MAJOR CLIMATE CHANGE-INDUCED RISKS TO HUMAN HEALTH IN SOUTH AFRICA

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Abstract

There are many climatic changes facing South Africa which already have, or are projected to have, a detrimental impact on human health. Here the risks to health due to several alterations in the climate of South Africa are considered in turn. These include an increase in ambient temperature, causing, for example, a significant rise in morbidity and mortality; heavy rainfall leading to changes in the prevalence and occurrence of vector-borne diseases; drought-associated malnutrition; and exposure to dust storms and air pollution leading to the potential exacerbation of respiratory diseases. Existing initiatives and strategies to prevent or reduce these adverse health impacts are outlined, together with suggestions of what might be required in the future to safeguard the health of the nation. Potential roles for the health and non-health sectors as well as preparedness and capacity development with respect to climate change and health adaptation are considered.

Keywords: air pollution; extreme weather events; infectious diseases; respiratory and cardiovascular diseases

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1. Introduction to South Africa

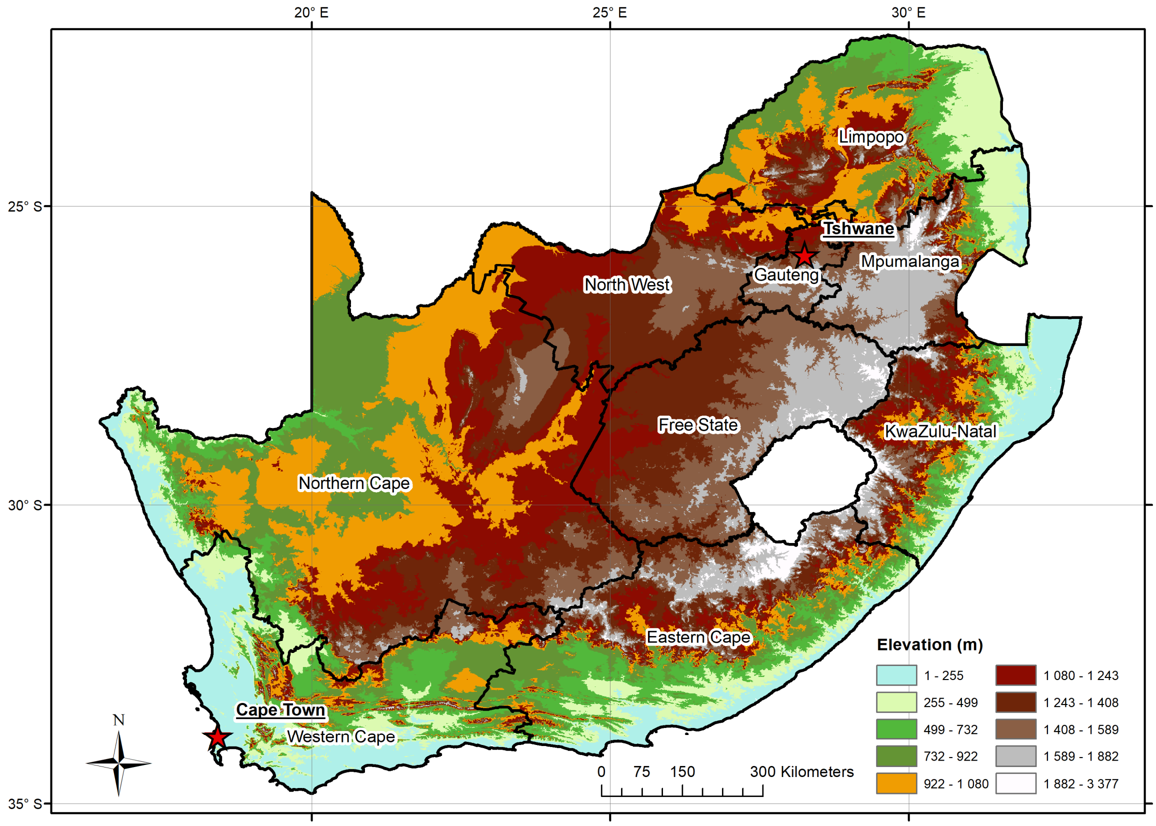
South Africa is facing major health challenges due to the impact of changes in the climate occurring at the present time and into the future. These issues come on top of the adverse socio-economic conditions experienced by many people in the country which relate to factors such as poverty, poor housing, malnutrition, limited access to medical facilities and the highest global prevalence of HIV/AIDS and tuberculosis. Thus, most of the population can be considered vulnerable to these climatic changes, with little resilience and limited capacity for adaptation (Kreftet al., 2017; DEA, 2017). Table 1 depicts selected societal parameters which are relevant when considering how climate changes, occurring currently and in the future, may be detrimental to the health of the South African population.

Table 1. Population characteristics in South Africa. The most recent figures available are shown. [www.healthdata.org/south-africa; www.oecdbetterlifeindex.org/countries/south-africa/; www.statssa.gov.za; www.gov.za/povertytrends; www.tbfacts.org/tb-statistics-south-africa; www.worldmeters.info/world-population/south-africa; http://www.statssa.gov.za/publications/EmployTrendsAgri/EmployTrendsAgri.pdf https://www.who.int/hiv/data/Country_profile_South_Africa.pdf?ua=1]

Parameter	**Figures**
Population (mid-2020)	59.3 million; 79% Black African, 9% White, 9% Colored, 3% Indian/Asian
International immigrants (mid-2020)	Constitute 7% of the population, mainly from Zimbabwe and Mozambique
Life expectancy (2018)	60 years males, 67 years females
Life expectancy at birth (2015-2020)	64 years
Death rate due to HIV/AIDS (2017)	273.1 per 100,000 population
Number living with HIV (2015)	6.2 million
Prevalence of HIV/AIDS in adults (2016-2018)	19% of the population
Deaths due to tuberculosis (2018)	63,000 (of whom 42,000 were HIV/AIDS positive)
Incidence of active cases of tuberculosis (2018)	520 per 100,000 population
Employment rate, ages 15-64 years (2017)	44%
Number employed in agriculture (2014); number employed in other outdoor occupations not recorded	700,000
Number living in poverty (2015)	More than 56 % of total population, whom 13.8 million live in extreme poverty
Education attainments (2018)	82% upper secondary, 7% tertiary

South Africa lies at latitudes 22 °S to 35 °S and at longitudes 17 °E to 33 °E. It is divided into nine provinces (Figure 1). Its topography ranges from sea level plains to mountains rising to over 3 000 meters. The Highveld area, encompassing South Africa's largest urban conurbation, is a plateau at 1 200 meters across the centre of the country. High atmospheric pressure over this plateau leads to mostly cloudless skies and, in combination with the altitude, results in relatively high solar ultraviolet (UV) radiation levels (South Africa Info, 2020; WHO, 2017).

