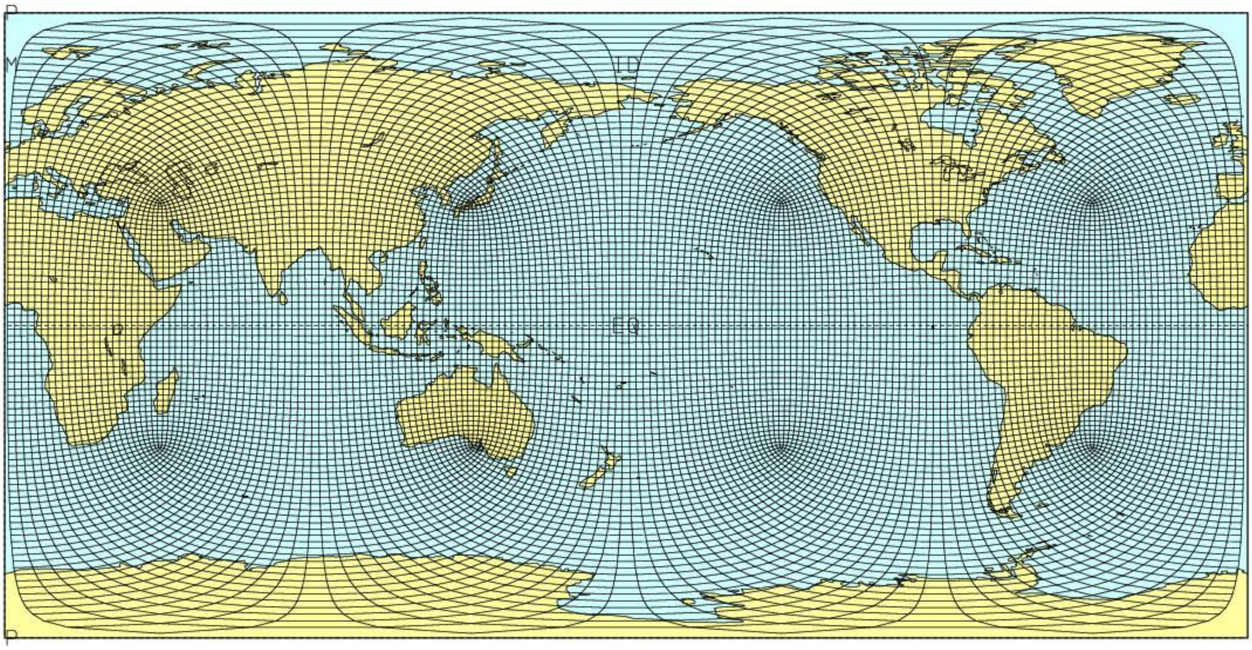


Figure 15: Quasi-uniform C48 CCAM grid, having a horizontal resolution of about 2° in latitude and longitude.

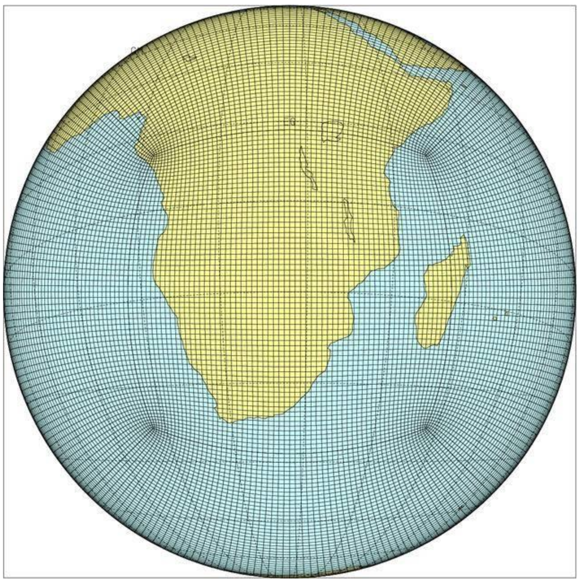


Figure 16: Stretched C64 CCAM grid, having a horizontal resolution of about 0.5° over southern Africa and the southwest Indian Ocean.

5.1.3 Bias-correction and the fire indices

All climate models are prone to systematic errors in their simulations of climate variables such as rainfall and temperature. Due to the fire indices being dependent on the meteorological variables of rainfall, maximum temperature, minimum relative humidity and wind speed, it is preferable for the model simulations of these variables to be bias-corrected prior to calculation of the FFDI. This was achieved through the calculation of the monthly observed climatologies of rainfall, maximum temperature and relative humidity, for 1961-1990, as described by the CRUTS3.1 data set of the Climatic Research Unit (CRU). These climatologies were subsequently subtracted from the corresponding CCAM simulated climatologies, thereby obtaining the monthly simulated biases. These fields were in turn used to correct the daily simulated values of rainfall, maximum temperature and minimum relative humidity. No wind climatology is available from CRU – in this case, the raw output fields of the model were used in the calculation of the fire indices. The standard formulation of the FFDI (e.g. Dowdy et al. 2010) is applied in the research. The FFDI depends on the calculation of a drought index defined by Keetch and Byram (1968), taking into account the required corrections pointed out by (Alexander 1990). The LFDI has been described by Meikle and Heine (1987).

5.1.4 Projected changes in the FFDI and LFDI over the Cape south coast and Cedarberg, and underlying climate trends

Simulations of the annual average number of days when the FFDI is rated as high, very high or extreme (FFDI > 12), for the period 1961-1990, show that relatively low values (less than 20 high fire danger days per year) are simulated to occur along the Cape south coast compared with assessments which used weather station data to calculate the FFDI (Figure 17a). The number of high fire danger days is significantly higher over the interior regions, and particularly over the Northern Cape (where the vegetation burning capacity is very low, or insignificant). All six downscaled climate models simulate similar spatial patterns of the numbers of high fire danger days over the Cape south coast and Cedarberg regions.

The spatial pattern of the relative occurrence of high fire danger days over the region for the LFDI is very similar to the FFDI representation (Figure 17b), but significantly more days of high fire danger are indicated by the LFDI. For example, the region where less than 20 days of high fire danger is simulated to occur annually is limited to a very narrow coastal strip for the LFDI, and a much larger portion of the northern interior is simulated to experience more than 200 high fire danger days per year compared with the FFDI (Figures 17a and 17b). This difference is largely due to the fact that the threshold for the high and extreme fire danger days is lower in the LFDI than in the FFDI and the consequent identification of a higher percentage of days as high or extreme.

The downscaled models project a robust pattern of drastic increases in the FFDI and high fire danger days, for the far-future time-slab 2080-2100 relative to the baseline period (1961-1990)

(Figure 18a). High fire danger days are projected to increase by 10 days or more over the interior regions adjacent to the Cape south coast – and increases of up to 40 days per year are projected for large parts of the southwestern Cape interior. Drastic increases in the number of high fire danger days are projected to have occurred already by the mid-future period of 2040-2060 over the interior, with smaller increases indicated for the 2015-2035 (near-future) period. Over the narrow coastal strip along the Cape south coast, increases of less than five days of high fire danger are projected, even for the far-future.

For the LFDI, the downscaled models project a robust pattern of drastic increases in index values and the number of high fire danger days, for the far-future time-slab 2080-2100 relative to the baseline period (Figure 18b). The patterns of change are similar to those for the FFDI across the different time-slabs, but the amplitude of the change is much larger. Drastic increases in the number of high fire danger days are projected for most of the interior regions for the far-future period. Over the narrow coastal strip along the Cape south coast, increases of between 10 and 20 days with high fire danger are projected. Already by the mid-future, drastic increases in the number of high fire danger days are projected (5-10 more days along the Cape south coast, and more than 20 days over the interior).

