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Eastern Nile Climate Assessment: Rainfall Analysis

(Final Report)

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1 Introduction

1.1 General Overview

The analysis of long-term changes in climatic variables is a fundamental task in studies on climate change detection. The climate trend is the general movement of a series over an extended period or it is the long-term change in the dependent variable over a long period. Generally, it is determined by the relationship between the two variables and their temporal resolution, using spatial and statistical methods. Rainfall trends are considered a key factor in climate, which plays a crucial role in the water cycle that influences the availability of fresh water.

On the other hand, the demand for freshwater across various sectors including water supply, energy production, agriculture and food security, and environmental preservation is steadily rising due to shifts in economic and social dynamics worldwide. Recognizing water as a fundamental element for socio-economic progress and environmental stability, requires meticulous consideration throughout the planning, development, and execution of projects. However, rainfall serves as a pivotal component in the hydrological cycle, influencing the availability of freshwater resources across terrestrial ecosystems through its intricate processes and transformations. Understanding rainfall patterns, both historically and in future projections is essential for informed decision-making in water resources development and management endeavors.

In the Eastern Nile Basin, rainfall has a very high variability in terms of amount and distribution, with climate change adding an extra pressure, leading to changes in seasonal patterns, as well as the spatial and temporal distributions. This produces higher uncertainties in the water resources management and development over the basin. Therefore, quantifying trends in rainfall across different temporal scales and projecting future trajectories becomes imperative for ensuring the sustainable management of water resources in the region.

For the above-mentioned reasons, this report combines the results of two rainfall analysis studies. The first study, assessed the historical changes in rainfall trend and patterns considering the period 1990 – 2020, while the second study [(2)], focused on analyzing the future projections of rainfall considering the years from 2020 – 2060. The whole area of the Eastern Nile Basin was considered for the analysis, including its four subbasins; Blue Nile, Baro-Akobo-Sobat, Tekeze-Setit-Atbara, and the Main Nile. For more information, refer to report (1) and report (2) which provide the detailed outcomes of the two studies.

Report (1): Eastern Nile River Basin Historical Rainfall Trend Analysis, ENTRO, 2024.
Report (2): Eastern Nile River Basin Future Rainfall Projections Analysis, ENTRO, 2024.

1.2 Objective

The main objective of this report is to establish meaningful comparisons between the current observations and future forecasts of the Eastern Nile Basin rainfall, by assessing the historical and projected rainfall trends, through statistical and spatial analysis of data from different sources for the period 1990 – 2060.

1.2.1 Specific Objectives

1. Collect and organize historical and projected rainfall data for the Eastern Nile Basin (ENB) from multiple satellite observations, and General Circulation Models (GCMs) within the Coupled Model Inter-comparison Project Phase 6 (CMIP6).
2. Conduct statistical and spatial analysis for the data showing the trends of historical and projected rainfall.

1.3 Study Area

The Eastern Nile Basin (ENB) extends from 3º N to 33º N, and 26º E to 40 º E covering an area of 1.8 million km^2. It is divided into 4 subbasins in four countries; Ethiopia, Sudan, South Sudan, and Egypt. The main Nile - from the confluence of Blue Nile and White Nile in Khartoum to the Nile delta - is the largest subbasin with an area of 789,140 km^2 (44 % total ENB area). The second subbasin is the Baro-Akobo-Sobat-White Nile in the west, that covers an area of 460,000 km^2 (26 % total ENB area), with two main tributaries originating from the Ethiopian hills and the Sudd wetlands. The third subbasin with the largest contribution is the Abbay-Blue Nile on the east that originates from the highlands of Ethiopia and extends from Lake Tana until it joints the White Nile in Khartoum covering an area of 310,000 km^2 (17 % total ENB area). Lastly the smallest subbasin is the Tekeze-Setit-Atbara subbasin on the east originating from the high lands of Ethiopia and covering an area of about 230,000 km^2 (13 % total ENB area) *(El-sheikh et al., 2017; Mersha, 2014; NBI, 2018)*.

The ENB has different climates as it extends through large latitudes, with wide range of elevations. It is host of extremities, ranging from the temperate cool rugged highlands of Ethiopia in the east, the humid wetland areas of South Sudan and Ethiopia in the south, to the hot dry deserts of Sudan and Egypt in the north. The area witnesses high variations in rainfall, ranging between 0 mm in the north, up to more than 2000 mm at the Ethiopian highlands considering the years 1981 – 2022.

The water resources of the basin appear to be sufficient in terms of quantity and quality looking at the great potential opportunities of water, however, the Eastern Nile Basin faces many water availability and accessibility challenges, and climate change is imposing additional burden. Most of the ENB can be considered as a water scarce region, with most of the Nile water generating from the Ethiopian highlands. The main Nile has a total yearly runoff of about 83.8 BCM, with contributions of about 64% (53 BCM per year) and 28% (23.6 BCM per year) by the Abbay-Blue

Nile and Tekeze-Atbara subbasin respectively, which both show clear wet and dry spells as a direct response to the seasonal rain patterns *(Yitayew & Melesse, 2011)*.

In terms of the socio-economic indicators, most of the population of the Eastern Nile Basin countries falls within the basin with different percent coverage (94% for Egypt, 99% for South Sudan, 87% for Sudan, and 38% for Ethiopia). Population figures are growing rapidly and expected to reach about 305 million in 2033, which will cause tension on water supply and affect food security level. All ENB countries except Egypt are categorized as poor developing countries. Majority of population are below poverty line, and people are totally dependent on natural resources for their livelihood. The high variability of rainfall poses challenges for the upstream and midstream countries of Ethiopia, South Sudan, and Sudan as they mainly practice rain-fed agriculture. The basin has potential for the production of different crops, pastoralist, forestry, and fisheries, as well as the potential for hydropower generation, which can contribute to poverty reduction.

Figure 1. 1 below illustrates the geographical extents of the study area, with its rainfall distribution.