Fig. 1. The topography and provinces of South Africa.



Rainfall over South Africa averages 464 mm annually which is low compared with the global average of 786 mm (South Africa Info, 2020). However, there are large variations throughout the country with the highest rainfall in the east, particularly over the mountains from Limpopo to the northern parts of Eastern Cape. Rainfall then decreases westward and is least in the semi-desert areas near the Atlantic Ocean. An illustration of some of these meteorological parameters as they relate to the capital cities of Cape Town and Tshwane (formerly called Pretoria) is shown in Table 2.

This article aims to describe the major climatic changes facing South Africa and how they can impact human health. Risks due to increases in ambient temperature, extreme weather events and air pollution are considered. Current strategies to prevent or reduce these effects are outlined, together with suggestions of what might be required in the future to safeguard the health of the South African population.

Table 2. Meteorological parameters relating to the cities of Cape Town and Tshwane (previously Pretoria).
[https://www.worldatlas.com/articles/15-biggest-cities-in-africa.html].

	Cape Town	**Tshwane**
Latitude/Longitude	33.9°S/18.4°E	25.7°S/28.2°E
Altitude	0-300 m	1340 m
Average hours of sunlight per day:		
summer	10.2	9.1
winter	6.8	8.6
Average day-time temperatures:		
summer	26°C	30°C
winter	19°C	21°C
Average night-time temperatures:		
summer	15°C	18°C
winter	8°C	5°C
Average rainfall:		
summer	25 mm	110 mm
winter	133 mm	8 mm

2. Recent and future climate changes in South Africa and their impact on health and behaviour

2.1 Temperature rise

2.1.1 Heat stress

The mean annual temperature in South Africa increased by at least 1 °C during the last 50 years which is 1.5 times the global average (Engelbrecht et al., 2015; Ziervogel G, et al., 2014; MacKellar et al., 2014). The rise has been particularly prominent over western parts of the country, including much of Western and Northern Cape, and in the east over Gauteng, Limpopo, and the east coast of KwaZulu-Natal. Temperatures in South Africa will continue to rise at a rate greater than the global average, with increases of 4 - 6 °C by the end of the century under a ‘business as usual’ scenario, compared with the 1961 - 1990 baseline (Maure et al., 2018; Engelbrecht et al., 2015). This is assumed based on projections using high greenhouse gas (GHG) emission future scenarios [e.g., the A2 scenario, inferring a world of continuously increasing population and high emissions from Assessment Report 4 (IPCC,

2007) and a Representative Concentration Pathway (RCP) that lead to concentrations in 2100 that produce a change in forcing of 8.5 W/m^2 (RCP8.5) from Assessment Report 5 (IPCC, 2014)] estimate that It is also projected that the number of ‘very hot days’ (defined as days with maximum temperatures higher than 35 ℃) will increase by 20 - 40 per year over the western and central interior parts of South Africa for 2016 - 2035 and by up to 40 - 80 days per year by 2046 - 2065 (DEA, 2017). The frequency, duration and intensity of heatwave events (defined by the South African Weather Service (SAWS) as ‘temperatures exceeding the average maximum temperature of the hottest month for that particular region by 5 °C for at least three consecutive days’) (SAWS, 2017) in South Africa are projected to increase (Mbokodo et al., 2020). Climate projections under a ‘business as usual’ scenario for the periods 2010 to 2039, 2040 to 2069 and 2070 to 2099 indicate that heatwave frequency will increase across all these time periods with the highest frequency of heatwaves expected during 2070 to 2099 (Mbokodo et al., 2020). Parts of South Africa that are experiencing less than 20 heatwave events per year in the current climate are projected to experience more than 40 such events by the end of the century (Mbokodo et al., 2020).

These temperature increases will have major detrimental impacts on health. First there will be an adverse effect on both morbidity and mortality. Although difficult to quantitate, figures that relate the increased risk of death due to temperature rises have been estimated by taking the annual mortality rates and mean surface air temperatures in approximately 40 countries in past years and projected into the future. Mora et al (2017) found that approximately 30% of the world’s population was already exposed to temperatures which lead to excess deaths, and the percentage will rise to 74% by 2100 if greenhouse gas emissions grow. Carleton et al (2020) reported that one day at 35 ℃ leads to an increase in the all-age mortality rate of around 0.4 deaths per 100,000 relative to a day at 20 ℃. No data were included from sub-Saharan Africa in these two studies, an area described in this context as “high uncertainty”. In addition, no account has been taken of possible adaptation to high temperatures, such as using cooling air conditioning, or of the protection offered by higher living standards and income.

Regarding South Africa, Wichmann (2017) correlated the daily ambient apparent temperatures with the daily all-cause mortality in Cape Town, Durban and Johannesburg over the period 2006-2010. There were almost half a million deaths out of a population of about 12 million during this period. An increase in mortality of 0.9% per 1 ℃ increase in the daily ambient apparent temperature for all ages was found, with a significant increase to 2.1% in the over 65-year-old age group. Furthermore, in a country-wide survey of mortality data covering all 52 municipalities, hot temperatures (hot was defined as the 99th percentile of site-specific daily maximum temperatures) were associated with a 0.34% increased risk of death from all-causes. This represents approximately 1700 deaths per year between 1997 and 2018 (Scovronick et al., 2018).