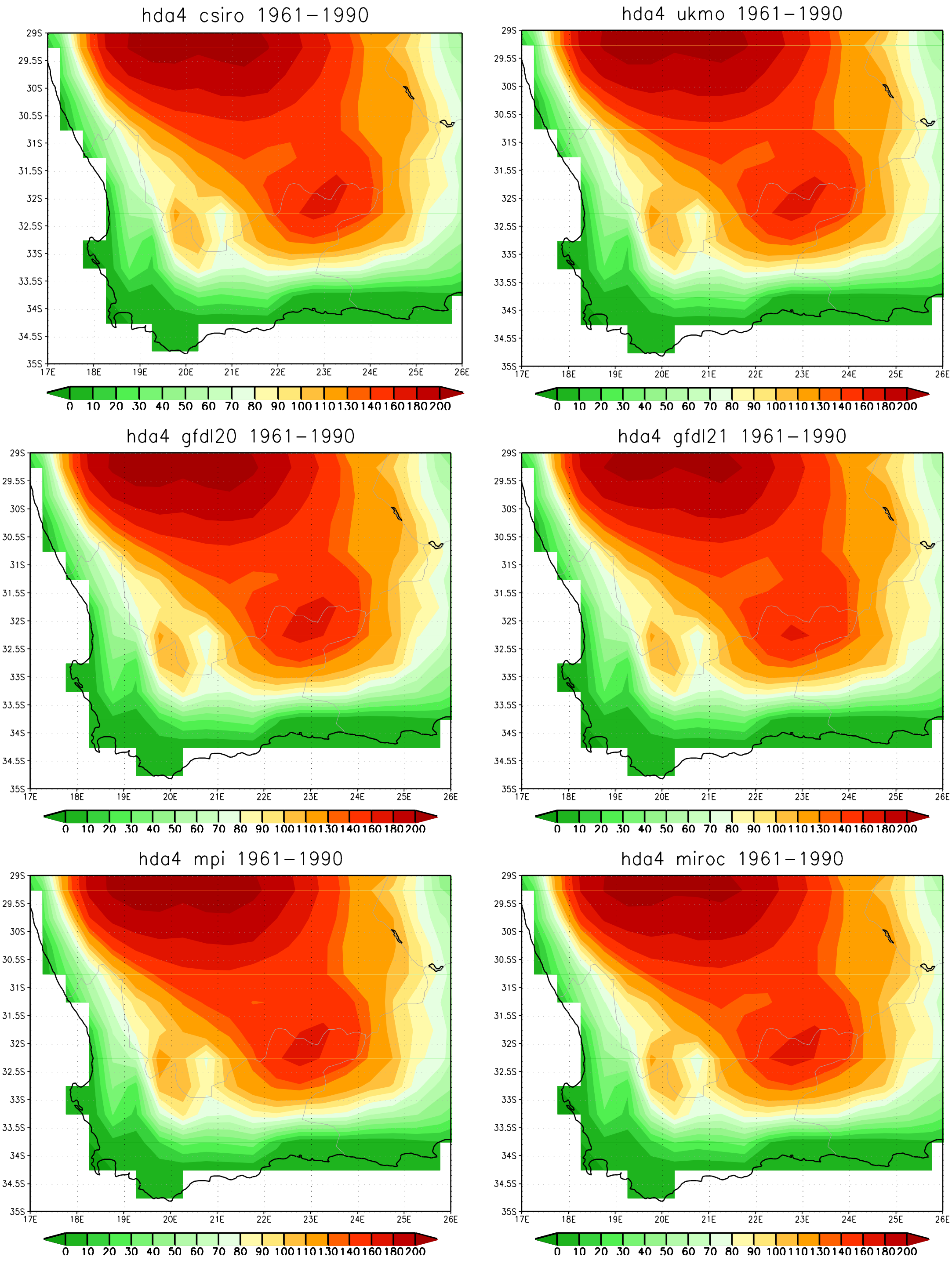


Figure 17a: Model simulations of the average number of days per year when the FFDI value is rated as high, very high or extreme (LFDI > 12), for the period 1961-1990. The six models show simulated climatologies for the six different downscaled climate models.

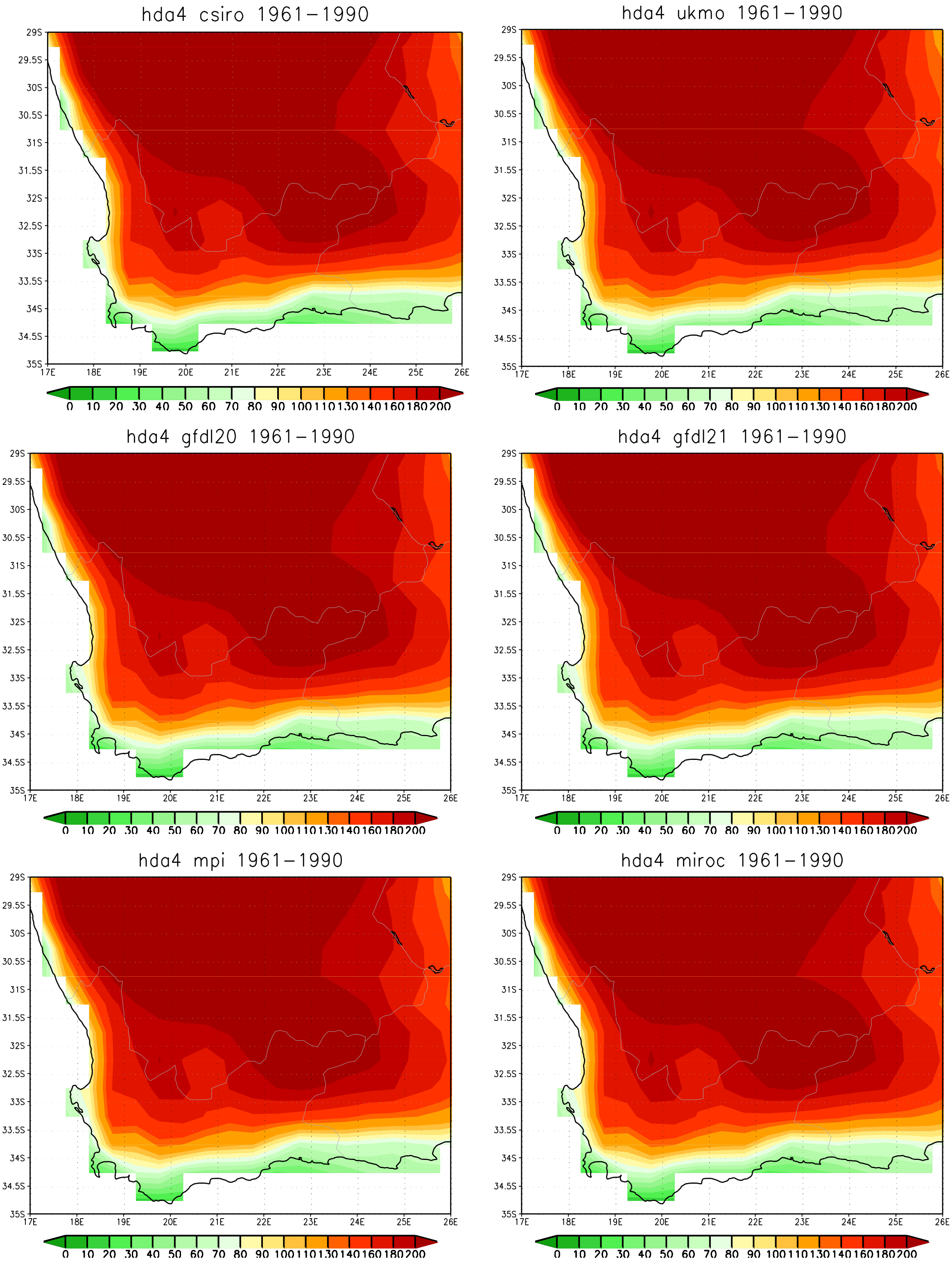


Figure 17b: Model simulations of the average number of days per year when the LFDI value is rated as high or extreme (LFDI > 59), for the period 1961-1990. The six models show simulated climatologies for the six different downscaled climate models.

