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Droughts and floods over the upper catchment of the Blue Nile and their connections to the timing of El Niño and La Niña Events

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Abstract

The Blue Nile originates from Lake Tana in the Ethiopian Highland and contributes about 67 % of the discharge in the main Nile River. Previous studies investigated the relationship of sea surface temperature (SST) in the Pacific Ocean (Nino 3.4 region) to occurrence of floods and droughts in rainfall and river flow over the Nile basin. In this paper we focus on the dependence of occurrence of droughts and floods in the upper catchment of the Blue Nile on the timing of El Niño and La Niña events. Different events start in different times of the year and follow each other exhibiting different patterns and sequences. Here, we study the impact of this timing and temporal patterns on the Nile droughts and floods. We analyze discharge measurements (1965–2012) at the outlet of the upper catchment of the Blue Nile in relation to the El Niño index. When an El Niño event is followed by a La Niña event, there is a 67 % chance for occurrence of an extreme flood. The association of start dates of El Niño with occurrence of droughts in the upper catchment of the Blue Nile is evaluated. An El Niño event that starts in (April–June) is associated with a significant drought occurrence in 83 % of the cases. We propose that observations as well as global model forecasts of SST during this season could be used in seasonal forecasting of the Blue Nile flow.

1 Introduction

The Nile is the longest river in the world, with a length of 6650 km, and it flows through ten countries (Jury, 2004). The two main tributaries, the White Nile and Blue Nile, join to form the main Nile River in Khartoum, and the seasonal Atbara River joins the Nile approximately 500 km downstream. The Blue Nile originates from Lake Tana in the Ethiopian Highland, at elevations of 2000–3000 m, and contributes about 67 % to the main Nile discharge. The Upper Blue Nile River Basin is 176 000 km^2 in area (Conway, 2000). The rainfall regime follows the seasonal solar heating above the Ethiopian Plateau, and the rainy season extends approximately from June to September. The

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two main tributaries of the Blue Nile in Sudan are the Rahad and Dinder. The rainy season in Ethiopia is known locally as Kiremt (Seleshi and Zanke, 2004), and rainfall is highly variable both temporally and spatially (Gissila et al., 2004).

The Blue Nile sustains the life of millions of people in Ethiopia, Sudan and Egypt. Rainfall has a great impact on the social and economic life in the region. Scarcity of rainfall leads to drought, while excessive intense rainfall may lead to flood. For example, during the 1984 drought in Sudan, Khartoum received only 4.7 mm of rain between May and October (Eltayeb, 2003). This led to crop failure and consequently a famine hit Sudan, leading to massive migration of people in search of food and water. Floods reflect the other extreme in rainfall fluctuations. There are many factors which affect the severity of flood, such as terrain slope, soil type and amount of water in the soil. On the 4 August 1988, Khartoum received 216 mm of rainfall during a 24 h-period. This situation became disastrous when the Nile level also rose about 7 m above normal, which led to wide-spread property damage. These two natural extreme disasters were associated with significant anomalies in the Pacific sea surface temperature (SST): the El Niño (1983) and La Niña (1988) events.

During the last few decades, there has been a wide recognition that natural oscillations in the state of the Pacific Ocean have a significant impact on the patterns of weather and climate around the world (e.g. Amarasekera et al., 1997; Eltahir, 1999). The dominant among these oscillations is known as the El Niño–Southern Oscillation (ENSO) which has a return period of about 4 yr. Though distant from Africa, ENSO is significantly correlated with rainfall variations over the eastern side of the African continent, but the signs of the correlations and their phase relative to the seasonal cycle vary from region to region (Camberlin et al., 2001). Eltahir (1996) found that 25 % of the natural variability in the annual flow of the Nile is associated with El-Niño oscillations and proposed to use this observed correlation to improve the predictability of the Nile floods. Wang and Eltahir (1999) recommended an empirical methodology for medium and long-range (~6 months) forecasting of the Nile floods using ENSO information, while Amarasekera et al. (1997) showed that ENSO episodes are negatively

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correlated with the floods of the Blue Nile and Atbara rivers which originate in Ethiopia. De Putter et al. (1998) presented a study of decadal periodicities of the Nile River historical discharge of the Roda Nilometer (Cairo, Egypt) and suggested that high frequency peaks could be linked to ENSO. Abtew et al. (2009) analyzed monthly rainfall observations from a 32-rain gauge monitoring network in the Upper Blue Nile Basin and found that high rainfall is likely to occur during La Niña years and low rainfall conditions during El Niño years. He also found that extreme dry years are highly likely to occur during El Niño years and extreme wet years are highly likely to occur during La Niña years. Finally, Seleshi and Zanke (2004) reported that June to September rainfall in the Ethiopian highlands is positively correlated to the Southern Oscillation Index (SOI) and negatively correlated to the equatorial eastern pacific SST.