Heat exhaustion and stress are likely to lead to a significant increase in respiratory, cardiovascular and renal diseases, as well as in mental disorders (Varghese et al., 2010; Atha, 2013). In addition, temperature increases may cause a deterioration in the quality and quantity of food products, including grains, vegetables, and meat, leading to malnutrition and worries about food safety standards (DEA, 2013). How the population will deal as a society with these changes in temperature is not known. Perhaps people will tend to remain indoors and, if so, whether their accommodation provides adequate insulation is important. Housing poverty is relatively common in South Africa with 11 % of the Black African population and 6 % of the Coloured population in 2016 living in tin or corrugated iron sheds, informal dwellings and squatter settlements which have no insulation (Statistics South Africa, 2016). By 2018, 13 % of all households resided in such dwellings (Statistics South Africa, 2018). This number is likely to rise in future years due to migration from rural areas to cities and immigration from neighbouring countries. Low-cost government housing is also poorly insulated, resulting in large temperature variations and higher indoor temperatures compared to ambient temperatures (Naicker et al., 2017; Wright et al., 2017). It is important to ensure that schools are well insulated, which is not always the case currently (Bidassey-Manilal et al., 2016). For example, by 2018 more than 350 shipping containers were converted to provide schools in areas of need throughout the country, but these have little or no insulation (One, 2018). Other more traditional schools built of bricks and mortar are old and are often poorly maintained, particularly in rural parts of the country. The same lack of insulation applies to many medical facilities, such as clinics and hospitals, especially in rural settings (Wright et al., 2017), and to other public buildings. In addition, shade needs be provided in playgrounds, sport facilities and school grounds.

2.1.2 Outdoor work

Those who work outdoors are at particular personal risk of the adverse effects of temperature rises, in addition to the associated loss in productivity (Mathee et al., 2010). The largest numbers of outdoor workers in South Africa are employed in forestry and conservation, followed by agriculture and then the construction industry (Statistics South Africa, 2019). In a study of more than 200,000 miners in South Africa, a mortality rate of 3.3

deaths per thousand miners per year was found if temperatures exceeded 34 ℃ compared with an annual rate of 0.7 per thousand miners when temperatures were between 31 and 33 ℃ (Wyndham, 1965). Measures to protect the health of such workers include ensuring that dehydration does not occur, allowing adequate rest periods, providing adequate clothing, headgear and sunscreen, and avoiding working in the hottest part of the day (Mine Health and Safety Council, 2001). A recent study in the Western Cape indicated that, while efforts were made by forestry workers to protect their health while working outdoors, there remained a need to improve working conditions and personal awareness of the risks of overexposure to the sun (Rother et al., 2020). Similarly, the barriers to reducing occupational heat stress experienced by mining workers in Ghana have been assessed (Nunfam et al., 2020). It was concluded that both employees and employers require adequate knowledge of adaptation strategies to reduce such stress.

2.1.3 Vulnerability (HIV/AIDS)

South Africa is already suffering from the highest incidence in the world of both tuberculosis and HIV/AIDS (IHME, 2017) (Table 1). In 2017, it was estimated that about 60 % of those living with HIV were also infected with tuberculosis. As social, nutrition and housing problems may escalate with increasing temperatures and heatwaves, the risk of death in already infected people may increase. In 2019, 71 % of adults and 47 % of children living with AIDS were receiving antiretroviral therapy (Avert, 2019). In times of heat stress, factors such as reduced access to medical care, restricted drug supplies, and non-adherence to dosage regimes may occur, leading to an increase in those with active HIV infections (UNAIDS, 2020; Talman et al., 2013). In addition, there is thought to be an increased risk of mother-to-child transmission of HIV during hot weather by diminishing drug adherence, prolonging rupture of membranes and promoting genital infections in the mother and by increasing the baby's intake of breast milk which contains HIV (Chersich et al., 2019). Estimates of the impact of heat exposure on birth outcomes in South Africa have not been undertaken thus far.

2.1.4 Malaria

Regarding other infectious diseases, there are likely to be changes in several as temperatures rise in South Africa. The most common of these is malaria. Approximately 95% of malaria infections in South Africa are caused by the protozoa *Plasmodium falciparum* which is transmitted to humans by the bite of female *Anopheles arabiensis* mosquitoes, endogenous in the malaria regions. Transmission is highest in the wet summer months, conditions which favour the development of both the vector and the protozoa plus the frequency of biting and feeding of the vector (Adeola et al., 2019; Weiss et al., 2014). There were 9500 indigenous cases of malaria as well as 8700 imported cases in South Africa in 2018 (WHO, 2020). Local transmission via mosquitoes occurs in low-lying areas of KwaZulu-Natal, Mpumalanga, and Limpopo where 10 % of the population (approximately 4.5 million people) is at risk of contracting the disease (Statistics South Africa, 2018). It can also occur in other provinces from immigrants who were infected in neighbouring countries. A likely increase in future years in the incidence of malaria over South Africa has been predicted by modelling (Tanser et al., 2003). In addition, a shift from the west to the south and east parts may occur and spread of malaria to the Highveld (Ziervogel et al., 2014). More focused modelling considered the daily number of malaria cases and daily climatic data (mean maximum and minimum temperatures, relative humidity, and rainfall) for the Mutale local municipality in northeast Limpopo during 1998 to 2007. There were almost 16,000 malaria cases in this period. The combination of the mean monthly minimum temperature (above 18 ℃) and the total monthly rainfall (above 460 mm) were the most significant climatic variables for predicting malaria transmission, with a two-month lagged effect (Adeola et al., 2017).

2.1.5 Other infectious diseases

Further mosquito-borne infections are found in South Africa at lower prevalence than malaria. Firstly, an Arbovirus carried by mosquitoes, *Aedes aegypti* and *Aedes albopictus,* causes dengue fever in humans which has been reported in a limited number of cases in South Africa (Simo et al., 2019) following spread to many tropical and subtropical areas of the world in the past 60 years (Messina et al., 2019). Secondly, Rift valley fever virus affects both humans and domestic animals, especially sheep, and is spread by biting insects including mosquitoes. There have been several outbreaks reported in people who deal with sheep in South Africa (Archer et al., 2013). Thirdly, West Nile fever virus is carried by mosquitoes belonging to the genus *Culex,* and infects humans following the insect bite. It is found in migratory birds which could inhabit new areas of South Africa with rising temperatures (Chauhan et al., 2020). In all these cases, increased temperatures can reduce the time between blood meals required by the mosquito and accelerate development of the protozoa or virus within the insect. They may also lead to shifts in locations where mosquitoes can breed and change the length of the seasons, for example mosquitos hibernate over winter. Modelling predicts a large increase in mosquito-borne human infections in future years in South Africa as rising temperatures, together with increased rainfall, will lead to increased vector survival, reproduction, and biting rate with longer seasonal transmission (Craig et al., 2004; Coetzee et al., 2013; Adeola et al., 2019).

