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Potential predictability of the Ethiopian summer rains: Understanding local variations and their implications for water management decisions

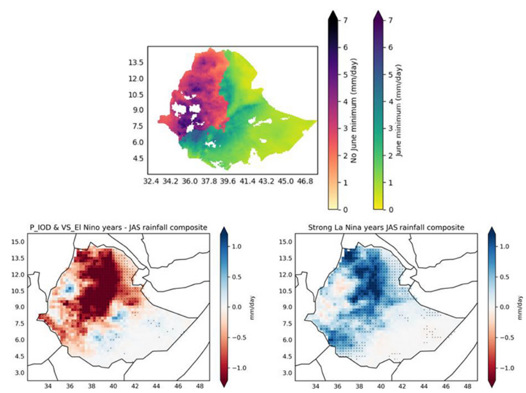
Meron Teferi Taye [a,*], Ellen Dyer [b], Katrina J. Charles [b], Linda C. Hirons [c]

[a] *International Water Management Institute, East Africa and Nile Basin Office, Addis Ababa, Ethiopia*
[b] *School of Geography and the Environment, University of Oxford, Oxford, United Kingdom*
[c] *National Centre of Atmospheric Science (NCAS), University of Reading, Reading, United Kingdom*

HIGHLIGHTS

- Ethiopia has complex climate conditions that make it difficult to apply forecasts at appropriate scales for water management decisions.
- National and sub-national correlation and composite analyses between rainfall in Ethiopia and equatorial SSTs were performed.
- The analysis identifies spatial variability of relationships, and interactions, that offer additional information to support development of seasonal forecasting.
- For water managers in Ethiopia, extreme conditions in different zones simultaneously are uncommon, with different drivers, offering up opportunities for adaptation based on early forecasts.

GRAPHICAL ABSTRACT



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ABSTRACT

Understanding the influence of large-scale oceanic and atmospheric variability on rainfall over Ethiopia has huge potential to improve seasonal forecasting and inform crucial water management decisions at local levels, where data is available at appropriate scales for decision makers. In this study, drivers of Ethiopia's main rainy season, July–September (JAS), are investigated using correlation analysis with sea surface temperature (SST). The analysis showed local spatial variations in the drivers of JAS rainfall. Moreover, the analysis revealed strong correlation between March to May (MAM) SST and JAS rainfall in particular regions. In addition to the influence of SSTs, we highlighted one of the mechanisms explaining the regional pattern of SST influence on Ethiopian rainfall, the East African Low-Level Jet. Moreover, examining the occurrence of large-scale phenomena provided additional information, with very strong ENSO and positive IOD events associated with drier conditions in most part of Ethiopia. A sub-national analysis, focused at a scale relevant for water managers, on the Awash basin, highlighted two distinct climate zones with different relationships to SSTs. June was not included as part of the rainy season as in some areas June is a hot, dry month between rainy seasons and in others it can be used to update sub-seasonal forecasts with lead time of one month for JAS rainfall. This highlights the importance of understanding locally relevant climate systems and ensuing sub-seasonal to seasonal forecasts are done at the appropriate scale for water management in the complex topography and climatology of Ethiopia.

* Corresponding author.
E-mail address: meron.taye@cgiar.org (M.T. Taye).

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1. Introduction

Ethiopia is known for its complex topography that is characterized by various climate types ranging from humid climate covering the Ethiopian highlands to the west of the Rift Valley, to arid climate zones to the east of the Rift Valley where lowlands and semi-deserts are located (Viste et al., 2013; Berhanu et al., 2014). These climate variations impact water resources management and use throughout the country and affect water availability situation of various sectors. In addition to the various climate zones, the interannual variability of rainfall in Ethiopia is high (Viste et al., 2013; Zhang et al., 2016; Nicholson, 2016). In a country with over 100 Million people (CIA, 2019), that is experiencing growing urbanization (CSA, 2013), industrialization, and more extreme climate events (e.g. Li et al., 2016b; Mera, 2018), understanding the large-scale atmospheric and oceanic processes that control interannual rainfall variability is crucial to managing the limited water resources efficiently and equitably among different users (Zhang et al., 2016).

The annual cycle of rainfall in Ethiopia can be characterized by three main seasons: June to September (known locally as Kiremt, which is the main rainy season), February/March to May (known locally as Belg, second rainy season), and the dry season October to January (known locally as Bega). Most previous studies on the link between large-scale atmospheric/oceanic phenomena and Ethiopian rainfall have focused on the June to September (JJAS) rainfall (e.g., Korecha and Barnston, 2007; Block and Rajagopalan, 2007; Segele et al., 2009), while fewer have focused on the February/March to May rainfall (e.g. Eden et al., 2014). In almost all cases the influence of Pacific Ocean sea surface temperatures (SST), in the form of the El Nino Southern Oscillation (ENSO), have been established with El Nino events associated with decrease in rainfall (Gissila et al., 2004; Diro et al., 2011a; Nicholson, 2014; Berhane et al., 2014). However, it is noted that the local influence of this phenomena varies spatially across the country. For example, Gissila et al., 2004 found forecasts of JJAS rainfall over central western Ethiopia using a linear regression model of Pacific and Indian Ocean SST anomalies in the preceding March, April and May can outperform climatology or persistence. Diro et al., 2011a performed similar analysis which showed that, as well as the equatorial Pacific, the midlatitude northwest Pacific and Gulf of Guinea also influence JJAS rainfall over Ethiopia. They noted the relative strength of these influences exhibited variations in different parts of the country and emphasized the need to explore local variations when using the relations for seasonal forecasting purposes. Hence, there is a knowledge gap in previous studies in the aspect of identifying which local areas are linked to which influencers/teleconnections and their relevance for specific sectors such as local water management issues. For instance, local water management decisions based on larger national or basin-wide precipitation cycles might provide misleading interventions due to the complexity of Ethiopian climate. Therefore, choosing the relevant season for a specific region guided by water management applications and understanding the link with different teleconnections would be more relevant, the knowledge gap this research attempts to address in the context of sub-national scale.

To explore the impact of large-scale SST drivers on the spatial variability of seasonal rainfall at local scale, the analysis of the current study focuses on the Awash river basin in Ethiopia. The river basin, strategically highly relevant for Ethiopia, hosts a variety of different types of water users, complex hydro-climatological conditions, and a complicated water governance situation (Mosello et al., 2015), which makes it an interesting case study in the context of rainfall variability and water management applications. The basin experiences the devastating impacts of climate extremes (Taye et al., 2018), including drought in the 2015/16 El Nino event, followed by high rainfall and flooding in 2017 in different parts of the basin (UN Office for the Coordination of Humanitarian Affairs (OCHA), 2016; UN Office for the Coordination of Humanitarian Affairs (OCHA), 2017). These events could have been more readily managed with robust, actionable weather and climate information on seasonal and sub-seasonal timescales. It is, therefore, important to understand the drivers of sub-seasonal to seasonal variability of the basin's rainfall to improve water management and resilience to climate extremes.

This paper builds on existing understanding of the large-scale drivers of JJAS rainfall in Ethiopia by exploring the national and sub-national variability within the Awash river basin. Such an approach is required in order to explore if applying our understanding of the potential predictability of these drivers is able to improve practical planning and decision-making at local scales. If regional scale information can be shown to be reliable, it highlights the potential of sub-seasonal to seasonal forecasts in facilitating planning for climate and weather-related extremes that may vary over the management area. For instance, for water managers at sub-basin scale to adapt to potential local drought or flood situations. With this in mind, this study will aim to answer the following questions:

- How does the influence of large-scale drivers of Ethiopian summer rainfall vary locally at regional and sub-regional scales?
- Is the relationship between large-scale drivers and local rainfall evident ahead of the start of the summer season?
- How can potential predictability help inform local water management decisions?

The outline of the paper in the following sections start with describing the Awash river basin for the sub-national case study (Section 2.1), followed by observational datasets used in the analysis (Section 2.2). The methods used to establish links between rainfall and large-scale drivers are described in Sections 2.3 to 2.6. Results are presented in Section 3 with details of the national and sub-national scale analysis. Discussion of results in comparison with previous studies and implications for water resources management are given in Section 4. The last section provides conclusions.

2. Material and methods

2.1. A subnational case study: The Awash River basin

The Awash River drains the central and eastern highlands of Ethiopia and is part of the great east African Rift Valley (Fig. 1). Over an area of 110,000 km^2, the basin slopes from 3000 m above sea level (masl) to 250 masl in the lower reaches (Fig. 2a), with climate zones varying from humid highlands to arid lowlands. The Awash basin is of strategic importance to Ethiopia's national economy, accounting for an estimated 30% of GDP (Borgomeo et al., 2018), with major cities, such as the capital Addis Ababa, growing industries and large-scale irrigated farms relying on the Awash river and associated groundwater (Fig. 2d). Many people living in the basin are highly reliant on rainfall for their livelihoods, such as small-scale farming and pastoralism. Water management is overseen by the Awash Basin Development Office, who divide the basin into three operation areas - upper, middle, and lower basins - based on climatological, physical, socio-economic, agricultural, and water resources characteristics (Edossa et al., 2010). Their activities, identified through engagement with members of the Awash Basin Development Office and Ministry of Water, Irrigation and Electricity (MOWIE) since 2015, include water allocation planning and flood management for which climate information at sub-seasonal to seasonal scales are highly relevant.