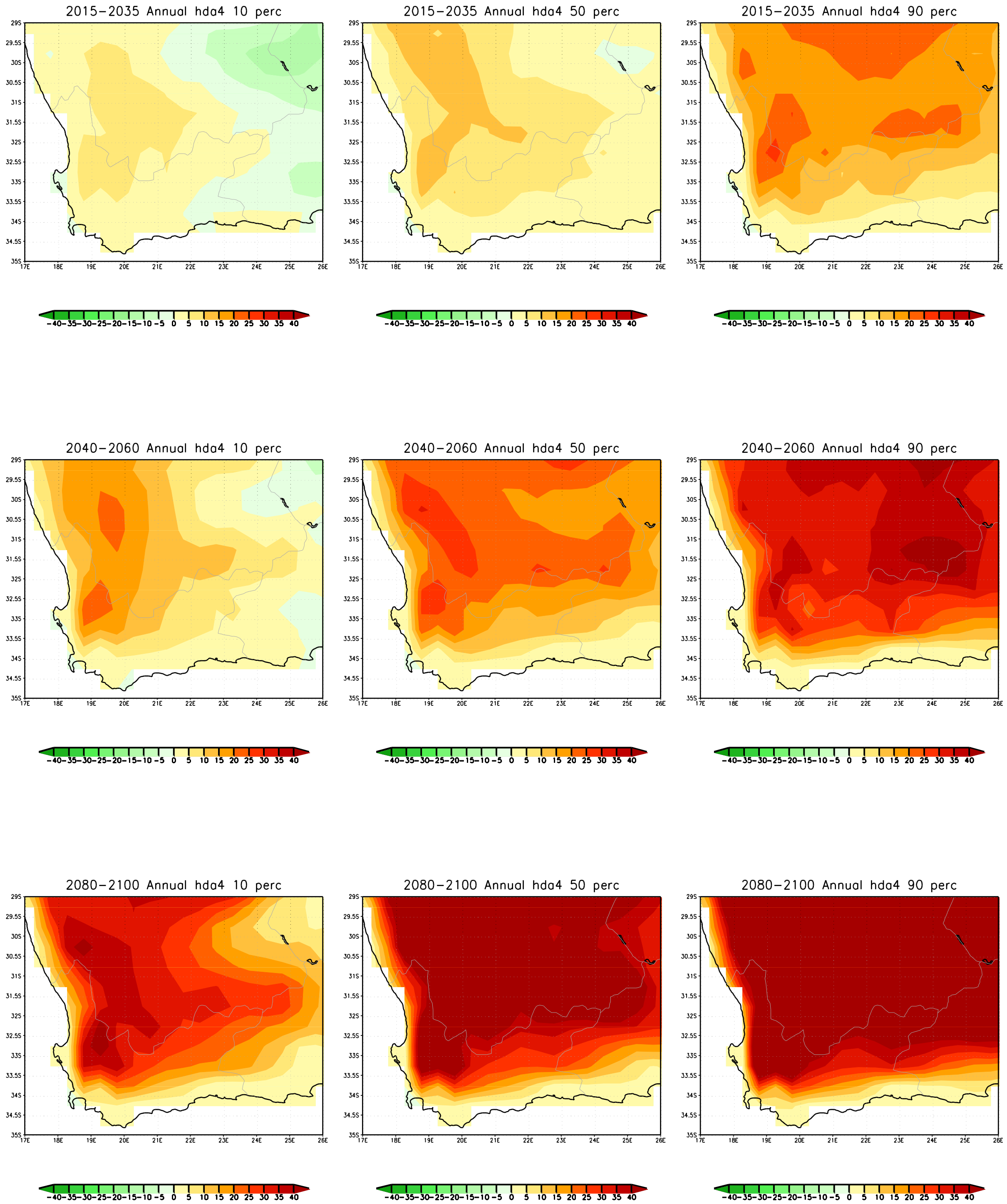


Figure 18a: Model projected changes in the number of days per year when the FFDI value is rated as high, very high or extreme (FFDI > 12), for different future time-slabs, relative to the baseline period 1961-1990. For each time-slab, the 10^{th} percentiles, median and 90th percentile of the ensemble of projected changes are shown.