Tick-borne diseases also occur in South Africa, one being Crimean-Congo haemorrhagic fever virus, commonly carried by *Hyalomma truneatum* in Africa (Hoogstraal, 1979; Rochlin and Toledo, 2020). This virus is found in a wide range of hosts including livestock in which it is asymptomatic and from which it is transmitted to humans by tick bites. It affects the nervous system causing neurological symptoms which precede the haemorrhagic symptoms and there is a high mortality rate in humans. This infection was first reported in South Africa in 1981 (Gear et al., 1982). Tick-borne diseases are uncommon in the country although they are likely to increase in incidence perhaps due to rising temperatures causing changes in the location of the tick vectors, increased tick survival with shortened life cycles and lengthening of the season of tick activity (Ogden et al., 2020).

Schistosomiasis (also called bilharzia) is the commonest parasitic infection globally and was estimated to affect four million people in South Africa in 2011 (Mbabazi et al., 2011). Species of the parasitic flatworm called schistosomes are released from their hosts, freshwater snails, into water. They can then infect the urinary tract and intestines of humans (Colley et al., 2014). The prevalence of the disease is highest in schoolchildren who also have the most severe symptoms. Schistosomiasis is endemic in the north and east of South Africa, an area covering about a quarter of the country (Magaisa et al., 2015). The major sources of the schistosomes include unclean water supplies, poor sanitation and recreational facilities, inadequate infrastructure, and clustering of snails around irrigation schemes and dams (Magaisa K et al., 2015). An analysis of climatic conditions in the endemic areas has indicated that the schistosomes are very sensitive to low temperatures, which inhibits their development in the snail hosts (Moodley et al., 2003). This may help to explain why schistosomiasis is not found in parts of South Africa at higher altitudes, but it also means that, with increasing ambient temperatures, there is the possibility of spread to these areas. One study of school children in Maputaland, northern KwaZulu-Natal, demonstrated that infection occurred most frequently in the hottest and wettest parts of the year, conditions which are likely to favour schistosome transmission and development of the snail hosts (Saathoff et al., 2004).

The final category of human disease to be included in terms of modulation by increased ambient temperatures is skin cancers. This aspect is considered separately in Section 2.2 below as a second climatic variable, namely exposure to solar UV radiation, is recognized as the major environmental cause of these tumours (Green et al., 1999).

2.2 Solar UV radiation

Cutaneous melanoma (CM) and keratinocyte skin cancers (squamous cell carcinoma, SCC, and basal cell carcinoma, BCC) occur in South Africa affecting populations of all skin colours but especially those with fair skin (Norval et al 2014). In 2000-2004, the age-standardized annual incidence per 100,000 of BCC was 3.0 and 1.7 in Black African men and women respectively, and 198 and 113 in White men and women respectively; of SCC was 3.0 and 1.6 in Black African men and women respectively, and 70 and 32 in White men and women respectively; and of CM was 4.9 and 2.9 in Black African men and women respectively, and 19.7 and 13.8 in White men and women respectively (Norval et al, 2014). CM is fatal if left untreated while the keratinocyte cancers are rarely fatal but are disfiguring and debilitating (Diepgen et al., 2002). In each of the three types of skin cancer, the incidence rate increases with age. At diagnosis in South Africa, the mean age for the keratinocyte cancers was mid-60s and for CM was mid-50s (Norval et al 2014), and there were 1659 deaths due to skin cancer, most probably CMs, in 2017 (World Cancer Research Fund, 2020; World Life Expectancy, 2020). As the collection of data relating to skin cancer incidence or death is not complete in South Africa, any trend in incidence or death rate cannot be determined (Wright et al., 2019).

The levels of solar UV radiation in South Africa depend on latitude, ozone, aerosols, albedo and cloud cover. In the summer months, the entire country experiences values for the solar UV Index (UVI – a metric describing the level of solar UV radiation at the Earth's surface with values above 11 considered extreme) of 10 or higher. In the winter months, there are moderate UVI values in the highest latitude regions with those nearer to the Equator having UVI values reaching a maximum of 9 (Hovila et al., 2020). Thus, there is the potential for the South Africa population to experience overexposure to sunlight, either as chronic or intermittent acute irradiation, leading to an increase in the risk of skin cancer. As an illustration of this, Arnold et al. (2018) estimated the number of CM cases in South Africa in 2012 attributable to UV radiation exposure as 72 % overall, which is amongst the highest in the world, with 83 % in men and 62 % in women aged over 30 years.

With the implementation of the Montreal Protocol in 1987 and its subsequent Amendments, depletion of the stratospheric ozone layer, brought about by the emission of ozone depleting substances, is being gradually repaired. The ozone layer provides an effective screen for solar UV-B radiation and hence its recovery should provide protection against skin cancer development (van Dijk et al., 2013). However, unlike some areas of the world, particularly near the Poles, there has been little change in the ozone layer over South Africa in the past decades (Bernhard et al., 2020) and it is predicted that solar UV-B radiation will increase after 2050 in some tropical and mid-latitude regions due to decreased cloud cover caused by climate change (Eleftheratos et al., 2020). Therefore, the behaviour of the South Africa population regarding personal exposure to the sun will be critical in determining whether the incidence of skin cancer will increase or not in future years.

