CZECH UNIVERSITY OF LIFE SCIENCES PRAGUE

Faculty of Forestry and Wood Sciences

Master Thesis Work

Impact of climate change on precipitation in the Cuvelai-Etosha basin

Amakutuwa Paulus Natango

2010

Certification

I, Paulus Natango Amakutuwa, declare that this Diploma thesis, submitted in partial fulfillment of requirements for the degree of M.Sc., in the Faculty of Forestry and Wood Sciences of the Czech University of Life Sciences Prague, is wholly my own work unless otherwise referenced or acknowledged.

Prague,

Acknowledgments

I would like to thank my thesis supervisor, prof. Ing. Kupka Ivo CSc. (Department of Silviculture) and doc.Ing Štibinger Jakub CSc.(Faculty of Environmental Sciences, Department of Constructions and Planning) for leading my work.

I would also like to thanks Ing. Martin Hanel and Ing. Adam Vizina (Faculty of Environmental Sciences, Department of Water Resources and Environmental Modeling)for their commitment and patience in guiding me with my work,

I would thank the Namibia Meteorological Service for provinding the climatic data used for analysis in this study.

Thanks goes to the Almighty Jahovia too, for making it all possible.

Abstract

The Cuvelai-Etosha basin is located on one of the most aridic part of Southern Africa, one of the regions that are more varnuable to climate change. This study will focus on the impact of climate change on precipitation of the basin. The context of the study is based on climate analysis of the basin precipitation, using precipitation data recorded over the years at Ombalantu, Oshikuku and Okaukuejo weather stations. Additionally, the study also use global climate models (GCMs) for evaluations. Climate change variation are the key features of this study. The impacts of this variables are then used to analyse their overall impact on the precipitation of the basin. Precipitation response is managed by a large number of varieties, however this study will only try to focus on the impact that might be caused by the change in weather and climate. The study will then look at any variation in the analysis results and try to predict from this any impact caused by climate change. Dry and wet seasons in the country which are caused by tropical air masses flowing from southern Angola and dry air mases from the dry Namib and karahali desert in the south, makes up two distinctive precipitational seasons, which are also used to analyse seasonal variation in precipitation.

Key words: Cuvelai-Etosha basin, GCMs, Climate Change, Arid, Precipitation

"There is also high confidence that many semi-arid areas (e.g. the Mediterranean Basin, western United States, southern Africa and north-eastern Brazil) will suffer a decrease in water re-sources due to climate change." (IPCC AR4 2007)

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1. Introduction

Namibia is one of the driest countries in the world with increasing aridity, with highly variability in precipitation. The country has an annual precipitation of 25-700 mm (Amakali, 2008). Only a small area in the northern part of the country receives sufficient rainfall and this is where much of the country population is located. The Cuvelai-Etosha basin (CEB) falls within this area too and it is home to about 40% of the country population (Korberg *et al*.1996). A large number of people in this area depend on the basin, as their important source of water for almost every use. High salinity of groundwater in the central parts of the basin makes this water less usable and only wells dug after the rainy season can be used for few months. With increasing temperature locally and globally, variability in precipitation and water availability has made it hard for both the people and the environment in the CEB.

Whether climate change causes changes in precipitation today is not a scientific debate anymore because many scientific studies have already proven this. The relevant question is how big the changes are. There are several reasons, why climate change cause changes to precipitation. One of the most important changes has to do with the general physics of water, when water heats up, it expands. However, it is hard to notice the change on a small scale, but in large reservoirs or in the case of the Cuvelai-Etosha basin, the effect is quite large.

The form in which precipitation occurs depends largely on temperature, which is also influenced by many other parameters such as elevation. A good example is capped mountains in tropical regions. The amount of precipitation is determined by the amount of water vapour available in the atmosphere and the way that lead to the condensation of water vapour into liquid or solid form through cooling in the atmosphere.

Precipitation occurs mostly in areas with conditions that favour condensation and tropical areas where there is high water vapour in the atmosphere. The Cuvelai-Etosha basin is located in a dry area with relatively small evaporation of water from the surface, thus there is less water vapour in the atmosphere that favour precipitation conditions and even in wetter seasons, much of water vapour tend remain in the atmosphere, because of conditions and high temperatures that doesn’t favour condensation.

Aim of this study is to asses the changes in precipitation of the Cuvelai-Etosha basin that might be caused by climate change. The study uses two sets of data for assessing the hypothesis; observed precipitation from 3 stations (Okaukuejo, Oshikuku and Ombalantu), which are all within the study area, and modelled precipitation data from 3 Global Circulation Models (GCM’s) HadCM3Q0, HadCM3Q3 and HadCM3Q16. In the study, both observed and GCM precipitation will be analysed for any changes over time and the results will be used for comparisons.

2. Literature review

Climate, Weather and its impact on precipitation distribution and intensity have all received increased interest in research recently, due to the unpredictability of events and ability of these events to cause life-threatening catastrophes such as floods. Uncertainty in predicting precipitation events and how they affect human activities and natural systems have gained popularity in research. The behaviour of water has already been studied for millennia, or at least the three past millennia Greek philosophers who discussed the question of the balance between; net evaporation (evaporation minus precipitation) over the ocean and the net precipitation (precipitation minus evaporation) over the land (dooge J.2007).

Interest to do this study is also based on questions to answer events such as; recent seasonal floods in the study area. In the past 3 years, northern Namibia has been affected by seasonal intense floods, which hit most of the northern parts of Namibia, of which much of the area is within the Cuvelai-Etosha basin. In 2008 and 2009, the President of Namibia, Mr Hifikepunye Pohamba declared a state of emergency because of the floods in the north and north-eastern Namibia, the area including the CEB.

2.1 Precipitation and water in climate change study

Precipitation in this study is referred to any form of water, such as rain, snow, sleet, hail, dew or frost that falls to the earth's surface from the atmosphere. Precipitation measurement, is often referred to as precipitation or simply as rainfall, which is measured as the actual depth of liquid water which has fallen on the ground in a collecting (measuring) gauge, after frozen forms have melted, and is recorded in millimetres [mm] or inches [In].

Our planet support life because of the presence of water on it. Water on our planet exists both on the earth surface and the atmosphere around it. The distribution of this water on the planet and around, is balanced by the temperature around the earth surface. If the earth were five per cent closer to the sun, water could only exist in its hydrosphere as water vapour; if the earth were five percent further from the sun, water could only exist in its hydrosphere in frozen form (Dooge J.).There have always been some changes to our atmosphere such as the increase in atmospheric water vapour content, changes in event intensity, and Extreme events due to global and climate change, water scarcity is expected to be an ever increasing problem in the future.

Rainfall occurs mostly in areas with conditions that favor condensation and tropical areas where there is high water vapour in the atmosphere. The Cuvelai-Etosha basin is located in a dry area with relatively small evaporation of water from the surface, thus there is less water vapour in the atmosphere that favour precipitation conditions and even in wetter seasons, much of water vapour tend remain in the atmosphere, because of conditions and high temperatures that doesn't favour condensation.There are different ways in which precipitation may changes due to change in climate as listed bellow (Thomas et.al, 2007):

1) Changes in the frequency of precipitation events
2) Changes in the intensity of precipitation event
3) Combination of the first 2
4) Changes in type of precipitation
5) Changes in duration of precipitation events

Changes in the frequency of precipitation events are described as those changes in the number of occurrence of precipitation events. In this study, Annual precipitation frequency will be analysed to determine any change in annual precipitation distributions. Precipitation intensity is measured as the rate at which precipitation falls, usually in millimetres per hour. Precipitation intensity is normally inversely proportional to its duration Changes in the precipitation event are thus defined as the change in the rate, at which precipitation fall per one event.

Another way to analyse precipitation changes, is to evaluate the trends of the proportion of precipitation falling in a specific class interval compared with the total mean precipitation (Thomas *et al*. 2007).

Trenberth et al. (2003) hypothesized that, due to changes in global temperature, on average, precipitation will tend to be less frequent, but more intense when it does occur, implying greater incidence of extreme floods and droughts, with resulting consequences for water storage.

Furthermore, it is very likely that heavy precipitation events with high intensity will become more frequent and greater risks of floods, droughts and a decrease in average precipitation in region will become more common. s such as the study.

2.2 Floods

Floods are commonly caused by extreme heavy precipitation events, which are projected to become more frequent over most regions throughout the 21st century. The Cuvelai-Etosha basin has been affected over the past 3 years (2006-2009) by seasonal floods. Guido van Langenhove, head of hydrology in Namibia, reported during the time of the 2008 northern Namibian floods that; the Cuvelai area was a disaster, with the floods at the highest level seen in over 35 years and president Hifikepunye Pohamba, described it as to be experiencing one of the worst natural disasters in and a lot blamed climate change for the floods (IFRC, 2009). The worst affected regions by the 2009 floods were; Omusati, Ohangwena, Oshana and Oshikoto, which all fall within the Cuvelai basin. Fig. 2.1 bellow show the situation in 2009 floods.

Photo: A flooded crop field

Flooded households in the Ohangwena region.

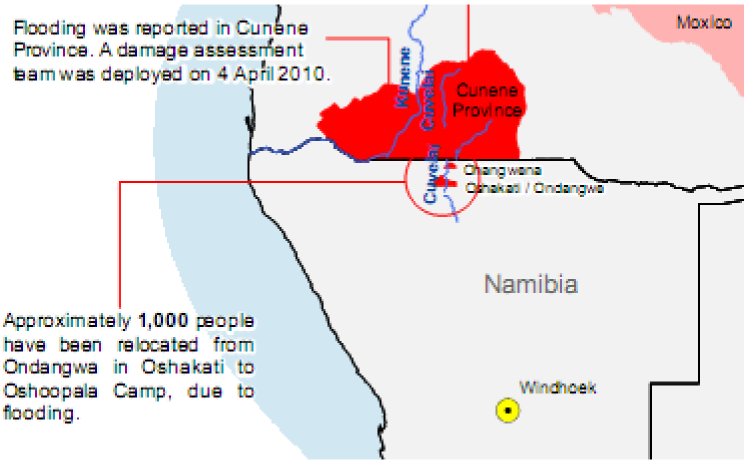
***Fig. 2.1** Flooded crop field and household in the CEB. (IFRC, 2009)*

In 2010 New floods have been reported in northern Namibia, with an estimated 1,000 people displaced (IFRC, 2009)The current rainfall over northern Namibia and southern Angola may again add to the flooding that is already being experienced in the Cuvelai.

Table 1. *Overview of 2008 and 2009 northern Namibia floods.*

	2008 Floods	**2009 Floods**	**2010 Floods**
AffectedArea/Region	Oshana, Ohangwena, Omusati and Oshikoto	Omusati, Ohangwena, Oshana, Oshikoto, Caprivi, Kavango and Kunene	Caprivi Region, Omusati, Ohangwena, Oshana and Oshikoto
Fatalities/Damages	○ 42 deaths ○ 4,500 Displaced people	○ Up to 300,000 affected people and 276,000 displaced (IFRC,2009) ○ Damaged crops and Infrastructures (School, roads and houses) ○ At least 112 people have died(*Agence France-Presse, 2009*)	○ 1,000 + 8,000 – 9,000 estimated people displaced (ROSEA, 2010) ○ Some roads flooded in the Caprivi Region. ○ 4 health facilities only accessible by boat or by crossing through Botswana or Zambia (ROSEA, 2010).
Duration	February-March 2008	March–April 2009	-

From the table, it is clear that the 2009 floods were more devastating than those of 2009, and judging from the flood overview table, and the rainy season not yet over for the 2009/2010 rainy season, one can say that floods are becoming more frequent and dangerous each year in the area.


Flooding was reported in Cunene Province. A damage assessment team was deployed on 4 April 2010.

Approximately **1,000** people have been relocated from Ondangwa in Oshakati to Oshoopala Camp, due to flooding.

Fig. 2.2 *Floods in the CEB from the flood report as of 9 April 2010 (UN,2010).*

Fig. 2.2 from the reports on Southern Africa floods shows the affected areas (Angola/ Namibia) including the study region (circled in red).

Then Namibian Economist (specialist business publication) reported in December of 2008 that the floods which began in early February 2008, killed 42 people by early March. Another estimated 250,000 people, in the regions of Oshana, Ohangwena, Omusati and Oshikoto, were left stranded without outside access except by helicopter, with another 65,000 People facing displacement (The Namibian Economist, 2008). These floods are however associated with changes in climate, that is causing more intense precipitation events, that are less frequent.

3. Study Area

3.1 Background

The Namibian part of the Cuvelai-Etosha basin (CEB) is situated in the north-central part of Namibia and covers an area between the Okavango and Kunene Rivers and ends up in the Etosha pan. It lies within the Omusati, Ohangwena, Oshikoto and Oshana region. The Cuvelai is an endoric river, that has no discharge to the the sea, and it is some 430 Km in length, originating in the Southern part of Angola (Heyns, 1995) and has a total area of about 30 000 Km² (Kolberg *et al*, 1996). The basin is made up of shallow pans known as Iishana, which form a delta like rivers ending up in the Etosha pan. The basin covers a large area along the northern Namibian borders with Angola down to the Etosha pan. The area between Iishana watercourses is mostly used for crop and livestock farming. The CEB basin is sub divided into four sub-basins by the Ministry of Agriculture, Water and Forestry (MAWF) as listed bellow and illustrated in **Fig. 3.1** (Paul *et al* 2007).

- Tsumeb
- Cuvelei-Iishana
- Niipele-Odila
- Olushandja

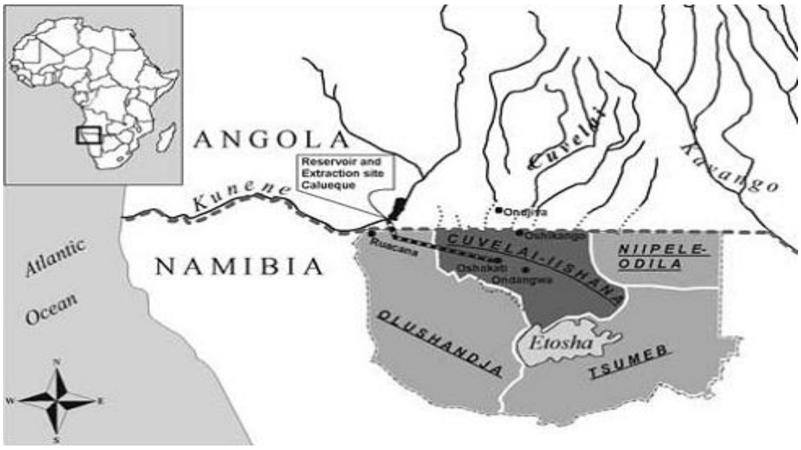


Fig. 3.1 *The Cuvelai-Etosha basin and its sub-basins (Cuvewaters).*

The Etosha pan which is part of the CEB has an elevation that ranges from 1,071 m to 1,086 m and has an area of 6,133 Km² (McGinley, 2007). The CEB is located in the Etosha National park (ENP), a government owned national park that is home to many wild mammals and other wild species in the country. The ENP is one of the biggest national parks of its kind in the world, and the biggest in the region. The Etosha national park got its name after the Etosha pan (Martin, 2005). **Fig. 3.2** and **3.3** show the location of the study area and the course of the basin.