A number of studies attempted to use oceanic and atmospheric variables as predictors in seasonal hydrologic forecasting over East Africa (Mutai et al.1998; Hastenrath et al., 2004; Philippon et al., 2002; Yeshanew and Jury 2007; Mwale and Gan, 2005; Williams and Funk, 2010, 2011), however no study focused on the June to September rainfall in Ethiopia. In this study, we analyze river flow and rainfall observations with the goal of evaluating the impact of El Niño on drought and flood conditions in the upper catchment of the Blue Nile. Not all El Niño and La Niña events are the same (see Fig. 1), they have different timing and character. In fact, different events start in different times of the year and their sequence exhibits different impacts. In this paper we focus on the dependence of occurrence of droughts and floods in the upper catchment of the Blue Nile on the timing and sequence of El Niño and La Niña events. In particular, we attempt to identify the sequence of Pacific Ocean seasonal SST conditions that most affect drought and flood conditions over Ethiopia in order to provide recommendations for possible use as input to seasonal water resources forecasting systems. This would have great economic and social value for the management of water resources in the region.

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2 Data and methods

2.1 Observation data

Discharge measurements between 1965 and 2012 from Eldiem station (Fig. 2) located at the border between Sudan and Ethiopia about 120 km upstream from Elrosieres dam (Fig. 2) are used in this study. The gauge station measures water level and discharge at the outlet of the upper catchment of the Blue Nile. The data at Eldiem station from 1997 to 2001 were missing, and these missing data points were filled by using the nearest station to Eldiem, Rosieres, noting that there are no contributing tributaries between the two stations. The discharge data represents the catchment hydrology better than the rainfall data from scattered set of stations. In fact, Duethmann et al. (2012) concluded that the rainfall data has a relatively large uncertainty due to errors in measurement, wind, and high spatial variability of precipitation in the mountainous regions. The density of rain gauges networks is often low, and the gauges are often unequally distributed.

For this reason, we use multiple precipitation datasets: the global dataset of monthly precipitation from the Global Precipitation Climatology Project (GPCP) version 2.2 (Huffman et al., 2011), which is a satellite/gauged-merged rainfall product available from January 1979 to December 2010 with a resolution of 2.5°; The Climate Research Unit (CRU, land only) 0.5°×0.5° resolution monthly precipitation dataset (Mitchell et al., 2004), which is a purely gridded gauge product; and the University of Delaware (UDEL) monthly global gridded high resolution station (land) data (0.5°×0.5° resolution) available from 1900–2010 (http://www.esrl.noaa.gov/psd/).

In order to identify El Niño conditions, the Nino 3.4 index between 1965 and 2011 was downloaded from the NOAA website (http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ensoyears.shtml). An El Niño event is identified if the 5 month running mean of SST anomalies in the Niño 3.4 region (5° N–5° S, 120°–170° W) exceeds 0.4 °C for 6 months or longer (Trenberth, 1997). The data from the

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Niño 3.4 region was preliminarily analyzed in relation to several precipitation observational datasets.

3 Results and discussion

3.1 Relation of Pacific SST and discharge at Eldiem station

Figure 3 shows the discharge at the Eldiem station and its association with El Niño and La Niña years, with the upper panels zooming on two specific sets of episodes. As can be seen from these figures, El Niño years such as 1972 and 1987 are associated with low discharge, while La Niña years, for example 1988, are associated with relatively high discharge. This result is more clearly and quantitatively depicted in Fig. 4, which shows the monthly precipitation (June-July-August-September) averaged over all El Niño, La Niña and normal years. This confirms the results of previous studies that El Niño is mostly associated with below average rainfall, and La Niña with above average rainfall (Eltahir, 1996; Wang and Eltahir, 1999; Amarasekera et al., 1997; De Putter et al., 1998; Camberlin et al., 2001; Abtew et al., 2009).

The JJAS discharge anomalies for the full analysis period are shown in Fig. 5, along withsome thresholds: any discharge anomaly above 6.813 km^3, 1× standard deviation, is considered as extreme flood and any discharge anomaly below –6.971 km^3 as a extreme drought; any discharge anomaly between 3.486 km^3 (0.5× standard deviation) and 6.971 m^3 is considered as flood conditions, and any discharge anomaly between – 3.486 km^3 and – 6.971 km^3 as a drought. Finally, any discharge anomaly between – 3.486 km^3 and 3.486 km^3 is considered as normal. The normal events cover about 38 % of the total number of years, while the number drought and flood events contribute another 30 %, and extreme drought and flood contribute some 32 %. This classification is in line with observed floods and droughts in this region, and in line with the classification of the Ministry of Water Resources and Electricity of Sudan. In Fig. 5, nine extreme flood years can be identified, and among them there are three at or close to

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record floods (1988, 2006 and 2007). There are nine cases of extreme drought conditions, five of flood, and seven of drought.