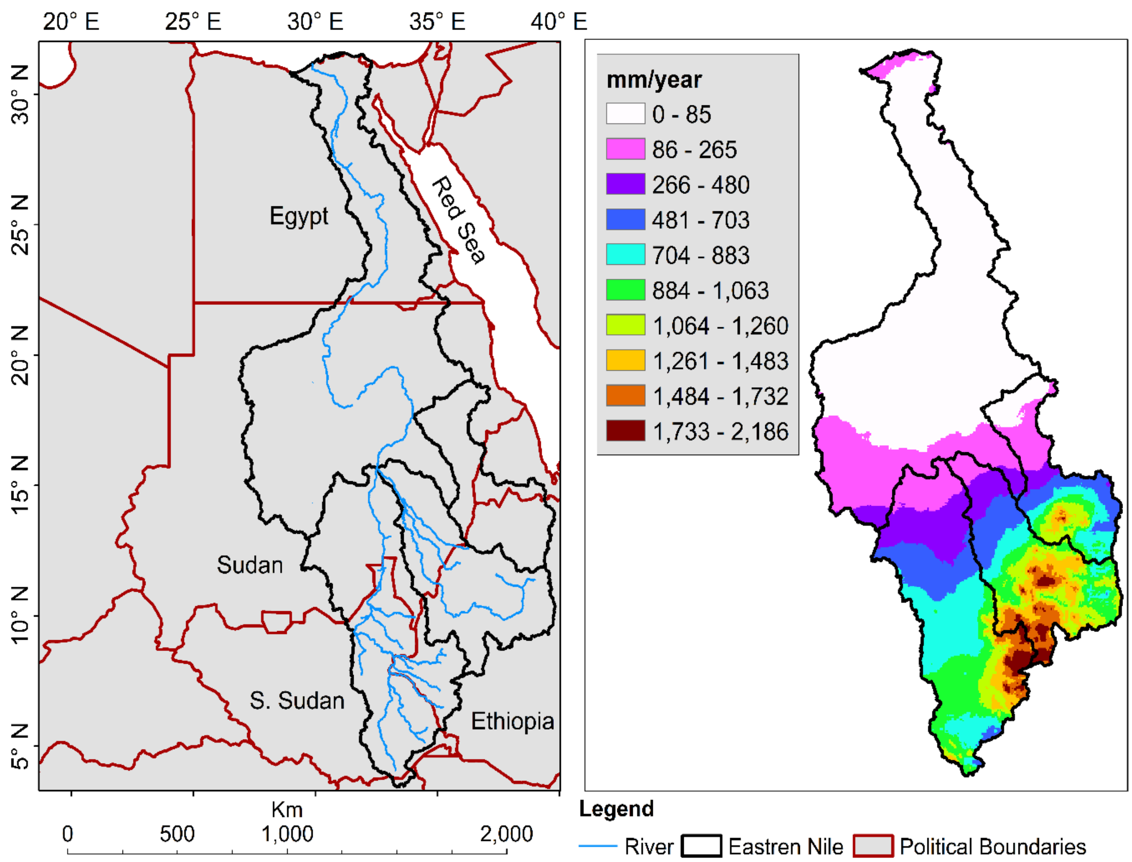

Figure 1. 1 (Left) Eastern Nile Basin geographical extent, (Right) The mean annual rainfall for Eastern Nile Basin from 1981-2022 using CHIRPSv2 dataset.

Wide range of literature and previous researches were review during conducting the above-mentioned 2 studies. More information about the findings and gaps of the literature review can be found in the detailed reports of the studies.

2 Material and Methods

The methodology of this study consists of number of steps. Firstly, different historical rainfall satellite datasets, as well as rainfall projection products were selected to be considered for the study. That was followed by downloading and correcting this data before analysis. Subsequently, set of techniques were undertaken for the analysis of the rainfall data, to finally come up with informative description and comparison of the historical rainfall trends, and the future rainfall projections in the Eastern Nile Basin.

The study considers the four subbasins of the Eastern Nile Basin; namely, the Blue Nile basin, Baro-Akobo-Sobat basin, Tekeze-Setit-Atbara basin, and Main Nile Basins. However, to follow the variation of the physical and climate conditions of the Main Nile, and to reduce uncertainty in the analysis, the Main Nile sub-basin was further divided into the Upper Main Nile basin and the Lower Main Nile basin. Historical rainfall data of the years 1990 – 2020, as well as rainfall projections for the years 2020 – 2060 was considered for the analysis.

2.1 Data sourcing

2.1.1 Historical rainfall data

Five datasets were selected to conduct the historical rainfall trends analysis in the Eastern Nile Basin. The selection was made based on the spatial coverage, data record length, temporal and spatial resolution of the datasets, the type of data input (calibrated with gauge data or not), as well as the performance of products observed in previous studies for Eastern Nile Basin region and countries. The selected products are:

1. Climate Hazards Group InfraRed Precipitation with Station Data (CHIRPS)
2. African Rainfall Climatology Version2 (ARC2)
3. Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks–Climate Data Record (PERSIANN-CDR-CCS)
4. Tropical Applications of Meteorology using Satellite Data (TAMSAT)
5. Global Precipitation Climatology Centre (GPCC).

Detailed description of the selected products can be found in report (1). Table 2. 1 summarizes the selected historical rainfall products' characteristics.

Table 2. 1 Summary of the selected historical rainfall satellites characteristics

Dataset	Spatial Resolution	Temporal Resolution	Length of Record	Type of Data
CHIRPS	0.05° (5.5 km)	Daily	1981-present	Satellite and ground data
ARC2	0.1° (11 km)		1983-present	Satellite, ground data, and weather prediction models
PERSIANN-CDR	0.25° (27 km)		1983-present	satellite data and machine learning techniques
TAMAST	0.0375° (4 km)		1983-present	satellite data, climate reanalysis products, and ground data
GPCC	0.25 (27km)		1891 - present	Gridding of ground data

2.1.2 Rainfall projection data

The GCMs rainfall projection is generally produced considering different Shared Socio-economic Pathways scenarios (SSPs) based on greenhouse gases emissions. CMIP6 considered five SSPs, with varying assumptions about human developments including: population, education, urbanization, gross domestic product (GDP), economic growth, rate of technological developments, greenhouse gas (GHG) and aerosol emissions, energy supply and demand, land-use changes, etc. These SSPs are: SSP1 (SSP126) that considers sustainability, taking the green road with low challenges to mitigation and adaptation, SSP2 (SSP245) that represents the middle of the road, with medium challenges to mitigation and adaptation, SSP3 (SSP370) that represents the rocky road, with high challenges to mitigation and adaptation, SSP4 (119) that represents inequality, with low challenges to mitigation and high challenges to adaptation, and lastly SSP5 (SSP585) that represents fossil-fueled development, with high challenges to mitigation and low challenges to adaptation. Eight Global Circulation Models (GCMs) from the Coupled Model Inter-comparison Project Phase 6 (CMIP6) have been used. The models were carefully selected based on the literature review, and according to their superior performance and high-resolution in climate modeling both globally, as well as regionally (Eastern Nile Basin). The selected models are: MIROC6, MPI-ESM, MRI-ESM2, and ACCESS-CM2, GFDL-ESM4, NorESM2-MM, BCC-CSM-2MR, and GFDL-CM4, which are accessible through the Earth System Grid Federation portal.

Detailed description of the selected products can be found in report (2). Table 2. 1 summarizes the selected rainfall products' characteristics.

Table 2. 2 Summary of selected rainfall projection CMIP6 models characteristics

No	Model's Name	Calendar Type	Country	Resolution	Ensemble	Scenarios
1	GFDL-ESM4	365 days	USA	1.3°×1°	r1i1p1f1	1.ssp119 2.ssp126 3.ssp245 4.ssp370 5.ssp585
2	GFDL-CM4	365 days	USA	1.3°×1°	r1i1p1f1	1.ssp245 2.ssp585
3	NorESM2-MM	365 days	Norway	0.94°×1.25°	r1i1p1f1	1.ssp126 2.ssp245 3.ssp370 4.ssp585
4	BCC-CSM2-MR	365 days	China	1.1°×1.1°	r1i1p1f1	1.ssp126 2.ssp245 3.ssp370
5	ACCESS-CM2	365 days	Australia	1.9*1.3	r1i1p1f1 r1i1p1f3	1.ssp370 2.ssp585
6	MPI-ESM	Standard (366 days)	Germany	0.9°×0.9°	r1i1p1f1	1.ssp119 2.ssp126 3.ssp245 4.ssp370 5.ssp585
7	MRI-ESM	Standard (366 days)	Japan	1.125°×1.125°	r1i1p1f1	1.ssp119 2.ssp126 3.ssp245 4.ssp370 5.ssp585
8	MIROC6	Standard (366 days)	Japan	1.4°×1.4°	r1i1p1f1	1.ssp119 2.ssp126 3.ssp245 4.ssp370 5.ssp585

Sources of the historical and future rainfall data are described in details in report (1) and (2). Daily data in NetCDF format was downloaded and used for the analysis. Historical rainfall of 31 years (1990 – 2020), as well as 40 years of future data (2020 – 2060) was analyzed.