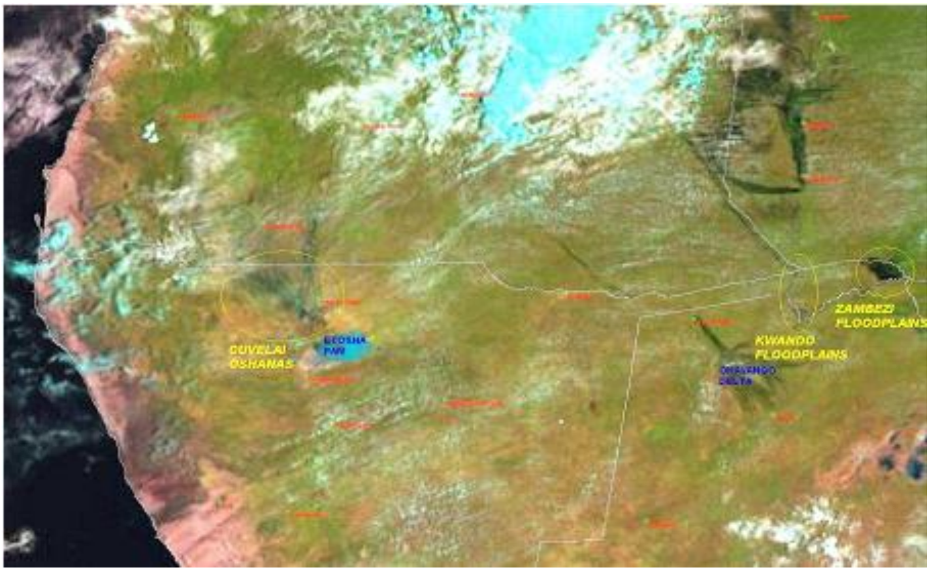
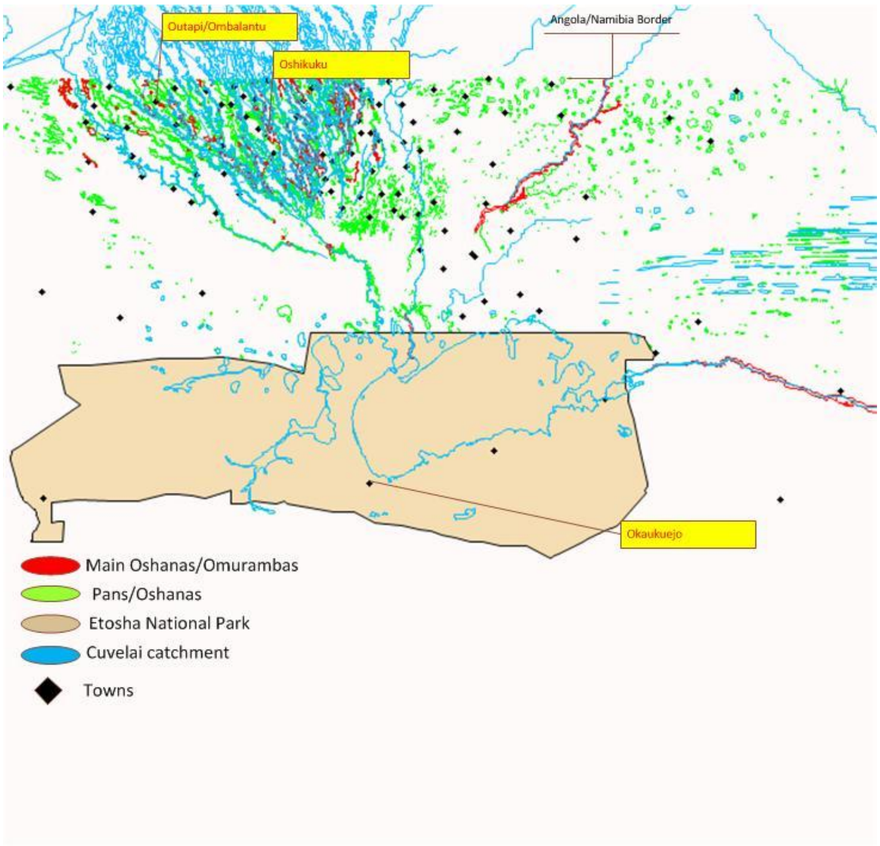


***Fig. 3.2** Aerial view of northern Namibia and the Cuvelai-Etosha basin(Cuvelai/Oshanas & Etosha pan).*



Scale: 1:20,000

Fig. 3.3 *Map of Iishana(Cuvelai river system), Cuvelai pans and Etosha pan in the ENP (Etosha National Park). Highlighted in yellow, are the location of station where observed precipitation used in data analysis were recorded.*

Together, the Cuvelai and Etosha pan make's up the Cuvelai-Etosha basin. The basin is one of the most populated areas in the country. It is made up of sparsely distributed wells and settlements where crop farming is very common. The area is an extremely flat plain, covered with white sands.

3.2 Climate

The climate within the basin area is generally influenced by global atmospheric circulation, elevation and continental location. Generally it is semi arid, which is wetter from the north-eastern region to extremely dry south-western region. Namibia has an average 10 hours of sunshine per day and an average daily temperature of 25°C. Absolute maximum and minimum temperatures can vary between -10°C and +40°C; monthly mean temperature ranges from 26°C in November to 16°C in July. Daily average temperature within the study area varies between 17°C in winter and 25°C in summer. These climatic conditions contribute to a unique hydrological cycle.

3.3 Precipitation in the study area

Precipitation in the basin occurs in the summer months (October-April) and is highly variable in terms of quantity, timing and coverage. Most storms in the area come from the east moving westward to south-westward, thus the easterly parts receive more and earlier rainfall than the west (Mendelsohn *et al*, 2000). Due to the climate of the region, much of the water from precipitation evaporate fast or infiltrate to the ground. Namibia and southern Angola receive less than 2 mm/day under present-day conditions in summer, and the rainfall reductions that are predicted under climate change are up to about 1.5 mm/day (Hudson, 2002).

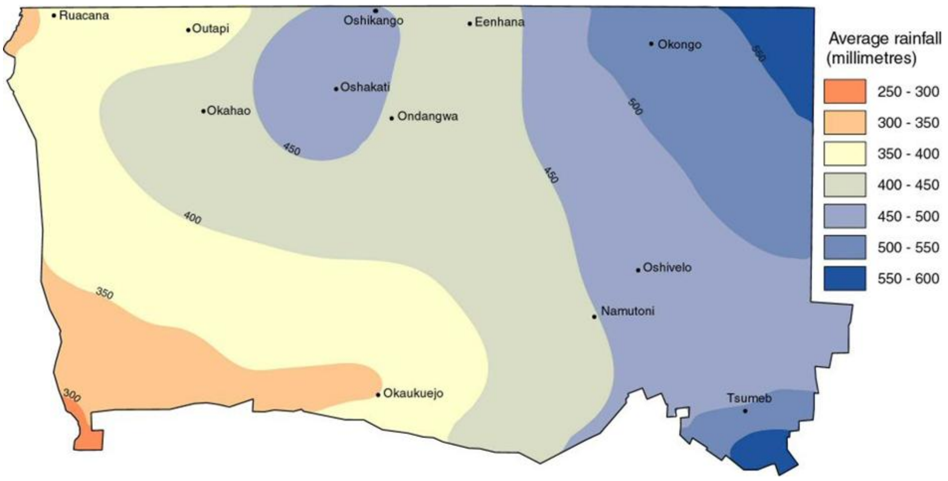


Fig. 3.4 Average precipitations in the study area. (MET 2010)

Okaukuejo and Ombalantu (referred to as Outapi) used in recording observed precipitation for this study are highlighted in **Fig. 3.4**.

Table 2. *Guide and descreption of station used in observed data analysis.*

	Ombalantu	**Oshikuku**	**Okaukuejo**
Geographical Location	17°30'40"S +14°59'14"E	17° 38' 60"S; +15° 28"' 0E	-19° 10' 48"S, +15° 55' 12"E
Elevation [m]	1107	1086	1100
Region	Omusati	Omusati	Kunene
Sub-basin	Olushandja	Cuvelai-Iishana	Olushandja
Notes	Ombalantu (also referred to Outapi in some maps) is the far northern station used in data analysis.	Oshikuku is probably the most populated of all the 3 station.	Okaukuejo is the far southern station in the studied region and the less populated.

The basin receives average annual precipitation of approximately 300 mm in the south-west and 550 mm in the north-east as illustrated in **fig. 3.4,** that adds up to the interconnected water channels flowing from highlands in Angola to the southern lowlands of Namibia into the Etosha Pan. The interconnected water channels in between, works as pathway for flooding that recharges ground water aquifers in the area. These water channels carry water only seasonally, during the rainy season.

The Etosha pan retains water annually in the months between January and April. The pan's surface is a flat floor of saline sandy-clay that is poorly drained, allowing for easy waterlogging. When dry, the whitish clay cracks into hexagonal salt-encrusted fragments (Annex 3) with the pH between 8.8 and 10.2 (McGinley, 2007, 2007). Three rivers (Ekuma, Oshigambo and Omuramba Ovambo) supply the input to the Etosha pan. The rivers flow mostly during the rainy season, depending on the amount rainfall, however in dry years the rivers might not flow at all, In this case, it forms a series of disconnected pools (Paul *et al.* 2007).

- Lake Oponono: Situated on the north , lake Oponono is connected to the basin by Ekuma river and receives its input from the Cuvelai perennial watercourses (Iishana) and the Cuvelai river.
- Oshigambo River: Another important source of input , situated to the north of the pan, is the Oshigambo river. The Oshigambo river receive it's input from Angola through the Cuvelai/Iishana system.
- Omuamba Ovambo River: Another input to the pan that is situated to the north-east of the pan. The river receives its input from a catchment on the northeast of Etosha through an extension of the main body, the Fisher's pan.

3.4 Geology

Generally, the whole area within the CEB is characterized by a 500 m profile of thick semi- to unconsolidated sediments, which belongs to the Kalahari sequence. Four geological formations as described bellow can be found in the study area.

Ombalantu formation: The area is made up of red, semi-consolidated but fried variability scarified mudstones, almost entirely consisting of clay whilst others contain an appreciable amount of silt and sand sized grains Formation around Outapi in the map (**Fig. 3.1**).

Beiseb: mainly reddish in colour, but also light green to white near the Etosha pan consisting of sandstones , mudstone clasts as well as pebbles of various cherts that are set in a matrix of fine to medium-grained argillaceous, calcareous and dolomite sandstones.

Andoni formation: most pervasive, contain white medium-sized sand grains, light greenish clay sands and nearly around 90 percent of the sand is quartz. The remaining part is made up of chalcedony, feldspar and chert.

Olukonda formation: reddish brown in colour, consist of poorly sorted, consolidated sand and sandstones, and is very similar to the Ombalantu formation.

4. Climate research

4.1 Climate

Climate is a meteorological condition, characterized by temperature, precipitation, atmospheric pressure, wind and atmospheric water vapour of a particular region over a long period of time, from one month to millions of years or simply the aggregate of weather over a long period of time.

The US history encyclopaedia describe The word climate, as delivered from a Greek work '*klima*' meaning inclination because it was originally thought to depend only on the height of the sun above the horizon modified in parts by special local characteristics.

To understand and research on a particular regional climate, we need to know and understand the characteristics of the region and what characterize the regional climate. The world climate can be classified into several categories (classification). The most widely used form of classification is the 'Köppen climate classification' originally developed by Wladimir Köppen, which in use since 1948. (Beck, 2005)

Global climate classification were constructed in order to designate the manifold existing local climates and to determine spatial vegetation's of the world. Most climate classification uses monthly temperature and precipitation data, based on environment characteristics.

4.2 Climate Classification (Köppen)

Köppen climate classification was first invented by a German climatologist Wladimir Köppen in 1884with several later modifications by Köppen himself notably in 1918 and 1936. Different aspects of global and regional climate change have been investigated on the basis of the climate classification according to Köppen classification. Today the most widely used classification is that of Köppen

1939. The classification is based on the characteristics of the mean annual cycle of temperature, precipitation and seasonality of precipitation (Beck et.al, 2005).

Köppen climate classification scheme divides the climates into five major groups and several type and subtypes. Each particular climate type is represented by a 2 to 4 letter symbol (Annex1).

1) **Group A: Tropical/megathermal climates**
    - ❖ Mean Temperature of the coldest month exceed +18ºC

2) **Group B: Dry (arid and semiarid) climates (Precipitation R (cm), Temperature T (ºC))**
    - ❖ R‹2T+28 (where the summer rain is dominant)
    - ❖ R‹2T+14 (where no pronounced annual cycle is observed)
    - ❖ R‹2T (Winter rain dominant)

3) **Group C: Temperate/mesothermal climates**
    - ❖ Mean Temperature of the coldest month is between /-3ºC and -18

4) **Group D: Continental/microthermal climate**
    - ❖ Mean temperature of the warmest month exceed +10ºC
    - ❖ Mean temperature of the coldest month below -3ºC

5) **Group E: Polar climates**
    - ❖ Mean temperature of the warmest month below 10ºC

4.2.1 Study area according to climate classification (GROUP B: Dry (arid and semiarid) climates)

Group B of the Koopen climate classification is based on regions with precipitation that is less than potential evapotranspiration. The Cuvelai–Etosha basin fall within type B of the Koppen climate classification, dry climates. And can further be sub classed to arid/semiarid climate (Bsh).

According to Koppen climate classification; A semi-arid climate or steppe climate describes climatic regions that receive low annual precipitation, usually between 250-500 mm of precipitation. They are described as climates (BSk and BSh) which are intermediates between the desert climates (BW), (an example of the Namib desert on the western part of the study area) and humid climates in ecological characteristics (an example of the humid regions in Angola), and agricultural potential (common practice in CEB).

Desertification is one of the most feared environmental threats facing these regions. With fear on global warming, and a decrease in precipitation, much of these areas face desertification. With much of the poorest people in the world living in these areas, with less available technology and resources, it is however a serious problem and further desertification of already degraded land can be expected to increase in future. **Fig. 2.5** shows changes in climate type B, in Africa, and it can be clearly seen how dry ecosystems are increasing, most probably due to desertification.

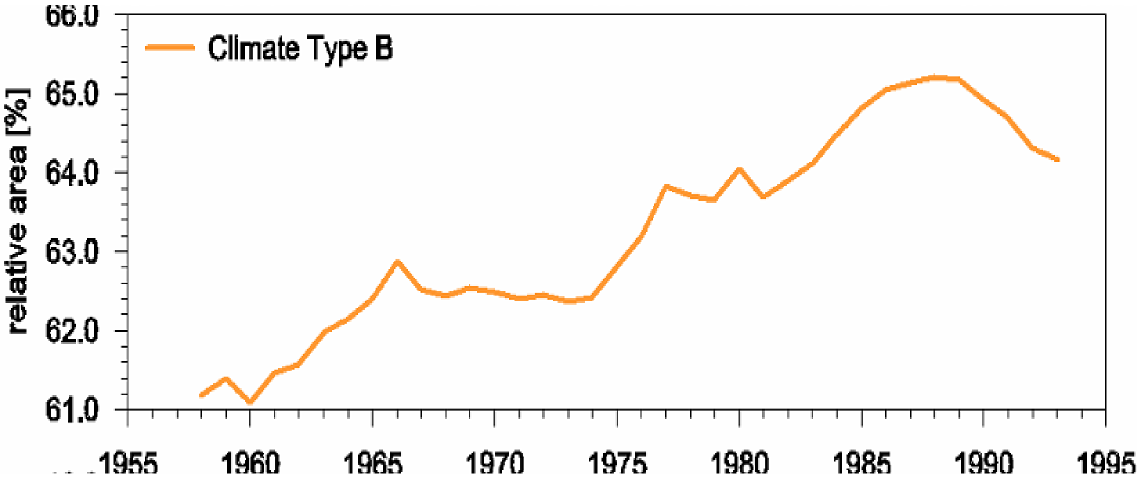


***Fig. 4.1** Time series of the relative area (percentage of Africa) occupied by climate group B of the Köppen climate classification. (Beck, 2005)*

4.3 Climate System

To understand climate and climate change, we need to understand the ‘‘climate system‘‘. The climate system is made up of the following components;

a) Atmosphere
b) Oceans
c) Terrestrial and Marine biosphere
d) Cryosphere
e) Land surface

The collective interaction of these components determines the earth’s surface climate. These interactions occur in the flow of energy in different forms, by exchanging water, through flow of various other radioactively important gases (including. carbon dioxide and methane) and through the cycling of nutrients. The climate system is powered by the input of solar energy, which is balanced by the input of infrared (‘‘heat‘‘) energy back to space. Solar energy is the driving force for the motion of the atmosphere and ocean, the fluxes of heat and water, and of biological activities (Christensen *et al*, 2007).

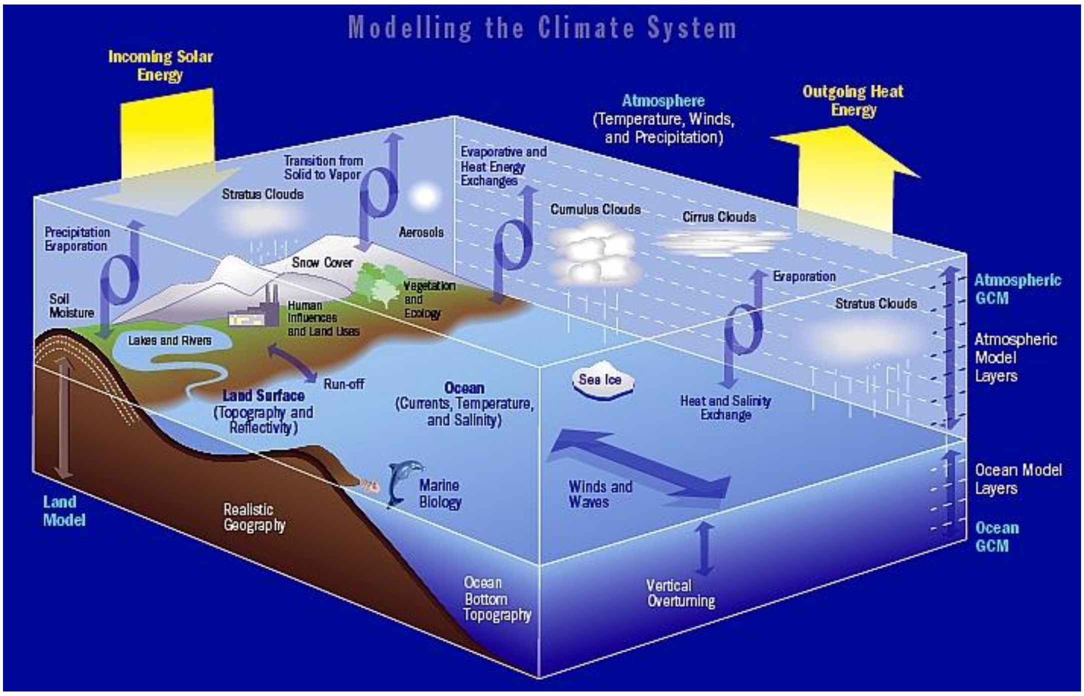


***Fig. 4.2** Schematic overview of the components of the global climate system and their interactions (*William, 2009*)*

4.4 Intergovernmental Panel on Climate Change (IPCC)

Established in 1988 by the World Meteorological Organisation (WMO), and the United Nation Environmental programme (UNEP) both organisation of the United Nations (UN); IPCC is a scientific intergovernmental body with a duty of evaluating climate change due to human activities.