One of the distinct features of the basin from a climate perspective is, unlike other highland parts of the country (e.g. western Ethiopia), the two seasons March to May (MAM) and June to September (JJAS) are separated by a dry June month for most part of the basin (Fig. 2b). Therefore, in our analysis we focus on MAM and JAS seasons. This focus on the JAS season makes our study different from previous studies (Gissila et al., 2004; Diro et al., 2011a; Nicholson, 2014; Berhane et al., 2014) on the influence of large-scale drivers on the main rainy season's

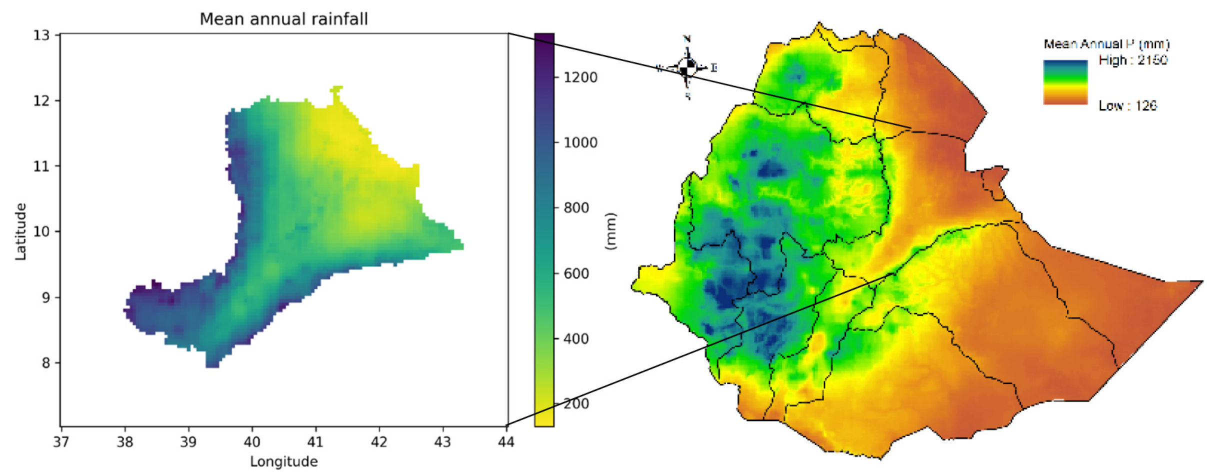

Fig. 1. Spatial rainfall distribution in the Awash basin in Ethiopia (left), as mean annual rainfall in millimeters, and in the context of Ethiopia and national rainfall distributions (right) using CHIRPS data for the period 1981–2018.

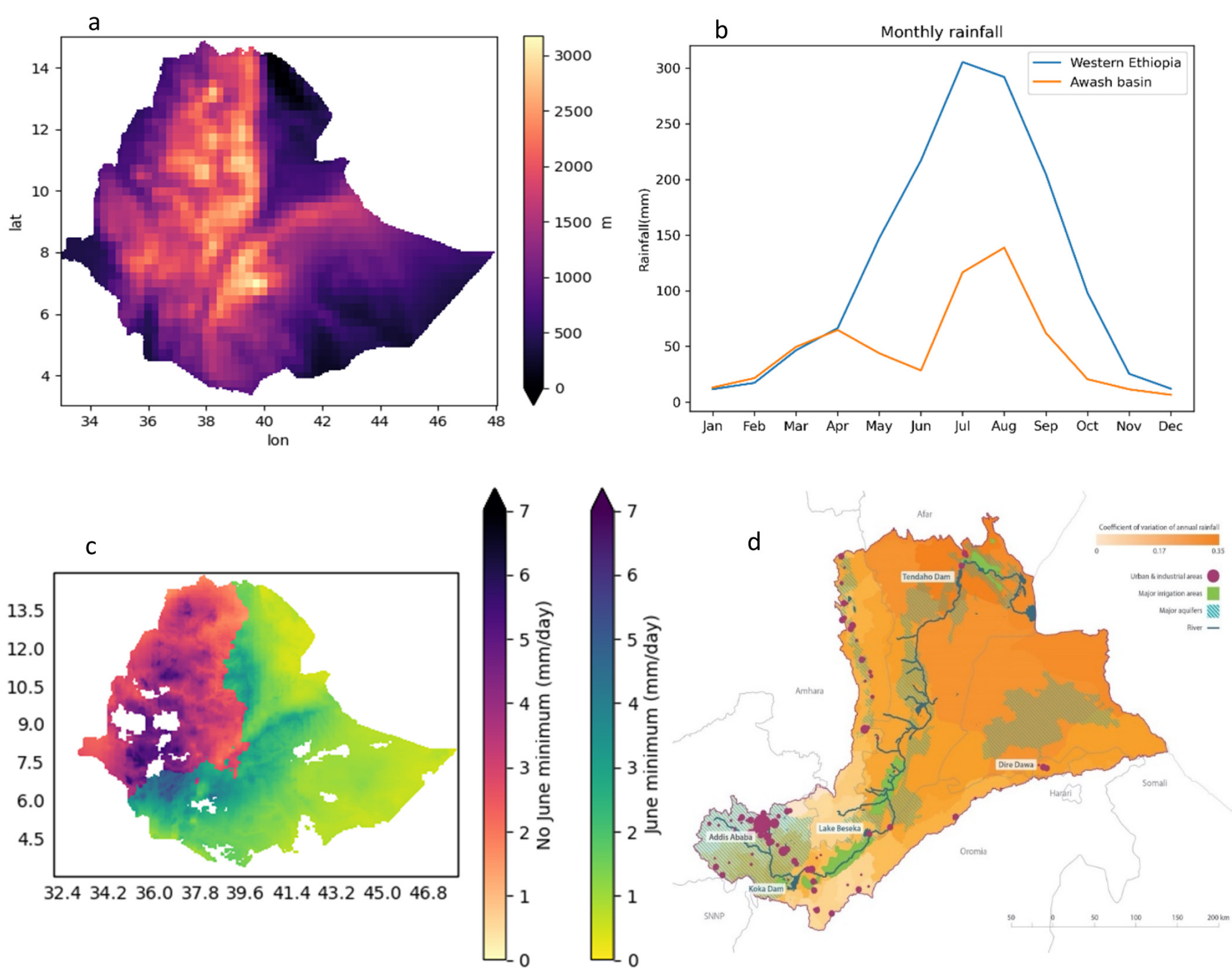

Fig. 2. Surface elevation map of Ethiopia from ERA5 reanalysis data in meters above sea level (a), Monthly rainfall averaged over the Awash basin in millimeters using CHIRPS data for the period 1981–2018 – showing the June minimum separating the two seasons in MAM and JAS (b), Annual rain rate (mm/day) averages differentiated for regions where there is a June minimum between MAM and JAS seasons (yellow-blue) and regions where the is no June minimum between MAM and JAS (orange-purple) using CHIRPS data for the period 1981–2018 (c), Awash basin map with major towns, irrigation areas, aquifers, river network and rainfall coefficient of variations (Grasham and Charles, 2020) (d).

rainfall in Ethiopia usually referred as June to September (JJAS). This June minimum rainfall is common in the East and South of the country (Fig. 2c) covering most of the lowland areas. Hence, choosing an appropriate season of study, designed to match the annual cycle of rainfall in the Awash basin, will mean results will be directly applicable to the region and more relevant for local water management decisions in a given localized area. This study will show the benefits of using an applications-guided approach such as this using the Awash basin as an example.

2.2. Observational datasets

Monthly rainfall over Ethiopia is taken from the Climate Hazards Group Infrared Precipitation with Stations v2.0 (CHIRPS). CHIRPS is a blend of satellite-based rainfall estimates and gauge data (Funk et al., 2015). CHIRPS is available at a 0.05°x 0.05° horizontal resolution from 1981 to present (http://chg. geog.ucsb.edu/data/chirps/). Monthly global sea surface temperature (SST) data are taken from the Met Office Hadley Centre at a 1° X 1° horizontal resolution from 1871 to present (HadISST; Rayner et al., 2003). Lower-tropospheric winds (850 hPa) and specific humidity fields are taken from the ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) (C3S 2017, Hersbach et al., 2020). ERA5 variables are available at 0.25° X 0.25° horizontal resolution from 1979 to present. Two atmospheric features are investigated in this study using these ERA5 fields: the southerly flow of the East African Low-Level Jet (EALLJ) and westerly moisture flux across the northern edge of Central Africa (CAF). The EALLJ is defined as averaged meridional wind from 5S—10N, and 35-55E at 850 hPa, with this regional definition previously used by Li et al. (2016a, 2016b) in a study of JJAS rainfall in Ethiopia. The CAF is defined as averaged westerly moisture flux at 850 hPa in 5-12 N and 10-30E. For consistency among datasets, the common analysis period used is 1981–2018. This study also considered indices of ENSO and the Indian Ocean Dipole (IOD). El Niño and La Niña events were defined using the Oceanic Niño Index (ONI) from NOAA (2019) https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. The ONI values are obtained by calculating 3-monthly mean SST anomalies for the Nino 3.4 region. Anomalous values of 0.5 up to 1, 1 to 1.5, 1.5 to 2.0, and above 2.0 correspond to weak, moderate, strong, and very strong El Niño intensities, respectively. Similarly, for La Niña −0.5 to −1.0 is weak, −1.0 to −1.5 is moderate, and less than −1.5 is strong La Niña. Events with 5 consecutive overlapping 3-monthly periods of above or below these threshold values defines the intensities. For the IOD events the Australian Government Bureau of Meteorology listed 11 negative IOD and 10 positive IOD events since 1960, when reliable records of the IOD began, to 2016. We have used the years since 1981 listed in their website at http://www.bom.gov.au/climate/iod/. The months used to define IOD events are from May to October (Australian Government Bureau of Meteorology, 2019).

