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RESEARCH ARTICLE

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Inter-annual hydroclimatic variability in coastal Tanzania

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Abstract

Climatic controls regulate the coupled natural and human systems in coastal Tanzania, where mangrove wetlands provide a wealth of ecosystem services to coastal communities. Previous research has explained the precipitation seasonality of eastern Africa in terms of the local monsoons. This research examines a wider range of hydroclimatic variables, including water vapour flux, evapotranspiration, runoff, and ocean salinity, and the sources of low-frequency atmosphere–ocean variability that support mangrove productivity and associated ecosystem services. Results confirm previous work suggesting that the northeast monsoon (*kaskazi*) largely corresponds to the "short rains" of October–December and extends through February, while the southeast monsoon (*kusi*) corresponds to the "long rains" of March–May and the drier June–September. The Indian Ocean Dipole (IOD) and, to a lesser extent, El Niño–Southern Oscillation (ENSO) are important modulators not only of precipitation (as has been shown previously) but also of water vapour flux, evapotranspiration, runoff, and salinity variability. During *kaskazi*, positive (negative) hydroclimatic anomalies occur during positive (negative) IOD, with a stronger IOD influence occurring during its positive phase, when seasonal anomalies of precipitation, evapotranspiration, and runoff exceed +50, 25, and 100%, and nearby salinity decreases by 0.5 practical salinity units. During *kusi*, the contrast between the positive and negative IOD modes is subtler, and the pattern is dictated more by variability in "long rains" months than in the dry months. The coincidence of the positive IOD and El Niño amplify this hydroclimatic signal. Because previous work suggests the likelihood of increased tendency for positive IOD and increased moisture variability associated with El Niño events in the future, wetter conditions may accompany the *kaskazi*, with less change expected during the *kusi*. These results advance understanding of the key environmental drivers controlling mangrove productivity and wetland spatial distribution that provide ecosystem services essential to the well-being of the human population.

KEYWORDS

climate, mangroves, observational data analysis, ocean, rainfall, seasonal, Tanzania, teleconnections, Tropics

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1 | INTRODUCTION

Climate plays an important role in ecosystem and economic resiliency (Erwin, 2009), especially near ecotones that support large human populations (Rivera-Monroy *et al.*, 2011a; 2011b). In regions with extreme poverty, livelihoods tend to depend disproportionately on natural capital (Barrett *et al.*, 2011), making these ecosystems even more susceptible to the effects of climatic thresholds, variability, and change. Previous case studies (e.g., Ngwenya and Mosepele, 2007; Béné *et al.*, 2009; Coomes *et al.*, 2010) show that when households are faced with adversity, people turn to fisheries, thus increasing stress on already depleted fish stock. The situation is exacerbated during times of reduced freshwater runoff, which can reduce the marine ecosystem productivity and increase the risk of chronic poverty. Accordingly, it is important to elucidate how hydroclimate influences the interactions of such coupled natural and human systems (Collins *et al.*, 2011).

Mangroves play significant ecological, economic, and cultural roles in fisheries-dependent coastal communities in tropical Africa (Diop *et al.*, 2002), including coastal Tanzania (McNally *et al.*, 2011; Vo *et al.*, 2012; Gaiser *et al.*, 2015; Mangora *et al.*, 2016; Robertson *et al.*, 2018). The Tanzanian coastal region is identified by the World Wide Fund for Nature as a priority area because mangrove forests are under intense exploitation pressure for wood products and conversion to other land uses (Mangora *et al.*, 2016). Changes in nearby land use away from mangrove wetlands are linked to reductions in the variety and economic value of ecosystem services (Bennett *et al.*, 2009), with changes frequently being nonlinear (Barbier *et al.*, 2008). The effects of hydroclimatic variability on mangrove forests and the ecosystem services they provide, including runoff and salinity changes, are indisputable (Twilley and Rivera-Monroy, 2009; Punwong *et al.*, 2013a; 2013b; 2013c; Rovai *et al.*, 2016; Rivera-Monroy *et al.*, 2017).