Temperature is an allied concern as there is evidence that a rise could promote cutaneous carcinogenesis. This was first proposed by van der Leun et al (2008) who found that the incidence of keratinocyte cancers correlated with the average daily maximum temperatures in the summer in ten regions of the United States. The incidence of SCC was higher by 5.5 % per 1℃, and of BCC higher by 2.9% per 1℃. Piacentini et al (2018) extended this study by calculating the effect of global warming on the incidence of these tumours using climate change models in which global warming was considered as optimistic (due to great efforts to reduce greenhouse gas emissions), low intermediate, high intermediate and pessimistic. The percentage increase in the incidence of SCC by 2100 compared with 2000 was 5.8, 10.4, 13.8 and 21.4 and for BCC was 2.8, 4.9, 6.5 and 9.9 for each scenario, respectively. It is not clear how ambient temperature affects the probability of tumour development although Calapre et al (2016) demonstrated that cell cycle arrest and apoptosis of keratinocytes induced by exposure to UV-B radiation were reduced in conditions of heat stress (temperature of 39 ℃). Thus, damaged cells survived, and the risk of initiating skin carcinogenesis was enhanced. As there are several decades of delay between DNA damage caused by UV radiation and the development of skin cancer (van Dijk et al 2013), it is too soon to know whether the rise in ambient temperature in South Africa will result in a perceptible increase in the incidence of skin cancer.

2.3 Extreme weather events: heavy rainfall, drought, and dust storms

2.3.1 Rainfall

Rainfall in South Africa is typically highly variable in time, area and distribution (Qwabe, 1999). Places with medium to high annual rainfall such as the central interior and the eastern Highveld as well as the mountains of the western and southern Cape, the Drakensburg, eastern escarpment and places along the coast of KwaZulu Natal that receive more than 1,000 mm per annum (Schulze, 2001) experience heavy rainfall and flooding. Tropical cyclones also contribute to flooding in the northern and eastern parts of South Africa during the summer months (Dyson and Van Heerden, 2002). Flash floods occur during intense convective storms in the summer months (October – March) over the central, northern, and eastern parts of South Africa. Death by drowning occurs regularly following flash flood events, particularly in low-income settlements alongside rivers that overflow their banks, for example as happened in Johannesburg in 2020 (IOL, 2020). The impacts of climate change on precipitation predict an increase in intensity and frequency of extreme precipitation in the north of KwaZulu-Natal with a decrease in annual precipitation in Cape Town (Abiodun et al., 2017). Whether these extreme rainfall events, namely heavy rain, flooding, and flash floods, will increase in a changing climate in South Africa is uncertain but thought likely.

Extreme rainfall events have a significant impact on public health and on a population's ability to sustain its livelihood. A major flooding event in Johannesburg resulted in a cholera outbreak in a large informal settlement that necessitated moving residents to more sanitary conditions (CSIR, 2014). Extreme rainfall also increases the prevalence of vector-borne diseases such as malaria (Anyamba et al., 2014). In Limpopo province, children under 5 years of age were especially vulnerable to diarrheal disease during heavy rainfall conditions with a higher number of cases being reported when precipitation was above average (Ikeda et al., 2019). Those living in poverty or with pre-existing medical conditions are also at particular risk of rainfall-sensitive diseases (Ahmed et al., 2009). Furthermore, high rainfall affects agricultural productivity, and the cost of staple foods, upon which low-income communities depend, increases (Feng et al., 2018, Kotir, 2011).

2.3.2 Drought

While heavy rainfall and flooding are projected to increase in certain areas of South Africa, dry conditions, such as in the western interior and the northern parts of the west coast, can lead to drought with negative impacts on food security and nutrition. For southern Africa, a characteristic of drought is its "creeping" nature: it starts without any significant initial event, but slowly intensifies, resulting in large impacts over time that may last several years (Malherbe et al., 2016). Droughts are an inherent feature of the climate of southern Africa (Tyson and Preston-Whyte, 2000) which experiences arid or semi-arid conditions owing to subsidence of air in large anticyclones for most of the year (Mason and Tyson, 2000).

Drought conditions have become more prevalent in Africa and future projections show an increased risk of severe droughts (Niang et al., 2018). Models have projected with medium confidence that droughts over East and Southern Africa will intensify in the 21st century (Seneviratne et al., 2012). Under business-as-usual scenario (RCP8.5), severe droughts of high intensity and long duration are forecast for the southern Cape (DEA, 2017). The health impacts of droughts include malnutrition due to reduced food production, and increased risk of diarrheal disease due to lack of water to ensure proper hygiene (McMichael et al., 2003). After droughts, there is a surge in mosquito numbers, leading to malaria outbreaks when the first rains fall, because of increased breeding sites and the absence of predators and competitors caused by the drought. Following an extended drought event between 2015 and 2016 in KwaZulu-Natal, the prevalence of stunting among children under 5 years of age rose because of increased food insecurity (Drysdale et al., 2020). Furthermore, the severe water restrictions imposed in Cape Town due to a severe drought between 2016 and 2018, led to economic losses in the agricultural sector and increased unemployment (United Nations University, 2018).

2.3.3 Dust storms

In drought-like conditions, dust storms occur from the combination of strong winds and loose dry soil surfaces in arid and semi-arid areas. Fine dust particles may be lifted high into the atmosphere and swept by strong winds in large amounts over long distances and even across continents (Gross et al, 2018). Depending on the weather conditions and particle size, dust can remain in the atmosphere for a few hours up to more than a week. Human activities including changes in land-use and agricultural practices leading to erosion influence the frequency and intensity of dust storms (Bekiswa, 2018).

In South Africa, there is no available repository or database of dust storms. Use of satellite data to detect dust storms has been reported sporadically by the SAWS. For example, in September 2013, one dust storm was identified over the Free State (Eumetsat, 2013), a province which has large agricultural areas that are sometimes left exposed or are overgrazed leading to dry, loose and bare sandy soil (Bekiswa, 2018). The suspended dust was present for four hours with wind gusts up to 65 km/h and long-range transport over a large distance in the South African interior affecting Gauteng – a province that houses more than 15 million people. Dust storms captured in the Free State via satellite imagery showed an increase in occurrence between 2006 and 2016 (Bekiswa, 2018). Also captured via satellite imagery, dust plumes turned skies red in September 2019 in Alexander Bay in the Northern Cape province (NASA Earth Observatory, 2019). The SAWS reported large dust storms that swept across most parts of the country in October 2014 (IOL, 2014) and January 2016 (Two OV News, 2016).