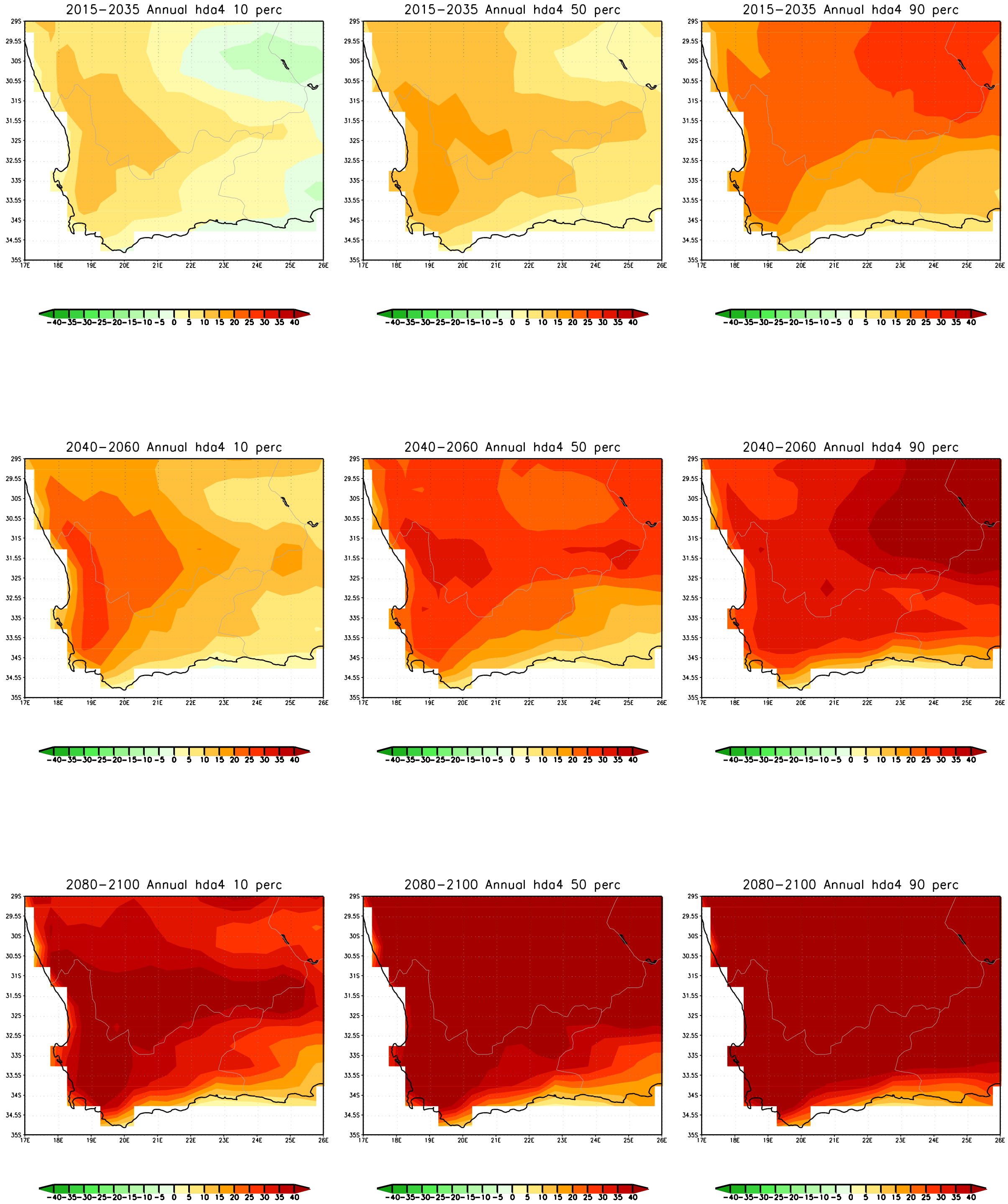
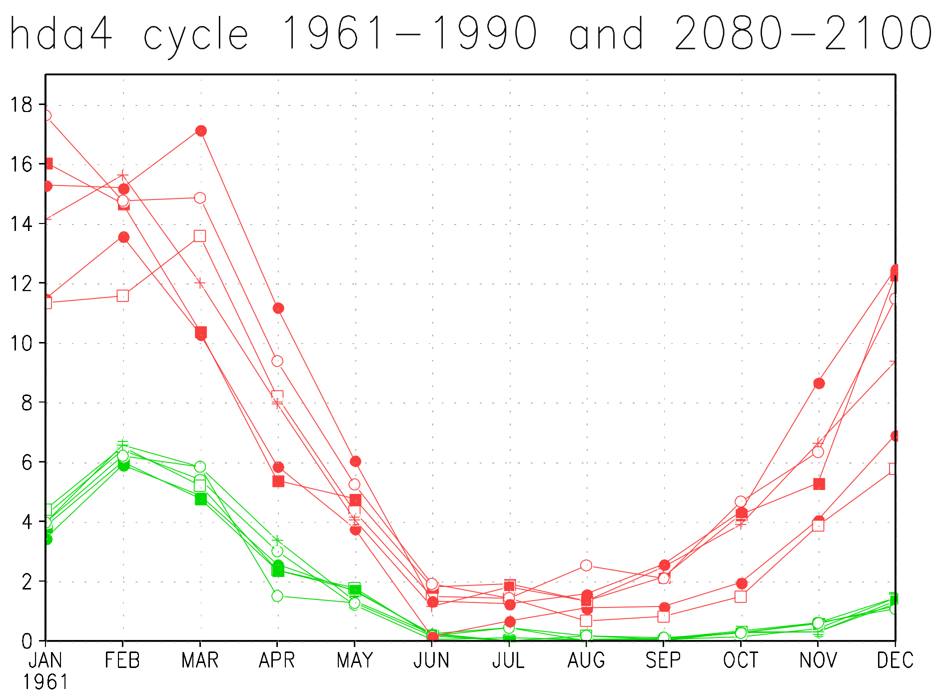


Figure 18b: Model projected changes in the number of days per year when the LFDI value is rated as high, very high or extreme (LFDI > 59), for different future time-slabs, relative to the baseline period 1961-1990. For each time-slab, the 10th percentiles, median and 90th percentile of the ensemble of projected changes are shown.

In the Cedarberg region (32.5 °S and 19.25 °E), the present day (1961-1990) annual cycle in the number of high fire danger days shows a distinct peak in the late summer (January to March), which forms part of the dry season over the region (Figure 19a top panel). During this time of the year, about 5 days per month are associated with a high fire risk according to the FFDI. The projected increases are drastic for spring and early summer (Figure 19a lower panel) – ranging between 5 and 12 more days of high fire danger per month. High fire danger days are now also projected to occur regularly during the winter months (very low fire risk is simulated for the region for the present-day climate in winter). These results suggest the potential of a future expansion of the length of the burning season over the Cedarberg region, with a significant increase in risk during an important part of the burning season, namely the late summer. The LFDI threshold for high fire risk is significantly less strict than that of the FFDI, at least for the Cedarberg region. Whereas the latter index indicates less than 10 days of high risk per late summer month, the former indicated more of 20 days of high risk per late summer month (Figure 19b). In contrast to the FFDI, the LFDI indicates significantly less risk during winter under the present-day climate. Days of high fire risk are projected to increase with 3 to 10 days per month, across the annual cycle, according to the LFDI. This, once again, indicates an extension in the length of the burning season in the future.



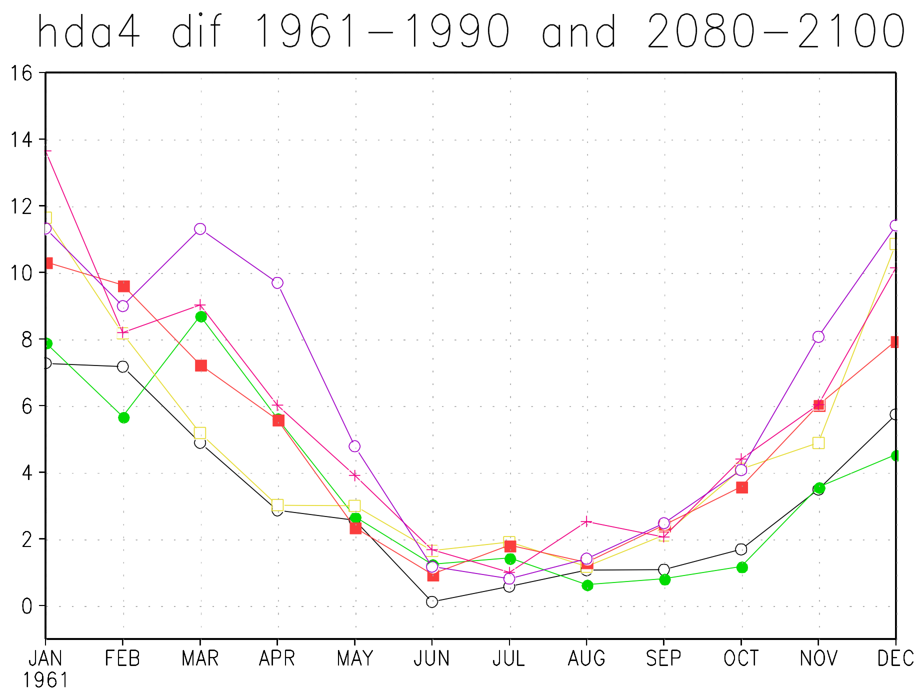
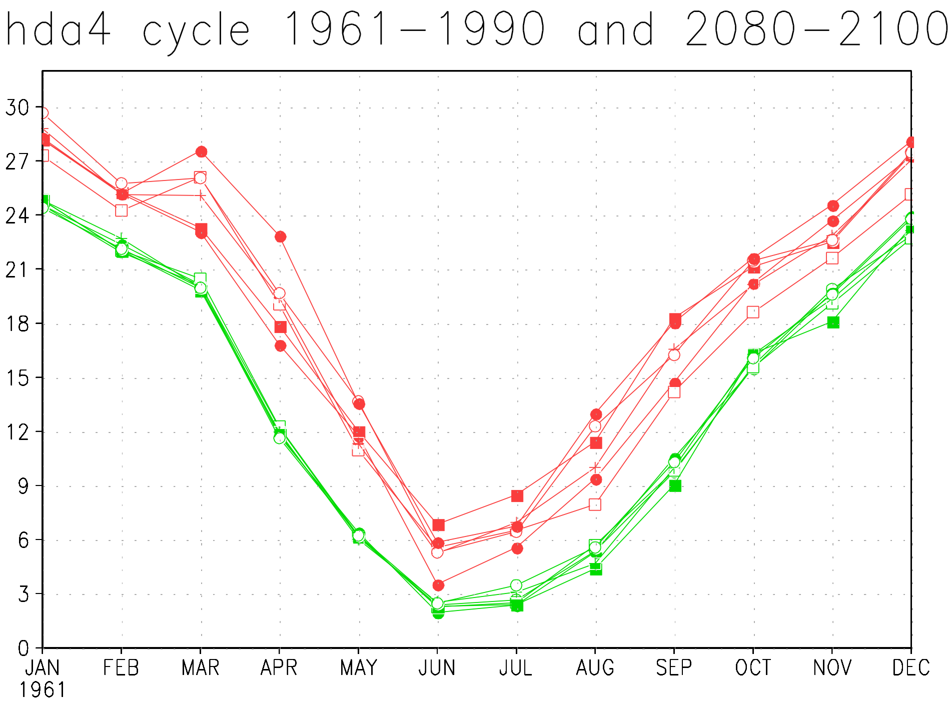