2.2 Data Analysis

The historical and future rainfall records were analyzed over the five Eastern Nile sub-basins (Baro-Akobo-Sobat, Blue Nile, Tekeze-Setit-Atbara, Upper Main Nile and Lower Main Nile). Each subbasin was analyzed separately to be able to detect the differences in their satellite observations and rainfall patterns, and to capture the various physical and climate conditions associated with each of them. Various tools, programming languages, and software were used for analyzing the rainfall data such as; Q/ArcGIS, Climate Data Tool (CDT), as well as R and Python codes. Firstly, initial presentation and reprocessing of the data; i.e. visualization, clipping to subbasins level, combining of separating daily data into one file for each year, and the conversion to GeoTiff (.tif) or Comma-Separated Values (.csv) formats and vice versa were conducted. The spatial distribution over the whole Eastern Nile Basin area was then produced to understand the spatio-temporal variations of rainfall, and have initial insights about the trends and changes taking into consideration the observations of the different historical and future rainfall products.

Moreover, the performance of the 5 satellites and the 8 CMIP6 GCMs over the 5 subbasins was assessed. CHIRPS rainfall data was selected to be used as a reference for the assessment of the other satellite rainfall products performance, to fill the gap of the data scarcity in the Eastern Nile countries, and as CHIRPS delivers reliable and complete data up to present, that is blended with ground data, and showed good performance, good precision, and relatively little bias over east Africa compared to ground observations.

Statistical analysis was conducted for the daily data to calculate the daily mean and standard deviation over each subbasin (produced from the rainfall values of subbasin cells). This was done using the Multi-band Zonal Statistics tool of QGIS, and the results were presented in GeoPackage format (.gpkg) and Comma-Separated Values format (.csv) in daily, monthly, and annual time steps. The resultant rainfall timeseries have then been undergone a further statistical and comparative analysis; including calculating and plotting box plots, scatter plots, rainfall trends, rainfall anomalies, rainfall frequency distribution, rainfall seasonality, as well as calculating and plotting the Standard Precipitation Index (SPI). Detailed description of these techniques can be found in report (1) and (2).

The additional step in this report is to link and compare the projected rainfall data against the historical rainfall records over the Eastern Nile Basin. Firstly, the annual data of all satellites, as well as the 5 best performing GCMs (GFDL-CM4, GFDL-ESM, NorESM2-MM, BCC-CSM2, and MPI-ESM as indicated in report 2) were plotted in box plots to evaluate their performance compared to historical rainfall over each subbasin. This analysis aimed to identify rainfall projection models that performed well compared to the historical records of CHIRPS and other satellites records (focusing on the best performing satellites), thus enabling the utilization of their projections to quantify future scenarios for each subbasin. Data of the best performing historical rainfall satellites (1990 – 2020), as well as the average of the best five GCMs for the two scenarios SSP245 (the most likely to happened) and SSP585 (the most pessimistic scenario) for projected data (2020 – 2060), were used for plotting the rainfall trends of each subbasin for the complete study period 1990 – 2020 in one graph.

3 Analysis and Results

3.1 Test of the satellites and GCMs performance

As mentioned before, the historical rainfall observations of the satellites and the future rainfall projections of the different GCMs were plotted together in box plots to evaluate their performance compared to CHIRPS. The following section shows the analysis of the box plot of each subbasin separately.

3.1.1 Baro-Akobo-Sobat (BAS)

Figure 3. 1 illustrates the box plot for Baro-Akobo-Sobat (BAS). By looking at the box plots of the different SSPs compared to historical rainfall observations, it can be clearly noticed that the future rainfall products (GCMs) showed different distribution of rainfall, which indicates high uncertainty in estimating the rainfall, with great variations in their central tendency (median) and their spreading or variability (interquartile range (IQR)). By comparing all historical and future rainfall products to CHIRPS, the 5 historical rainfall satellites demonstrated approximately closer median (rainfall estimation) compared to the GCMs.

It can be noticed that TAMSAT showed the best performance and highest consistency among the satellite datasets, as it presented low interquartile range (IQR), which means lower variability, with small range of rainfall values (min and max from whisker lines). It also estimated the closest median of rainfall compared to CHIRPS. That is followed by PERSIANN-CDR, with relatively small overestimation. On the other hand, GPCC managed to capture the rainfall median of CHIRPS accurately, however, it demonstrated high spreading (IQR), which indicates the inconsistency. Lastly, ARC2 also showed high variability and underestimation of the rainfall median, and can be considered as the satellite with the poorest performance.

On the other hand, although the GCMs present high uncertainty, it can be observed from the plot that MRI-ESM2 can be ranked as the best performing GCM compared to CHIRPS in all SSPs looking at its central tendency. That is followed by GFDL-ESM and MPI-ESM, which presented low range of overestimation and underestimation respectively, with also higher variability (IQR) in some SSPs that indicates lower consistency. Similarly, GFDL-CM4 demonstrated the best performance in the historical rainfall recorded by the GCMs. The remaining GCMs have not shown good performance (central tendency and IQR), with BCC-CM2 having the poorest performance compared to CHIRPS.