No mention of any health impacts was made in these dust storm reports, despite the known negative effects that such storms can have on the environment, climate system and atmospheric chemistry which can pose hazards to human health. Dust can reduce visibility and increase exposure to microorganisms, pollens, and harmful pollutants such as toxic metals

(Griffin, 2007). Thus, dust storms contribute towards air pollution and associated adverse health impacts (see section 4 for more on air pollution). They may cause, worsen and/or lead to increased hospital admissions due to respiratory symptoms (cough and wheezing) and diseases (asthma and pneumonia); cardiovascular diseases (myocardial infarction, stroke, heart failure and arrhythmias); and conjunctivitis and meningococcal meningitis (Griffin, 2007; Gross et al., 2018). Population subgroups such as children, pregnant women, newborns, and the elderly are especially vulnerable to these effects. The prevalence of dust storms is likely to increase in places in South Africa that will experience reduced rainfall and increased periods of water scarcity / drought in the future. While various model projections for rainfall show little coherence, positive trends in annual rainfall totals over the southern interior in summer rainfall areas is expected with drying in the north and south-west (DEA, 2018). Public awareness and actions including early warning detection systems of a dust storm event, avoiding outdoor activities during the dust storm and keeping the indoor air free from environmental dust, are needed in South Africa to protect human health.

2.4 Ambient and household air pollution

Ambient (outdoor) air quality concentrations are regulated in South Africa to protect public health. In many parts of the country, ambient air pollutant concentrations are "not safe to breathe", as they exceed National Ambient Air Quality Standards (NAAQS) (e.g., Venter et al., 2012; Hersey et al., 2015; Feig et al., 2016; Govender and Sivakumar 2019). Trend analysis is difficult for many areas due to low data recovery. However, using data from stations in Gauteng and Mpumalanga provinces, decreasing particulate matter concentrations with an aerodynamic diameter $\leq$ 2.5 µm ($PM_{2.5}$) concentration trends have been found at some monitoring sites, though it has been estimated at current rates of reduction that it will take several years in some sites, and decades in others, to reach compliance with the current ambient standards, and even longer to meet the upcoming stricter ones (Feig et al. 2019).

Household air pollution is also an important health threat in South Africa (Jafta et al., 2017; Engelbrecht et al., 2000; Hersey et al., 2015). A large proportion of the population resides in low-income communities where solid fuel burning is used for cooking, heating, and lighting, thus exposing people within these households to air pollution concentrations which can be up to six times the levels recorded in the ambient environment (Shezi and Wright 2018; Buthelezi et al., 2019; Adesina et al., 2020).

Exposure to high pollution levels is associated with a range of respiratory and cardiovascular illnesses, as well as neurodegenerative diseases, diabetes, perinatal conditions, and low birth weight (Ezzati and Kammen, 2002; Coker and Kizito, 2018; Zhu et al., 2020; Schikowski and Altuğ, 2020). In South Africa, those who rely on coal or wood to cook and heat their homes are most at risk (Shezi and Wright, 2018; Naidoo, 2019).

Assessing the health impacts of exposure to air pollution in South Africa is difficult due to the lack of data across all aspects including uncertainties in emissions, atmospheric chemistry, and exposure (Garland et al., 2017; Muyemeki et al., 2020, Altieri and Keen, 2019). The Global Burden of Disease estimated that in South Africa there were almost 27,000 premature deaths and approximately 800,000 Disability-Adjusted Life Years attributed to air pollution in 2016 (indoor and outdoor). Both figures were less than in 2006 (GBD, 2016). A study simulating premature mortality attributable to $PM_{2.5}$ from future fossil fuel use for electricity generation and transport predicted more than 10,000 avoidable deaths in South Africa for the year 2030 (Marais et al., 2019), although there were large uncertainties in community-based and local emission sources, such as from domestic and waste burning. Despite the lack of detailed studies, poor air quality is recognised as having a detrimental impact on the health of South Africans currently.

2.5 Air pollution and interactions with climate change

Climate change and air pollution influence each other (Rogelj et al., 2018, Brasseur, 2009). Mortality related to air pollution, specifically to tropospheric ozone and $PM_{2.5}$, is expected to increase in many parts of the world under climate change (Orru et al., 2017; Smith et al., 2014). Sources of ambient air pollution in South Africa include emissions from anthropogenic activities, including traffic, industrial activities, mining, and residential domestic solid fuel burning, and natural sources including volatile organic compounds from plants, pollen, wind-blown dust, biomass burning, and marine sources such as sea salt spray.

Due to the complexities of air quality and climate linkages, there remain large uncertainties about what impact a changing climate will have on air quality, and the resultant health burden, in South Africa (Niang et al., 2014). These complexities are increased by the lack of data regarding the current situation, which leads to difficulties when trying to simulate future air quality. Altered emissions and meteorological factors will influence air quality, as will changes in human behaviour that affect exposure to air pollution. Under a business-as-usual scenario RCP8.5 of climate change, it has been projected that changes in meteorology alone over South Africa will lead to an increase in $PM_{2.5}$ mass concentrations (Westervelt et al., 2016) by the end of the century. However, additional research is needed to quantify potential changes in anthropogenic and natural emissions in the region.

In South Africa, natural emission sources play a key role, as they are climate-sensitive and impact atmospheric chemistry and air quality. For example, large-scale biomass burning of the savannahs and grasslands decreases air quality and impact atmospheric chemistry in South Africa during late winter and early spring (Duncan et al., 2003; Archibald et al., 2010; Swap et al., 2013). This burning contributes to PM and ozone pollution both at ground-level and aloft. Climate change is expected to affect fire regimes in South Africa, although not uniformly (IPBES, 2018). Changes in meteorology could lead to an increase in fire danger days, most significantly in the interior of South Africa (Engelbrecht et al., 2015). However, under increasing dry conditions, it is also possible for the number of fires to decrease due to reduced available biomass (IPBES, 2018). Further research is needed to understand the impacts of climate change on all relevant natural sources of emissions in South Africa, including pollen, dust, biomass burning, biogenic volatile organic compounds, and lightning.