Figure 19a: Model projected changes in the annual cycle of the number of days per month when the FFDI value is rated as high, very high or extreme (FFDI > 12) over the Cedarberg region, for the future time-slab 2080-2100 and the baseline period 1961-1990. For each time-slab, the simulated cycles for all six ensemble members are shown (top panel) for present-day climate (green lines) and far-future climate (red lines). The bottom panel shows the projected monthly differences in the number of high fire danger days for 2080-2100 relative to 1961-1990.



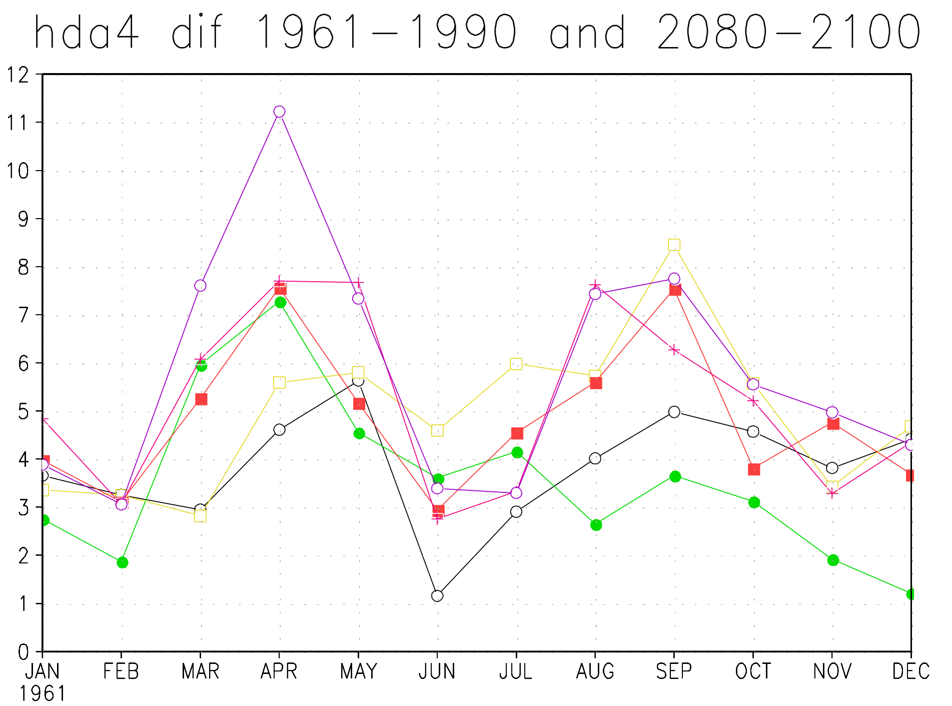
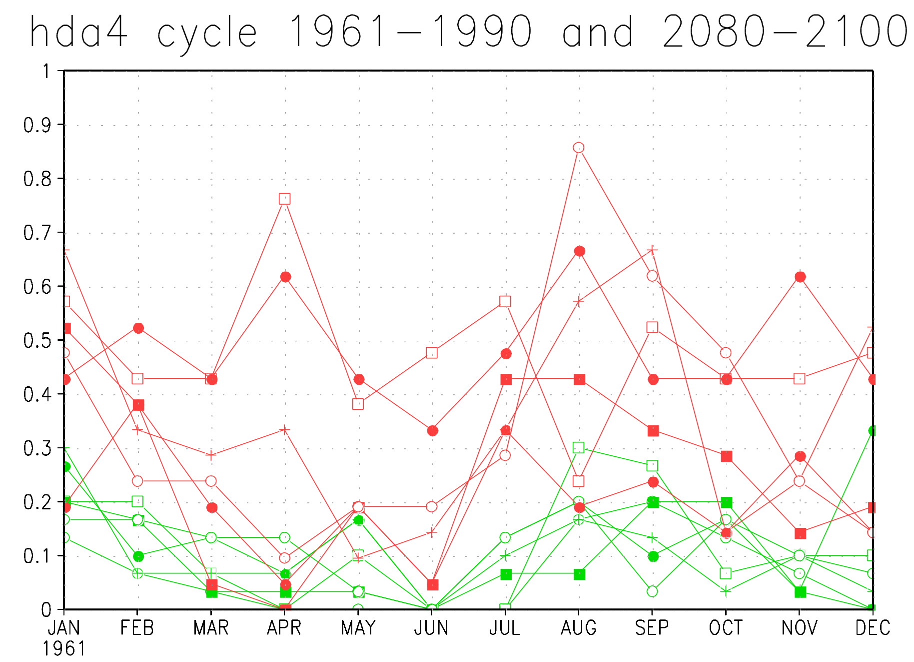


Figure 19b: Model projected changes in the annual cycle of the number of days per month when the LFDI value is rated as high, very high or extreme (LFDI > 59) over the Cedarberg region, for the future time-slab 2080-2100 and the baseline period 1961-1990. For each time-slab, the simulated cycles for all six ensemble members are shown (top panel) for present-day climate (green lines) and far-future climate (red lines). The bottom panel shows the projected monthly differences in the number of high fire danger days for 2080-2100 relative to 1961-1990.

For the Cape south coast region, the FFDI and LFDI provide very different descriptions of the present-day occurrence of high fire danger (Figures 20a and 20b). In the case of the FFDI, averages of less than 0.5 days per month are classified as high fire danger across the entire annual cycle. The comparable values for the LFDI are estimated to vary between 3 and 9 days. Relatively smaller increases in the number of days of high fire danger are projected to occur over the Cape southcoast region compared to the Cedarberg region, both across all the seasons and according to both fire danger indexes. The main drivers for this are the projected general increases in temperature and decreases in rainfall for the region. These increases are in the order of 0.5 days per month for the FFDI, and range between 1 and 3 days per month for the LFDI.