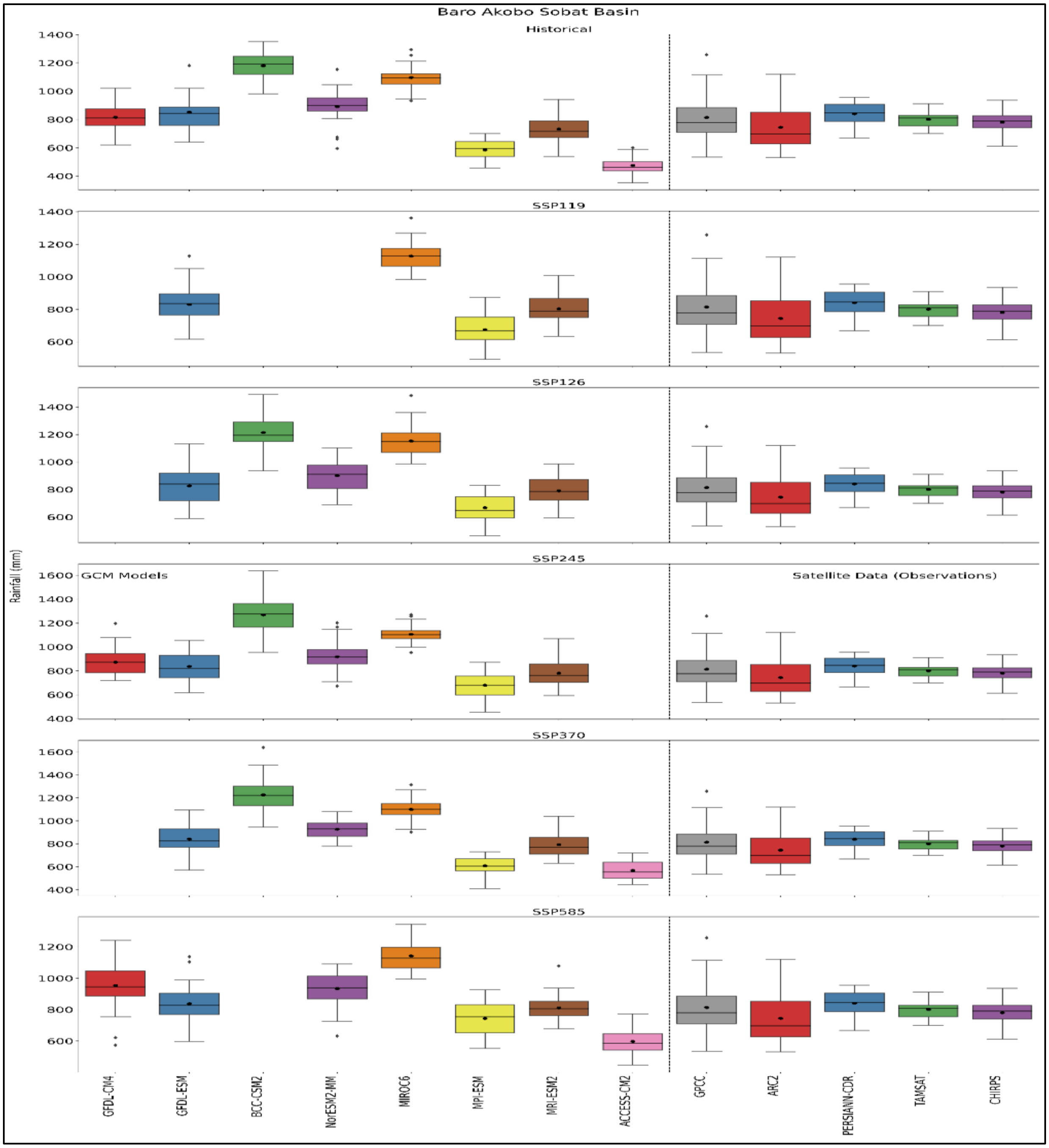

Figure 3. 1 Box plots - Baro-Akobo-Sobat

3.1.2 Blue Nile

By looking at the box plots of the Blue Nile (BN) in Figure 3. 2, higher variations in rainfall distribution of the 8 GCMs can be observed compared to the satellites' records. This also indicates high uncertainty in estimating the future rainfall. The 5 historical rainfall satellites demonstrated approximately closer median (rainfall estimation), and IQR (spreading) compared to CHIRPS than the GCMs.

Similar to BAS, TAMSAT followed by PERSIANN-CDR represent the best performing satellites looking at their rainfall distribution in the plot (median and variability) compared to CHIRPS. They demonstrate the highest consistency, however, PERSIANN-CDR showed slight overestimation of the rainfall median. ARC2 and GPCC presented higher spreading with considerable underestimation and overestimation respectively. GPCC can be considered to have the poorest performance among the other satellites.

On the other hand, despite of the high uncertainty associated with the future rainfall estimations, GFDL-ESM outperformed the other GCMs in all SSPs compared to CHIRPS, when looking at its rainfall distribution. It demonstrated a slight overestimation of the median. That is followed by the GDFL-CM4 model, which also demonstrated close estimation of the rainfall median, with higher overestimation compared to CHIRPS.

The remaining GCMs could not capture the distribution of the Blue Nile rainfall accurately, having much higher or lower estimations with varying spreading levels. MIROC6 recorded the worst performance among the group, with very high central tendency and higher variability (spreading) compared to CHIRPS.

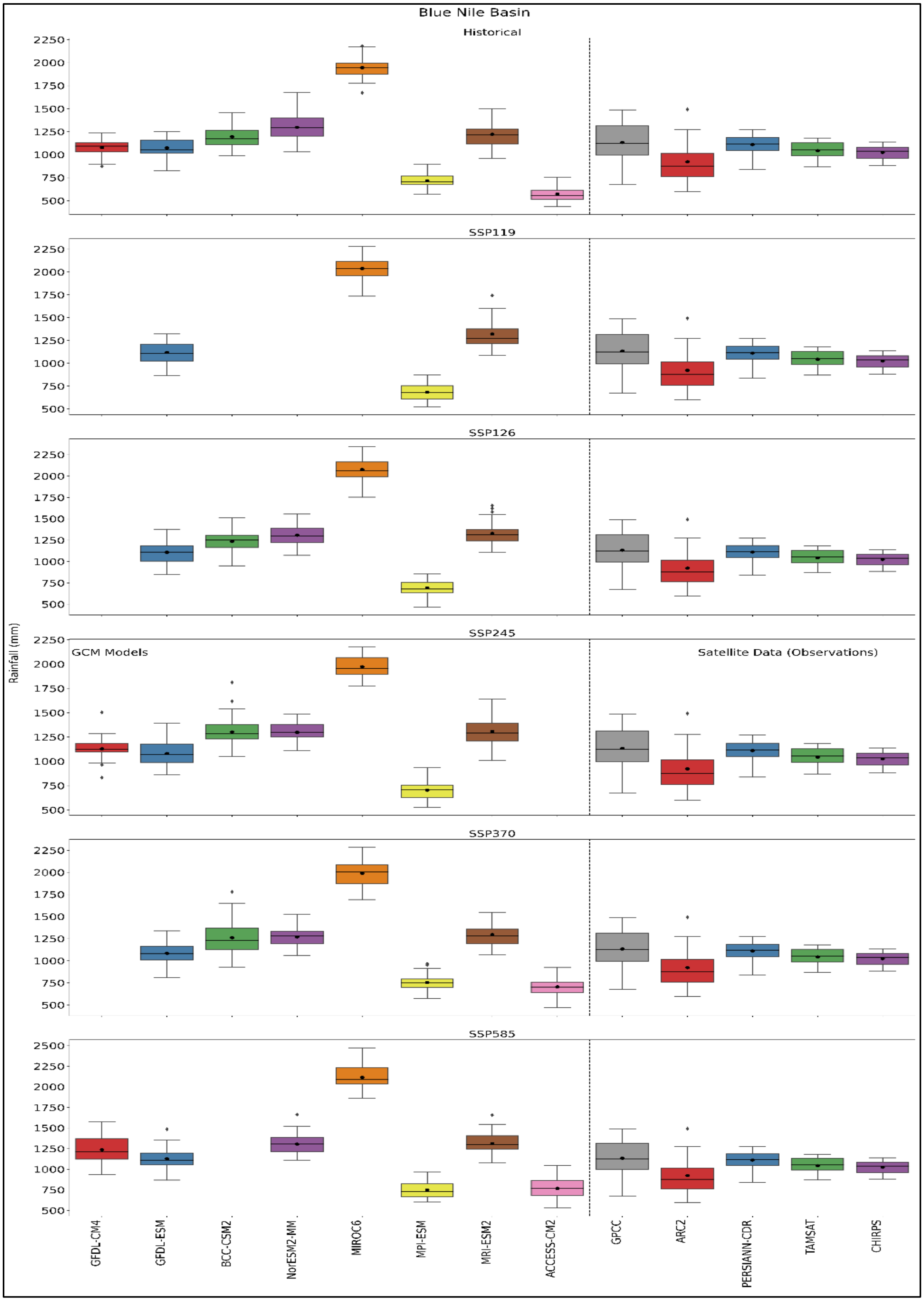

Figure 3. 2 Box plots - Blue Nile

3.1.3 Tekeze-Setit-Atbara

In Tekeze-Setit-Atbara (TAS), also high uncertainty is noticed in the rainfall distribution especially for the GCMs (Figure 3. 3). Similar to the previous subbasins, TAMSAT also outperformed, having accurate rainfall median and similar spreading compared to CHIRPS. PERSIANN-CDR and GPCC showed higher and lower central tendency respectively, while ARC2 captured the rainfall median, however, it showed high variability or spreading (IQR).

On the other hand, it can be noticed that NorESM2-MM followed by MRI-ESM2 can be considered the best performing GCMs compared to the rainfall distribution of CHIRPS data, with low underestimation and overestimation observed by the first and the second respectively. MRI-ESM2 also presented higher variability (IQR).

The remaining GCMs have not shown good performance. The demonstrated high underestimation of the rainfall median when looking at their central tendency, except MIROC6 which indicated high spreading with high overestimation of the median compared to CHIRPS. MIROC6 can be ranked as the product with the poorest performance in Tekeze Setit Atbara.