Although the total mangrove area in Tanzania is still being defined (Mangora *et al.*, 2016), mangroves are widely distributed along the Tanzanian coastline and on the islands of Zanzibar (i.e., Unguja and Pemba). Mangrove extent reported for 1989 ranged from 115,467 ha (Semesi, 1992) and 128,683 ha (Spalding *et al.*, 2010) to 245,600 ha (Spalding *et al.*, 1997). The most recent estimate (158,100 ha) is provided by Tanzania's Ministry of Natural Resources and Tourism (Ministry of Natural Resources and Tourism (MNRT) of Tanzania, 2015). Despite this uncertainty in the total area of this productive coastal forested wetland, it is recognized that half of the total mangrove area is located in the Rufiji River Delta block as defined in the National Mangrove Management Plan, followed by the Tanga and Kilwa blocks and estuaries of the Ruvu, Wami, Pangani, and Ruvuma Rivers (Mangora *et al.*, 2016).

Because of the great diversity of geomorphological settings where mangroves develop even at the same latitude (Rivera-Monroy *et al.*, 2017), there are qualitative and quantitative differences in the ecosystem services provided by different mangrove ecotypes (i.e., riverine, fringe, basin, scrub; Ewel *et al.*, 1998). These services include shoreline stabilization, enhancement of water quality, nutrient cycling, and provision of shelter, breeding, and nursery grounds for coastal species. Indicators of mangrove ecosystem structure and function such as biological diversity, net primary productivity, carbon storage, and habitat can be associated with particular types of environmental settings, all of which are subject to the influence of hydroclimatic variability.

The mangroves of coastal Tanzania have been utilized by humans since at least the ninth century AD (Food and Agriculture Organization (FAO) of the United Nations, 2017). Human impact can be both a cause of (when used as an extractive industry) and a potential solution to (when protected for use as a nursery habitat for shrimp and fisheries) the extreme poverty in the area (McNally *et al.*, 2011). Some have suggested that the absence of local control on mangroves is associated with resource mismanagement and perceived environmental injustice (Beymer-Farris and Bassett, 2012). Therefore, strategies for improved conservation in this region have been proposed (Hansen *et al.*, 2010). Such strategies include not only coastal areas, but also large watersheds (e.g., Rufiji basin) that control the structure and productivity of mangrove wetlands, where water availability shows major inter-annual and decadal fluctuations (Armanios and Fisher, 2014; Brown *et al.*, 2016; Hirvonen, 2016).

The interplay and feedbacks between climate, geomorphology, vegetation, and disturbance on such sensitive ecosystems in tropical eastern Africa have created “tipping points” that have led to environmental and ecological change in the geologic past (Ivory and Russell, 2016). Hydroclimatic change and variability affect mangrove ecosystem structure and function and therefore coastal communities that are supported by goods and services from mangrove wetlands. Concerns about water availability are amplified when considered in the context of the pressures of a changing climate and saltwater intrusion in coastal aquifers due to rising sea levels (Ellison, 2015). These aquifers are even more susceptible during periods of drought, which are largely driven by rainfall patterns. “Shared vulnerability” to extreme droughts can cause mangrove deforestation and poverty to become mutually reinforcing (Barrett *et al.*, 2011).

2 | PURPOSE

The purpose of this research is to advance understanding of the hydroclimatic features and forcing mechanisms that in turn support the availability of critical mangrove ecosystem services in coastal Tanzania (Figure 1). Manatsa *et al.* (2011) found that