The drastic increases projected in the number of high fire danger days over the Cape south coast and Cedarberg regions (Figures 18, 19 and 20) are driven mainly by increases in temperature, as shown by the model simulated annual average temperature and rainfall anomalies over the southwestern Cape for all six ensemble members, for the period 1961-2100 (Figure 22). Strong trends in temperature, with increases occurring at a rate of about 2 °C per century, have occurred over the period 1961-2010. By the end of the century, temperature increases as high as 4 °C are projected, relative to the 1961-1990 baseline period over the southwestern Cape. It can be seen that the region’s climate is projected to drift towards a significantly warmer state, never observed in recorded history, and also somewhat drier compared to the present-day climate.



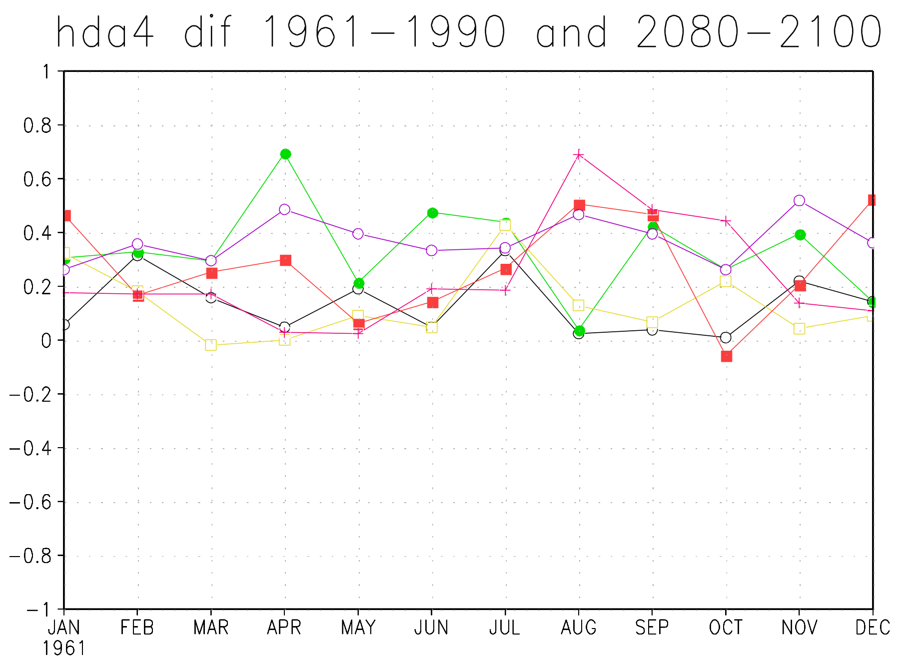
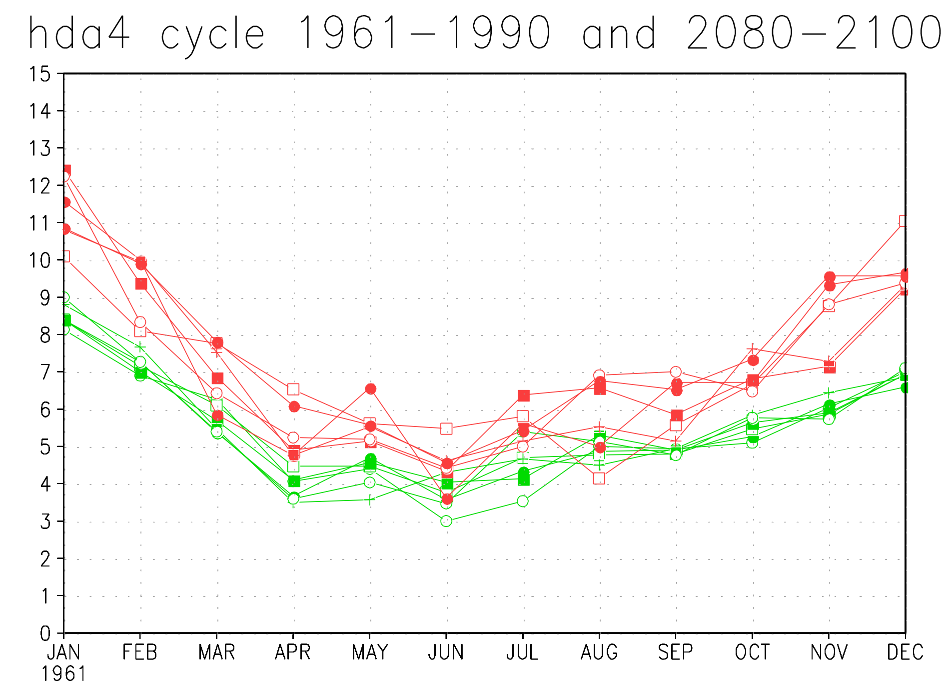


Figure 20a: Model projected changes in the annual cycle of the number of days pear month when the FFDI value is rated as high, very high or extreme (FFDI > 12) over the Cape south coast region, for the future time-slab 2080-2100 and the baseline period 1961-1990. For each time-slab, the simulated cycles for all six ensemble members are shown (top panel) for present-day climate (green lines) and far-future climate (red lines). The bottom panel shows the projected monthly differences in the number of high fire danger days for 2080-2100 relative to 1961-1990.



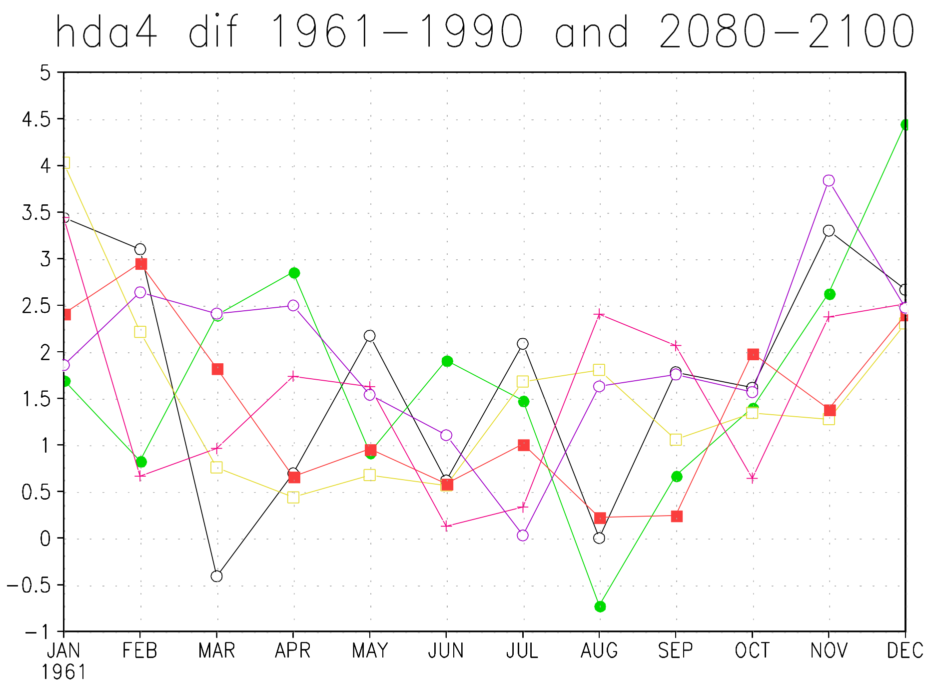


Figure 20b: Model projected changes in the annual cycle of the number of days pear month when the LFDI value is rated as high, very high or extreme (LFDI > 12) over the Cape south coast region, for the future time-slab 2080-2100 and the baseline period 1961-1990. For each time-slab, the simulated cycles for all six ensemble members are shown (top panel) for present-day climate (green lines) and far-future climate (red lines). The bottom panel shows the projected monthly differences in the number of high fire danger days for 2080-2100 relative to 1961-1990.