2.3. Correlation analysis

To identify the drivers of rainfall we have explored the long-term and spatial scale of rainfall over Ethiopia through correlation analysis with SSTs and a selection of atmospheric drivers using 850 hPa winds and moisture flux. This includes a combination of global and regional-scale influences. It is well known that slowly varying processes, such as changes in SST, effect the large-scale atmospheric circulations, and can provide predictability on seasonal timescales (Funk, 2019). It is important to note that the monthly rainfall averaged over Ethiopia, and specifically also over the Awash basin, have no increasing or decreasing trend for the common period of analysis 1981–2018 (Figures given in supplement material, S1 & S2), therefore the data was used directly without the need of detrending for the correlation analysis. Correlation analysis of the JAS Ethiopian rainfall with JAS global SST, MAM global SST, and June global SST was performed to identify different modes of variability and how they influence predictability of rainfall in the main rainy season (JAS). Due to the nature of the local annual cycle of rainfall over the Awash basin (Fig. 2b), June is separated from the commonly used JJAS season and analyzed as an additional predictor for the JAS season. Due to this feature of the regional annual cycle of rainfall it is likely that locally June may respond differently to large-scale drivers. However, this analysis will only investigate if there is potential predictability in the JAS rainfall based on the characteristics of large-scale environmental conditions during the preceding June.

The correlation analysis was performed with the null hypothesis assuming no correlation between rainfall and large-scale variables. Pearson's correlation analysis is used and the significance of the correlations is tested at statistical significance level of 95% or at α 0.05. This initial analysis helped us to identify regions of interest for further analysis based on the significant positive or negative correlations obtained with Ethiopian JAS rainfall (Figures provided in supplement materials, S3-S6). Fig. 3 shows the regions that emerged as significant following the correlation analysis, with all regions showing some lead time in their correlation with JAS Ethiopian rainfall. Regions in the Pacific including Nino 3.4 and Warm Pool Gradient are correlated with JAS and June SSTs. The Atlantic Ocean and the Mediterranean regions have signals in MAM season. The Indian Ocean region is selected based on Fig. S6. Correlations with the Indian Ocean are weaker for regionally averaged Ethiopian rainfall, thus two regions in the basin which were highlighted by Fig. S6 a) and b) were tested. However, one of these regions, the WIO, had stronger correlations with a seasonal lead time, and is therefore included for analysis in this study. The details of these regions from which average SSTs are calculated and the oceans they represent are provided in Table 1.

Using the selected regions' average SSTs further correlation analysis was conducted with Ethiopian JAS rainfall to understand the spatial variations across the country. Similar to the previous analysis this correlation analysis was performed with null hypothesis of no correlation

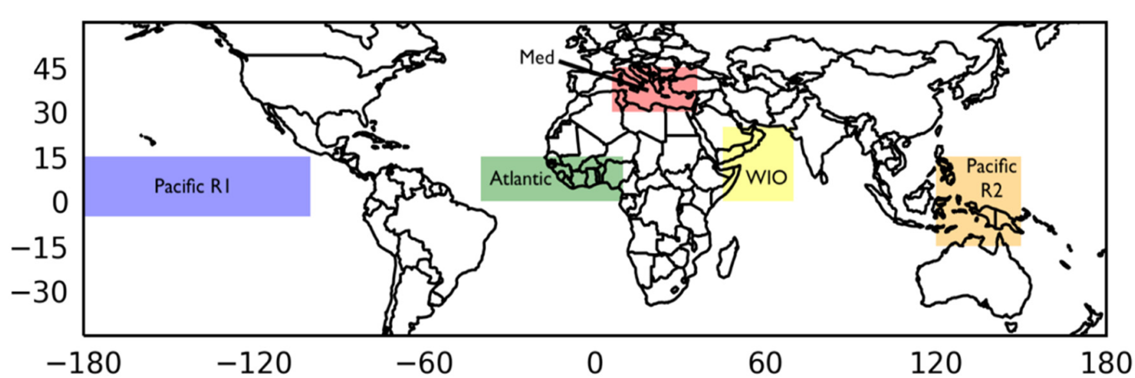

Fig. 3. Global SST regions that showed influence on Ethiopia's JAS rainfall based on correlation analysis at significance level of $\alpha = 0.05$.

Table 1
Global SST regions used in this study with their longitude and latitude bounds based on their correlations with JAS Ethiopian rainfall.

No.	Region representing	Code	Lon-Lat box
1.	Pacific region	Pac R1	5S-15N & 100 W–180 W
2.	Pacific region	Pac R2	15S-15N & 120E-150E
3.	Atlantic region	Atla	0-15 N & 10 W–60 W
4.	West Indian Ocean region	WIO	0-25 N & 45E-70E
5.	Mediterranean region	Med	30 N–45 N & 6E-36E
6.	Nino 3.4 region	Nino 3.4	5S-5N & 120 W–170 W
7.	Warm pool gradient in the Pacific	WPG	(5S—5N & 160E-150 W) – (0-15 N & 110E-150E)

between rainfall and SSTs and was tested at statistical significance level of 95% or at α 0.05. Correlation values which are statistically significant are marked with blue and red colours in the figures presented throughout this paper. Areas left with white are either not statistically significant or areas with no correlation.

2.4. Objective regionalization

Moreover, we have conducted objective regionalization of Awash's JAS rainfall based on hierarchical climate regionalization as in Badr et al. (2015) using a tool from the R statistical language (https://cran.r-project.org/web/packages/HiClimR/index.html). HiClimR is a tool for Hierarchical Climate Regionalization applicable to any correlation-based clustering to divide an area into smaller regions that are homogeneous with respect to a specified climatic metric, in this case JAS rainfall. This analysis provides additional information on which part of the basin experiences similar rainfall conditions that can be linked with the different drivers of rainfall.

2.5. Composite analysis

In addition to the correlation analysis composite analysis was conducted to understand the relationships between different phenomena. For the spatial scale JAS Ethiopian rainfall, the composite analysis was done based on ENSO and IOD years. The positive and negative events of ENSO are taken from El Niño and La Niña years and their intensities. ONI definitions of events were used to categorize El Niño events into weak, moderate, strong, and very strong. For La Niña events, the categories are weak, moderate, and strong as described in Section 2.2. In this analysis we concentrated on events from moderate to very strong. Table 2 lists these different intensity events with the years since 1981; all recorded 'very strong' El Niño years have occurred in this period. Similarly, with the IOD events we have used the positive and negative IOD years as listed in Table 3. Given that studies have shown ENSO and IOD are not completely independent drivers of rainfall (e.g. Yang et al., 2015; Stuecker et al., 2017), it is acknowledged that separating individual impacts may not be easily done. However, for the purposes of this study their combined effect is considered.

Table 2
El Niño and La Niña years since 1981 and intensities from moderate to very strong.

El Niño			La Niña	
Moderate	Strong	Very strong	Moderate	Strong
1986–87	1987–88	1982–83	1995–96	1988–89
1994–95	1991–92	1997–98	2011–12	1998–99
2002–03		2015–16		1999–00
2009–10				2007–08
				2010–11
Total number of years				
8	4	6	4	10

Table 3
Positive and negative IOD years since 1981.

IOD	Years	Total no. of years
Negative IOD	1981, 1989, 1992, 1996, 1998, 2010, 2014, 2016	8
Positive IOD	1982, 1983, 1994, 1997, 2006, 2012, 2015	7

Composite maps were produced using the difference between the long-term average JAS rainfall (1981–2018) and the average years of the events. For instance, for the very strong El Niño years we used Eq. (1). Similarly, all the other events were assessed, and composite maps were produced.

$$vse\_df = JAS\_RF\_vse - JAS\_RF\_base \tag{1}$$

where: vse_df is the difference of rainfall in very strong El Nino years from long term average.

JAS_RF_vse is average JAS rainfall of very strong El Nino years.
JAS_RF_base is long-term average JAS rainfall over Ethiopia.

Composite significance was determined using a method described by Boschat et al., 2016 and originally created by Terray et al., 2003. This method determines whether a composite is significantly different from the variation in the overall dataset by comparing the values found in the composite with a distribution of composites, of the same time length, which are randomly determined. This study used a distribution of 1000 randomly selected composites and a critical probability of 0.05. Composite differences which are statistically significant are marked with stippling in the figures presented throughout this paper.

2.6. Sub-national scale analysis

Composite analysis of SSTs based on the wettest and driest years of the Awash basin as in Eq. 2 were performed for sub-national scale study. Wettest and driest years were selected based on the 20th and 80th percentile from the baseline timeseries from 38 years of data (1981–2018). The wettest and driest years were selected separately for the upper and lower Awash basin as listed in Table 4. The wettest or driest years for the sub-basins varied for the JAS rainfall. For instance, the upper basin experienced the driest year in 2015 while the lower basin experienced the driest year in 1984. Similarly, the wettest year is 1988 in the upper part of the basin and 1998 in the lower part of the basin.

$$wet\_sst\_df = SST\_wet - SST\_base$$

$$dry\_sst\_df = SST\_dry - SST\_base \tag{2}$$

where: wet_sst_df is the difference in SST of wettest years from long term average.

dry_sst_df is the difference in SST of driest years from long term average.
SST_wet is the average SST in wettest years in JAS season.
SST_dry is the average SST in driest years in JAS season.
SST_base is the long-term average global SST in JAS season.

3. Results

3.1. Correlation analysis

The influence of the equatorial Pacific Ocean SST on Ethiopian JAS rainfall is observed in many instances from the regions identified in Table 1. While positive correlations in the north-eastern part of Ethiopia are observed with Pac_R2 (Fig. 4b), negative correlations are

Table 4
Wettest and driest years of the upper and lower Awash basin based on the JAS season rainfall.