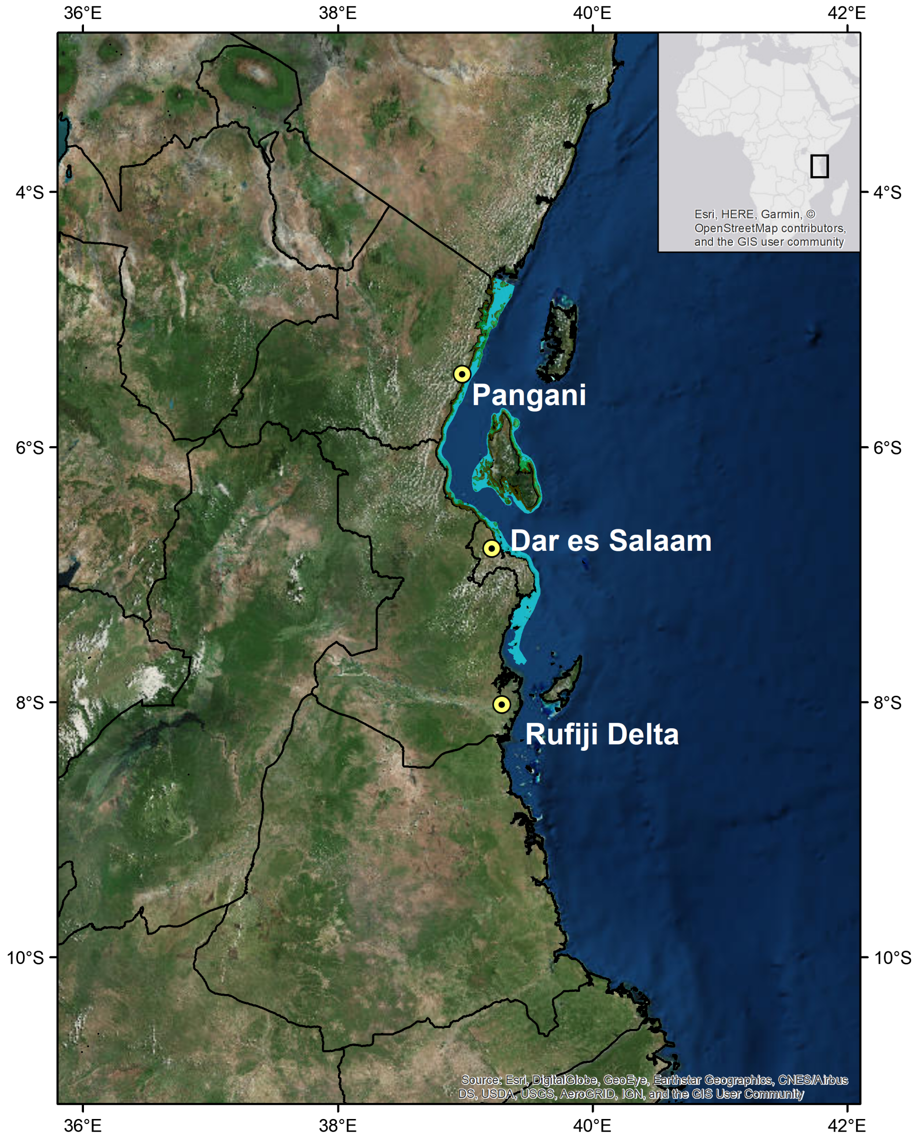

FIGURE 1 The study area. Mangroves are shown in blue green [Colour figure can be viewed at wileyonlinelibrary.com]

southeastern African October–December precipitation is modulated by low-frequency atmosphere/ocean circulation variability associated with the Indian Ocean Dipole (IOD; Saji *et al*., 1999; Li *et al*., 2003) to a more direct extent than El Niño–Southern Oscillation (ENSO). However, little research has been conducted on the monsoon seasonality of such forcing mechanisms on Tanzanian hydroclimatology, especially with the individual water balance components characterized. This study explores more closely the strength of these relationships.