Figure 6 shows examples of the relation between SST anomalies in the Nino3.4 region in different seasons and JJAS discharge anomalies at Eldiem station. A negative correlation between the Nino3.4 SST anomalies in April-May-June (AMJ) and the JJAS discharge anomalies at Eldiem is evident in the middle panel of Fig. 6. For example the large El Niño of 1987 is associated with below average discharge and the La Niña of 1988 is clearly associated with above average discharge.

This relation is less evident in the case of JFM (upper panel) and, to a lesser extent, JAS (lower panel) SST anomalies. The same plot was made with SST anomalies for other seasons; FMA, MAM, MJJ and JJA (not shown here), and FMA and MAM also showed lower correlations compared to the MJJ and JJA anomalies. Figure 6 thus illustrates that the rainfall in the upper Nile River catchment is highly sensitive to the SST during AMJ.

The impact of the start date of El Niño on the drought of the upper catchment of the Blue Nile is further illustrated in Table 1. The first column in Table 1 shows the starting season of El Niño, the second and third columns then indicate whether there was an extreme drought or drought episode during the same year (JJAS) over the upper catchment of the Nile, while the fourth column shows whether there was no drought. The flow year column shows the start year of each El Niño event, while the length column refers to the duration of the El Niño episode expressed in number of months.

Table 1 shows that for the six episodes in which El Niño started in AMJ, four times an extreme drought occurred, and one time drought conditions prevailed, with only one year having normal conditions. When El Niño started in JJA, there were two droughts out of two events. More mixed results are found when El Niño starts in JAS (cases of both drought and no drought equally distributed). Finally, when El Niño starts late in ASO, it tends to be relatively short, and for the years available there is no drought event (in the same year) for four times (while there were one case of flood and one of extreme flood).The results of Table 1 thus suggest that there is a relation between El

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Niños starting in AMJ and drought conditions in Ethiopia, while no effect is found when El Niños start late in the year in ASO.

La Niña is normally associated with floods in the upper catchment of the Blue Nile (Eltahir, 1996; Wang and Eltahir, 1999; Amarasekera et al., 1997). In Table 2 the role of the start date of the La Niña season is explored in terms of its relation with flood conditions in the upper catchment of the Blue Nile (in the same year). The first column in Table 2 shows the season of the start of La Niña, and from Table 2 it is clear that La Niña events can last for up to three years, as in 1973–1975 and 1998–2000.

When La Niña started in AMJ of 1988, there was one extreme flood (in the same year), when it started in AMJ of 1973 and extended for 3 yr, there was no flood (in the same year), and one flood and one extreme flood in the following years. When La Niña started in JJA, there was no flood in 1970 and there were extreme flood conditions in 1998 and 2010. When La Niñ a started in JAS of 2007, there was an extreme flood. When La Niña started late in ASO, there were no floods recorded, and in one case (2011) there was even a strong drought. Therefore, in general, when La Niña started in AMJ, JJA and JAS, 67 % of the times there was a flood or extreme flood, showing that the rainfall and the monsoon in this catchment is sensitive to AMJ, JJA and JAS SST in the Pacific Ocean.

As mentioned in the introduction, in this paper we also explore the importance of the sequence of El Niño followed by La Niña in relation to flood conditions in the Upper Nile catchment. In the last 40 yr when El Niño was immediately followed by La Niña conditions there were extreme flood records in the upper catchment of the Blue Nile in 1988, 1998, 2007 and 2010, i.e. 67 % of the cases of extreme flood (Table 3). The minus sign in Table 3 represents the end of the El Niño period, and the positive sign represents the start of La Niña. If we look at the period from the 1980s to present, it can be concluded that when El Niño is followed by La Nina, in the four recent sequential events there was extreme flood in the Blue Nile. In this analysis we excluded the events of 1983 and 1995, because La Niña started late in ASO. From the previous analysis in Table 2 and

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Table 1, it is evident that when El Niño or La Niña starts late in the year, it does not impact rainfall in the Upper Nile catchment.

The following example illustrates the added value of knowing the timing of El Niño and La Niña for predicting extreme floods. In the 48 yr of analysis (1965–2012) there were 9 extreme floods, so the chance of having an extreme flood in any year during this period was 19 %. If however we have additional knowledge about the occurrence of a La Niña year, this possibility of an extreme flood increases. In fact, during this period we have 14 La Niña years, and among them 6 extreme floods were observed. As shown in Table 3, when El Niño is followed by a La Niña year (with La Niña not starting late in ASO or ending early in MAM) the chance of getting and extreme flood increased to 67.