The decarbonization of the energy sector, which is needed to reach climate goals, can have positive impacts on future air quality (Rogelj et al, 2018; Shindell et al., 2018; Rafaj et al., 2018). If current and planned energy, climate and air quality policies are enacted, it is estimated that global emissions of sulphur dioxide (SO_2) would decrease by ~75%, nitrogen oxide (NOx) by ~20% and $PM_{2.5}$ by ~25% in 2040 compared with 2015 (Rafaj et al., 2018). This would lead to improvements in air quality but would still leave 40% of the South African population exposed to annual $PM_{2.5}$ concentrations above World Health Organization Air Quality Guidelines' Interim Target-3 (15 µg/m^3), which is also the target value set by the South African NAAQS for 2030 (current target in 2021 South Africa is 20 µg/m^3) (Rafaj et al., 2018). More action is needed to decrease anthropogenic emissions.

Simultaneous exposure to extreme temperatures and high levels of ozone and $PM_{2.5}$ can worsen health impacts beyond the sum of their individual effects (Schnell and Prather 2017). This can be a concern for residents who live in urban areas, which often have high pollution levels and experience an 'urban heat island' effect – where warmer temperatures are measured in an urban area compared to the surrounding rural area (Gartland, 2008; Schnell and Prather, 2017). Though not fully understood, growing evidence suggests that there is a significant temperature-induced increase (6% change (95% CI: 3.4, 9.3) per 10 µg/m^3 increase in PM_{10} at lag 0-1 days) in air pollution-related hospital admissions linked to cardiovascular diseases in some cities in South Africa (Lokotola et al., 2020). This merits attention given that South Africa's Air Quality Priority Areas (areas identified as being highly polluted or potentially so in the future) correspond geographically with the projected highest heat risk areas for communities in South Africa (CSIR, 2019).

3. Actions required to ameliorate the detrimental impacts on human health

According to the Intergovernmental Panel on Climate Change (IPCC), mitigation and adaptation are the two main ways in which the impacts of climate change on health can be ameliorated. South Africa's 3rd Biennial Update Report to the United Nations Framework Convention on Climate Change (March 2019) details the country's National Greenhouse Gas Emissions Inventory and the national mitigation actions, including the Carbon Tax Bill. The Bill has helped to keep GHG emissions below values predicted, had mitigation strategies, such as Industrial Emission Standards, not been implemented. Mitigation efforts will result in net benefits for health as climate impacts will be decreased (Haines et al., 2009). The public health benefits of stringent mitigation pathways in line with 1.5 °C of global warming can be larger than the initial mitigation cost (IPCC, 2018). The most cited health co-benefits resulting from such efforts are related to the improved access to affordable and clean energy (for the socio-economically disadvantaged) and reduced air pollution levels, but benefits can also be achieved across the transport, food and agriculture sectors (Haines et al. 2009).

Adaptation is defined as '*the process of adjustment to actual or expected climate and its effects. In human systems, adaptation seeks to moderate harm or exploit beneficial opportunities. In natural systems, human intervention may facilitate adjustment to expected climate and its effects*' (IPCC, 2018). Public health adaptation strategies to protect against extreme heat include activities such as raising awareness, for example, in schools or clinics, providing shade and water at taxi ranks and other public places, establishing urban forestry projects for shade, retrofitting public buildings for optimal thermal comfort, setting policy, planning, design and building standards, and including extreme heat concerns in air quality management programs (EPA, 2020).

In addition, broad policy consideration is needed (Hobbhahn et al., 2019). Not only do health policies need to address direct climate change impacts on health, together with policies in other sectors, they need to consider the indirect impacts, such as increased drought affecting food and water security, and wildfires causing air pollution. A healthy, climate-smart food system for the country should be considered in the context of relevant agricultural policies and legislation. Importantly, the provision of better living and socioeconomic conditions for all South Africans as outlined in the country's National Development Plan 2030 (South African Government, 2012) is key to aiding resilience and adaptation efforts.

3.1 Role of the health and other sectors

The health sector has an important role to play in ameliorating the impacts of climate change. The proposed National Health Insurance will give equal access to care and treatment for all South Africans with particular emphasis on disease prevention and health promotion, key factors in protecting communities against the health risks of climate change (Wright et al., 2019). In addition, the health sector maintains information data systems and databases needed, for example, to track climate-sensitive diseases other than malaria, which is a notifiable disease in South Africa (Chersich and Wright, 2019). However, given the already strained healthcare system, its ability to respond remains uncertain. The World Health Organization promotes the 'Health in All Policies' approach which integrates health into environmental and disaster risk management policies, thus bolstering efforts to prevent the adverse effects of climate change on human health (WHO, 2014).

A critical role for the health sector is recording of data required for the analyses of the impacts of climate change on disease prevalence. The healthcare system in South Africa faces challenges such as lack of capacity and financial support and, despite attempts to improve quality of care, it is not optimal (Maphumulo and Bhengu, 2019). Health data are often lacking from primary healthcare facilities (The Africa Report, 2020) and where they do exist, they may not be in the appropriate temporal or spatial scale for application in climate analyses. Data are typically paper based, thus prone to error and loss, and require entry into electronic systems which is labour intensive and time consuming. Biometric data collection would be an improvement benefitting climate change and health research.

3.2 Preparedness, disaster risk management and public awareness

Preparedness for a society resilient to climate change is critical and the early detection of trends in diseases due to alterations in the climate is vital to facilitate effective interventions (Ebi et al., 2017). The National Climate Change Response Plan describes potential health challenges including vector- and water-borne diseases, heat stress and diseases related to air pollution exposure. It calls for increased data collection and research on links between climate and health and tracking of climate-related diseases as part of a national Monitoring and Evaluation System (DEAT, 2004). A significant recent advance in policy has been the Disaster Management Amendment Act No.16 of 2015, which now explicitly calls for the inclusion of climate change in disaster risk assessments (DEA, 2018)**.** This is applicable across all spheres of government and includes the development of early warning mechanisms.

Table 3. International and national commitments by South Africa to address climate change and human health risks.