No.	Upper Awash		Lower Awash	
	Driest years	Wettest years	Driest years	Wettest years
1.	2015	2007	1984	1999
2.	1987	2011	1987	2017
3.	2014	2008	2015	2010
4.	2002	1998	1982	1994
5.	1997	2012	1991	2007
6.	1986	1985	1983	2000
7.	2018	2017	1989	1988
8.	1984	1988	1990	1998

observed in most parts of Ethiopia with Pac_R1, except the south and south-eastern part (Fig. 4a). The well-known Nino3.4 region also has a negative correlation similar to Pac_R1 (Fig. 4c). Similarly, the warm pool gradient, which is estimated as the difference between two regions SST, the west pacific and the Nino 4 region as in Hirpa et al. (2019) showed negative correlation with most parts except the south-eastern area below the rift valley region (Fig. 4d). All these results confirm the influence of the equatorial Pacific SST on the JAS rainfall over most of Ethiopia whether as per the defined Nino regions or wider SST area coverage in the Pacific. The influence of the equatorial Pacific has been previously explored by Diro et al. (2011a), finding similar overall correlations for the region as Nino 3.4 and Pac_R1. They argue that the influence of a warmer SST change is translated by subsidence over northeast Africa, a weaker Tropical Easterly Jet (TEJ), a shift in the African Easterly Jet, and a weaker EALLJ. The higher negative correlation values (deeper red) are mostly co-located with the highland areas with the presence of a specific type of vegetation called "Dry evergreen Afro-Montane Forest and Grassland complex" (Fig. 4 on Biomes of Ethiopia document, FDRE, 2017).

In terms of identifying the potential predictability of the JAS rainfall based on the preceding SST conditions, the equatorial Pacific showed its influence with the June SST through the Nino3.4 regions and the WPG (Fig. 5). The correlation is negative showing high SST values in the equatorial Pacific are associated with rainfall deficit in most parts of Ethiopia. On the other hand, MAM season SST associations with JAS rainfall is seen from the other oceanic regions mainly on the north-eastern part of the country (Fig. 6). The regions include the Atlantic Ocean (Fig. 6a), Pacific Ocean (Fig. 6b), West Indian Ocean (Fig. 6c) and the Mediterranean region (Fig. 6d). In all cases, the SST regions showed positive correlations with rainfall in north-eastern Ethiopia (including Awash basin's downstream region). It is also striking that the same region in Ethiopia is influenced by the four oceanic regions, which might be helpful in improving the predictability of JAS rainfall in the region.

3.2. Composite analysis

Results of composite analysis based on ENSO indices are presented for the strongest positive and negative events, i.e. 6 very strong El Nino years and 10 strong La Nina years. Composite maps of JAS rainfall are shown for very strong El Nino years (Fig. 7a) and strong La Nina years (Fig. 7b). Very strong El Nino events are associated with drier than normal JAS rainfall in most parts of the country. Conversely, La Nina events bring wetter conditions in most western and northern parts of the country. In both cases, south and south-eastern Ethiopia are not influenced by the changes in the equatorial Pacific SST, which

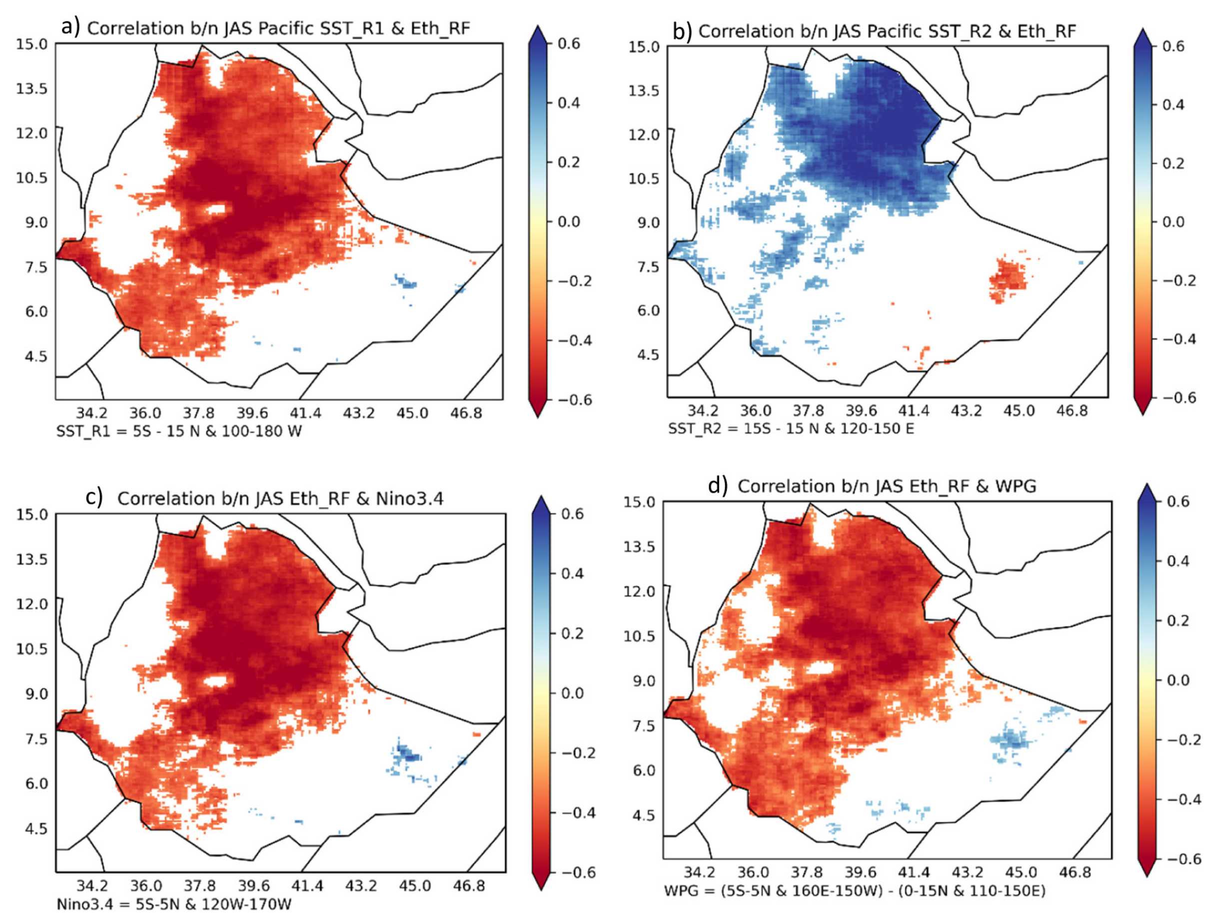

Fig. 4. JAS Ethiopian rainfall correlation with different area averaged SST regions in the Pacific Ocean (a) Pac_r1 (b) Pac r2, (c) Nino 3.4, and (d) WPG.

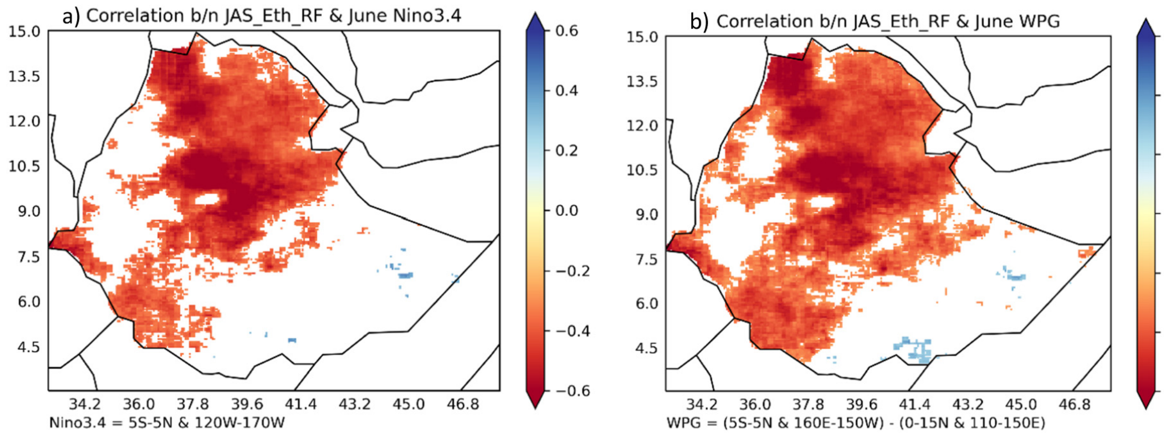

Fig. 5. JAS Ethiopian rainfall correlation with June SST for the regions of (a) Nino 3.4 and (b) WPG in the Pacific Ocean.

is consistent with Fig. 4. The results in the composite maps based on the IOD show a mixed picture. Positive IOD years are associated with drier JAS rainfall in parts of the central highlands, where the western highland part of the Awash basin is located (Fig. 7c). The negative IOD years are associated with slightly weaker and less coherent wetter conditions in the north-eastern area (Fig. 7d), similar to the MAM SST influences seen before in Fig. 6. Generally, the positive phase of the IOD occurs during El Nino years, and conversely the negative phase of the IOD occurs during La Nina years (e.g. Yang et al., 2015; Stuecker et al., 2017). While this is not always the case, it is shown here that the combined effect of ENSO and IOD events results in stronger correlations with JAS rainfall. Very strong El Nino years and positive IOD years result in much lower rainfall in most parts of the country that receives JAS rainfall (Fig. 7e). Conversely combining strong La Niña years with negative IOD years shows stronger positive correlations in the northern and western parts of the country (Fig. 7f).

It is worth noting that the results presented in Fig. 7 are not coherent across the whole country, but there are parts of the country where the correlations are either of the opposite sign, weak, or non-existent. This suggests that these signals are modulated locally, likely by factors such as the complex underlying topography as well as the seasonality of the area. For example, the absence of correlation between rainfall and these large-scale drivers of variability in south-eastern Ethiopia can be explained by the climatological lack of JAS rainfall in these regions.