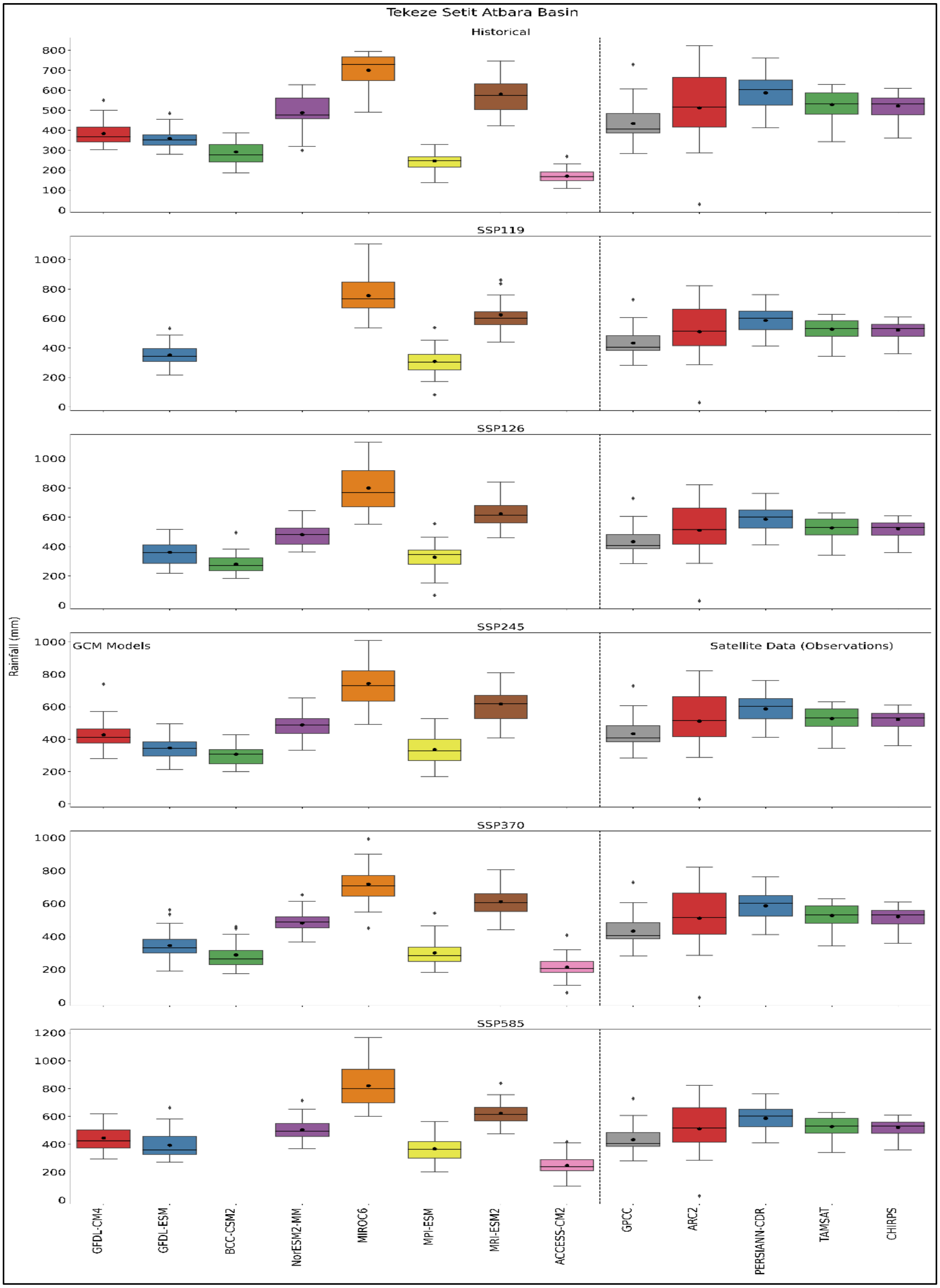

Figure 3. 3 Box plots - Tekeze Setit Atbara

3.1.4 Upper Main Nile

Figure 3. 4 below shows the box plots for the Upper Main Nile. Opposite to the previous subbasins, the GCMs showed higher consistency in their rainfall distribution compared to the satellite products (lower IQR). However, this does not guarantee the good performance.

By comparing CHIRPS with the other satellites, all of them managed to capture close value of the rainfall median. TAMSAT and PERSIANN-CDR have shown the highest consistency and reliability in estimating annual rainfall over the Upper Main Nile. Their good performance is proved by their central tendency and variability (IQR), which show a slight overestimation by the two products, and higher spreading of PERSIANN-CDR. GPCC also performed well, with slight underestimation and number of outliers. ARC2 can be considered as the satellite with the poorest performance compared to CHIRPS, having the highest overestimation and the highest spreading which indicates the lowest consistency and reliability.

On the other hand, looking at the box plots of the GCMs, it can be observed that MRI-ESM2 showed the best fit with CHIRPS data in terms of the central tendency (median) and variability (IQR) in all SSPs (highest consistency and best performance). Moreover, the performance of GFDL-ESM and BCC-CSM2 can also be considered as good performance, followed by GFDL-CM4. All of them presented slight underestimation of rainfall.
The other GCMs demonstrated rainfall distribution with lower estimation of the median, except MIROC6 that presented much higher rainfall values. MIROC6 can be ranked as the rainfall product with the worst performance among the group.

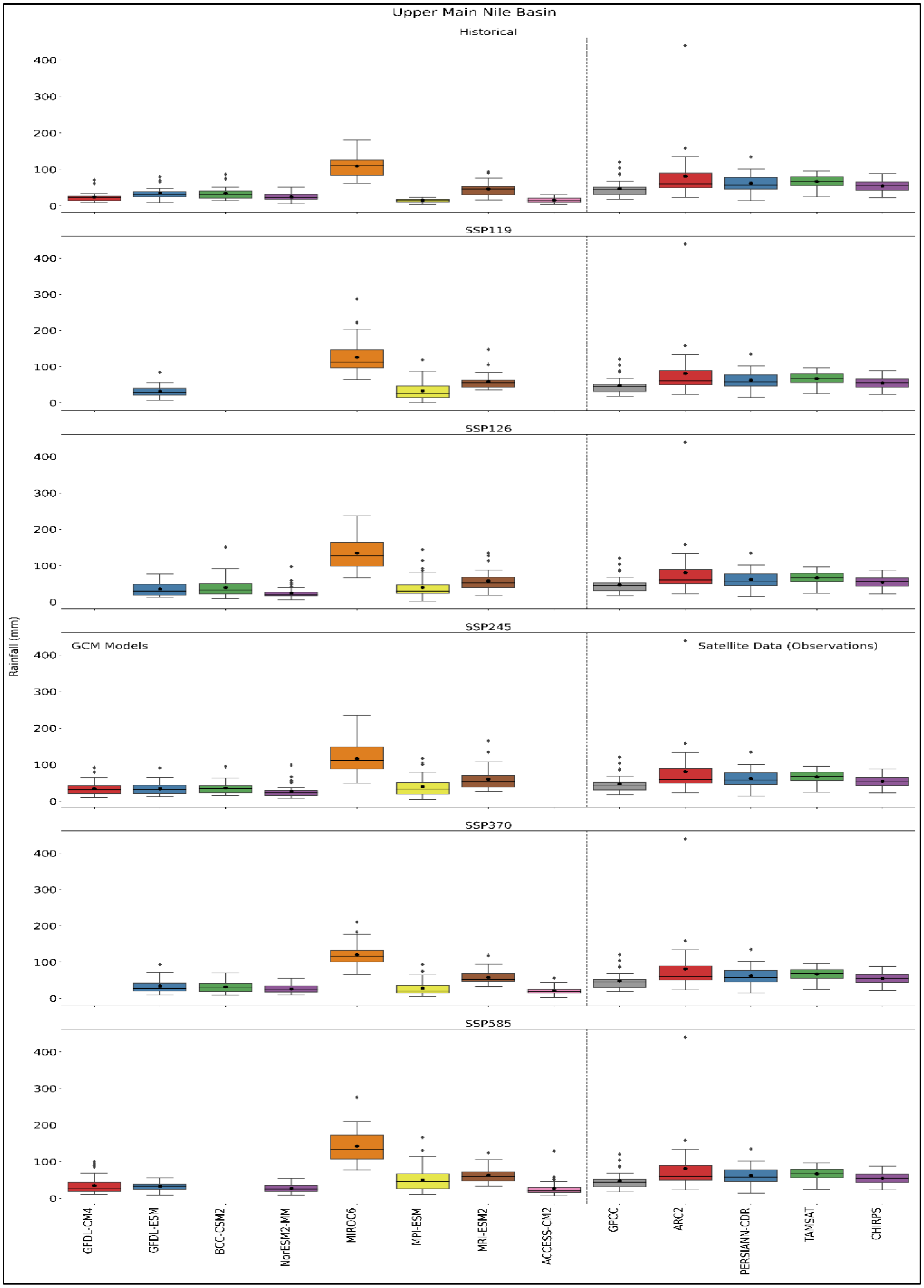

Figure 3. 4 Box plots - Upper Main Nile

3.1.5 Lower Main Nile

The Lower Main Nile is subjected to high uncertainty in estimating accurate rainfall both historically and in the future. This uncertainty can be clearly noticed by looking at the rainfall distribution (bow plots) of the historical rainfall satellites and the future rainfall GCMs Figure 3. 5 in below.