Results of this research will provide the basis for addressing future ecological–socioeconomic research questions in coastal Tanzania, such as how changes in hydroclimatology driven by global and regional climate variability affect soil properties (e.g., nutrient content, porewater salinity), surface water salinity patterns, and carbon storage and sequestration rates. External drivers that impact mangroves—including climatic variability, nutrient availability, and stream discharge—are dynamic and complex. These drivers in turn affect the risk of coastal Tanzanian communities falling into poverty traps (McNally *et al*., 2011) due to the intrinsic dependence on mangroves of coastal communities, both directly and through changes in ecosystem services and their sustainability. Consideration of the hydroclimatic controls advances understanding of the coupled climate–ecological–socioeconomic interactions (Terjung, 1976; Hutchison *et al*., 2014). This knowledge is important in coastal Tanzania, where hydroclimatological changes might have acute detrimental impacts on the well-being of the rapidly increasing population in the coming decades (e.g., Cohen, 2003).

3 | ATMOSPHERIC AND OCEANIC CIRCULATION VARIABILITY

Two major modes of low-frequency variability coupled between the ocean and atmosphere are known to have major impacts in tropical and subtropical eastern Africa. First, the

IOD impacts climate variability in equatorial eastern Africa (Gamoyo *et al*., 2015) and is characterized by a see-sawing of atmospheric pressures, temperatures, and flow anomalies between the western and eastern equatorial Indian Ocean. With its phases typically beginning in May or June, reaching a peak in August through October, and decaying in November or December (Lim and Hendon, 2017), the IOD is well-recognized as an important predictor of eastern African rainfall (Chen and Georgakakos, 2015).

Additionally, ENSO is known to be associated with environmental impacts in eastern Africa, with coastal Tanzania experiencing rainier than average wet seasons during El Niño and below average precipitation during the cold- (La Niña-) phase (Ogallo, 1988; Kijazi and Reason, 2005). Impacts of this precipitation variability include anomalous greening (Anyamba *et al*., 2002) and abundant cassava harvests (Oluwole, 2015) during El Niño and generally opposite effects during La Niña episodes.

The strongly positive (negative) IOD is typically associated with the El Niño (La Niña) phase of ENSO (Luo *et al*., 2010), but either mode can occur independently of the ENSO phase (Ashok *et al*., 2003). Further research suggests that the synergistic impacts of ENSO and IOD are of particular importance in forcing eastern and southern African rainfall patterns, especially in the October–December period (Reason *et al*., 2000; Otte *et al*., 2017). Specifically, the combination of a positive IOD with an El Niño event results in positive precipitation anomalies and the "greenest" normalized difference vegetation index (NDVI) anomalies (Detsch *et al*., 2016).

There are some indications of future changes to the IOD associated with warming near-equatorial eastern Africa, with suggestions of a decreased intensity of both positive and negative IOD events (Cai *et al*., 2013) but increased frequency of positive IOD events (Cai *et al*., 2014). Chu *et al*. (2014) predicted a strengthening relationship between the positive IOD and El Niño through 2099. Collectively, these studies suggest a possibility for changing surface water availability and drought probability, which would have a long-term impact on coastal net primary productivity.

4 | DATA AND METHODS

Monthly mean precipitation, evapotranspiration, and runoff data were collected from NASA's Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) data set. These data are available at a $0.1 \times 0.1°$ spatial resolution over the period from 1982 to present. Thus, in this research, the "normals" period is considered to be from 1982 to 2010. This data set offers advantages over other sources, such as ECOCLIMAP-V1 (Masson *et al*., 2003), ENACTS (International Research Institute for Climate and Society, 2017), Global Precipitation Climatology Centre (Schneider *et al*., 2011), WorldClim 2.0 (Fick and Hijmans, 2017), and Africa Rainfall Climatology Version 2.0 (National Oceanic and Atmospheric Administration, 2017) in terms of the spatial resolution and period of available data, access to the data, and inclusion of all relevant variables except wind, water vapour flux, and salinity.