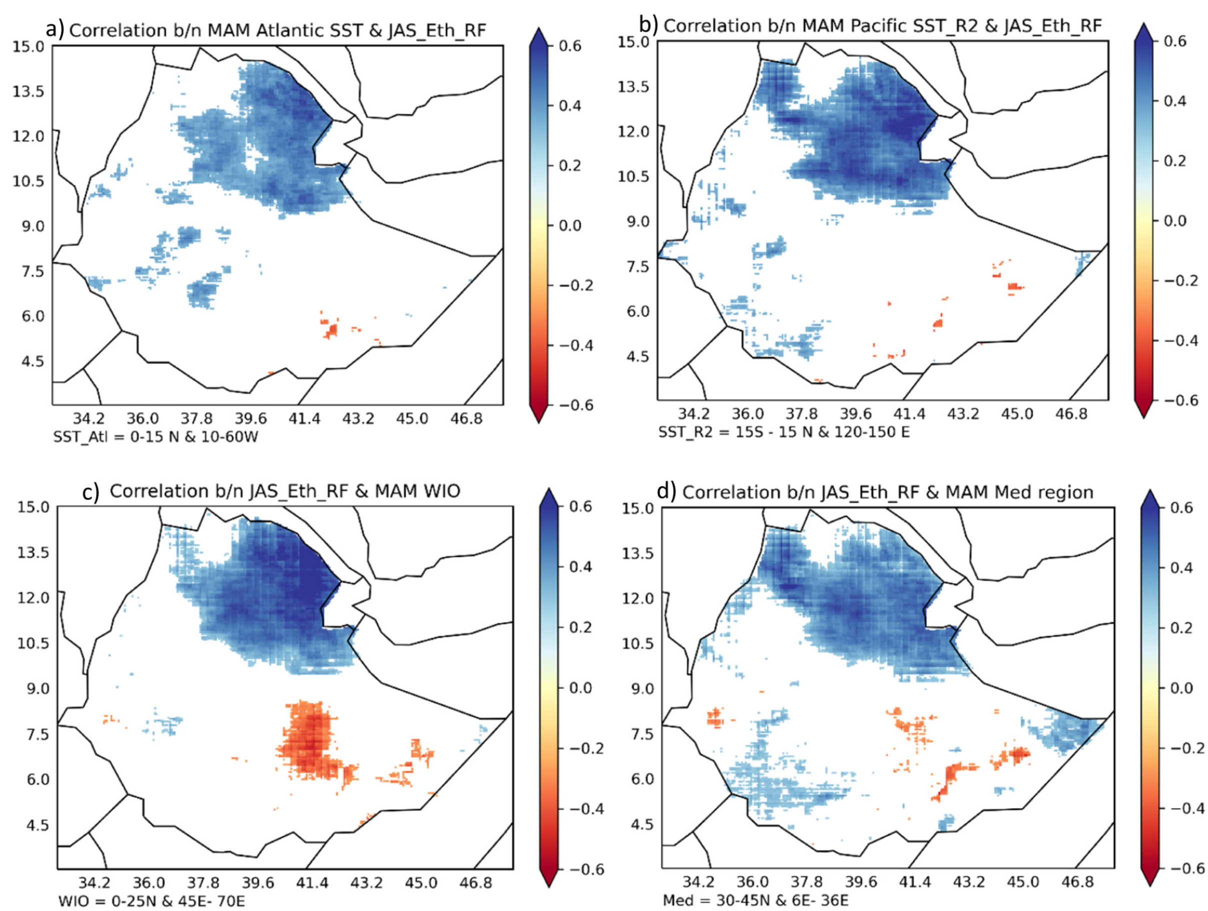

Fig. 6. JAS Ethiopian rainfall correlation with MAM SST for regions in the Atlantic Ocean region (a), Pacific Ocean region (b), West Indian Ocean (c), and the Mediterranean region (d).

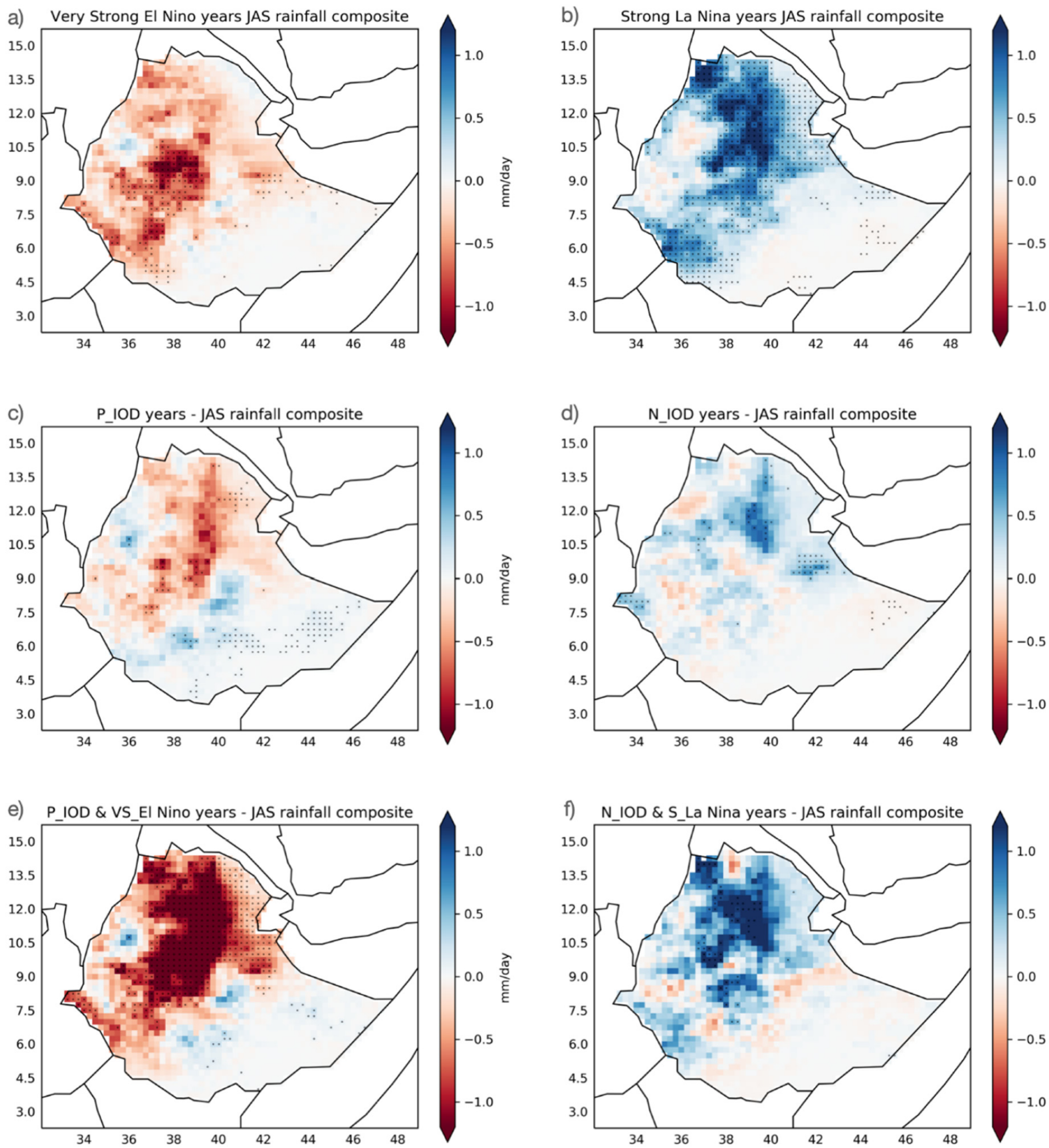

Fig. 7. Composite maps of JAS rainfall for very strong El Nino years (a), strong La Nina years (b), for positive (c), negative IOD years (d), for common years of very strong El Nino & positive IOD years (e) and strong La Nina & negative IOD years (f).

The annual rainfall in this region is barely 200 mm (Fig. 1), with extremely low JAS rainfall (Fig. 8). The south-eastern part of Ethiopia has a more similar annual distribution of rainfall to the Horn of Africa, exhibiting a bimodal distribution with a MAM as the first rainfall season and OND as second rainy season (Dunning et al., 2016).

3.3. Sub-national scale analysis: Awash basin's rainfall correlations with SST

The focus of the previous section was the influence of large-scale drivers on JAS rainfall across all of Ethiopia. Here the focus is on the Awash basin (Section 2.1) to give the sub-national context and to explore the spatial variability in the influences on rainfall and implications that may have for water resource management. This is crucial because if the drivers of variability at this sub-regional scale can provide reliable predictability, this is a scale relevant for a variety of the key water management planning decisions, such as on dam operations, flood management, and water allocation.

Based on the correlation results in Section 3.1 (Figs. 4-6), the Awash basin lays in such a way that can be divided into two broad regions: upper and lower (Fig. 9a). To confirm this split we have compared results found from the objective regionalization of JAS rainfall based on hierarchical climate regionalization. The result of the clustering is as shown in Fig. 9b. This regional split agrees with the correlation results in Figs. 4–6 and is in line with the water management aspect of the basin where the upper part is mostly dominated by water needs for urban centers, hydropower, and agricultural activities and the lower part dominated by pastoralist water needs and large-scale low land irrigation.