3.2 Relation of Pacific SST and observed precipitation in the upper catchment Nile River basin

In the previous sections we evaluated the relations between Nino 3.4 SST anomalies and discharge at the upper catchment of the Blue Nile. We now turn our attention to the relation between SST anomalies and precipitation. Figure 7 shows the JJAS rainfall anomalies over the upper catchment of the Blue Nile from 1982 to 2008 along with the discharge anomalies at Eldiem station. A good correlation between GPCP, CRU, UDEL and discharge anomalies is found, although the extreme discharge floods in 1988, 2006, 2007 and 2008 appear underestimated in the all rainfall data. This indicates that the GPCP, CRU and UDEL datasets are generally representative of the precipitation variability over the region.

Figure 8 shows the correlation between GPCP, CRU and UDEL precipitation anomalies over the Ethiopian highland and the Eldiem discharge with the Nino 3.4 SST anomalies for the entire analysis period and for different seasons. The corresponding 2-tailed *t* test values are then reported in Fig. 9, which also gives the threshold for statistical significance at the 95 % confidence level.

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We find a negative correlation in all seasons, indicating that a positive (negative) SST anomaly, i.e. El Niño (La Niña) conditions, tends to lead to drought (flood) conditions. The correlations are maximum in magnitude in the AMJ through ASO seasons, i.e. the late spring late summer period, and tend to decrease in the earlier and later seasons. Also, the correlations are higher for precipitation than for discharge except for the CRU dataset during summer, and they show a different seasonal peak (MJJ for GPCP, AMJ for CRU and JJA for UDEL and discharge). Figure 9 shows that for all these seasons the correlations are significant at the 95 % confidence level, with higher significance for precipitation. These figures thus confirm the strong effect of El Niño anomalies on the hydrology of the Ethiopia highlands which feed the Nile River.

4 Conclusions

Rainfall has a great impact on the social and economic life in the Ethiopian region and upper Nile catchment. Scarcity in rainfall leads to drought while excessive, intense rainfall may lead to flood. Ethiopian rainfall is highly variable, both temporally and spatially, and the rainfall seasonality varies greatly from one region to another (Gissila et al., 2004). The Blue Nile contributes about 67 % of the main Nile discharge.

Compared to previous studies, our analysis focuses on and highlights the impact of timing and sequence of El Niño and La Niña on the drought and flood conditions over the upper catchment of the Blue Nile. This paper also highlights the role of Pacific SST anomalies in shaping the potential predictability of rainfall over tropical East Africa in both observational discharge at the mouth of the upper catchment of the Blue Nile and different observed precipitation datasets.

We find that that ENSO exerts a significant influence to the upper catchment of the Blue Nile. Droughts in the Blue Nile are sensitive to the timing of El Niño, with 80 % of drought cases when El Niño starts in AMJ, JJA and JAS. When El Niño starts in AMJ, 83 % of the cases resulted in drought. When El Niño ends early (DJF, JFM, FMA and MAM), there is almost no effect on the drought in the Blue Nile. When El Niño

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terminates late in MJJ (or after that) there is a high possibility of drought occurrence in the Blue Nile. When El Niño starts late in ASO (or after that) there is also no impact on the Blue Nile drought.

When La Niña started in AMJ, JJA and JAS, in 67 % of the cases there was a flood or extreme flood. There has to be an active event El Niño/La Niña during the season for development of the monsoon over Ethiopia (May to September), for this teleconnection to have an impact. We also find that in 67 % of the cases in which El Niño was followed by La Niña there were extreme floods in the Blue Nile.

An important conclusion is that JJAS rainfall in the upper catchment of the Blue Nile is highly sensitive to the NINO 3.4 SST anomaly during the early season of AMJ in Nino 3.4. This season is recommended by this study to be used in the seasonal forecasting of the Blue Nile. We also find that El Niño being immediately followed by La Niña conditions is conducive of extreme flood conditions in the upper Nile catchment, information that may also be useful in forecasting extreme floods over the region.

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Table 1. The effect of the start date of El Niño on the drought of the upper catchment of the Blue Nile during JJAS of the same year.

Start of El Niño	Extreme drought	Drought	No drought	Flow year	Length
AMJ (1965)	✓			1965	12
AMJ (1972)	✓			1972	11
AMJ (1982)	✓			1982	14
AMJ (1991)			✓	1991	14
AMJ (1997)	✓			1997	12
AMJ (2002)		✓		2002	10
JJA (2004)		✓		2004	7
JJA (2009)		✓		2009	10
JAS (1968)			✓	1968	18
			✓	1969	
JAS (1986)	✓			1986	19
	✓			1987	
ASO (1976)			✓	1976	6
ASO (1977)			✓	1977	6
ASO (1994)			✓	1994	7
ASO (2006)			✓	2006	5

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Table 2. The effect of the start of La Niña in the flood of the upper catchment of the Blue Nile.