Monthly mean west-to-east (u) and south-to-north (v) wind components and water vapour flux ($0.562 \times 0.562°$) at a 2-m height were acquired from the Japanese 55-year Reanalysis Project (JRA-55; Japan Meteorological Agency, 2014) through the Research Data Archive from National Center for Atmospheric Research/University Corporation for Atmospheric Research (NCAR/UCAR), for the area bounded by 37.9°E, 41°E, 4.6°S, and 10°S. The u and v components were used to generate a composite wind vector to identify the circulation-based monsoonal seasons. Key advantages of JRA-55 include (1) length and completeness of the time series for full observing system reanalysis using the most advanced data assimilation scheme, (2) incorporation of several new observational data sets, (3) new radiation scheme, (4) improvements offered by variational bias correction over the previous iteration (JRA-25), and (5) availability of companion data sets that permit the assessment of the impact of data assimilation (Kobayashi, 2016). Among the limitations of the data set noted by Kobayashi (2016), none affect wind or water vapour flux directly. To identify impacts of hydroclimatic variability on the critical (for mangrove health) variable of salinity, monthly mean salinity data from the surface to 5-m depth adjacent to the Tanzanian coast were acquired from the Simple Ocean Data Assimilation version 3.12.2 (SODA3) data set (Carton *et al*., 2018).

Positive and negative IOD years (i.e., generally corresponding to above-normal (below-normal) sea surface temperatures in the western Indian Ocean near Tanzania, respectively) and El Niño and La Niña phases of ENSO were assigned based on their designation by the Australian Government Bureau of Meteorology (2018), with positive IOD years in 1982, 1983, 1994, 1997, 2006, and negative IOD years in 1989, 1992, 1996, 1998, and 2010. El Niño (1982, 1986, 1987, 1991, 1994, 1997, 2002, 2004, 2006, and 2009) and La Niña (1983, 1984, 1988, 1989, 1995, 1998, 1999, 2000, 2005, 2007, 2008, and 2010) years, along with the four positive IOD + El Niño years (1982, 1994, 1997, and 2006) and three negative IOD + La Niña years (1989, 1998, and 2010) in the 1982–2010 period were also composited (Australian Government Bureau of Meteorology, 2018). Analyses were completed using the R Program and exported to ArcMap® for visualization as a raster. Bilinear interpolation was used to smooth the spatial distributions on the maps based on the analyses.

5 | RESULTS AND DISCUSSION

5.1 | General climatology

Mean annual temperature is about 27°C along Tanzania's coast, with minimal temperature seasonality. However, considerable precipitation variation exists by month, and from Pangani southwards to Dar es Salaam and Rufiji Delta (a north–south distance of approximately 200 km) within a given month (Figure 2). The "short rains" of October–December generally begin earlier in the season northwards along Tanzania's coast, while the March–May "long rains" and June–September dry season are also well-pronounced across Tanzania beyond the coast (Gamoyo *et al*., 2015). The short rains bring less precipitation than the long rains, even though both exhibit their peak precipitation when the intertropical convergence zone is overhead.

Wind flow remains onshore and generally light over coastal Tanzania throughout the year (Figure S1). A distinctive feature of the wind climatology is the monsoonal shift from southerly to northerly winds over the coastline around October/November, with the southerly airflow resuming by the end of March and reaching maximum monthly mean strength in June and July of 3.7 m s^{-1}. These circulation-based monsoon seasons are known locally as the "*kaskazi*," for the November–March northeast monsoon, and the southeast monsoon of April through October is known as the "*kusi*" (Membery, 2001; Mahongo *et al*., 2011; Figure 3).

The rainfall regime corresponds closely, but not perfectly, with the monsoonal circulation. Precipitation seasonality along the coast actually precedes the wind shift by approximately 1 month, as the most direct onshore flow occurs during the *kaskazi*/*kusi* transition, near October and March (Figure S1), signalling the onset of rainier conditions in coastal Tanzania (Figure 2). These results support those of Nicholson (2015), who found that in eastern Africa, zonal winds show the strongest relationships to the "short rains" of October and November. Seasonality in this research is defined based on the precipitation climatology—as the October-to-February (≈*kaskazi*) versus March-to-September (≈*kusi*) periods. From that perspective, the *kusi* is composed of the "long rains" and the dry months of June through September.