From climatology perspective, the upper part has a more uni-modal rainfall resembling the African Sahel rainfall (Biasutti, 2019) and north-

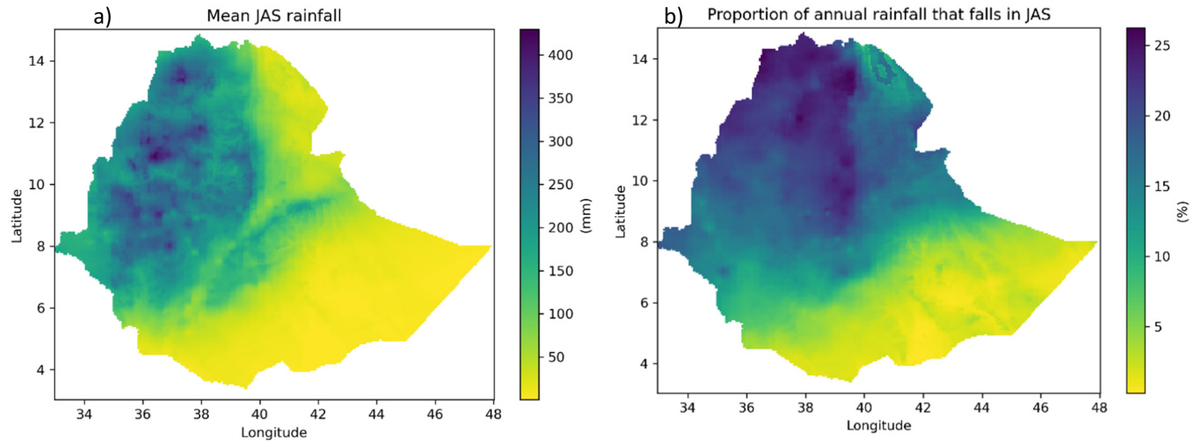

Fig. 8. Mean JAS rainfall distributions of Ethiopia in millimeters using CHIRPS data for the period 1981–2018 (a) and proportion of annual rainfall that falls in JAS season (b).

western Ethiopia, while the lower part has bi-modal rainfall characteristics with distinct MAM and JAS seasons separated by a June minimum in rainfall (Fig. 9c). This distinction is important, in part because the upper basin, without a clear June minimum, has the oldest dam (Koka) from which hydropower is produced, and large-scale irrigation water allocations are made. Berhe et al. (2013) states that the dam operates based on energy production at Koka Power Station rather than irrigation demands downstream of the reservoir. On the other hand, in the lower basin, there is a June minimum, and June is the hottest month of the year, and water users include large-scale irrigation projects that receive water from dam releases, drinking water supply for Metahara town, and pastoralists that require water for their livestock. Two additional water storages have become operational in the lower basin (Kesem and Tendaho) that are mainly used for lowland

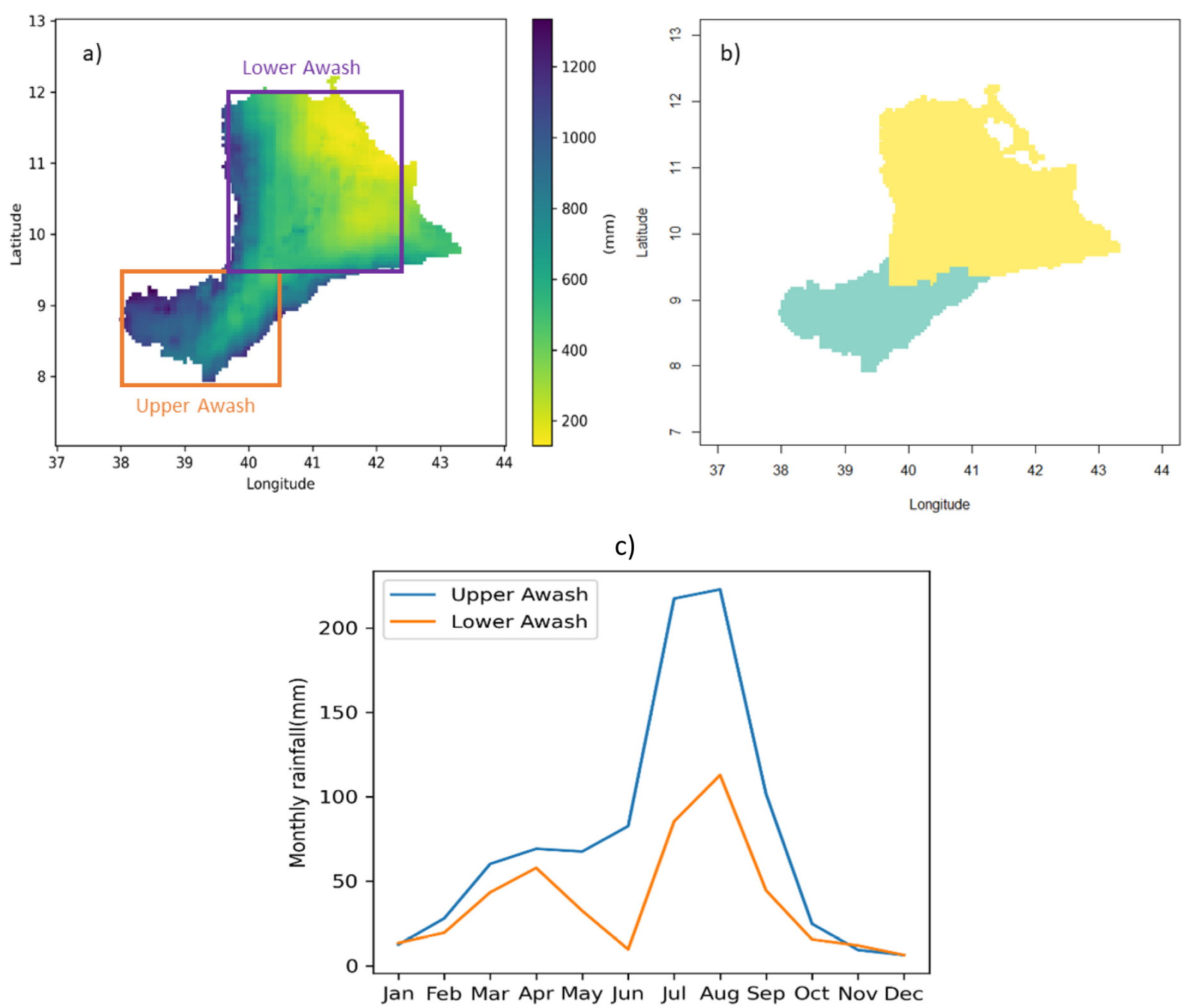

Fig. 9. Division of the Awash basin in to two parts based on rainfall pattern and specifically June's rainfall, the upper and the lower Awash (a), and objective regionalization of Awash JAS rainfall, clustering the basin in to two parts (b) (with 2 clusters and alpha = 0.01 for 99% confidence level), monthly rainfall distribution of upper and lower Awash (c).

irrigation projects (Tadese et al., 2019). Local water management in this basin is dependent on the distinct rainfall characteristics of the upper and lower part of the basin, which are observed to be influenced by two distinct SSTs correlations with JAS rainfall based on the basin's location on Figs. 4-6. The upper basin is mainly influenced by the Pacific Ocean SSTs while the lower basin is influenced by SSTs in Indian Ocean, Atlantic Ocean, Mediterranean regions and R2 of the Pacific Ocean (the eastern side).

In terms of identifying the predictability of JAS rainfall over the Awash basin better correlations were found with the month of May and June SST when looked at separately rather than the MAM seasonal average value. Fig. 10 shows the correlations of the upper and lower Awash basin JAS rainfall with the preceding monthly SSTs in all regions in Table 1. The upper Awash region is negatively correlated with most of the Pacific Ocean SST region indicators. In contrast, the lower Awash has both positive and negative correlations. The positive correlations are with SST regions to the east (east pacific (R2) and West Indian Ocean regions), the north (Mediterranean region), and the west (Atlantic Ocean region). One interesting finding regarding the West Indian Ocean is that, for the lower Awash basin, it shows higher positive correlation in May rather than June. This suggests the SST in the preceding March and April being more influential to the JAS rainfall than that of the May and June, which is clear from Fig. 10. Fig. 10 shows that for the Upper Awash Pacific regions, including Nino4 and WPG have long lead time correlations, while for the Lower Awash basin regions surrounding Africa have longer lead times, in particular WIO, along with the Pacific R2.

3.4. Lead time correlations: atmospheric drivers

Based on the correlations in Fig. 10 we have highlighted two atmospheric drivers of SST teleconnections which are not confined to the Pacific region. Pacific SSTs are commonly used in forecasting (Diro et al., 2011b; Korecha and Barnston, 2007; Korecha and Sorteberg, 2013) but an additional focus on SSTs in the Indian and Atlantic oceans may add valuable information, or context for seasonal forecasts in Ethiopia and the Lower Awash in particular. First, we investigate the correlation between the WIO region defined in Table 1. and Lower Awash JAS rainfall. There is a significant positive correlation with May SSTs but not June SSTs. We suggest that part of the reason for this is the connection between the EALLJ (defined in Section 2.2) and Indian Ocean SSTs. To begin with the connection between the EALLJ and Ethiopian rainfall is shown in Fig. 11a with a stronger southerly flow connected with more rainfall in north-western Ethiopia and less rainfall in south-eastern Ethiopia. Correlating Lower Awash JAS rainfall with 850 hPa meridional winds, as in Fig. 11c shows distinct positive correlations in the west of the Indian Ocean and along the East African coast. For both Lower Awash rainfall and EALLJ winds in JAS, there is a negative correlation with southern Indian Ocean SSTs, while in May there are stronger positive correlations with north western Indian Ocean SSTs. Hence, while concurrent JAS correlations are stronger in some parts of the southern Indian Ocean, there are correlations with lead times in the northern Indian Ocean. This can be understood through the changing meridional temperature gradient in the Indian Ocean and the modulation of the EALLJ onset (Riddle and Cook, 2008) and strength and its corresponding patterns of correlation with Ethiopian rainfall.