The IPCC reviews and assesses the most recent scientific technical and socio-economic information produced worldwide relevant to the understanding of climate change. The IPCC does not conduct any research nor does it monitor climate related data or parameters. Thousands of scientists from all over the world contribute to the work of the IPCC on a voluntary basis. Review is an essential part of the IPCC process, to ensure an objective and complete assessment of current information. Differing viewpoints existing within the scientific community are reflected in the IPCC reports.

The aims of the IPCC are to assess scientific information relevant to (IPCC, 2010);

- human-induced climate change
- the impacts of human-induced climate change
- options for adaptation and mitigation

4.5 Climate Change

The theory of CO2 warming the earth atmosphere dated back in the nineteenth century when Svante Arrhenius, a Swedish chemist who in the 1880’s, was curious on the effect of CO2 on global temperatures. Arrhenius decided in 1894 to calculate how the earth temperature would be affected by changing CO2 levels. He asked what would happen to the earth’s climate if CO2 levels were halved and also if they were doubled. In the case of doubling, he determined that average global temperatures would rise between 9-11°C (Korbert, 2007). Arrhenius discovery is still used in the most sophisticated climate models in operation today. (Korbert, 2007)

Climate change in IPCC usage refers to a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity. This usage differs from that in the United Nations Framework Convention on Climate Change (UNFCCC), where climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods (Christensen *et al*, 2007).

Understanding climate change is complicated, since there are a lot of factors involved, and it is not easy to understand their interactions. In recent years, climate change has become a global emergency and it is spoken of, all over the world. A complex interaction of human and the Earth system, including many other factors such as emissions, impacts and responses (annex 2)

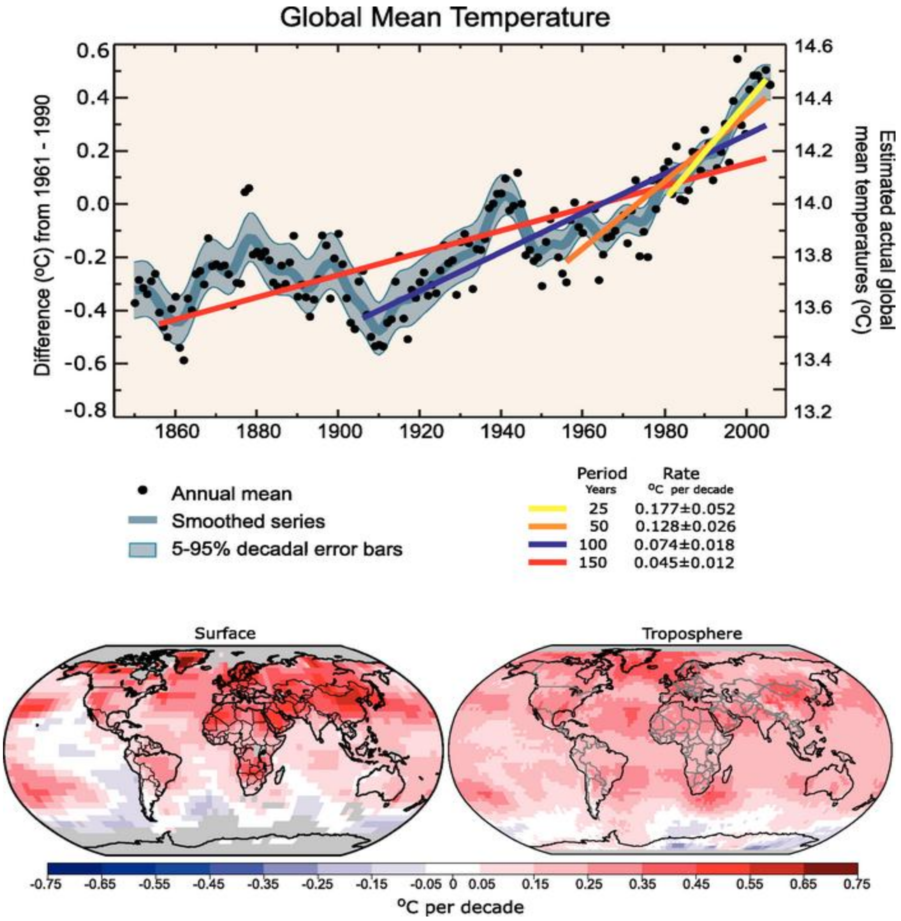


Fig. 4.3 *Annual global mean observed temperatures1 (black dots) along with simple fits to the data. The left hand axis shows anomalies relative to the 1961 to 1990 average and the right hand axis shows the estimated actual temperature (°C). Linear trend fits to the last 25 (yellow), 50 (orange), 100 (purple) and 150 years (red) are shown, and correspond to 1981 to 2005, 1956 to 2005, 1906 to 2005, and 1856 to 2005, respectively. To give an idea of whether the fluctuations are meaningful, decadal 5% to 95% (light grey) fitted.* (Christensen *et al, 2007)*

4.5.1 Causes of Climate change

Properties of gases like Carbon dioxide (CO_2), Nitrous oxide (N_2O) Methane (CH_4), and Chlorofluorocarbons (CFC) contribute to the warming of the earth. CFC's permit free passage of radiation from the sun through to the earth surface and absorb the re-radiated radiation from the earth (Houghton, 1997), their increase in the atmosphere means an increase in global temperature too, and their effect is known as the "Greenhouse effect" and the gases involved as greenhouse gases (GHG's), which are defined as any gas that absorbs radiation at specific wavelengths within the spectrum of radiation (infrared radiation) emitted by the Earth's surface and by clouds. The gas in turn emits infrared radiation from a level where the temperature is colder than the surface. The net effect is a local trapping of part of the absorbed energy and a tendency to warm the planetary surface.

Greenhouse effect is a state caused by the presence of radioactively active gases in the earth atmosphere (water vapour, carbon dioxide and ozone). These gases, including other greenhouse gases are relatively ineffective absorbers of radiation.

4.5.1.1 Carbon dioxide (CO2)

Carbon dioxide (CO2) is the most important anthropogenic GHG. Concentration of atmospheric CO2 has increase from 280 ppm to 381 ppm in 2006, with an annual rise of up to 2,53 ppm (Kolbert , 2007). In nature, carbon is cycled between three main reservoirs: The atmosphere in the form of carbon dioxide, the terrestrial biosphere and the oceans. Carbon dioxide annual emissions have grown between 1970 and 2004 by about 80%, from 21 to 38 gigatonnes (Gt), and represented 77% of total anthropogenic GHG emissions in 2004 (IPCC ASR4, 2007). The global increases in carbon dioxide concentration are due primarily to fossil fuel use and land-use change.

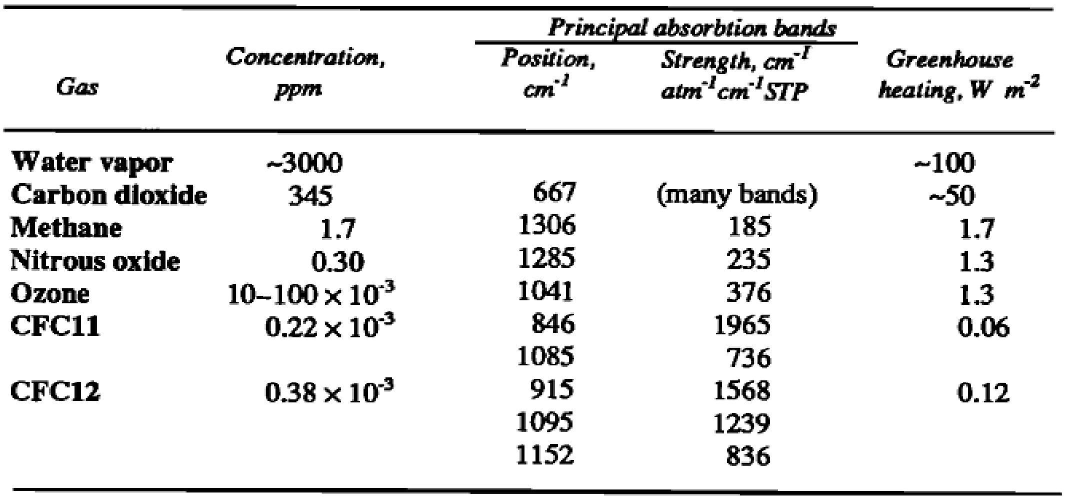
4.5.2.2 Other greenhouse gases

Water vapour (H2O), nitrous oxide (N2O), methane (CH4) and ozone (O3) are the other primary greenhouse gases in the Earth's atmosphere (Houghton et al., 1997). Since the Industrial revolution started, green house gases have increased in the earth's atmosphere. Global GHG emissions due to human activities have grown since pre-industrial times, with an increase of 70% between 1970 and 2004 (IPCC AR4, 2007).It is estimated that increased concentration of these gases has increased global mean earth temperatures by 0,5 °C since 1860 by the 1980's (Mitchel, 1987).

The contribution of individual gases to the greenhouse effect is determined by certain characteristics of gases and the atmosphere as listed bellow:

- Wavelength at which the gas absorb radiation
- The strength of absorption per molecule
- Concentration of the gas
- Absorption of other gases at the same wavelength

Figure 4.4 bellow show concentration of greenhouse gases and their heating due to trace gases as of 1987 and **Fig.4.5** of 2007.



Gas	Concentration, ppm	*Principal absorbtion bands*		Greenhouse heating, W m^{-2}
		Position, cm^{-1}	Strength, cm^{-1} $atm^{-1}cm^{-1}$ STP	
Water vapor	~3000			~100
Carbon dioxide	345	667	(many bands)	~50
Methane	1.7	1306	185	1.7
Nitrous oxide	0.30	1285	235	1.3
Ozone	$10\text{–}100 \times 10^{-3}$	1041	376	1.3
CFC11	0.22×10^{-3}	846	1965	0.06
		1085	736	
CFC12	0.38×10^{-3}	915	1568	0.12
		1095	1239	
		1152	836	

Fig. 4.4 *Concentration of greenhouse gases as of 1987 (Mitchel, 1987)*

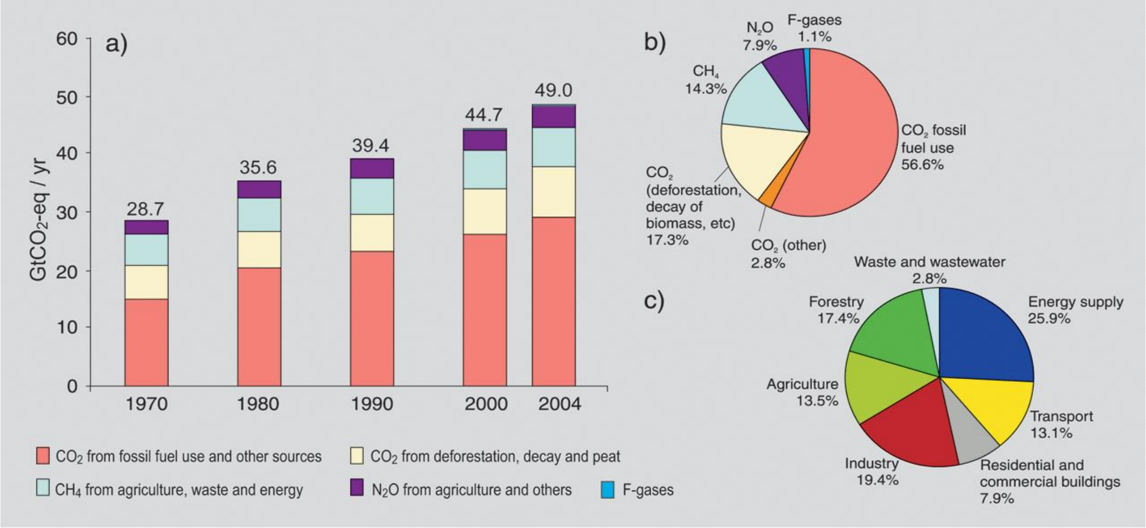


Fig. 4.5 *(a) Global annual emissions of anthropogenic GHGs from 1970 to 2004.(b) Share of different anthropogenic GHGs in total emissions in 2004in terms of CO2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO2-eq. (Forestry includes deforestation.) source (IPCC AR4, 2007)*

The Increase in methane and nitrous oxide are primarily due to agriculture activities (IPCC, 2007).

All gases absorb radiation at different wave length. Carbon dioxide, CO2 absorb strongly around the peak of the long wave spectrum. The effect of different gasses is also not the same; one molecule of dichlorodifluoromethane (CFC12) for example is about 100 000 times more affective in trapping long-wave radiation than one molecule of carbon dioxide (IPCC, 2007).

Albedo is the term used today to define the percentage of solar energy reflected back by a surface. Clouds, oceans, surface albedo and Forested areas strongly influence the earth albedo (IPCC, 2007).

4.6 Climate change and Precipitation

According to the IPCC, an increase in the average global temperature is very likely to lead to changes in precipitation and atmospheric moisture. According to long-term trends from 1900 to 2005 that have been observed in precipitation amount over many large regions by the IPCC working groups, Significantly increased precipitation has been observed in eastern parts of North and South America, northern Europe and northern and central Asia, however drying has been observed in the Sahel, the Mediterranean, southern Africa and parts of southern Asia (Bates, 2007).

All this is prediction came about because of changes in atmospheric circulation and increases in evaporation and water vapour in the earth atmosphere due to climate change. The distribution of water on earth is influenced by a lot of factors, including latitudinal variation. In Africa, where water resources are already a scarcity, precipitation are expected to increase in the tropical regions, and decrease in the sub-tropics and arid regions where mean precipitation are already very low.

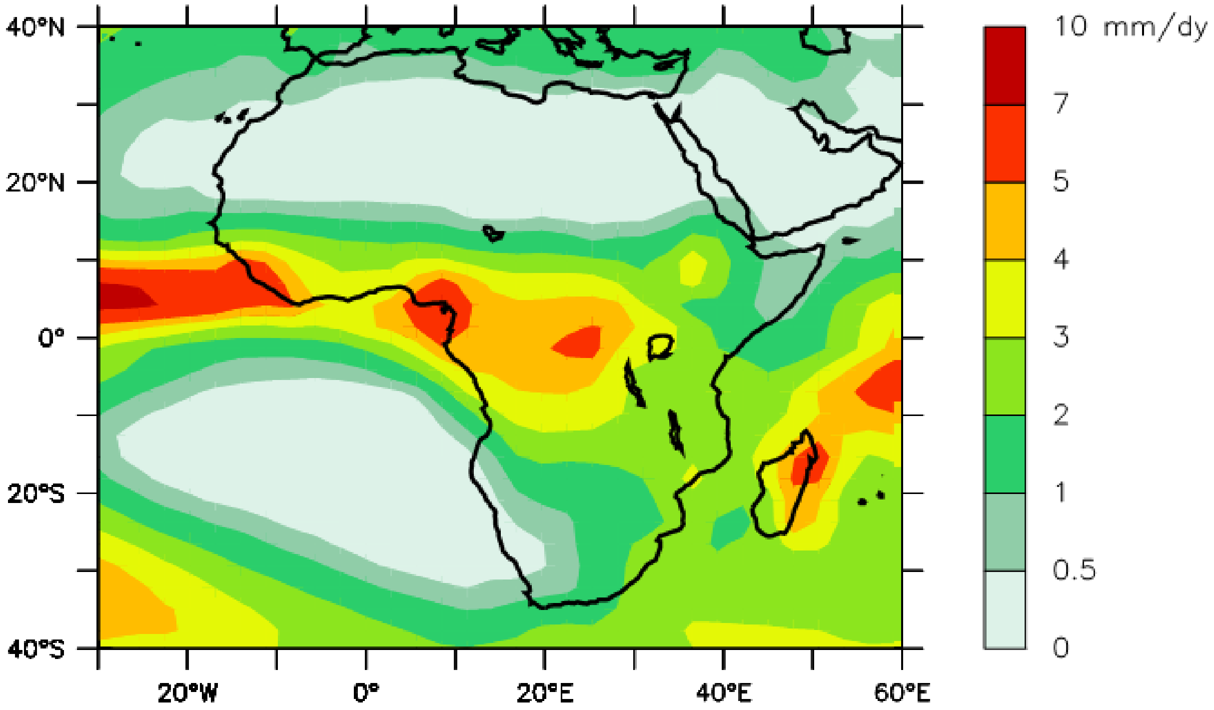


Fig. 4.5 Daily mean precipitation (mm/day) in Africa in the years 1980-1999. Source (Christensen, J.H., B. Hewitson).