Start of La Niña	Extreme flood	Flood	No flood	Flow year	Length
AMJ (1973)			√	1973	36
		√		1974	
	√			1975	
AMJ (1988)	√			1988	13
JJA (1970)			√	1970	18
			√	1971	
JJA (1998)	√			1998	33
			√	1999	
			√	2000	
JJA (2010)	√			2010	10
JAS (2007)	√			2007	11
	√			2008	
ASO (1983)			√	1983	5
ASO (1995)			√	1995	7
ASO (2011)			√	2011	7

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Table 3. El Niño followed by La Niña and extreme flood.

Year	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS	ASO	Remark
1970	–						+			Normal (above average)
1973			–		+					Normal
1988		–			+					Extreme flood
1998				–			+			Extreme flood
2007	–							+		Extreme flood
2010				–			+			Extreme flood

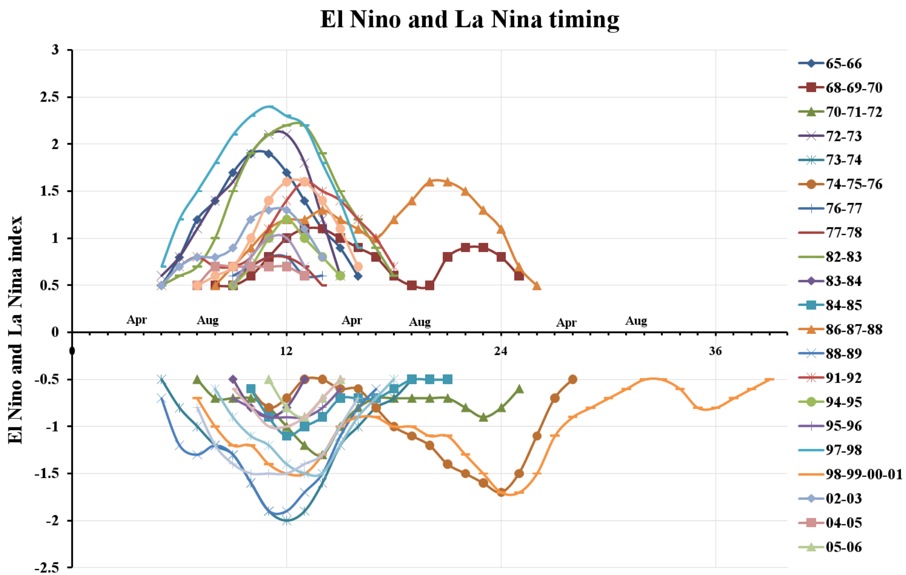

Fig. 1. El Niño and La Niña timing.

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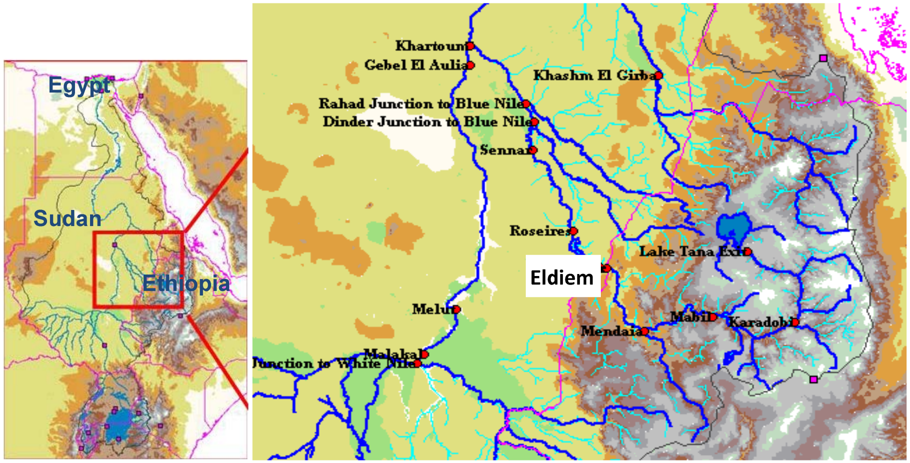

Fig. 2. The topography and geography of cities in the region.