Fig. 12 showed that the correlation between the Lower Awash and the Atlantic Ocean is higher in May than it is in June, and not significant in the Upper Awash. Therefore, in order to understand this further, Fig. 12a shows a correlation pattern between CAF moisture flux across the top of the Congo Basin region (defined in Section 2.2) and JAS Ethiopian rainfall which has similar boundaries to those shown in Fig. 9a and clearly distinguishes the division between Upper and Lower Awash. The correlation between this circulation feature and Atlantic SSTs in June and May is also shown (Fig. 10). Correlations in the Atlantic region highlighted earlier are the correlations which remain through both months, with warmer Atlantic SSTs associated with more westerly moisture flux, and higher rainfall in the north-western Ethiopia and the lower Awash.

Both of these moisture circulation features were highlighted as important moisture pathways by Viste and Sorteborg (2013c), but they also offer pathways to understand the lead time and spatial patterns of correlations between Indian and Atlantic Ocean SSTs with JAS Ethiopian rainfall.

3.5. Sub-national scale analysis: Awash basin rainfall based composite analysis

Composite analysis of SSTs based on the wettest and driest years of the Awash basin was used to improve confidence in the SST regions' influence on the Awash basin's rainfall. The results have confirmed the previously found relations with the different SST regions for the upper and lower Awash regions during the wettest and driest years of these basins. Fig. 13 illustrates the SST anomalies during the wettest and driest JAS rainfall years for upper and lower Awash basin. The signal in the west pacific are strong during both wettest (strong negative correlations) and driest (strong positive correlations) years confirming the influence of changes in equatorial Pacific Ocean temperature. The local impacts from the Mediterranean region and Atlantic Ocean are pronounced for lower Awash, stronger in the driest years.

4. Discussion

4.1. Spatial variation in influence of large-scale drivers of Ethiopian summer rainfall

The influence of large-scale drivers on Ethiopian summer rainfall was found to vary locally at regional and sub-regional scales. The

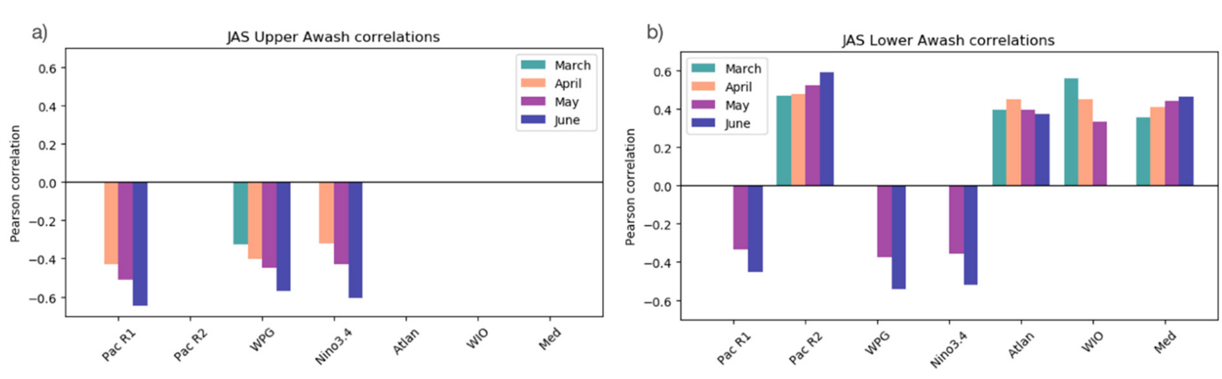

Fig. 10. Correlations of upper Awash (a) and lower Awash (b) JAS rainfall with different SST regions in the month of from March to June to identify potential predictability of JAS rainfall. Correlations are only shown for $p < 0.1$.

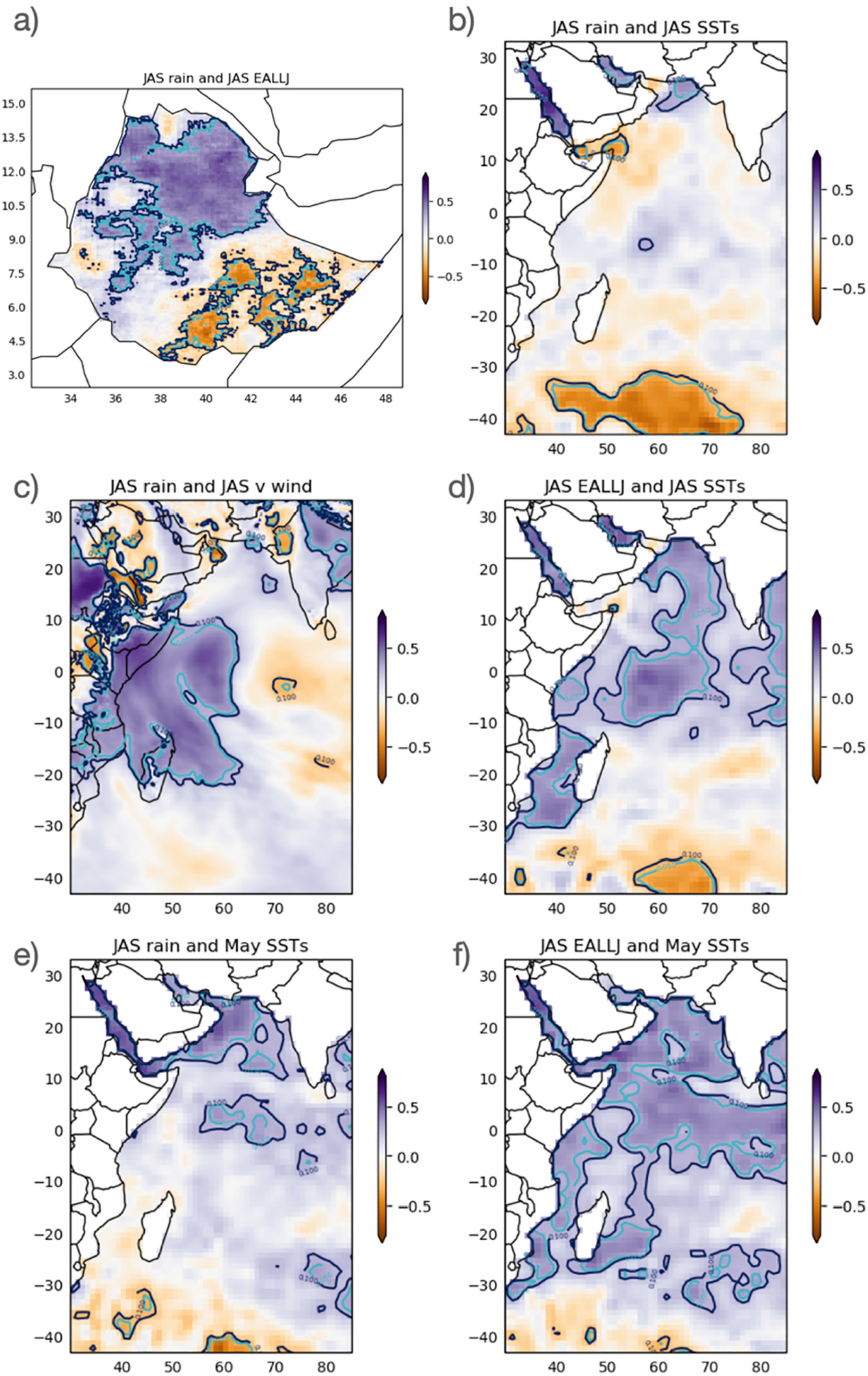

Fig. 11. Correlations between CHIRPS rainfall, ERA5 850 hPa winds, and HadISST SSTs over the 1981–2018 period, $p = 0.1$ shown with a dark contour. a) Correlation between EALLJ meridional winds (5S—10N, 35-55E) and Ethiopian rainfall in JAS, b) correlation between JAS Lower Awash rainfall and SSTs, c) correlation between Lower Awash rainfall and 850 hPa meridional winds in JAS, d) correlation between JAS EALLJ and SSTs. e) Correlations between JAS Lower Awash rainfall and May SSTs, and f) correlations between EALLJ winds and May SSTs.

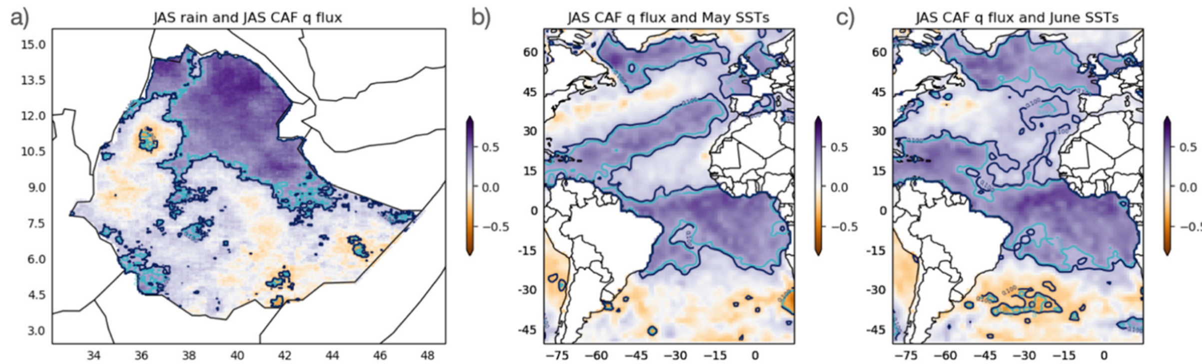

Fig. 12. Correlations between CHIRPS rainfall, ERA5 850 hPa winds, and HadISST SSTs over the 1981–2018 period, p = 0.1 shown with a dark contour. a) Correlation between JAS Ethiopian rainfall and 850 hPa moisture flux across the north of the Congo basin (5-12 N, 10,30E). Correlation between JAS moisture flux and Atlantic SSTs in b) June, and c) May.

influence of the Pacific region on Ethiopia's JAS rainfall is the major one and is mainly seen in the north-western and central part of the country, largely above the rift valley. The results confirm previous findings such as that of Korecha and Barnston (2007); Block and Rajagopalan (2007); and Segele et al. (2009) on the impact of the Pacific region on Ethiopia's main rainy season rainfall. The other regions in the Atlantic and Indian Oceans, and the Mediterranean have showed influence on Ethiopia's JAS rainfall with some lead times of up to a season (e.g. Fig. 6).