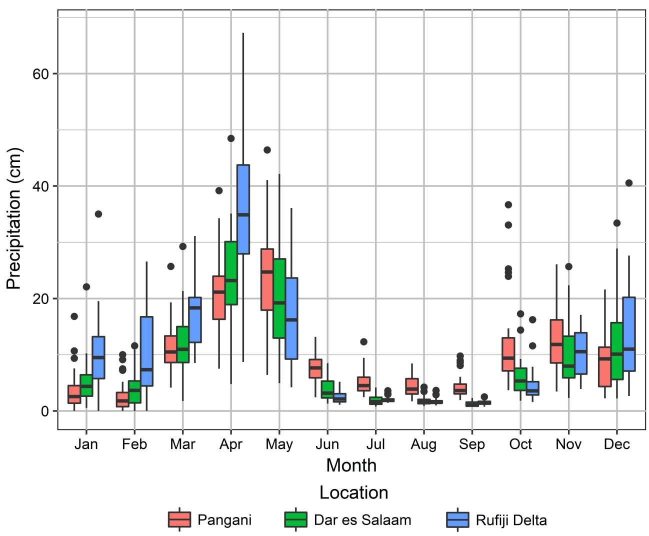

FIGURE 2 Boxplots of mean (1982–2010) precipitation (cm), for Pangani, Dar es Salaam, and Rufiji Delta. Medians are shown by the notched horizontal lines, interquartile ranges are within the coloured region, and the ranges, excluding the outliers (dots) are shown by the whiskers [Colour figure can be viewed at wileyonlinelibrary.com]

5.2 | Relationship of atmospheric and oceanic circulation variability to hydroclimatology of coastal Tanzania

Figure 4 shows mean seasonal *kaskazi* (October–February) and *kusi* (March–September) precipitation, and anomalies of each when the IOD exceeds ±0.4°C, ENSO Niño3.4 index exceeds ±0.8°C, and percentage anomalies during simultaneous positive and negative phases (as defined above) of both IOD and ENSO (1982–2010; Australian Government Bureau of Meteorology, 2018). While southern coastal Tanzania experiences slightly more *kaskazi* precipitation than northern coastal Tanzania, the dipole during positive/negative IOD years is notably different. Specifically, during *kaskazi* experiencing the positive phase of the IOD, northern coastal Tanzania shows stronger positive precipitation anomalies than southern Tanzania. Although ENSO acting alone contributes the same patterns to a lesser extent, greater amplification of this pattern occurs during the 4 years when the positive IOD is accompanied by an El Niño event (Figure 4). The negative phase of the IOD during *kaskazi* is associated with negative precipitation anomalies, especially in the central and southern coastal areas. La Niña alone has little influence on *kaskazi* precipitation, but simultaneous negative IOD and La Niña mitigate the IOD signal slightly (Figure 4). These patterns generally hold true for both the October–December and January–February subperiods of *kaskazi* (not shown).

Compared to the *kaskazi*, *kusi* precipitation is more uniform along the coast (Figure 4). While positive IOD is linked to slightly rainier than normal conditions during *kusi*, both the positive and negative IOD-influenced anomalies are weaker than for the corresponding IOD-influenced *kaskazi*; these results support previous findings (Owiti *et al*., 2008). Moreover, El Niño and La Niña seem to have little impact on *kusi* precipitation. Again, all of these patterns generally appear even when the *kusi* is subdivided into the "long rains" period of March–May and the dry months of June–September (not