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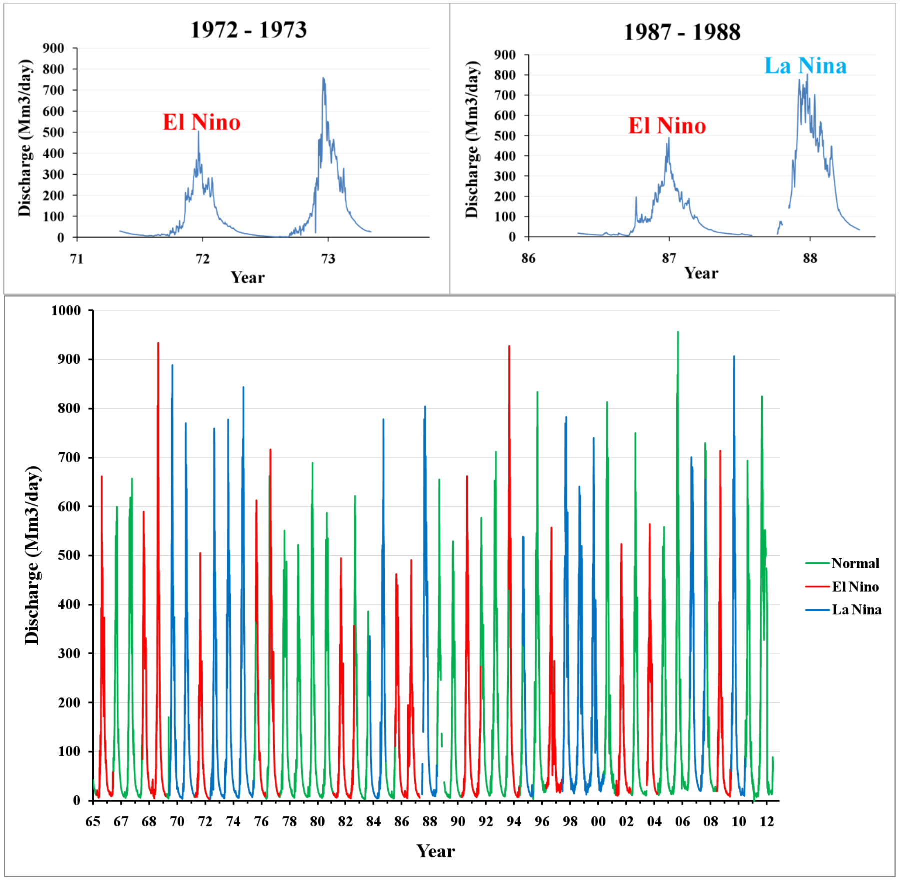

Fig. 3. The discharge of the Blue Nile at Eldiem station (1965–2012) and its association with El Niño and La Niña years in the lower panel, the red colour represents El Niño event periods, and Blue colour represents La Niña event periods, and the green colour normal event periods. The upper panel is a zoom on some El Niño and La Niña years.

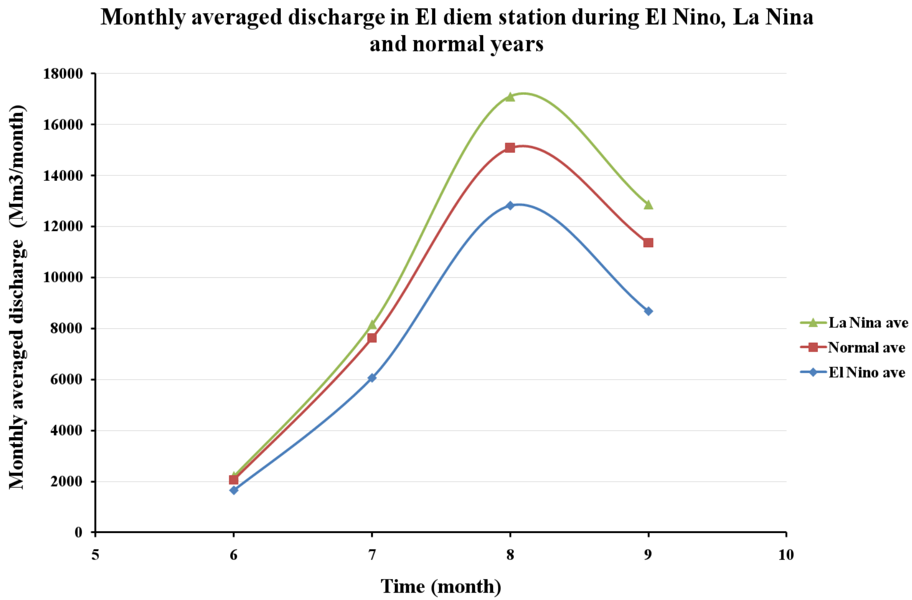

Fig. 4. Monthly discharge at Eldiem station averaged during El Niño (1965, 1986, 1969, 1972, 1982, 1983, 1986, 1987, 1991, 1992, 1995, 1997, 2002, 2994 and 2009), La Niña (1970, 1971, 1973, 1974, 1975, 1985, 1988, 1989, 1998, 1999, 2000, 2007, 2008 and 2010) and normal years (1966, 1967, 1976, 1977, 1978, 1979, 1980, 1981, 1984, 1990, 1993, 1994, 1996, 2001, 2003, 2005, 2006, 2011 and 2012).