Starting with the satellites estimates, the small IQR as well as the similar central tendency compared to CHIRPS indicates that GPCC is the best performing satellite showing low variability, and accurate rainfall estimates. The remaining 3 datasets (ARC2, PERSIANN-CDR, and TAMSAT) have shown high spreading of the data. This means they are uncertain and less reliable in estimating annual rainfall.

On the other hand, the results of the GCMs indicate that GFDL-ESM can be considered the best GCM among the group, as it showed the best fit with CHIRPS for all SSPs in terms of the rainfall median. However, its IQR is relatively high, indicating higher spreading than CHIRPS. That is followed by NorESM2-MM and GFDL-CM4, which both slightly underestimated the rainfall median compared to CHIRPS, with high variability (IQR0 in number of SSPs.

All other GCMs both overestimated the rainfall (high central tendency) and showed high spreading.

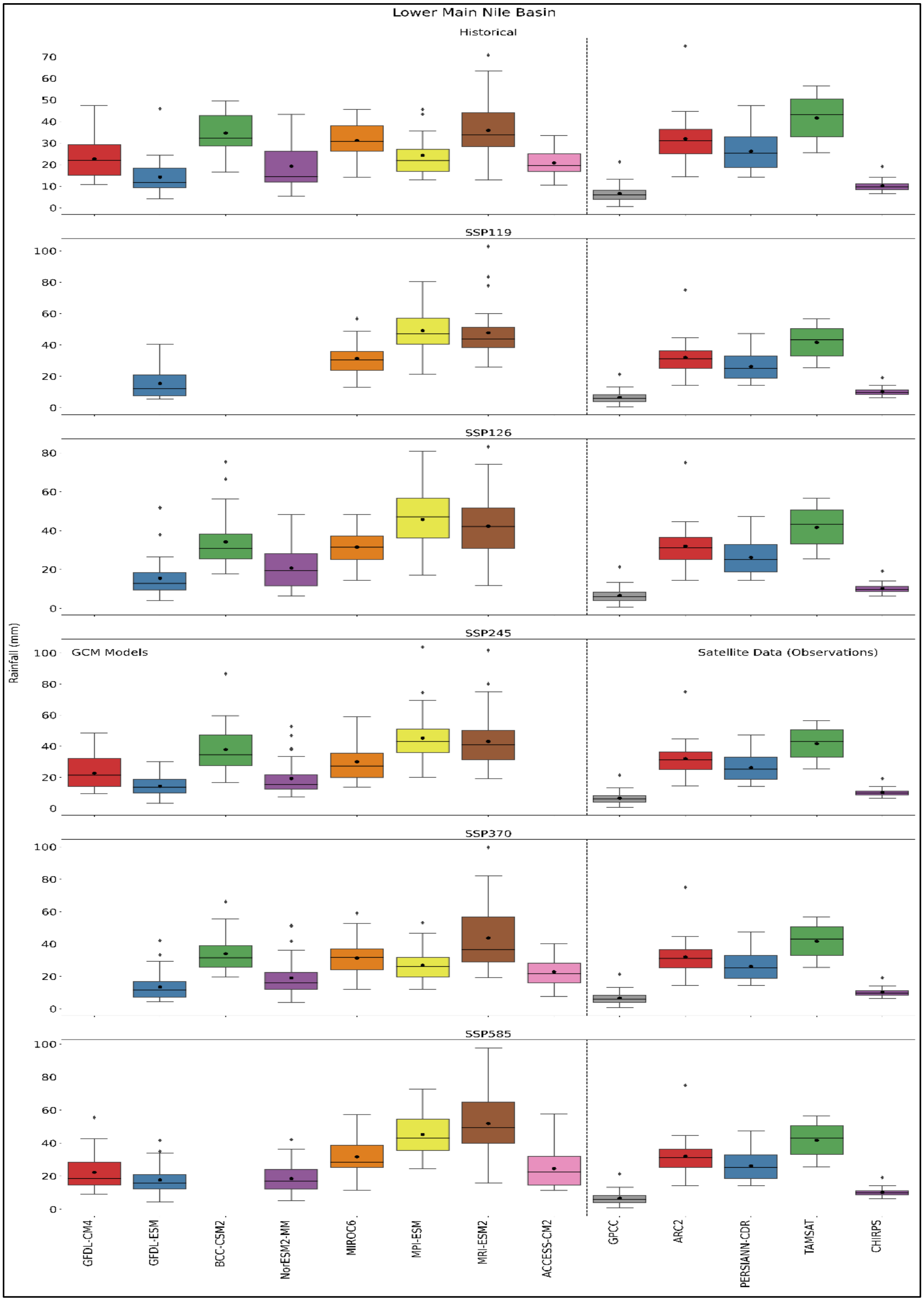

Figure 3. 5 Box plots - Lower Main Nile

3.1.6 Summary of the rainfall products performance evaluation

From the previous analysis of the different subbasins box plots, differences appeared in the ranking of the rainfall products over the different subbasins. However, this analysis was conducted in more details considering more statistical metrics (correlations, bias, variation, and error) for the comparison of the performance of the rainfall products. The results of the performance of the satellites and GCMs can be found in report (1) and report (2) respectively. Thus, the results of the box plots have been used together with the statistical evaluation results of report (1) and (2) to finally come up with a final evaluation for the performance of the historical and future rainfall products.

Starting with the satellite historical rainfall datasets, both results showed that TAMSAT outperformed the other products in Baro-Akobo-Sobat, Blue Nile, and Tekeze-Setit-Atbara, while GPCC showed the best performance in the Main Nile.

On the other hand, all the GCMs that demonstrated good performance in the Eastern Nile subbasins when evaluating the previous box plots, were found to have high match with CHIRPS considering the statistical metrics. The GCMs with the highest performance over the Eastern Nile Basin were found to be: GFDL-CM4, GFDL-ESM, MPI-ESM, NorESM2, and BCC-CSM2.

3.2 Historical and future rainfall trends

To visualize the changes in the rainfall patterns and compare the historical and future rainfall trends of the Eastern Nile subbasins, the rainfall trends plots were plotted for each subbasin over the period 190 – 2020. The annual rainfall data (annual sum) were plotted against time to show the overall trend in rainfall over time.