Fig. 4.5 Show precipitation daily mean distributions over the African continent. The area around the study area is represented by a 0,5 to 2 mm/day mean precipitation. Tropical areas, represented by 5-7 mm/day precipitation are expected to receive more precipitations in the future, and sub-tropical to arid regions represented by 0-3 mm/day are expected to experience a reduction in precipitation in the future.

The general reduction in rainfall over the land south of about 10°S in summer, and particularly over western regions, is associated with certain factors such as; reduction in the root-zone soil moisture content, reduction in cloud cover and a general reduction in evaporation (Hudson and Jones, 2002).

4.7 Climate change and the hydrological cycle

They hydrological cycle process start with the evaporation of water from oceans, water from the earth surface and transpiration of water from the plants, the combination being described as ‘evapotranspiration’. Evaporated water in the atmosphere is then distributed to location where it forms clouds, depending on all necessary conditions required for the formation of cloud such as temperature. Evapotranspirated water will then return back to the earth surface as precipitation. Precipitated water is kept in Oceans, accumulated on surface (in dams, lakes, rivers, etc.) and part of it is infiltrated to the ground, where it flows with underground water to the reservoirs and oceans, where the process of evapotranspiration will start again, creating the earth hydrological cycle as illustrated in fig X bellow.

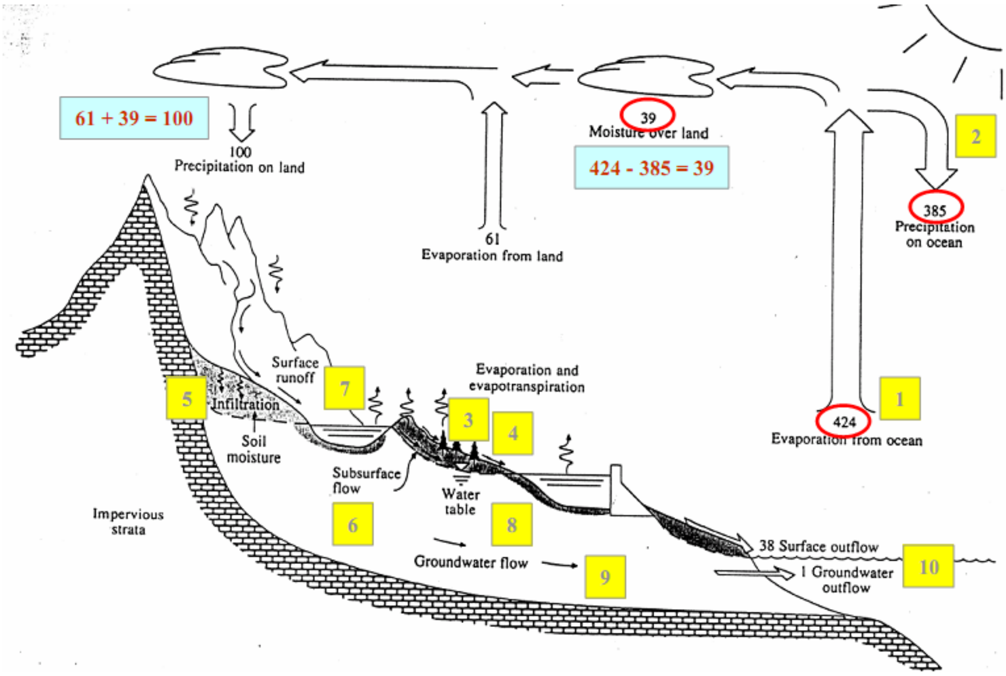


Fig. 4.6 *Hydrological cycle with global annual average water balance given in units relative to a value of 100 for the rate of precipitation on land; 1 Evaporation, 2 Precipitation, 3 Interception, 4 Overland flows, 5 Infiltration, 6 Subsurface flow, 7 Surface runoff, 8 Recharge, 9 Groundwater flow, 10 Overflow to oceans (Shamsi).*

Climate change can in many ways, have big effects to changes in hydrological cycle properties such as; changes in the seasonal distribution of precipitation, Increase in intensity, balance between snow and rain, increased evapotranspiration, reduction in soil moisture, reduction in wetlands and sea level rise. Other changes that climate change can cause to the hydrological cycle include the effect on plants, which can strongly influence amount of transpirated water from plants.

4.8 Climate Projections

Predicting weather and climate has always been a hard thing to do. Today there is yet no existing method of projecting confident projections of future climate, however we can use climatic scenarios which provide climatic data, that are spatially, compatible, mutually consistent, freely available and easily derivable for climate models (IPPC, 2007).

There are 3 basic types of scenarios of future climate;

- synthetic scenarios
- analogue scenarios
- scenarios from general circulation models

4.8.1 Global climate Models (GCM's)

The only way to predict the day-to-day weather and changes to the climate over longer timescales is to use computer models. (Pope, 2007) A Global Climate Model (GCM) is a mathematical model that uses equations of fluid dynamics and thermodynamics to simulate the interactions of the atmosphere, oceans, land surface and ice. These equations are the basis for complex computer programs commonly used for simulating the atmosphere or ocean of the Earth. GCM's provide climate predictions for both past, present and future climate. GCM's divide and analyse the earth atmosphere into regular vertical network of box/grid points.

The grids are classified by the area covering the earth surface, and the vertical height, which is also divided into different levels of the atmosphere. Different GCM's uses different resolutions, which are an important GCM characteristic. GCM's resolutions are given by the grid size, and much higher resolutions are used to give more details. Typically, todays GCM's can reproduce the past 150 years climate can predict up to 1000 years in future. (Pope, 2007) Generally, reproduced past climate are often limited, because they are based mostly on what we know about ancient climate.

GCM's require reliable climate change information in order to formulate adaptation policies (Hudson, 2002) However, GCM's are still unable accurately to reproduce seasonal patterns of today's climate on the regional and national scale. Extreme events such as cyclones and heavy rainfalls are often not captured by GCM's due to their coarse grid resolutions. However a solution to this can be, to use a Regional Climate Model (RCM's).

4.8.2 SRES scenarios (IPCC)

SRES refers to the scenarios described in the IPCC Special Report on Emissions Scenarios (SRES, 2000). The SRES scenarios are grouped into four scenario families (A1, A2, B1 and B2) that explore alternative development pathways, covering a wide range of demographic, economic and technological driving forces and resulting GHG emissions. The SRES scenarios do not include additional climate policies above current ones. The emissions projections are widely used in the assessments of future climate change, and their underlying assumptions with respect to socio-economic, demographic and technological change serve as inputs to many recent climate change vulnerability and impact assessments.

The SRES scenarios project an increase of baseline global GHG emissions by a range of 9.7 to 36.7 GtCO2 equivalents to (25 to 90%) between 2000 and 2030. In these scenarios, fossil fuels are projected to maintain their dominant position in the global energy mix to 2030 and beyond. Hence CO2 emissions from energy use between 2000 and 2030 are projected to grow 40 to 110% over that period. (Christensen *et al*, 2007).

For the next two decades, a warming of about 0.2°C per decade is projected for a range of SRES emission scenarios. Even if the concentrations of all greenhouse gases and aerosols had been kept constant at year 2000 levels, a further warming of about 0.1°C per decade would be expected. (IPCC, 2007)

Model experiments show that even if all radiative forcing agents were held constant at year 2000 levels, a further warming trend would occur in the next two decades at a rate of about 0.1°C per decade, due mainly to the slow response of the oceans. About twice as much warming (0.2°C per decade) would be expected if emissions are within the range of the SRES scenarios.

Best-estimate projections from models also indicate that decadal average warming over each inhabited continent by 2030 is insensitive to the choice among SRES scenarios and is very likely to be at least twice as large as the corresponding model-estimated natural variability during the 20th century. Today, different mechanisms and units for measuring changes in climate has been developed.

Radiative forcing is a measure of the influence that a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system and is an index of the importance of the factor as a potential climate change mechanism. Positive forcing tends to warm the surface while negative forcing tends to cool it (IPCC,2007).

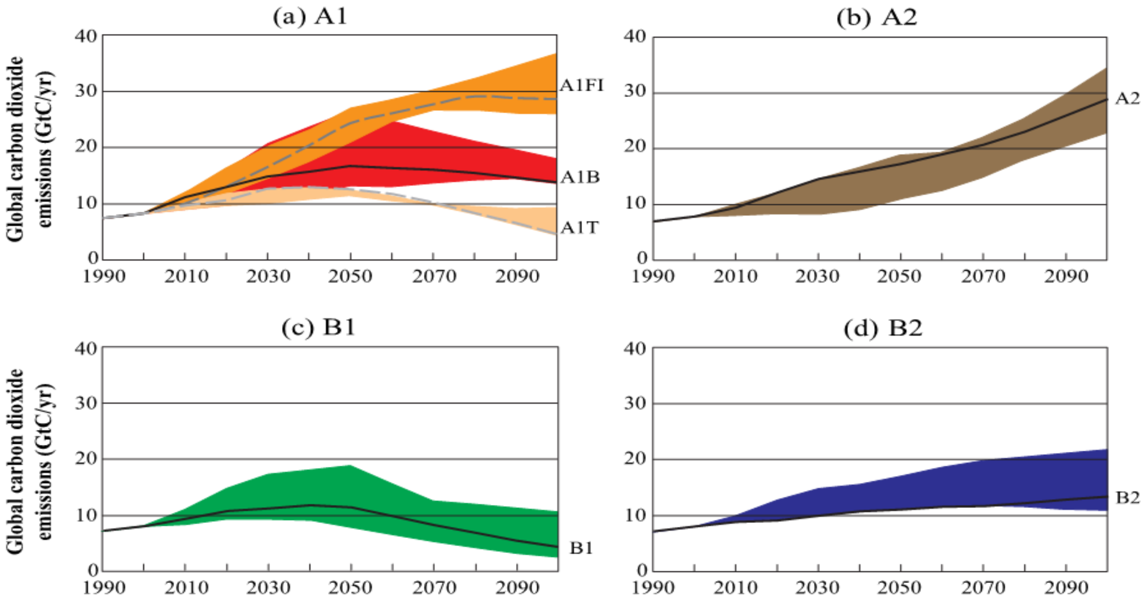


Fig 4.7 *Total global annual CO2 emissions from all sources (energy, industry and land-use change) from 1990 to 2100 in gigatonnes of carbon (GtC/yr) for the families and six scenario groups. The 40 SRES scenarios are presented by the four families (A1,A2,B1,and B2), (IPCC, 2007).*

5. Data Analysis and Methodology

Monthly observed precipitation records of 3 stations in the study area; Okaukuejo (1934-2007), Oshikuku (1931-1997) and Ombalantu (1930-1996) From the Namibia Meteorological Service (METEONA) are used to analyse long-term changes in precipitation. Historical data are probably recorded from old SADF (South African Defence Force) army bases or airports. More details on how the records were carried out where not provided.

Annual and seasonal average precipitations in each station were calculated from the observed data. The datasets were selected based on their homogeneity i.e. less errors and missing values.

The GCM data were obtained from the database of the ENSEMBLES project (http://ensemblesrt3.dmi.dk/). For the analysis we selected three simulations of the HadCM3 global climate model produced by the Met Office Hadley Centre (UK). These simulations were forced by the SRES A1B emission scenario and all simulations span the period 1951-2099. The resolution of this version of the model was 3.75° longitude by 2.5° latitude.

The simulations resulted from the perturbed physics ensemble experiment (Collins *et al.*, 2006). The HadCM3Q0 uses the standard parameter settings, while the HadCM3Q3 and HadCM3Q16 include parameter perturbations giving the lowest and largest response to external forcing (from the perturbed physics ensemble), respectively. From the archive we extracted monthly precipitation sums for a grid box covering the study area (coordinates of the grid box centre are 15° E 20° S).

The time series of the annual and the seasonal precipitations are analysed with R project for statistical computing, which is part of the General Public Licence (GNU) project and it is freely available under the GNU.

They goal of the analysing the data is to provide observed and modelled data statistical values and a well data representation of results. The process of data analysis was intended to provide the following from observed and modelled data;

- Annual precipitation amounts
- Annual precipitation averages
- Annual precipitation frequencies from observed precipitations
- Seasonal averages of precipitation
- Annual and seasonal relative and absolute changes

5.1 Study Periods

To analyse how precipitation is changing, it is necessary to evaluate proportion of precipitation falling in a specific period/time interval, and evaluate or compare results to a control period of precipitation. In this research, observed and modelled precipitation were divided into 3 groups and six periods.

Group 1 in the study represent observed and simulated precipitation during the year 1935 to 1996 which is further sub-divided into 3 Periods that describe past observed precipitation, Group 2 of the study represent current observations in climate, which is described for the period between 1997-2020. Group 2 has only period to it. Group 3, is intended to address future simulated precipitation from GCM's.

Observed precipitations were divided into 3 periods namely; Period 1 which is from 1935-1950 (15 years), Period 2 (control period) which is from 1951- 1975 (24 years) and Period 3 which is from 1976 – 1996 (20 years) respectively. For modelled precipitation data, both study groups and 4 periods were defined. Modelled data were analysed from period 2(1951-1975), which is also referred to as the control period to period 6(2075-2099). Summary of study groups and period is represented in **Table 3**.

Table 3. *Summary of study groups and study periods used in data analysis [A]-analysed data.*

Group	**Period**	**Time**	**Observed Precipitation dataset**			**Modelled Precipitation dataset**		
			Ombalantu	Oshikuku	Okaukuejo	HadCM3Q0	HadCM3Q3	HadCM3Q16
OBS. P.	**1**	1935-1950	A	A	A			
	2	1951-1975	A	A	A	A	A	A
	3	1976-1996	A	A	A	A	A	A
Future P.	**4**	2021-2050				A	A	A
	5	2075-2099				A	A	A

The classification of data into study periods 1 to period 5 is based on the corresponding and homogeneity of both sets of data. It was not however possible to Include simulated data in period 1 since GCM's datasets extracted were only available from the year 1950 onward.

5.2 Statistical Analysis

For statistical analysis we use basic statistical indicators to analyse observed and model precipitation as described bellow.

5.2.1 Mean Precipitation

In this study, mean precipitation (M) for all study periods were calculated. They are calculated from Total periodic precipitation (PT) divided by the number of years in the period (N).

$$M=PT/N$$

The findings are summarised in **Table 6.1** for observed precipitation and **Table 6.2** for model precipitation.

5.2.2 Moving averages

Moving averages, sometimes referred to as running averages, are statistical indicator, used in time series analysis, to calculate central tendency of the data. They are then used in plots to show climatic trends and eliminate fluctuations in the series (smooth up the trends). 10 and 25 years moving averages were included in almost all data plots. They show us a smoother representation of the time series and reduce randomness and error representation from the trends in plotting. In R, moving averages are calculated using the formula:

$$T_t = \frac{1}{2a+1} \sum_{i=-a}^{a} X_{t+i}$$

Where Tt = Trend of time/period (t)

a = duration of time series/period

5.2.3 Box Plots

Box Plots or boxplots are convenient way of displaying batches of data. Box plots use five values from a set of data as illustrated bellow in **Fig. 5.7**.

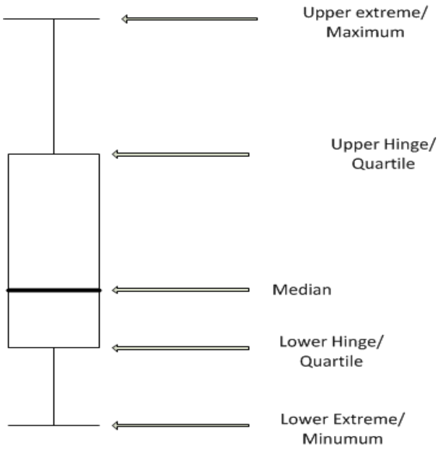


Fig. 5.7 *Boxplot configuration*

Box plots in this study were used in the discussion, to compare results and give a visual summary of results.

5.3 Errors and Missing values in datasets

Some of the datasets provided by METEONA had a few missing data, and probably some few errors. The errors found and their descriptions are discussed in the **table 4.**

Table 4. *Overview of Errors and missing values in the dataset.*

	Year	**Missing values**	**Errors encountered**
Okaukuejo	1951	4 missing monthly totals June - September	None
	1952	missing monthly totals May-September	
	1953	missing monthly totals for May-September	
Oshikuku	1935	missing monthly totals for May - June	None
	1940	missing monthly total May - September	
	1941	missing monthly totals April - June	
	1942	5 missing monthly totals for May - September	
	1943	missing monthly total for August	
Ombalantu	1930	None	Zero monthly totals for summer month recordings (January -April) a possible error in data recordings
	1931		Zero monthly totals for summer month recordings (January -April) a possible error in data recordings
	1940	Missing monthly totals for January	

In data analysis, datasets were selected based on the homogeneity of their data i.e. few errors and duration of the available data.