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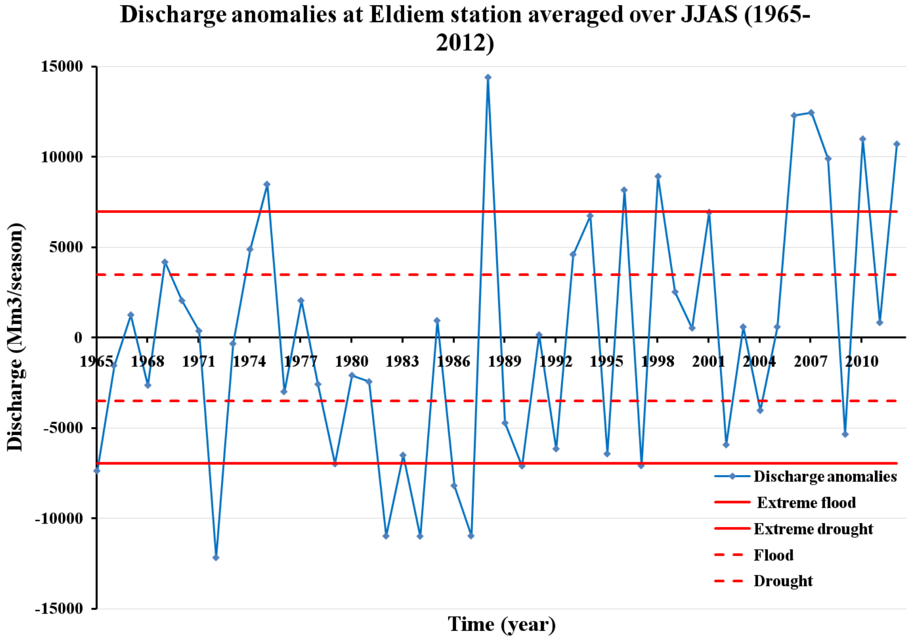

Fig. 5. The discharge anomalies at Eldiem station averaged over JJAS (1965–2012), the red line represent the threshold for the extreme flood/drought, and the dashed red line represents the threshold for drought/flood.

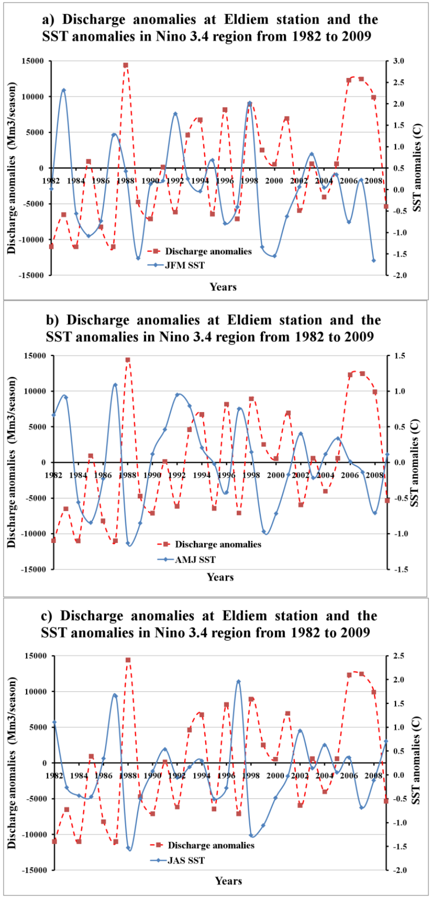

Fig. 6. The SST anomalies during **(a)** JFM, **(b)** AMJ, and **(c)** JAS in Nino 3.4 region and the discharge anomalies in Eldiem station.

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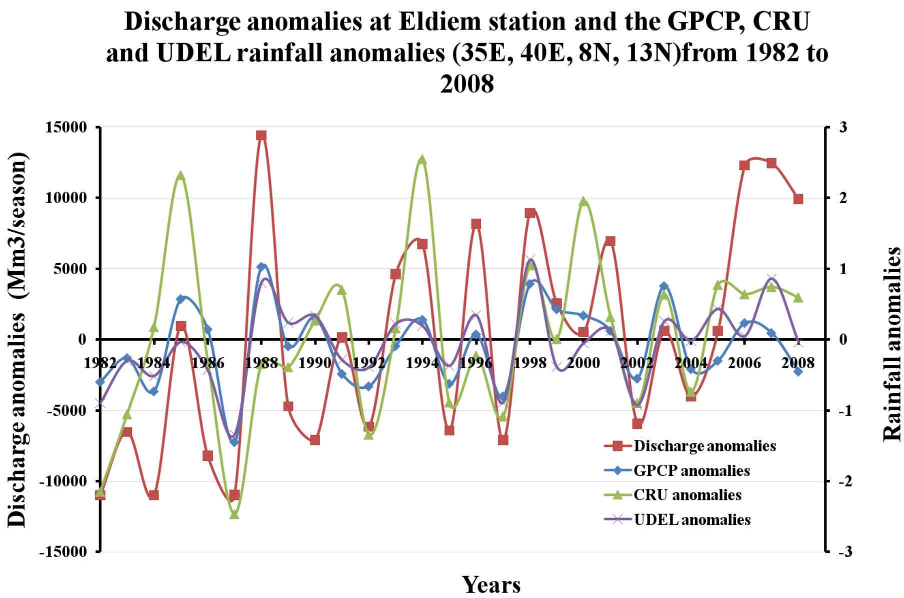