For the historical rainfall trends, the best performing satellite of each subbasin together with CHIRPS were used. On the other hand, and due to the high uncertainty appeared in projecting the future rainfall using the GCM, the average of the best five GCMs (GFDL-CM4, GFDL-ESM, MPI-ESM, NorESM2, and BCC-CSM2) was used for all the subbasins. Two scenarios from each GCM were considered; namely, SSP245 and SSP585 (the most likely to happen and the pessimistic scenarios)

3.2.1 Baro-Akobo-Sobat

Looking at Figure 3. 6 of Baro-Akobo-Sobat, differences can be noticed in the trends of the projected future rainfall. Generally, SSP585 projected lower future rainfall values than SSP245, while CHIRPS and TAMSAT recorded approximately similar amounts with time. It can be observed that the historical (1990 – 2020) and projected (2020 – 2060) annual rainfall of Baro-Akobo-Sobat show an increasing rainfall trend over the study period with approximately similar rate of change. Moreover, the satellites and GCMs demonstrated a continuous rainfall trend plot for 1990 – 2020 without a gap between the historical records and future projections.

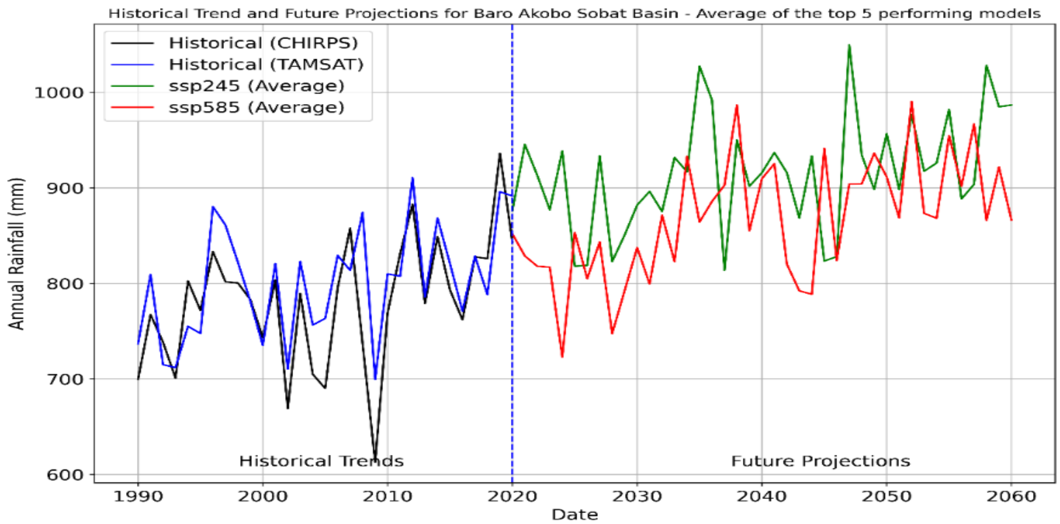

Figure 3. 6 Rainfall trend - Baro-Akobo-Sobat

3.2.2 Blue Nile

Figure 3. 7 illustrates the rainfall trend of the Blue Nile over 1990 – 2060. The historical rainfall records (CHIRPS and TAMSAT) can also be considered similar, while differences in the projected rainfall trends (SSP245 and SSP585) can be noticed, with higher estimation by SSP585. Similar to Baro-Akobo-Sobat, the satellites and the GCMs show continuation of the rainfall trend plot for 1990 – 2020 without a gap between the historical records and future projections. Generally, the rainfall is following an increasing trend over the study period (historical and future), with relatively slower rate than Baro-Akobo-Sobat.

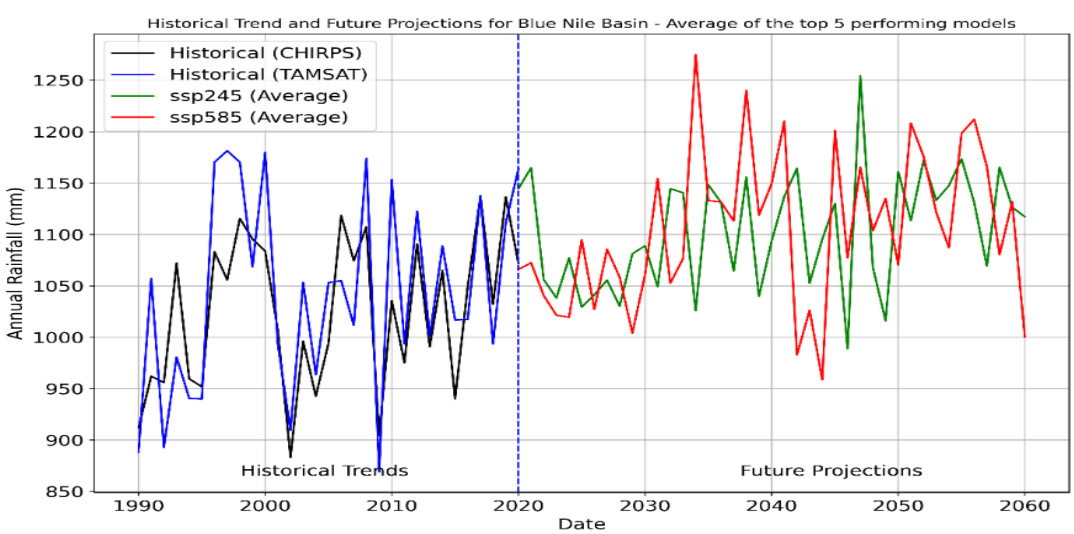

Figure 3. 7 Rainfall trend - Blue Nile

3.2.3 Tekeze-Setit-Atbara

Figure 3. 8 shows the rainfall trends of Tekeze-Setit-Atbara. It can be noticed that there is a gap between the historical and future rainfall trend plots when considering the best performing satellites (CHIRPS and TAMSAT). They recorded much higher rainfall than the GCMs. Both of the satellites show similar rainfall amounts over time with an increasing trend. On the other hand, differences in the projected future rainfall can also be observed between SSP245 and SSP585, with the later having higher amounts. However, both of them presented a no change to slightly increasing rainfall trend.

In order to link the historical and future rainfall trend plots, GPCC was added to the plot, which gave approximately better match with the future projection plots, to come up with a continuous rainfall trend that can be classified as a decreasing trend between 1990 – 2020 and a no change trend between 2020 – 2060. The rainfall over the complete 70 years can be considered to follow a decreasing trend.

3.2.4 Upper Main Nile

For the Upper Main Nile, the rainfall trends are plotted in Figure 3. 9 below. High differences between the rainfall trends of the different products can be noticed especially when looking at the historical rainfall plots. GPCC showed higher change of rainfall over time with a decreasing trend, compared to CHIRPS that presented an approximately no change trend. On the other hand, SSP585 projected higher rainfall than SSP245 especially during the last 10 years. It can also be noticed that there is a gap between the historical and future rainfall trend plots when considering CHIRPS (recorded higher rainfall than the GCMs). Thus, GPCC can be considered to be linked with the GCMs in order to assess the complete historical and projected rainfall trend. In general, the Upper Main Nile has shown a decreasing rainfall trend with a fast rate during 1990 – 2020, followed by a slightly increasing rainfall trend in the future (2020 – 2060). The rainfall over the complete 70 years can be considered to follow a decreasing trend.