6. Results

In this chapter, observed and simulated precipitation analyses are assessed. Firstly, observed total annual, seasonal and frequency precipitation are analysed, then follow the results from the climate models. Further, the observed and simulated precipitation is compared and the changes in precipitation are assessed.

6.1 Observed Annual Precipitation and Precipitation Frequency

Observed total annual values are important in studying rainfall trends and annual frequency. Computing Total annual precipitation for observed precipitation was the first step in the study. Total annual precipitation were calculated from available observed monthly data, by adding observed monthly values for whole year periods i.e. yearly sums. Calculated observed total annual values were then used to plot total annual precipitation (**Fig. 6.1**), annual precipitation frequency (**Fig. 6.2**) and to find differences in observed and modelled precipitation from GCM's.

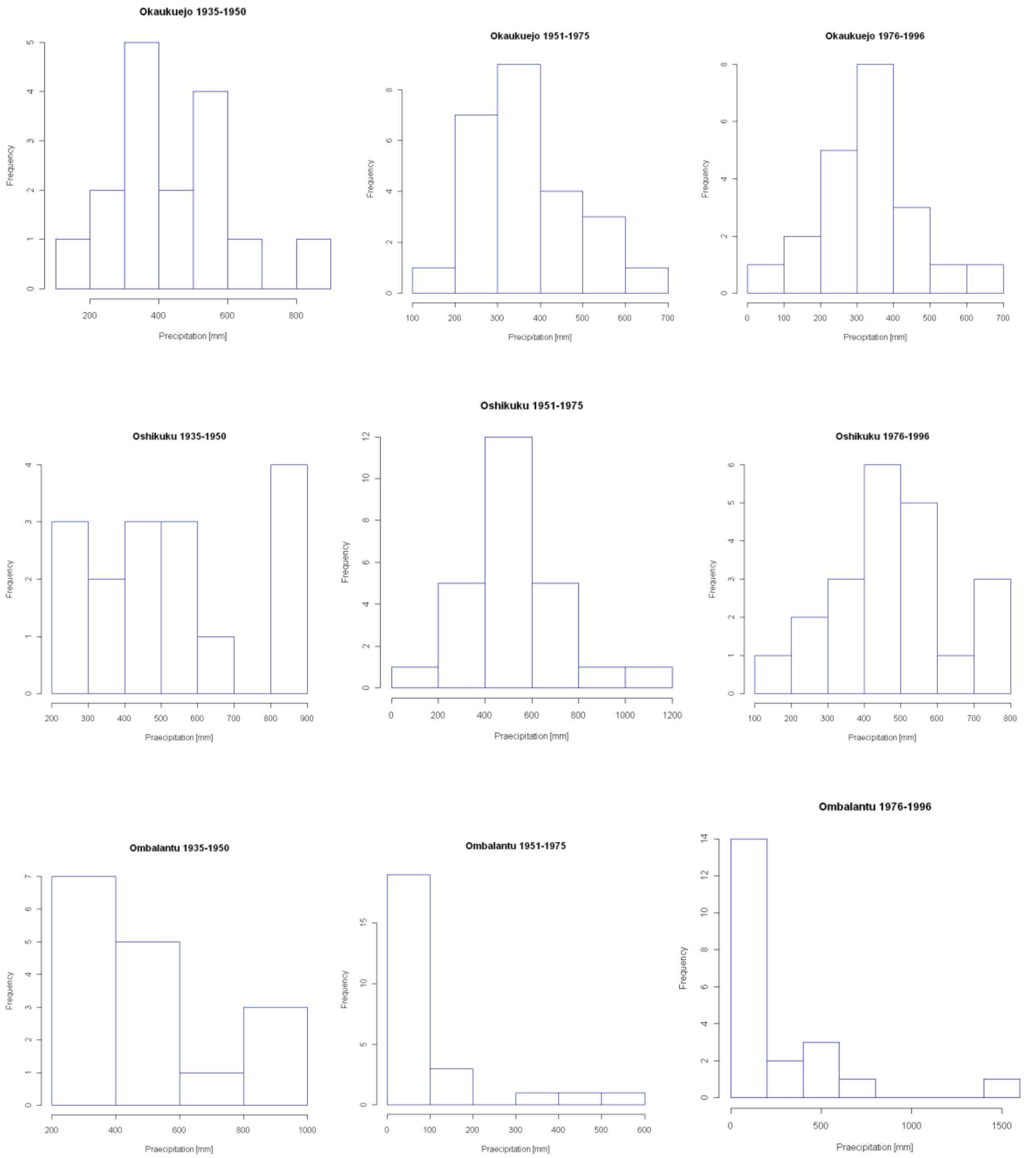
Precipitation is variable from place to place. This can be seen in the total annual precipitation plots (**Fig. 6.1**). And in table for the summary of observed results (**Table 6**) from the data, there is a common wet period from October through March (summer half year) and a dry period from April through September (winter half year) which are also used to distinguish winter and summer periods in this chapter.

Understanding precipitation distribution over time is also important in climate studies. Annual precipitation frequency of all study periods discussed in **table 4** were also assessed. Annual precipitation frequency shows precipitation distribution over time.

***Table 5**. Observed precipitation table of Results showing mean annual precipitation, minimum recorded precipitation and maximum observed precipitation for annual, summer and winter seasons. Period 1 (Per.1) 1935-1950, Period 2 (Per.2) 1951-1975 and Period 3 (Per3) 1976-1996*

Data source		**Annual Precipitations [mm]**			**Summer Precipitations [mm]**			**Winter Precipitation [mm]**		
		Per.1	***Per.2***	***Per.3***	***Per.1***	***Per.2***	***Per.3***	***Per.1***	***Per.2***	***Per.3***
Okaukuejo	**Mean**	430,37	370,24	326,25	399,29	343,06	300,27	31,08	27,18	29,41
	Min	184,40	181,70	96,00	172,50	181,60	87,10	0,00	0,10	2,10
	Max	821,70	637,40	632,60	778,30	572,90	582,40	97,50	64,50	118,90
Ombalantu	**Mean**	489,63	500,87	303,14	452,08	438,95	288,97	37,55	40,00	14,17
	Min	224,9	213,6	40,5	215,5	60,9	40	0	0	0
	Max	945,8	1022,3	697,5	815,8	940,3	652,5	261,5	204	53
Oshikuku	**Mean**	528,47	519,91	479,35	470,04	484,34	449,20	31,28	39,50	28,42
	Min	218,1	133,7	194,4	203,3	108,6	178,2	0	0,5	1
	Max	885,9	1100,4	777,5	794,4	1045,5	730,7	135,4	210,7	86,5
Averages of observations	Mean	482,82	463,67	369,58	440,47	422,12	346,15	33,30	35,56	24,00
	Min	209,13	176,33	110,30	197,10	117,03	101,77	0,00	0,20	1,03
	Max	884,47	920,03	702,53	796,17	852,90	655,20	164,80	159,73	86,13

Fig. 6.1 *Total annual precipitation of Okaukuejo (1934 – 2007), Oshikuku (1931 - 1997) and Ombalantu (1930 - 1996) with moving averages: in blue (10 years moving averages), red (25 years moving averages) and green (linear trends).*



Okaukuejo 1935-1950

Okaukuejo 1951-1975

Okaukuejo 1976-1996

Oshikuku 1935-1950

Oshikuku 1951-1975

Oshikuku 1976-1996

Ombalantu 1935-1950

Ombalantu 1951-1975

Ombalantu 1976-1996

Fig. 6.2 Observed precipitation frequency for Okaukuejo, Ombalantu and Oshikuku for study periods: per.1 1935- 1950, per.2 1951 – 1975 and per.3 1976 – 1996.

Results from observed annual precipitation show different characteristics in their plots (**Fig. 6.1**) that vary in annual precipitation distribution and annual precipitation amounts. As it can be seen in the plots, both analyses for total annual precipitation show a decreasing trend in observed precipitation, this is well represented at total annual plots (**Fig. 6.1**) the biggest slope in trend is represented by Ombalantu annual precipitation plot (**Fig. 6.1**). A summary of all observed precipitation is shown in **Table 5**.

Okaukuejo plots show a decreasing trend in annual total precipitation. Year 1992 in Period 3 had the less recorded annual precipitation amount of 96, mm and year 1950 in Period 1 had the highest recorded amount of 821.70 mm precipitation.

Oshikuku total annual precipitation shows a slight decrease in annual precipitation in period 3. Results are represented in annual plots **Fig. 6.1**. Although there have been fluctuations in the precipitation of Oshikuku, the decrease in period 3 precipitation is still visible, a probably better represented by 25 years moving averages. There is a difference in mean precipitation of up to 49.12 mm, from period 1 to period 2, of which 40 mm alone was between period 2 and period 3. (**Table 5**)

Ombalantu observed precipitation showed the most visible decrease in trend of all the analysed precipitation data (Fig 5.1.1). Again, total and mean precipitation for period 3 were the lowest, comparing to period 1 and 2. The lowest observed annual precipitation used in data analysis (40 mm) was also recorded at Ombalantu in period 3. A difference of 197.73 mm was also noted between period 2 and period 3 **(Table 5)**. Ombalantu recorded a maximum annual precipitation in 1954 (Period 2) of 1022,3 mm and its lowest 40 mm in 1987 (Period 3).

The annual frequencies of precipitation were also analysed. All studied stations showed a different distribution of precipitation. Judging from the frequency plots **Fig. 6.2**, higher annual precipitation was recorded in period 1 in all stations. Okaukuejo and Oshikuku analysis produced nearly similar frequency comparing to that of Ombalantu. Ombalantu had lower annual precipitation (0-200 mm) distributions in all periods. From the plots (**Fig. 6.2**), it can be seen that a large amount of Ombalantu precipitation were in period 1.

6.2 Summer (wet) and winter (dry) seasons

Analysis of changes in seasonal precipitation study is very important for climate change studies and other purposes such as in agriculture etc. Using R, summer and winter averages were calculated from monthly total precipitation. Observed total monthly precipitations were provided in the datasets. Total monthly precipitations datasets were used to:

1. Define summer seasons (October to March) and winter (April - September) used in data analysis.
2. Calculate annual, summer and winter totals.
3. Calculate means and moving averages for summer and winter precipitations.
4. Calculate summer relative changes and winter absolute changes.

Observed summer and winter precipitation of Ombalantu, Oshikuku and Okaukuejo are shown in **Fig. 6.3** to **Fig. 6.4** respectively. Because there is mostly no (0 mm), or little precipitation in winter months, absolute changes were calculated to analyse changes in winter seasons, instead of relative changes which are used to study changes in summer precipitation and annual periodical changes.

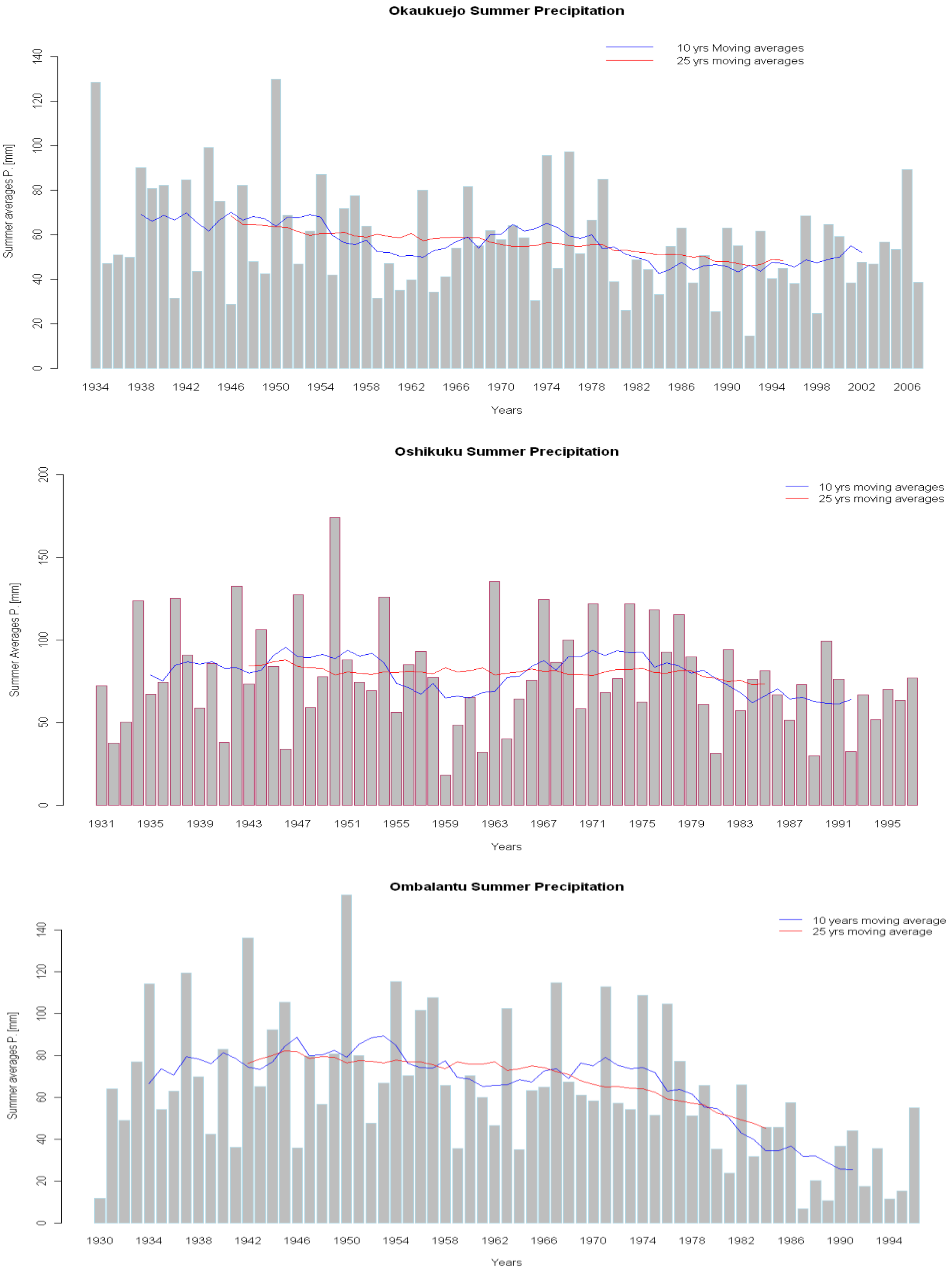


***Fig. 6.3** Plots of observed summer average precipitation of Okaukuejo (1934-2007), Oshikuku (1931-1997), and Ombalantu. (1930-1996).10 years moving averages (blue line) and 25 moving averages (red line).*

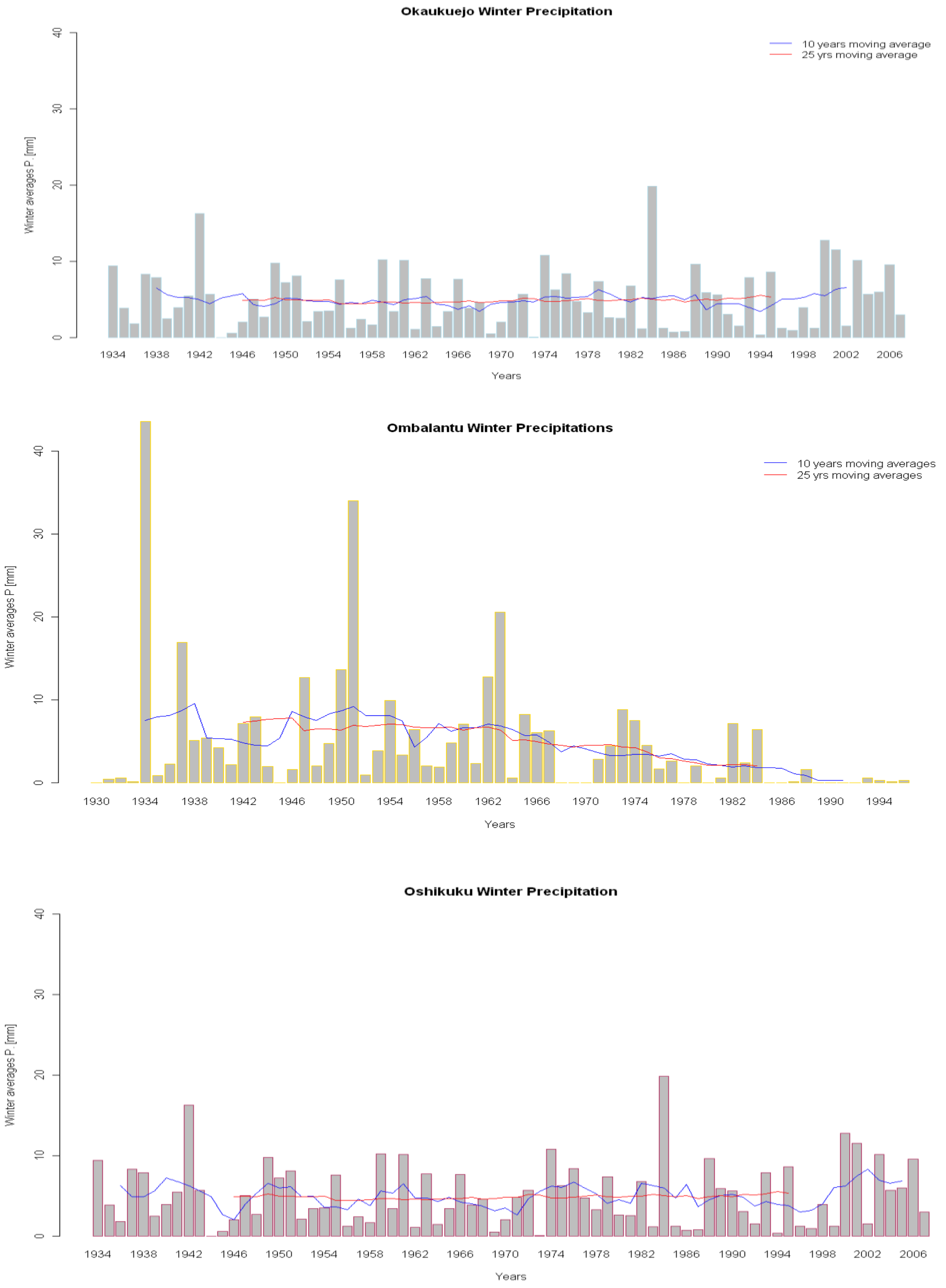


Fig. 6.4 *Plots of observed winter average precipitation of Okaukuejo (1934-2007), Oshikuku (1931-1997), and Ombalantu. (1930-1996); with 10 years moving averages (blue line) and 25 moving averages (red line).*

From the plots, it can be clearly seen that summer precipitation dominates in all observed precipitations. This is caused by different conditions such as atmospheric circulation, temperature, evaporation and water content in the atmosphere over the basin.