Commitments, actions, activities	**Description**
The Constitution of the Republic of South Africa (No 108 of 1996) Section 24 (1996)	Everyone has the right to have an environment that is not harmful to their health or well-being for both present and future generations.
Drought Management Plan (2005)	Focuses on institutional arrangements, integrated institutional capacity, disaster risk assessment and reduction planning, and response and recovery from drought.
Libreville Declaration on Health and Environment (2008)	The African Libreville Declaration on Health and Environment also supports actions from the Paris Agreement around adaptation particularly for maternal and child health.
National Climate Change Response Policy White Paper (2011)	A comprehensive framework to address climate change adaptation, mitigation, and resilience development. A response strategy is laid out and actions are prioritized, for example, integrated planning across sectors is a necessity.
Intended Nationally Determined Contribution (2015) (https://unfccc.int/)	Commits to addressing climate change based on science and equity. The need for financial and capacity support is emphasized to implement the proposed interventions, such as early warning system preparation.
Paris Agreement (2016)	South Africa is party to the Paris Agreement within the United National Framework Convention on Climate Change that deals with greenhouse gas emissions mitigation, adaptation, and finance.
The National Development Plan 2030 (2017)	South Africa's overarching guide mentions the need to address the disproportionate impacts of climate change on the poor, especially women and children.
The Climate Change Bill (2018)	Calls for action to build an effective climate change response and to ensure the long-term, just transition to a climate resilient and lower carbon economy and society within the context of sustainable development.

National Adaptation Plans of Action locally-called the National Climate Change Adaptation Strategy (2016)	Provides South Africa's vision is to transition to a climate-resilient South Africa and six strategic outcomes with suggested interventions must be met by 2028.
National Energy Strategy (2019)	Determines how to improve energy utilization which has implications for cleaner air and improved human health.
The South African Risk and Vulnerability Atlas (SARVA) website (2020) (http://www.csag.uct.ac.za/sarva/).	SARVA is portal with resources about climate change and spatial data sets to assess climate change impacts and risks.
Vulnerability Assessments at national, city and district municipality level (2020) (http://sarva2.dirisa.org/)	Several vulnerability assessments have been made to identify climate change impacts to South Africa. The assessments have proposed mitigation and adaptation actions to address these impacts.
Climate Change and Health Adaptation Plan 2014-2019 (2014); 2020-2024 (unpublished)	Co-ordinated by the National Department of Health, the plan for 2020-2024 has been drafted and submitted for approval. The plan's vision is for a 'climate-conscious South Africa'.
National Heat Health Action Guidelines for South Africa (unpublished)	The National Department of Health has developed this as a guide for extreme heat planning in South Africa related to the human health sector.

However, in the health sector, the development and implementation of such early warning systems is hampered by lack of data relating to climate-sensitive diseases. Research is needed to understand health issues in South Africa in a way that best informs interventions and preparedness, and accounts for the complex interlinkages. Some work on climate change preparedness and the establishment of early warning systems exists, for example, for malaria (Ikeda et al., 2017), though more is needed. The soon-to-be finalized 2020-2024 National Climate Change and Health Adaptation Plan has a strong call for action to establish and strengthen early warning systems for climate-sensitive diseases (Table 3). Other commitments exist and require continued implementation with appropriate financing. For example, the National Heat Health Guidelines call for sector leadership and stakeholder co-ordination to prepare adaptation plans, warning systems, information for public awareness-raising, and giving special care to vulnerable groups, such as the elderly, and attention to people exposed to heat in occupational settings. In addition, more work is needed to enforce existing air quality legislation, such as minimum emission standards and air quality by-laws. Climate change considerations should be included in air quality management and planning (Thambiran and Diab, 2010; Klausbruckner et al., 2016); more research is needed on linkages between air quality and climate, and resultant impacts, to provide a quantitative evidence base to support such policies.

Disaster risk management includes modelling and planning responses to climate and weather-related extreme events, including riverine flooding and storm surges. Vulnerability and disaster risk assessments are key elements. Given the anticipated increase in climate change-induced risks and extreme weather events for South Africa, there is a need for investment in disaster risk management activities that prevent impacts rather than serve only to provide relief (Davis-Reddy and Vincent, 2017). Early warning systems are required (Chapungu, 2020). For example, the South African Flash Flood Guidance system provides warnings within one to six hours of potential flash floods (DEA, 2017). Another operational early warning initiative is The World Meteorological Organization's Severe Weather Forecasting Demonstration Project (SWFDP) which forecasts the intensity and movement of rainfall and severe winds across southern Africa and issues flood warnings (Poolman and Chen, 2009).

Prevention includes raising awareness among the public for appropriate understanding of the risks and actions to protect health and livelihoods. Community education materials via radio, TV and social media are needed in local languages. For example, information about preventing diarrheal disease, which increases during periods of drought as well as when there is flooding (Ikeda et al., 2019), is required in primary healthcare settings. The public also need to be aware of other health outcomes that are likely to increase with climate change. One example of this is drinking clean and sufficient water as well as seeking shade and limiting vigorous outdoor activities as important strategies during heatwaves. While the government has a critical role to play in public awareness campaigns, so too have Non-Governmental Organizations, businesses, educational facilities, and the media.

3.3 Education, training, and capacity building

South Africa is committed to including education on climate change and to training in educational policy. Appropriate content and materials for disparate audiences and settings are required. While an explanation of what climate change means is included in the National Curriculum and Assessment Policy, little is discussed regarding precautions individuals can take to protect their health (DEA, 2017). Training for teachers, health professionals and environmental health practitioners at tertiary institutions about climate change and health should be included.

4. Conclusions

Many of the existing health stressors in South Africa will be impacted adversely by climate change although there is a lack of quantitative modelling at present to provide accurate figures. Rising temperatures and regular heatwaves in South Africa are anticipated to lead to a general increase in overall mortality and morbidity in the future. This would occur on top of existing problems relating to societal inequalities. Several vector-borne diseases are likely to become more common and to spread into new areas of the country. The incidence of skin cancer may also rise. Drought and heavy rainfall events are projected to increase in different parts of the country leading to possible increases in malnutrition and water-borne diseases. Air pollution levels will be altered by a changing climate, which is of concern as current levels do not comply with national standards, and any effects on health are rarely considered in air quality planning. Whether changes in the climate will result in severe health issues for South Africa will depend largely on the provision of better living and socioeconomic conditions as outlined in the National Development Plan 2030, in conjunction with improved policies and mitigation interventions. Adequate education regarding personal protective behaviour, vector control and ready access to medical care and treatment will also be important.

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