Fig. 7. Rainfall and discharge anomalies over Ethiopian Highlands during JJAS.

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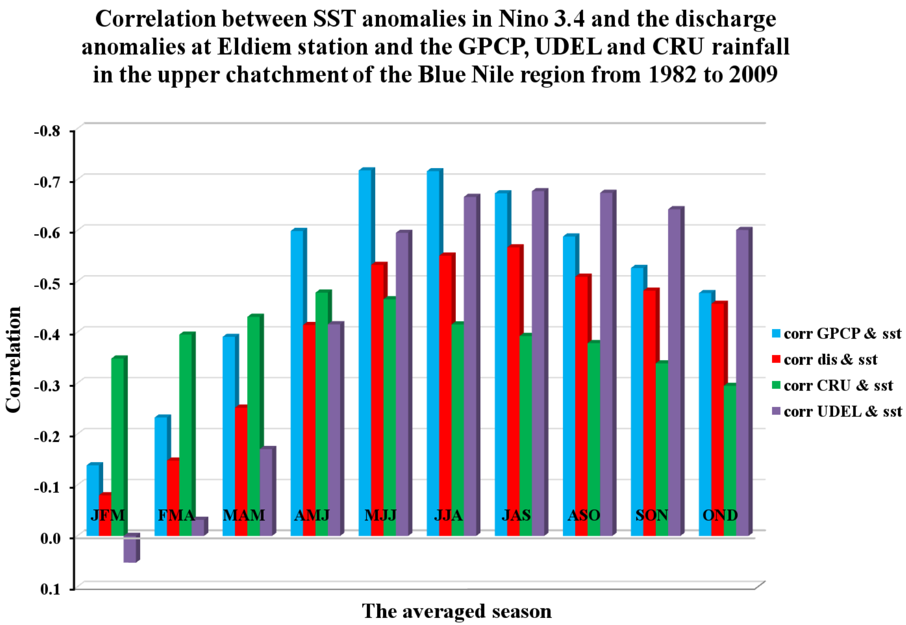

Fig. 8. Correlation between SST anomalies in Nino 3.4 region and the upper catchment of the Blue Nile in Ethiopian Highlands from 1982 to 2009.

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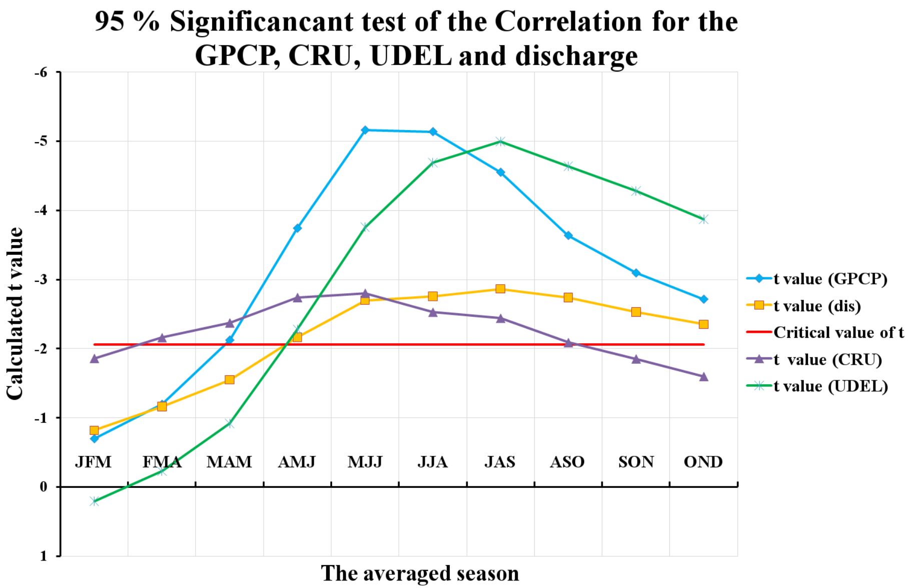

Fig. 9. 95 % significance test of the correlation for the GPCP, CRU, UDEL and discharge.