For Okaukuejo, there has been a slight decrease in summer precipitation and almost a constant trend in winter precipitation. Overall there has been a decrease in mean summer precipitation with a difference of 99.02 mm between period 1 and period 3. Summer precipitation totals has also decreased, with the lowest total observed precipitation of 87.10 mm in period 3. On the other hand, winter precipitation has increased but annual winter precipitation totals remained constant with only slight changes.

Ombalantu also experienced a decrease in total and mean summer precipitation from period 1 to period 3. There is a mean precipitation difference of up to 163.22 mm between period 1 and period 3. Lowest summer observed total and mean precipitation has also been recorded in period 3. Ombalantu winter precipitation plot (**Fig. 6.4**) shows different precipitation distribution comparing to the other observation plots. Annual winter averages were the highest in Ombalantu observation, with a record of more than 40 mm in 1934, just before the start of study period 1.

Oshikuku station didn’t experience many changes, or it showed almost constant trend in summer and winter average precipitation. Both annual precipitation totals and precipitation mean experienced little decrease from period 1 to period 3. Difference in summer precipitation means between period 1 and period 3 was only 2.86 mm, however the difference was a bit bigger (11.08 mm) between period 2 and period 3.

6.3 GCM's Annual Precipitations

Precipitation data from GCM's were treated in the same way as those of observed precipitation. Plots and all statistical calculations were done with R. Like with observed precipitations, total annual precipitations for the whole time series were calculated from monthly precipitation and plotted (**Fig. 6.5**). Modelled precipitations were divided into 2 groups and 3 periods.

Table 6. *Simulated precipitation table of Results showing mean annual precipitation, minimum precipitation and maximum precipitation for annual, summer and winter seasons. Period 2 (Per.2) 1951-1975 and Period 3 (Per.3) 1976-1996.*

Data Source	ID	Annual Precipitation [mm]		Summer Precipitation [mm]		Winter Precipitation [mm]	
		Per.2	*Per.3*	*Per.2*	*Per.3*	*Per.2*	*Per.3*
HadCM3Q0	**Mean**	645,10	741,72	447,89	529,51	196,67	207,82
	Min	320,99	379,07	229,19	265,24	62,33	106,19
	Max	1026,65	1038,62	819,78	852,94	307,78	338,58
HadCM3Q3	**Mean**	514,86	538,88	412,90	433,38	100,71	105,50
	Min	*276,45*	*262,78*	*211,90*	*160,73*	18,46	7,42
	Max	788,32	825,91	568,79	729,50	227,88	196,68
HadCM316	**Mean**	677,12	654,87	391,44	399,68	278,01	255,19
	Min	398,77	365,49	179,55	135,30	68,36	125,14
	Max	998,10	961,44	613,57	659,90	527,73	373,93

Results from GCM's data analysis showed a lot of similarities and differences. Similarly, summer precipitation dominates comparing to winter precipitation in all studied periods. Extreme annual values i.e. minimum and maximum annual precipitation shows lot variability within the study periods. Model HadCM3Q0, for instance, simulated a minimum annual value of 320.99 mm and a maximum of 1026,65 (difference = 705,66 mm) during period 2 (**Table 6**).

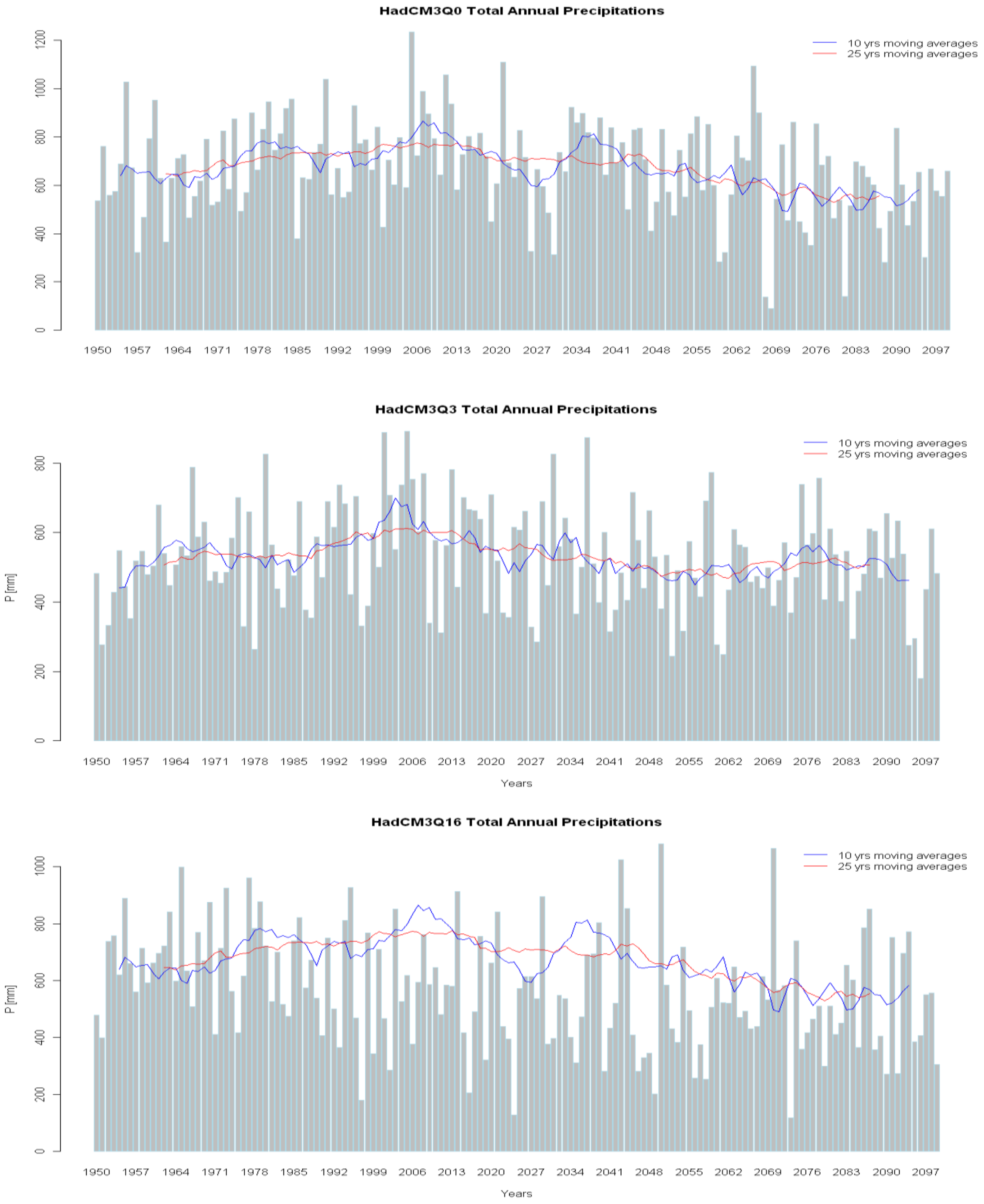


Fig. 6.5 *Total annual precipitation plots for GCM (HadCM3Q0, HadCM3Q3 and HadCM3Q16) for 1951-2099. Blue line (10 years moving averages) red line(25 years moving averages).*

From the 149 years of simulated precipitation from HadCM3Q0, HadCM3Q3 and HadCM3Q16 models (**Fig. 6.5**); simulated precipitation are surely higher in amounts than observed precipitation (**Fig. 6.1**). Small variability exists between period 2 and 3, but higher variability exists between individual model simulations. Overall, HadCM3Q3 simulated lower precipitation totals than HadCM3Q0 and HadCM3Q16. Both model plots (**Fig. 6.5**) showed some decreasing in precipitation trends, however judging from the number of years, the trends show a small decline in annual precipitation.

HadCM3Q0, the first model to be analysed showed a decline in mean annual precipitation of up to 96, 62 mm between period 2 and period 3, Although extreme annual values (minimum and maximum precipitation) show stability or less variability, comparing to differences in mean annual precipitation.(**Table 6**). The highest simulated precipitation by HadCM3Q0 were within this decade 2000-2010 (Fig 5.3.1) with the highest annual precipitation recorded of 1234.32 mm.

Of all analysed models, HadCM3Q3 simulated the lowest mean annual precipitation for both period 1 and 2. Similarly like HadCM3Q0, the highest recorded annual precipitation for HadCM3Q3 was again in the decade 2000-2010 (**Fig. 6.5**). Variation in mean annual precipitation between period 1 and period 2 is smaller (24,02 mm), comparing to variations in HadCM3Q0 for the same periods.

HadCM3Q16, the last model analysed, contrary to the previous discussed models had a decrease in both total annual precipitation and mean precipitations between period 2 and period3 **(Table 6)**. This increase is better represented in plots by moving average lines (**Fig. 6.5**). Annual mean precipitations has also decrease a lot from period 2 to period 4 by 133.46 mm in precipitation. The highest recorded annual precipitation of 998.1 mm and highest mean precipitation, 677.11 mm were all recorded in period 2, and lowest annual precipitation (913.41 mm) and lowest mean precipitation were recorded in period 4.

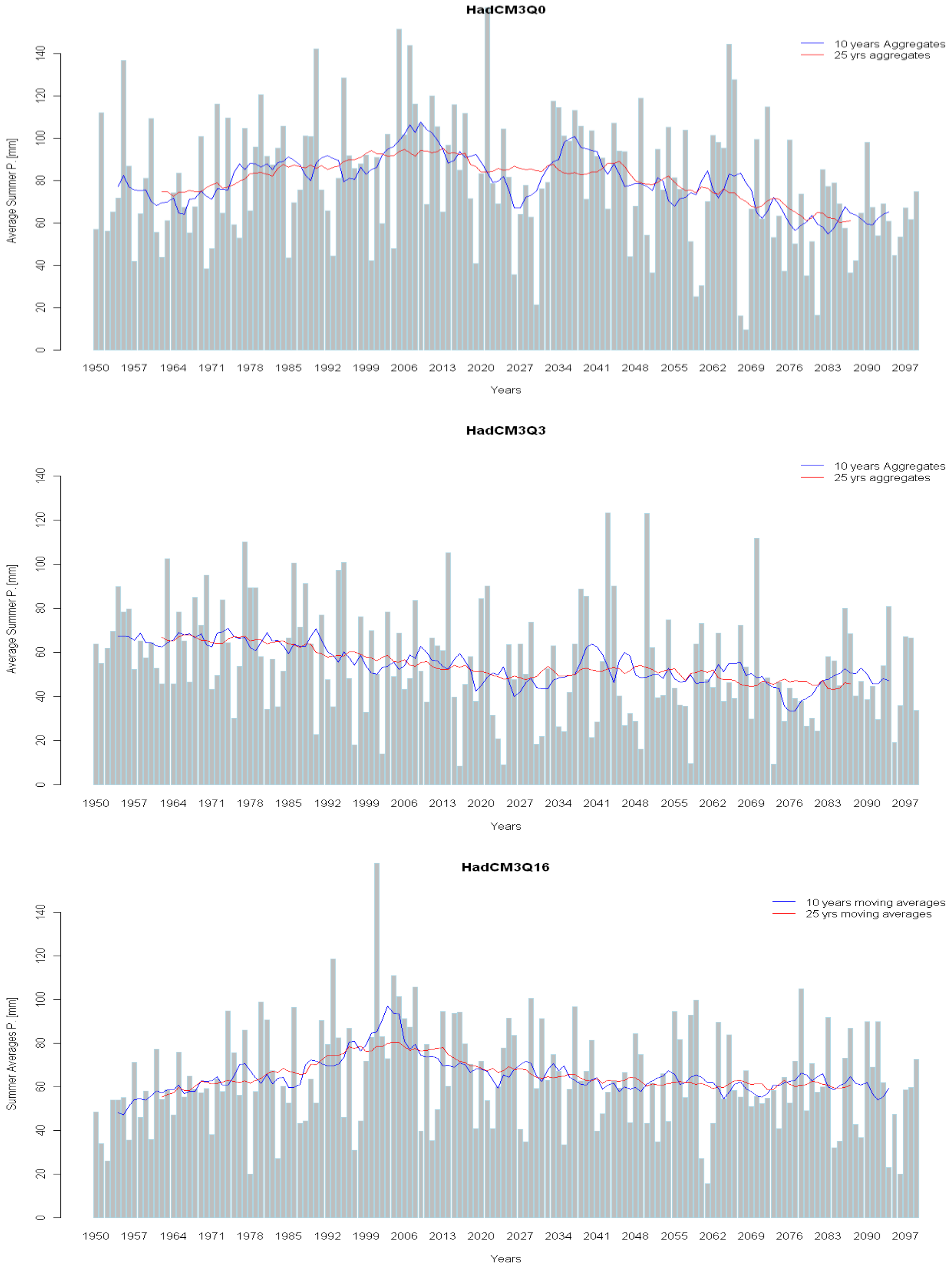


__Fig. 6.6__ HadCM3Q0, HadCM3Q3 and HadCM3Q16 __summer__ average precipitation plots 1951-2099. 10 years moving averages (blue line) and 25 moving averages (red line).