Local spatial variations in the drivers of rainfall was observed. For instance, distinct variation in rainfall correlations were evident between regions, including divisions across the Rift Valley (e.g. Figs. 13a, 6c). Local variations that are likely modulated by complex topography (Fig. 2a) resulted in signals that are not similar in cases where the influence of ENSO and IOD indices were investigated (Figs. 7-9). Drier conditions result for most areas when very strong El Nino and positive IOD events occur together. However, while wetter conditions are associated a stronger La Nina, this relationship is not as strong when La Nina and negative IOD events occur together.

There are parts of the country where the influence of large-scale drivers is not seen for JAS rainfall. Two low-correlating regions were observed in opposite parts of the country: the east, where JAS is in dry season (Fig. 8), there is no observed correlation in all analyzed cases in this study, owing to the fact that the climatology of the eastern part of Ethiopia is mostly similar to the larger East Africa/Horn of Africa climate where JAS is not a rainy season; and in western Ethiopia where JAS is a rainy season but there are low correlations in areas covered by rainforests, an observation which corresponds with findings by Viste and Sorteberg (2013a) and Young et al. (2014).

The Awash basin showed the local variations at sub-regional scale. This was evident by the different ocean regions its rainfall correlated to, which divided the basin broadly into two sub-basins. The upper basin rainfall is mainly influenced by the Pacific region while the lower basin rainfall has additional influences from Atlantic, Indian and Mediterranean regions.

4.2. Evidence of relationship between large-scale drivers and local rainfall evident ahead of the start of the summer season

This study showed evidence that there is relationship between large-scale drivers and local rainfall with varying lead time, offering different opportunities to strengthen forecasting. Strong correlations were demonstrated between June SST in the Pacific Ocean and rainfall in JAS (Fig. 5), providing a lead time of only one month, highlighting the potential for refinements to seasonal forecasts at the start of the summer rainfall, which can be applicable in the case of upper Awash basin. Lead time of a season is possible through the influence of MAM changes in SST of Atlantic, Indian and Mediterranean regions with rainfall that occurs in JAS. The season ahead lead time corresponds to the lower Awash JAS rainfall. Two atmospheric circulation features that explain the mechanism for the teleconnection in the Indian and Atlantic oceans were investigated; the meridional flow over the East African coast (EALLJ), and the zonal flow across Central Africa (CAF). These are both potential moisture pathways, as has been highlighted in this and other studies (Li et al., 2016a, Viste and Sorteberg, 2013b). With such a mechanistic understanding of these lead time correlations regions such as the Indian and Atlantic oceans could be a valuable source of extra

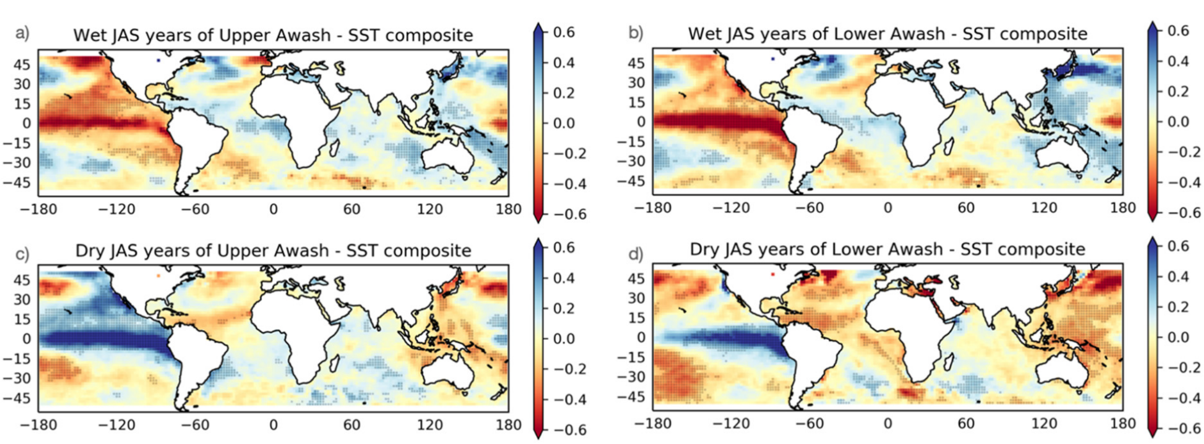

Fig. 13. Composite maps of global SST during wettest years of upper Awash JAS rainfall (a), wettest years of lower Awash JAS rainfall (b), driest years of upper Awash JAS rainfall (c)l and driest years of lower Awash JAS rainfall (d), areas covered with grid boxes show statistical significance composite values.

information to seasonal forecasts. Korecha and Sorteberg (2013) indicated that the National Metrological Agency uses ENSO and Pacific SSTs for forecasts, but the other regions found in this study could be a useful addition especially if the sub-national scale is of interest, such as was shown in the case of Awash.

4.3. Sub-national scale analysis: tailoring climate services for water managers

Water managers in the Awash basin make decisions about water storage and release for industry, agriculture and domestic water supply and the environment, and for flood management. Rainfall variability makes these decisions challenging and has been linked to significant impacts on productivity in the basin (Borgomeo et al., 2018), as well as severe impacts for the poorest that can take years to recover (Dercon et al., 1999). Improved sub-seasonal rainfall forecasts can be used to inform water management decisions and improve responsiveness to variability.

The location of the Awash basin in a marginal zone between two climate zones, splitting the basin into two regions is critical to differentiate the different regional drivers. From the results there are various ways in which these can inform water management in the Awash basin. The extremes experienced in upper and lower basins differed, with the wettest and driest years showing different patterns; while 3 of the 8 driest years corresponded between the two parts of the basin, the differences in the other 5 years offer an opportunity to consider how water can be managed at a basin scale to minimize the impact of the uneven distribution in rainfall extremes. Further work is needed to characterize the different scenarios for extreme weather and appropriate basin-scale management approaches to mitigate them.

Discussions with water managers in the basin have highlighted a number of decisions that could be supported by seasonal forecasts (Grasham and Charles, 2020). In the upper basin, where population and industry are concentrated and rainfall is higher, a key focus of water management is on reservoir releases for flood management. Using June rainfall to update seasonal forecasts for the JAS rainfall season can provide early warning for earlier releases of water and other flood management interventions. While for the lower part of the basin, where rainfall has a higher coefficient of variability (Fig. 2d), a longer lead time is possible, with changes in MAM able to be used to enhance seasonal forecasts for the JAS rainfall. This additional time could enable critical emergency disaster responses for pastoralist populations to start earlier, such as fodder stockpiling and planning for emergency water to support pastoralist populations. Advanced warning could have helped mitigate the 2015/16 drought that impacted almost 10 million people, for example.

Lastly, the interactions between ENSO and IOD years can help provide early warning of when the JAS rainfall is likely to be weak, which might influence planning on large-scale operations, such as dam releases, to support large-scale irrigated agriculture, but can also inform small scale agriculture, such as planting a smaller area and using water saving mechanisms (Klemm and McPherson, 2017; Edossa et al., 2006). Targeting sub-seasonal to seasonal forecasts at scales appropriate for users, especially in areas of complex climatology, can ensure knowledge of locally relevant connections in climate systems are maximised to improve outputs for water management and disaster response. Further research is needed to investigate the reliability of using this information in statistical models for seasonal forecasting that depend on statistical correlations between SSTs and rainfall.

5. Conclusions

This study has highlighted the heterogeneity of Ethiopia's climate through one of the crucial parameters, rainfall. Given that Ethiopia is highly dependent on rainfall for livelihoods and productivity (World Bank, 2006) and has been impacted by the negative consequences of droughts and floods (Li et al., 2016b), this study underscores the importance of seasonal to sub-seasonal climate information at a national and sub-national scale through understanding the large-scale oceanic and atmospheric influences of rainfall in Ethiopia. The study showed the importance of sub-national scale analysis to consider local influencing factors and improve the quality of climate information, as well as enabling it to be better tailored for users. Initial analysis highlighted the important and spatially varying role of the month of June, supporting the decision to separate it from the remaining JAS season in our analysis. For the Awash basin, the study identified different ways in which this forecasting information can improve advice available to water managers. For example, in the upper basin, observed June rainfall can be used to update seasonal outlooks for the JAS rainfall season while for the lower part of the basin the observed changes in MAM rainfall can be used to update seasonal outlooks for the JAS rainfall. Equally the areas of influences differ, with the Pacific Ocean region the most important for the upper basin, while the influence of local SSTs from the Atlantic, Indian Ocean and Mediterranean regions are additional factors to be considered with the Pacific region SSTs for the lower part of the basin. This study provides novel evidence of how observed climatic conditions in the preceding months can improve and refine seasonal to sub-seasonal outlooks for the JAS season. Further it has shown that such information could be valuably used by decision makers in the Awash river basin to allocate water, plan water use and plan emergency responses to the extremes of water scarcity and flooding that are common experiences of the basin.

CRediT authorship contribution statement

Meron Teferi Taye: Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Visualization, Writing - original draft, Writing - review & editing. **Ellen Dyer:** Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing - review & editing. **Katrina J. Charles:** Funding acquisition, Writing - review & editing. **Linda C. Hirons:** Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.142604.

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