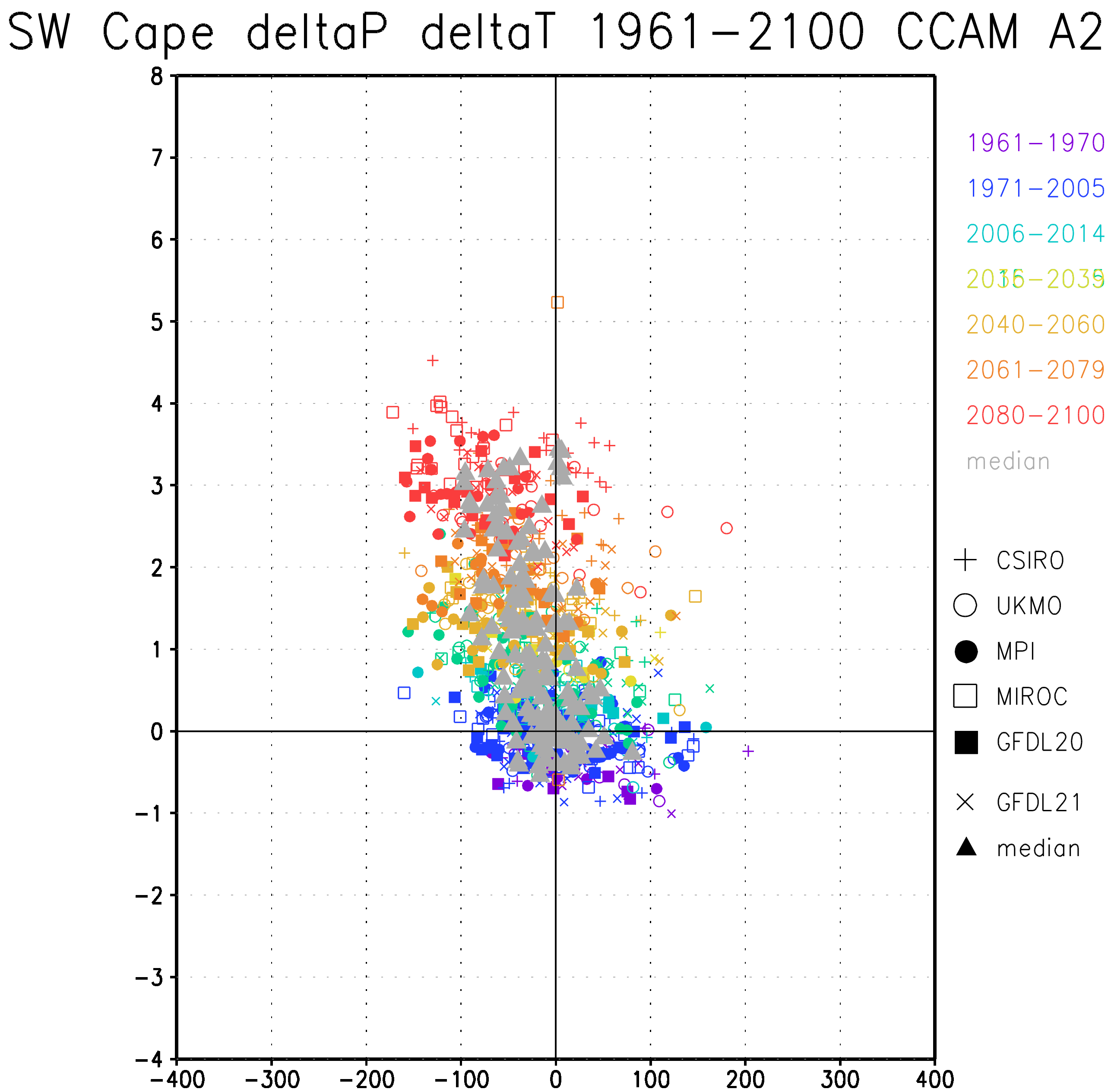


Figure 21: Model simulated trends in average annual temperature anomalies (y-axis) and annual rainfall anomalies (x-axis) for the historical period 1961-2012 (bias-corrected using observations) and projected trends until 2100 (A2 emission scenario).

Further insights into the present-day and future occurrence of high fire danger days over the south coast study area are provided by a comparison of the Self-Organising-Map (SOM) classification of synoptic-types under present and future climates (Figures 22a and 22b). Under the present-day climate, nodes 10, 15 and 20 (associated with north-westerly flow ahead of an approaching frontal system) are associated with the highest ratios of high fire danger days – 12.7 % of all days exhibiting a node 10 pattern are associated with high fire danger days, with the corresponding values being 8.6% for node 15 and 13% for node 20 (Table 12). For the far-future, these values are projected to increase to 19.1, 12.6 and 21.9 %, respectively, with almost all other synoptic types also becoming more indicative of high fire danger days in the context of the generally warmer climate.