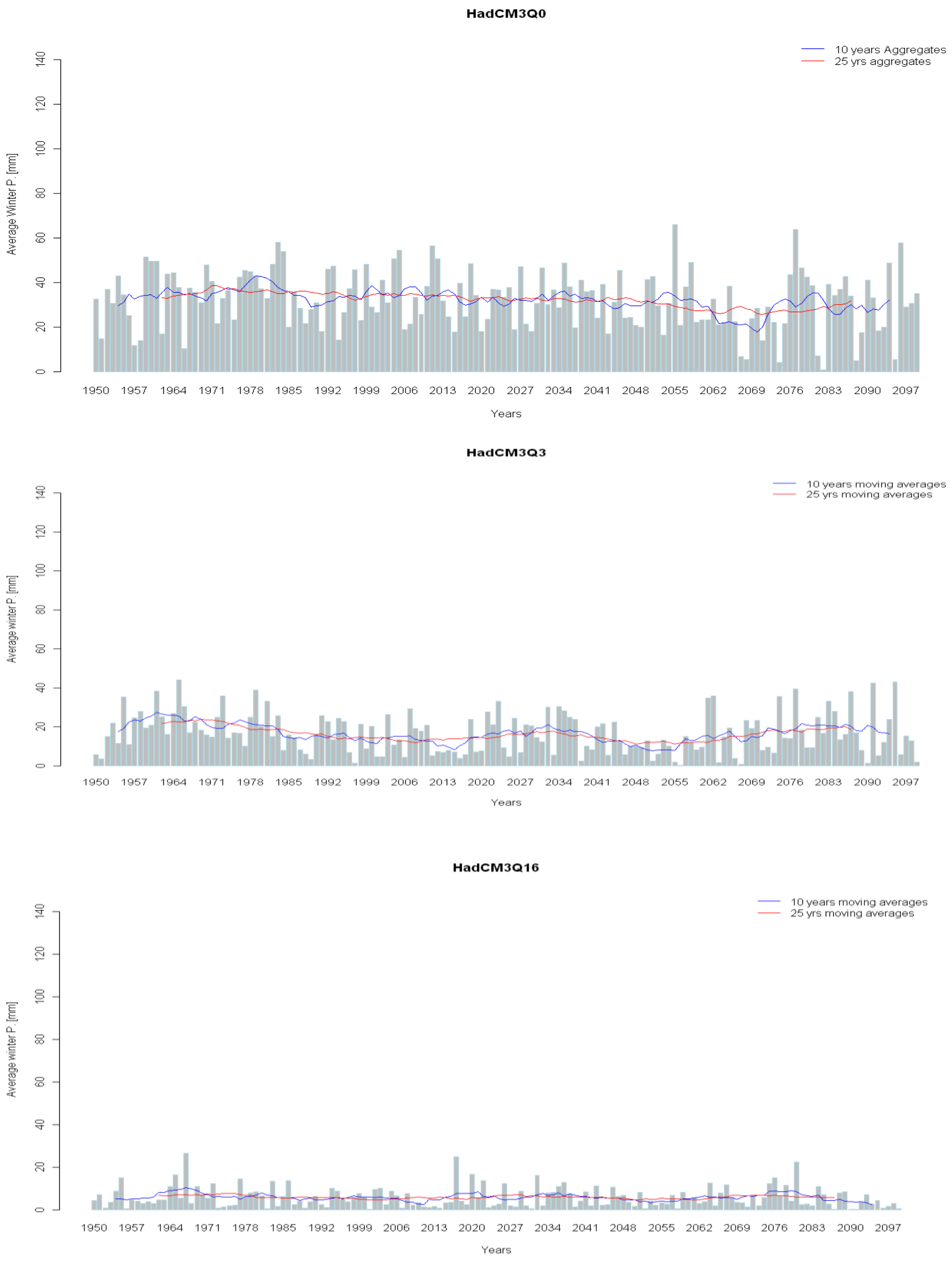


Fig. 6.7 *HadCM3Q0, HadCM3Q3 and HadCM3Q16* ***winter*** *average precipitation plots 1951-2099. 10 years moving averages (blue line) and 25 moving averages (red line).*

From the simulated seasonal plots, it can be clearly seen that summer precipitation dominate in modelled precipitation. This is probably cause by different conditions such as atmospheric circulation, temperature, evaporation and water content in the atmosphere over the basin.

HadCM3Q0, had a slight increase in both total and mean annual precipitation between period 2 and period 3, however a decrease in precipitations can also be seen from the end of period 3 to century the end. Winter precipitations have also experienced a slight increment. Of all models, HadCM3Q0 again simulated the highest values for summer and winter mean precipitation. HadCM3Q0 mean summer precipitation showed a variation of up to 81.62 mm between period 2 and period 3. Lowest winter values of 62,33 mm were recorded in period 2 and highest total annual winter precipitation of 338,58 mm were recorded in period 3 (**Table 6**).

HadCM3Q3 seasonal analysis produced different plots from that of HadCM3Q0 simulations with moving averages showing a constant decline in summer average precipitation from the early simulated years to the mid-century (**Fig. 6.6**). However withing the studied periods, summer precipitation means had little variation, but a vizible difference could be seen between the highest (maximum) recorded precipitation of Period 2 (568.79 mm) and period 3(729,50 mm). Winter mean precipitations didn’t change much between period 2 and period 3, but again, there were still notable variation in extreme values. HadCM3Q3 recorded the lowest annual winter precipitation of all modelled winter precipitation (7,423) in period 3, and highest annual winter precipitation of 227, 82 mm in period 2.

Contrary to HadCM3Q3, HadCM3Q16 summer mean precipitation plots (**Fig. 6.6**) clearly shows a rise in precipitation from period 2 to current years, before it start to decrease again till the end of the simulation. In HadCM3Q16, winter precipitation represented 40% of total precipitations. HadCM3Q16 simulated the highest winter and summer precipitations with little variation between them, comparing to other simulations.

6.4 Results of changes in precipitation

6.4.1 Relative Changes

Relative changes are used to compare absolute changes (increase or decrease) to some reference point's values. In this research, relative changes are used to plot results of changes in periodic precipitation compared to a reference period (1976-1996) for observed precipitations.

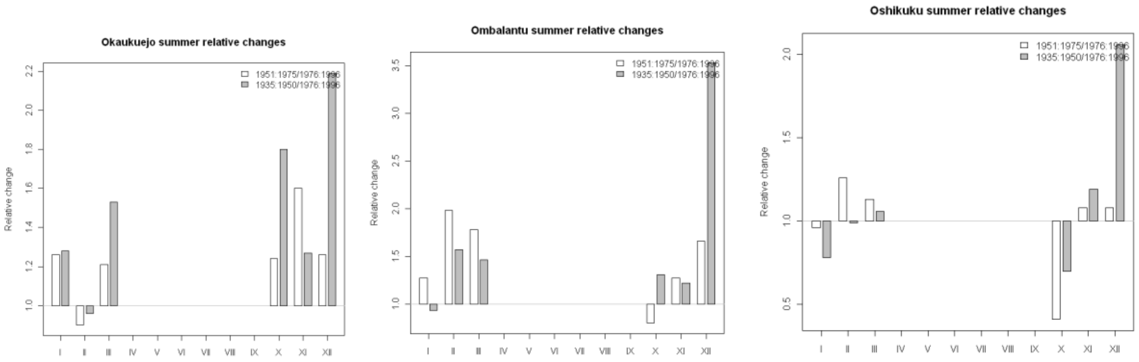


Fig. 6.8 Summer relative changes for observed precipitation (from left to right: Okaukuejo, Ombalantu and Oshikuku) for 1935-1950/1976-1996 (grey) and 1950-1975/1976-1996.

From the plots (**Fig. 6.8**), we can judge that; comparing to period 3 (control/reference period) precipitations, Okaukuejo monthly observation were higher in period 1 and period 2 comparing to period 3, with the only increment in the months of February. Overall, Okaukuejo experienced the most changes between period 1 and period 3. Monthly precipitation were at least twice much during period 1 than in period 3, in the months of October and December. Notable changes have also been experienced in the months of March for period 1 to period 3. There has been also visible relative changes between period 2 and period 3 in March monthly precipitation, where precipitation in period 2 were almost 1,5 times higher than those of period 3.

Similarly, Ombalantu also had smaller monthly precipitation in period 3 comparing to period 1 and 2, for all months, except October of period 2, and January of period 1, where monthly precipitation where slightly higher in period 3. Bigger changes were again in December precipitation from period 1 to period 3, where precipitation were almost 3,5 times higher in period 1 comparing to period 3. Contrary to Okaukuejo observations, where period 3 had higher precipitations in February for both period 1 and 2, Ombalantu February precipitation for period 3 were almost 2 times lower than those of period 1 and 2.

Again, bigger changes can be seen in the month of December, where similar to Okaukuejo and Ombalantu observations, precipitation has dropped from period ,1 to period 3, by almost a half. Similarly, Ombalantu has notable increase in October precipitation from period 1 to period 3, with a bigger change between period 2 and period 3, unlike to Okaukuejo.

6.4.2 Absolute Changes

We use absolute changes to describe the actual decrease or increase in precipitation from a reference period (control period). In this study, absolute values are used to analyse changes in winter precipitation which cannot be analysed by relative changes due to 0 mm in some winter monthly records. Results for winter monthly precipitation changes are plotted bellow.

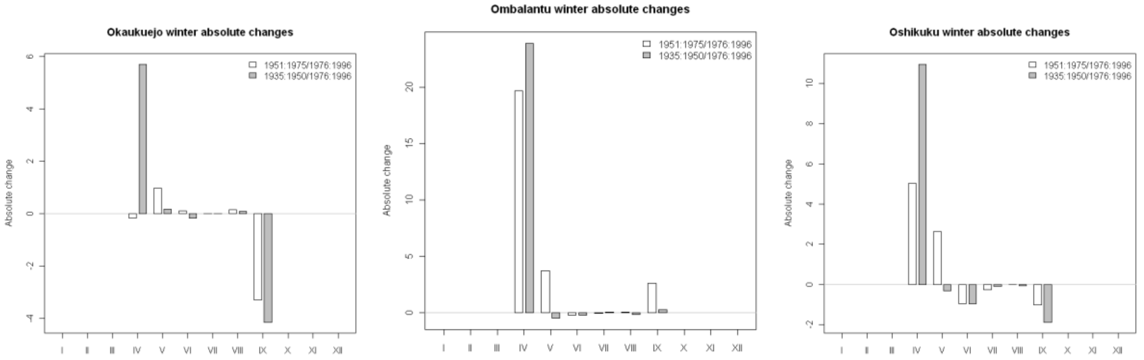


Fig. 6.9 *winter absolute changes for observed precipitation (from left to right: Okaukuejo, Ombalantu and Oshikuku) for 1935-1950/1976-1996 (grey) and 1950-1975/1976-1996.*

From the above plots, Notable Changes in precipitation can be seen in the beginning of winter season for all analysed observed precipitation, with a large difference in period 1 to period 3. Ombalantu experienced the largest changes of more than 20 mm precipitation during this period, followed by Oshikuku which experienced changes of more than 10 mm and last Okaukuejo with changes of nearly 5 mm in April precipitation. Similar changes are also remarkable in Ombalantu observed precipitation for period 2 to period 3. Another visible change from the plots is the rise in winter end month of September for Okaukuejo (4 mm) and Oshikuku (2 mm).

A summary of relative changes (annual and winter) and absolute changes (winter) is shown in **Table 7** bellow.

Table 7. *Periodic relative (annual and summer) and absolute changes (winter) for observed and simulated precipitation between Period 1 (Per1), Period 2 (Per2) and the reference period (RP) period 3.*

Data Source	**Relative annual Changes**		**Relative summer Changes**		**Absolute winter Changes**	
	Per1/RP	Per2/RP	Per1/RP	Per2/RP	Per1-RP	Per2-RP
Okaukuejo	1,32	1,13	1,33	1,14	1,67	-2,23
Ombalantu	1,62	1,65	1,56	1,52	23,38	25,83
Oshikuku	1,10	1,08	1,56	1,52	2,86	11,07
Observed averages	**1,35**	**1,29**	**1,49**	**1,39**	**9,30**	**11,56**
HadCM3Q0		0,87		0,85		-11,15
HadCM3Q3		0,96		0,95		-4,79
HadCM3Q16		1,03		0,98		22,81

Judging from the table above, larger changes are visible in winter season. In all observed precipitations, both period 1 and period 2 experienced larger precipitation than period 3, however model simulated differently in precipitation relative changes between period 2 and period 3, but had also similar results for winter seasonal changes. Changes between periods are also larger between period 1 and period 3 comparing to period 2 to period 3, in both annual, summer and winter seasons.

6.5 Comparison of Observed and Simulated Results

For comparing observed and simulated results, relative changes (annual and summer) and absolute changes (winter) for observed precipitation were averaged. Simulated results are then compared to the averaged changes. Results of comparison are illustrated in the table bellow.

Table 8. *Differences between simulated and observed (OBS.) changes.*

Comparison of results	Annual	Summer	Winter
HadCM3Q0/OBS.	0,67	0,61	-22,71
HadCM3Q3/OBS.	0,74	0,68	-16,35
HadCM3Q16/OBS.	0,80	0,70	11,26

From the table, it is visible that bigger differences in the results where between those of HadCM3Q0 and observed precipitation, with annual differences of up to 33%, summer 39% and difference of up to 22.71 mm in mean precipitation. In winter, HadCM3Q16 had smaller differences from all models simulations, with a difference of 11.26 mm precipitation.

6.6 Future Precipitation

In this study, future precipitation refers to the study period 4 and 5. The results for future projection are based on the analysis of precipitation simulations from the GCM's. The results of the analysis are summarised in (**Table 9)** showing future precipitation projections of mean annual precipitation, minimum precipitation and maximum precipitation for annual, summer and winter seasons. Period 4 (Per.4) 2021-2050 and Period 5 (Per.5) 2075-2099.

Table 9. *Table of Results with future precipitation projections of mean annual precipitation, minimum precipitation and maximum precipitation for annual, summer and winter seasons. Period 4 (Per.4) 2021-2050 and Period 5* (Per.5) *2075-2099.*

Data source		**Annual Precipitations [mm]**		**Summer Precipitations [mm]**		**Winter Precipitation [mm]**	
		Per.4	Per.5	Per.4	Per.5	Per.4	Per.5
HadCM3Q0	Mean	703,21	555,26	512,90	365,35	190,31	189,91
	Min	311,96	139,38	127,85	97,61	101,27	4,07
	Max	1110,67	854,45	970,19	593,97	292,33	382,56
HadCM3Q3	Mean	520,45	506,92	413,63	398,55	106,82	108,37
	Min	284,85	178,88	238,09	126,00	34,70	31,62
	Max	872,61	755,90	238,09	683,68	228,97	214,40
HadCM3Q16	Mean	534,14	496,37	304,06	273,60	230,07	222,77
	Min	128,14	272,01	53,09	115,10	75,05	40,95
	Max	1079,94	851,37	739,31	484,93	454,52	485,70

From the table above, precipitation averages are higher than historical and current precipitation averages. Annual precipitation range between 128,14 mm (HadCM3Q16) and 1110,67 mm (HadCM3Q0) in period 4, with a mean range of 496,37 mm (HadCM3Q16) in period 5, to 703,21 mm (HadCM3Q0) in period 4. Although the smallest annual precipitation is simulated in period 4, period 5 projections will have lower precipitation than period 4. Overall, summer precipitation still dominates in both simulations with HadCM3Q16 simulations showing the weakest ration between summer and winter average precipitation.

7. Discussion and Conclusions

7.1 Discussion of results

The approach and results of this study are somehow similar to researches done in the same area and in similar areas. Confirmation of the study results is strongly based on the analysed precipitation observations from all datasets and models data. Both Observed and models results vary widely from one to another, even though they share some similarity. In thus section, box plots are used to assess both sets of data used in the analysis. The outcomes are plotted bellow in **Fig. 7.1** to **Fig. 7.3**.

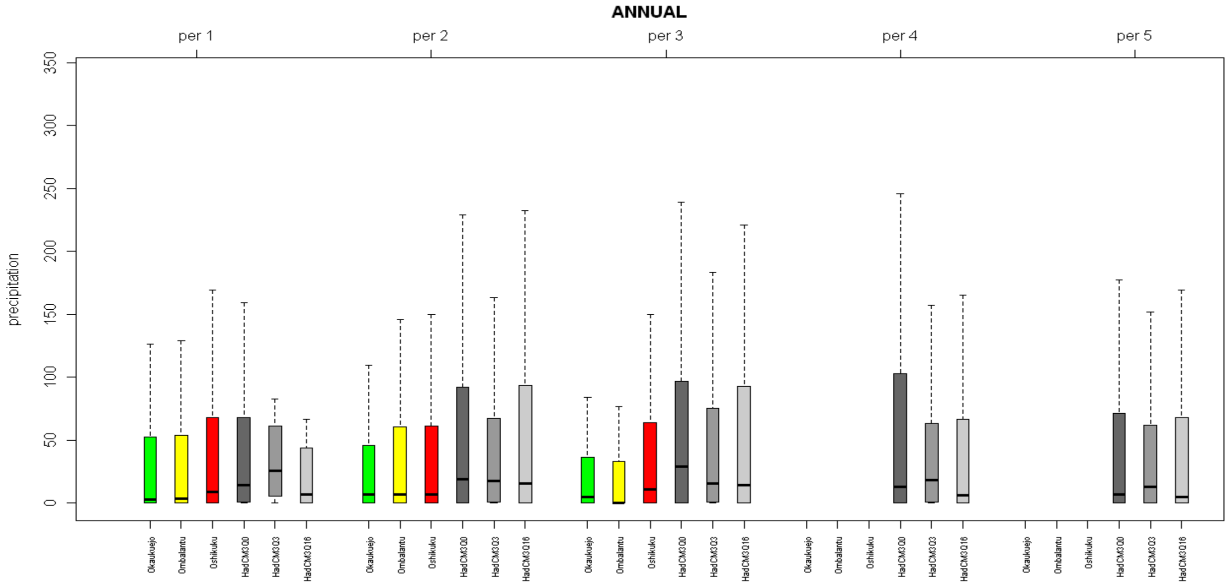


Fig. 7.1 *Summary of observed and simulated annual precipitation Observed: Okaukuejo (green), Ombalantu (yellow), Oshikuku (red)*

Simulated precipitation from the models is surely the largest in all cases than observed precipitation by as much as 80% (Table 5.6) in annual precipitation. As illustrated in the plot above (**Fig. 7.1**), both sets of data have a similar interquartile range (the width of the boxes) but have very high variability in the distribution of extreme yearly precipitation in both sets of analysed precipitation data. Observed precipitation show a decline in total annual precipitation, with the highest decline observed at Ombalantu.