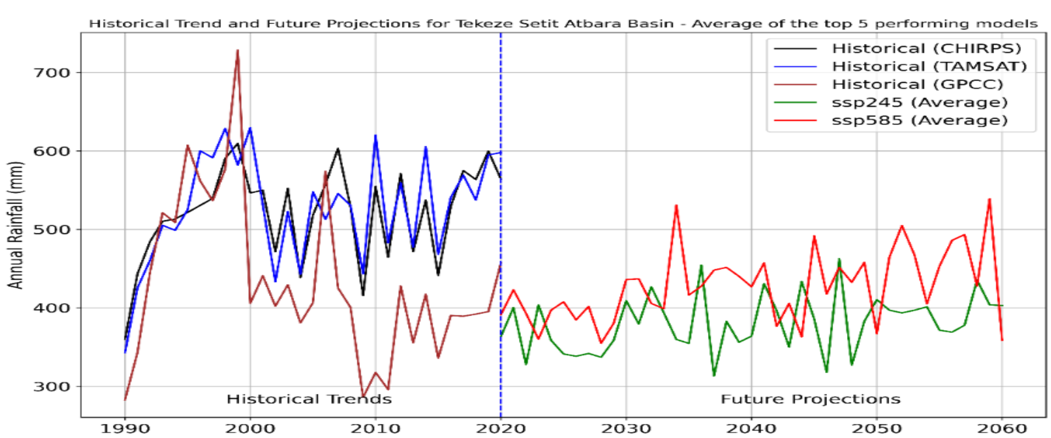

Figure 3. 8 Rainfall trend - Tekeze-Setit-Atbara

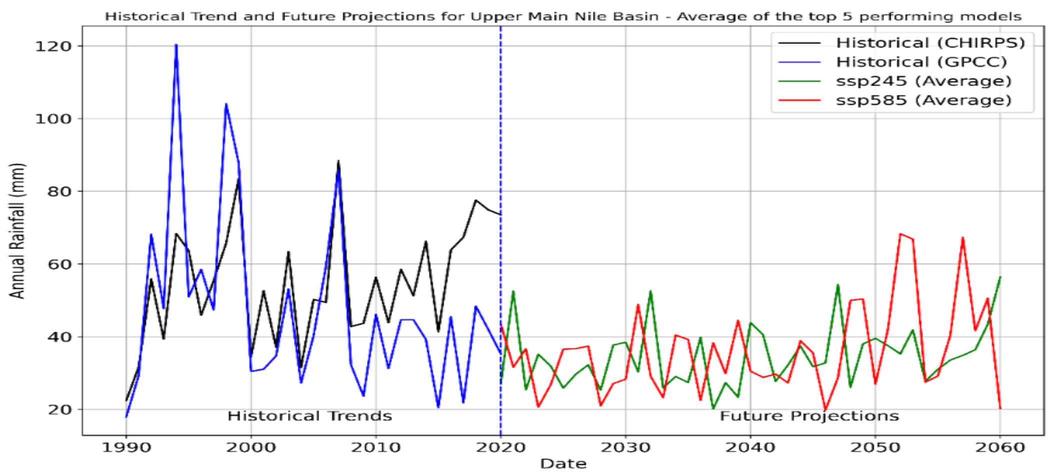

Figure 3. 9 Rainfall trend - Upper Main Nile

3.2.5 Lower Main Nile

The rainfall trend for the Lower Main Nile is shown in Figure 3. 10 below. It can be noticed that the GCMs have estimated much higher rainfall for the future compared to the satellites' historical records. This resulted in a gap between the historical and future rainfall trend plots. CHIRPS recorded higher rainfall than GPCC, and SSP245 projected higher rainfall than SSP585.

The 2 satellites are showing a no change trend in 1990 – 2020, and that is also the case for the GCMs. However, generally the rainfall of the Lower Main Nile over the complete 70 years can be considered to follow an increasing trend.

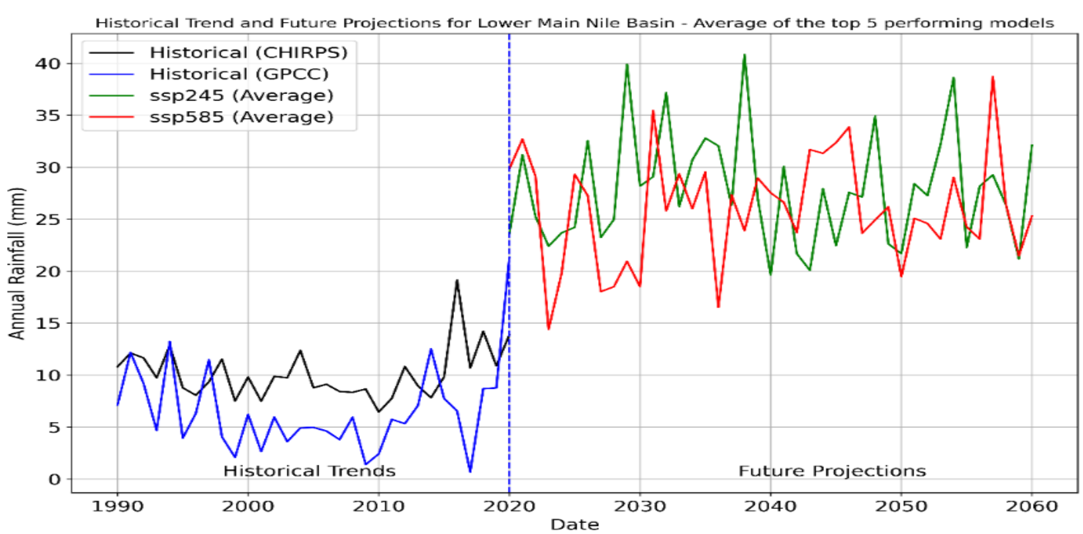

Figure 3. 10 Rainfall trend - Lower Main Nile

4 Conclusions

This report combines the results of two rainfall analysis studies which aimed to evaluate the historical trends and future projections of rainfall over the Eastern Nile Basin. The years 1990 – 2020, and the years 2020 – 2060 were considered for the historical and future rainfall analysis respectively. The historical data was acquired from number of satellites; namely, CHIRPS, ARC2, PERSIANN-CDR, TAMSAT, and GPCC. On the other hand, data from number of Global Circulation Models (GCMs) were used as projections of the future rainfall; namely, MIROC6, MPI-ESM, MRI-ESM2, and ACCESS-CM2, GFDL-ESM4, NorESM2-MM, BCC-CSM-2MR, and GFDL-CM4.

Different analysis techniques were adopted during the two studies. However, this report focused only on the results of the historical and future rainfall products performance assessment, as well as the results of the rainfall trends over the complete study period. TAMSAT outperformed the other products in Baro-Akobo-Sobat, Blue Nile, and Tekeze-Setit-Atbara, while GPCC showed the best performance in the Main Nile. On the other hand, the GCMs with the highest performance over the Eastern Nile Basin were found to be: GFDL-CM4, GFDL-ESM, MPI-ESM, NorESM2, and BCC-CSM2.

Regarding the rainfall trends, Baro-Akobo-Sobat and the Blue Nile were found to have increasing rainfall trends over the years 1990 – 2060. The other three subbasins demonstrated uncertainty in detecting the rainfall trends. Generally, Tekeze-Setit-Atbara and the Upper Main Nile have shown a decreasing rainfall trend with time, while the Lower Main Nile has shown an increasing trend.

The results of this study provide important inputs for all water resources management related sectors, and can be used by the different stakeholders, researchers, and policy makers to inform decision-making process.

5 Recommendations

The following points are recommended as continuation for this work:

- Expand the analysis to downscale the analysis and focus on smaller regions to understand the localized variations in the rainfall patterns associated with the various physical characteristics. That is expected to improve the accuracy and reliability of the rainfall products, especially the GCM CMIP6 models considering their coarse resolution.
- Further bias corrections are recommended based on the produced best-fit distributions to improve the reliability of the satellite and GCMs rainfall estimations.
- Conduct further research to assess the impacts of changing rainfall patterns on various sectors, such as agriculture, water resources, environment, and socio-economic conditions, to inform adaptation strategies.
- Explore the attribution of the observed changes in historical rainfall trends to natural variability versus human-induced climate change, using advanced statistical methods and climate models, in order to determine the most likely scenario to happen in the future.
- Encourage collaboration and data sharing among researchers, meteorological agencies, climate modelers, and policymakers within the ENB to enhance the availability and accessibility of rainfall data for research and decision-making purposes, as well as to develop more robust and reliable climate models.