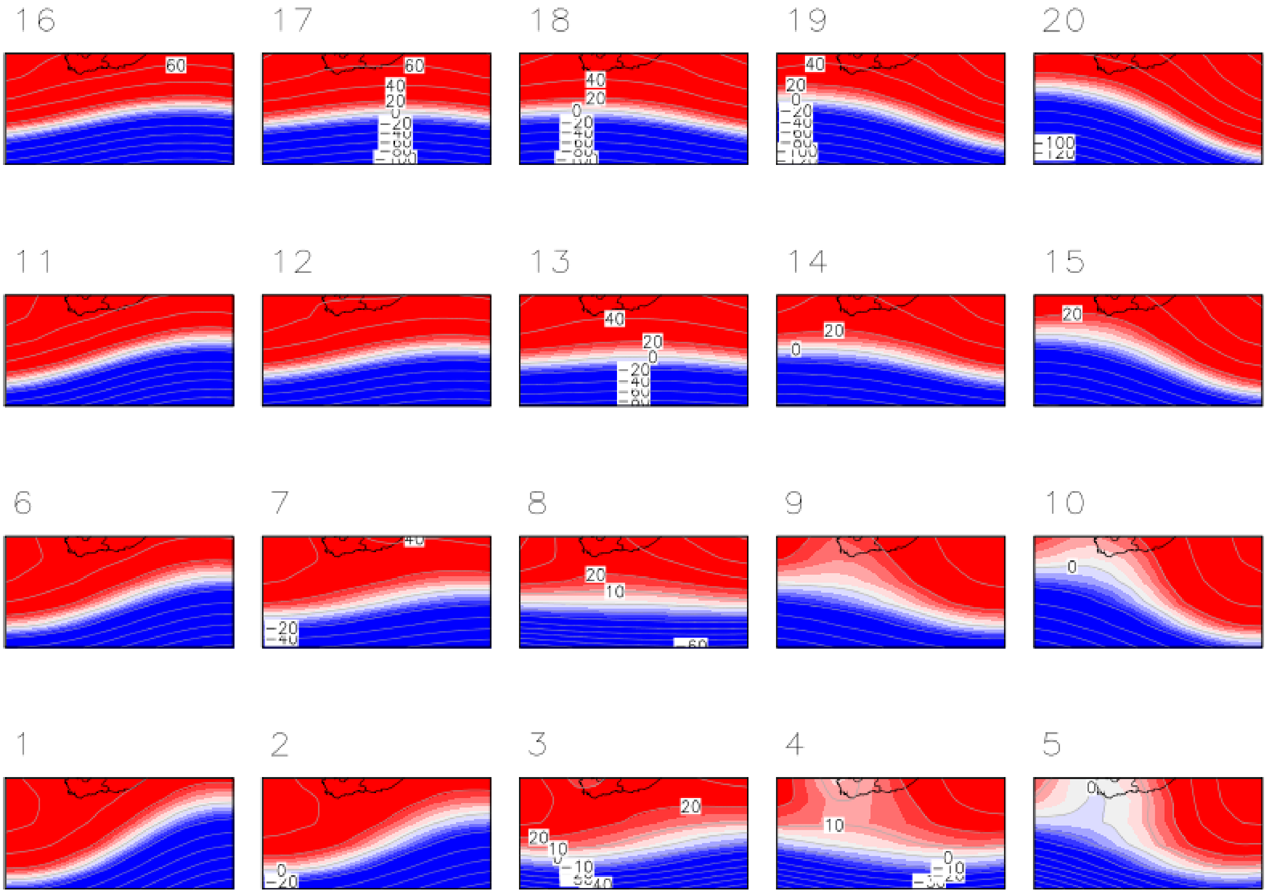


Figure 22a: Different synoptic types occurring over the Cape south coast region under present-day climate, according to a 5x4 Self-Organising-Map (SOM) classification.

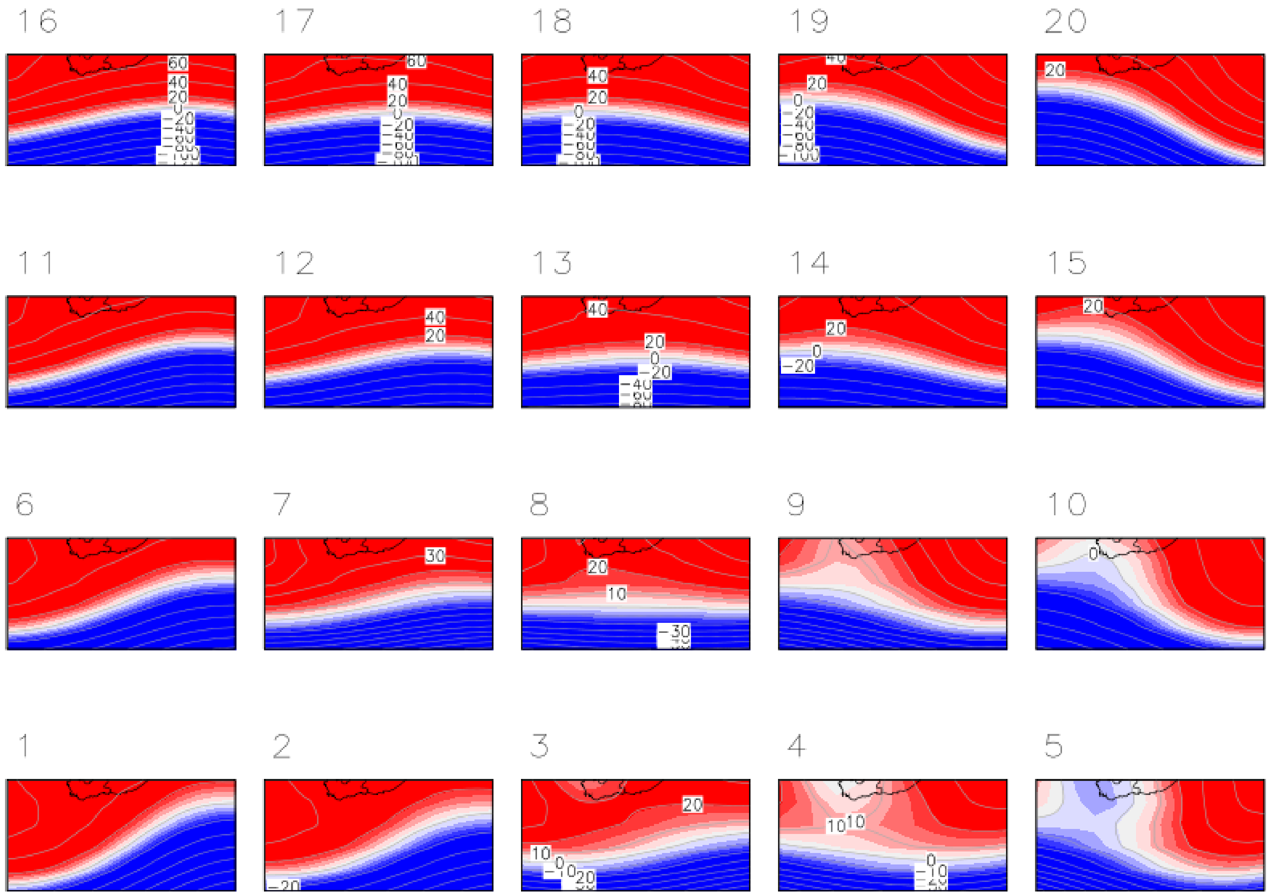


Figure 22b: Different synoptic types occurring over the Cape south coast region under a far future climate (period?), according to a 5x4 Self-Organising-Map (SOM) classification.

The ratio of the frequency of high fire-danger days associated with a specific synoptic type, relative to the frequency of occurrence of the node is depicted in Table 12 for all nodes in the SOM, for both the present-day and far-future climatologies. The fire indices used in these calculations are the FFDI values for the Cape south coast region.

Table 12: The ratio of the frequency of high fire-danger days associated with a specific synoptic type, relative to the frequency of occurrence of the node, for all 20 nodes in the 5x4 SOM, for both the present-day (1961-1990) and far-future climatologies.

Synoptic Type	Percentage of node days associated with high fire danger – present-day climate	Percentage of node days associated with high fire danger – future climate
1	0	0
2	0	0.4
3	0.1	0.6
4	1.2	2.2
5	5.1	7.2
6	0	0
7	0.7	0.7
8	1.6	3
9	2.9	6.3
10	12.7	19.1
11	0.1	0
12	0.6	0.7
13	1.2	2
14	4	6.1
15	8.6	12.6
16	0.5	1.5
17	1.7	1.9
18	1.2	6.3
19	4.6	8.1
20	13	21.9

5.1.5 Conclusion

The bias-corrected simulations of a regional climate model were used to project FFDI attributes over the Cape south coast and Cedarberg region under conditions of climate change (enhanced anthropogenic forcing). The projections indicate a robust signal of increases in high fire danger days, for the mid-future (2041-2070) and far-future (2071-2100) periods.

The tendency of the LFDI to predict more high and extreme fire days than the FFDI, combined fact the LFDI has now been accepted as the national standard, means that fire fighters may be put on higher levels of readiness more frequently than is necessary which has significant cost implications. One solution to this could be to do an assessment of the historical occurrence of fire start days using both these indices to determine which one is the better predictor of the actual occurrence of fires.

6. OUTPUT 2.6 (RISKS TO COMMUNITIES AT THE WILDLAND-URBAN INTERFACE)

This section has been put into a separate report: "Risk to communities at the wildland-urban interface" by Greg Forsyth and David Le Maitre (Report No: CSIR/NRE/ECOS/ER/2015/0075/B). This will be used to help fire managers assessing and map the fire risks along the wildland-urban interface in their Fire Protection Associations.

7. ACKNOWLEDGEMENTS

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