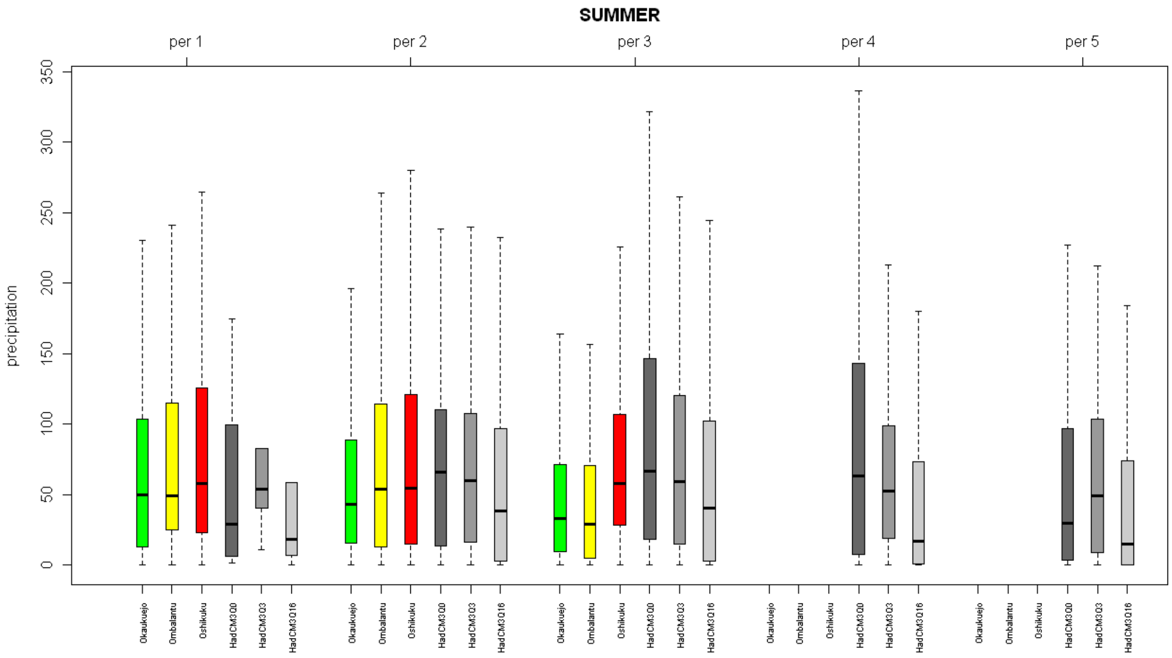


Fig. 7.2 *Summary of observed and simulated summer precipitation. Observed: Okaukuejo (green), Ombalantu (yellow), Oshikuku (red).*

As summer precipitation dominates in the region, the distribution and variability in summer precipitation is more similar to that of annual precipitation. High variability in summer precipitation was simulated by the models as also projected by Hudson and Jones, 2002, This apply only for period 3, in period 2 the variability in simulations corresponds quite well to that of observations. In period 1, surprisingly, the variability in GCMs is smaller than in observations. Extreme observed values (maximum and minimum) of summer precipitation showed a decline from period 1 to period 3, although period 2 on average had the highest recorded maximum summer precipitation.

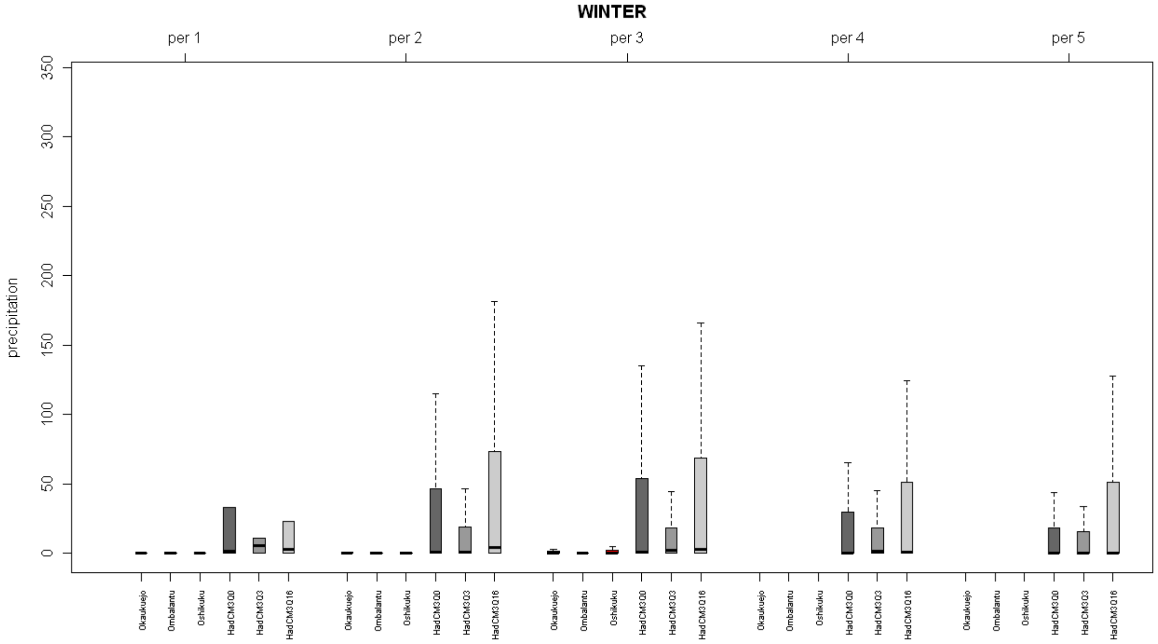


Fig. 7.2 *Summary of observed and simulated winter precipitation. Observed: Okaukuejo (green), Ombalantu (yellow), Oshikuku (red).*

Both models generally overestimated winter precipitation in all periods. Although there have been some changes in observed winter precipitations too, the changes were not of bigger magnitude comparing to the model simulations. Out of all 3 GCM's HadCM3Q3 produced better winter simulations that are closer to observed precipitation, although they are still higher than all winter observation in all periods.

7.2 Datasets evaluation

Assessment of future precipitation is very hard to do from this study, since simulated precipitation contrasts in many cases to observed precipitation. Comparison of simulated results to observed precipitation reveals the serious discrepancies between the two datasets. Uncertainty also remains on the accuracy of observed datasets, since we don't know the method that was used in recording the data. A possibility of using RCM's might have produced closer results, but there are still very few regional studies done in Southern African climate. Bellow is the table that summarises the relation of observed and simulated results.

Table 10. *Datasets evaluation for model data and Observed (OBS.) data.*

Comparison of results	Annual relative changes	Summer relative changes	Winter absolute differences
HadCM3Q0/OBS.	67,39%	60,70%	-22,71
HadCM3Q3/OBS.	74,03%	68,37%	-16,35
HadCM3Q16/OBS.	80,12%	70,28%	11,26

From the table above, it can be clearly seen that models simulations are by far not corresponding to observed precipitation, especially in the seasonal distribution of precipitation. Winter precipitation where winter values are given in absolute changes and a minus (-) sign indicate that observed average precipitation were higher than those of model data.

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7.3 Conclusions

The main goal of the study was to analyse the impact of Climate Change on the precipitation of the Cuvelai Etosha basin, using available observed data and simulated data as described in Chapter 5. From the results of the analyses, the following conclusions were made.

Changes in precipitation have been noticed in all analysed observations and in simulated precipitation. Generally both results show a decrease in annual and seasonal precipitation. Different conclusions can be concluded on the findings as listed bellow.

- There is significant decrease in simulated and observed annual and seasonal precipitation
- Overall for all observed precipitation, there has been a 23.54% decrease in annual mean precipitation from study period 1 to period 3.
- Year-to-year variability in precipitation is increasing and this is strongly associated with changes in climate.
- Relatively large biases were found in all three GCM simulations with respect to observed data. This lessens the confidence in their future projections.
- Study results have showed consistent with the results of studies done in similar regions and locations.

With the above mentioned, we can conclude that the effect of climate change on precipitation is real, and it has a very negative effect to society and the country as a whole. With the above discussed changes in the variability of precipitation and extreme events, the region remain very susceptible to events such us flood threats and deforestation that can lead to further change in climate. Modernisation of towns, urban influences and a high population growth in the study area are some of the things that have grown since the early recording days, thus new living standards can also bring fear of more influence on the climate.

With the above mentioned, I conclude that climate change and it’s impact on the study area is certain, however further extended study and modelling of the area are still needed to assess this topic deeper.

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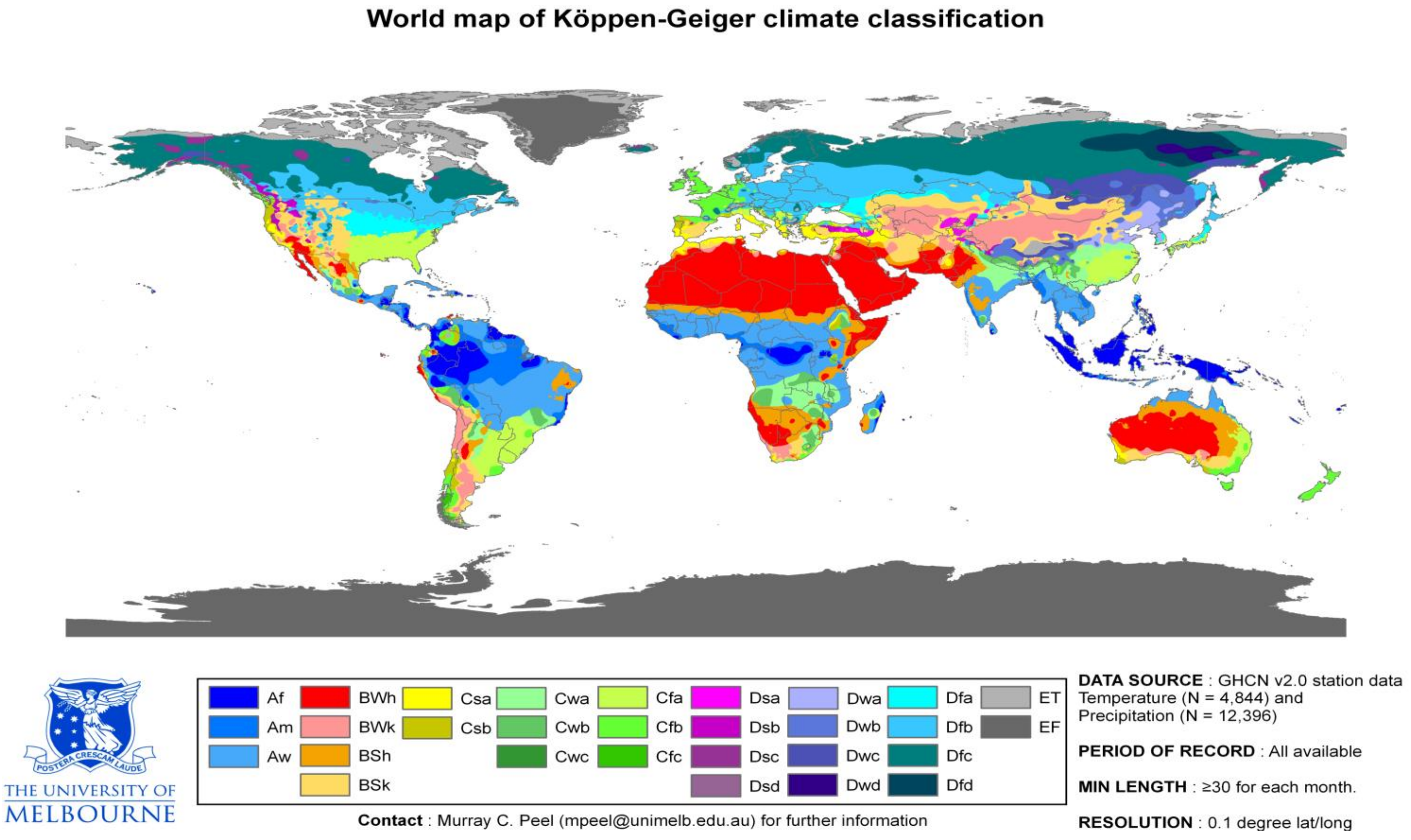
List of acronyms and Abbreviations

CEB	Cuvelai-Etosha basin
CFC	Chlorofluorocarbons
ENP	Etosha National Park
GCM	Global Climate Model
GHG’s	Greenhouse gases
IFRC	International Federation of Red Cross and Red Crescent
In	Measuring unit (inch)
IPCC	Intergovernmental Panel on Climate Change
MAWF	Ministry of Agriculture, Water and Forestry
METEONA	Namibia Meteorological Service
mm	Measuring unit (millimeter)
OBS.	observed precipitation
Per.4	Period 4
Per.5	Period 5
Per1	Period 1
Per2	Period 2
RCM	Regional Climate Model
RP	reference period
SADF	South African Defence Force
SRES	Special Report on Emissions Scenarios

UN	United Nations
UNEP	United Nation Environmental programme
UNFCCC	United Nations Framework Convention on Climate Change
WMO	World Meteorological Organisation

Annexes

Annex 1. Word map of Koppen-Genger Climate Classification



World map of Köppen-Geiger climate classification

DATA SOURCE : GHCN v2.0 station data Temperature (N = 4,844) and Precipitation (N = 12,396)

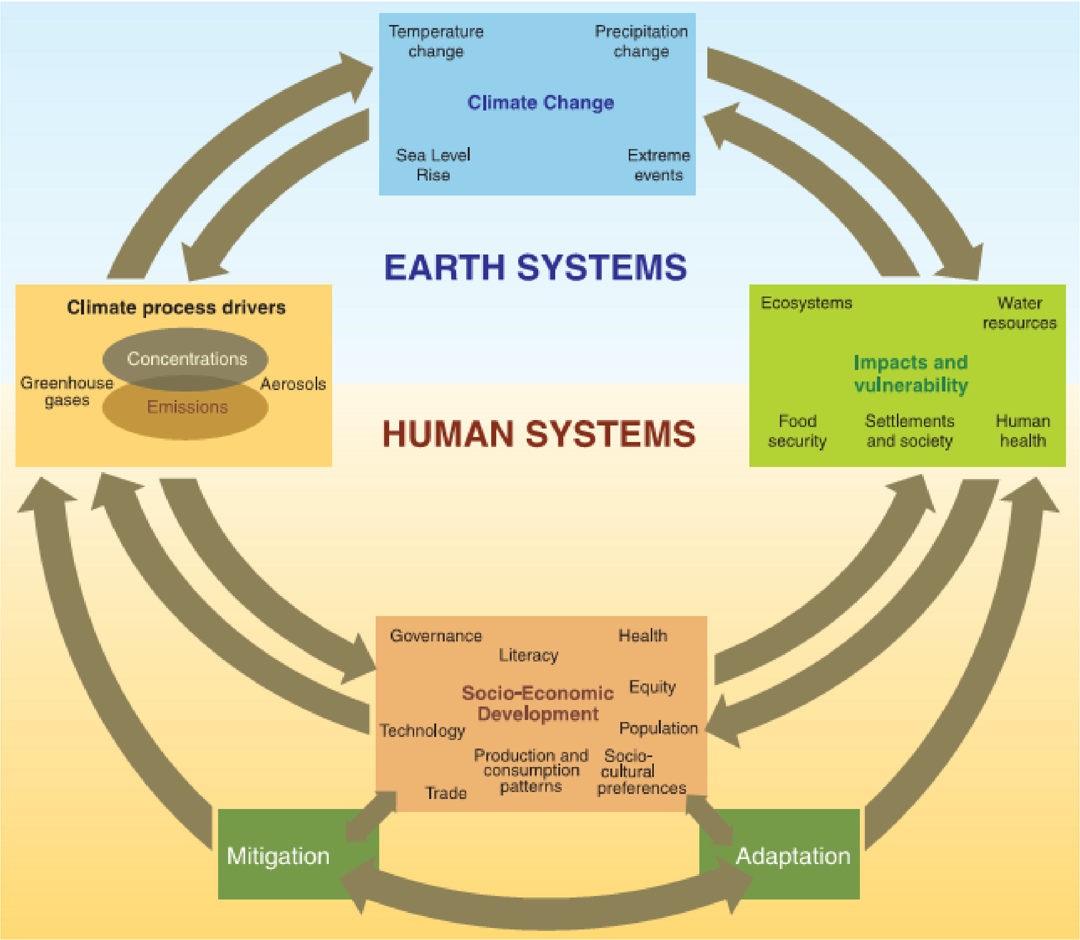
PERIOD OF RECORD : All available

MIN LENGTH : ≥30 for each month.

RESOLUTION : 0.1 degree lat/long

Contact : Murray C. Peel (mpeel@unimelb.edu.au) for further information

Annex 2. Schematic framework representing anthropogenig drivers, impacts and responses to climate change and their linkage (IPCC)



Annex 3. Namibia river during the dry seasonn, but fills with water in wet season