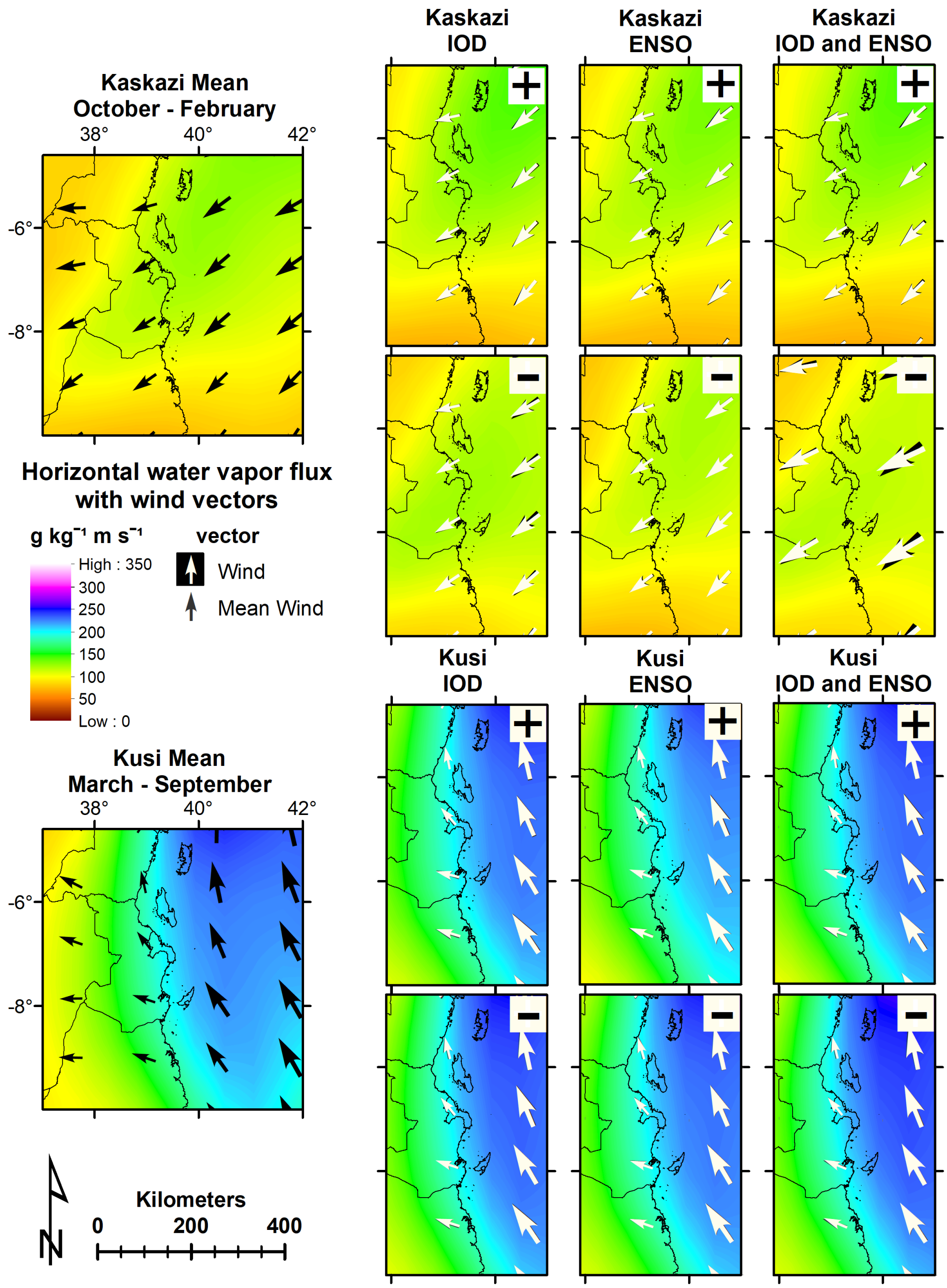

FIGURE 3 Mean monthly wind vectors (m/s) during *kaskazi* and *kusi*, along with water vapour flux (g kg^{-1} m s^{-1}) [Colour figure can be viewed at wileyonlinelibrary.com]

shown), but because the dry *kusi* precipitation is so sparse, percentage anomalies during IOD and ENSO positive/negative phases become exaggerated. Neither the negative phase of the IOD nor La Niña has much impact on coastal *kusi* precipitation (Figure 4). This result supports those reported by Nicholson (2017), who suggested that ENSO is weak and inconsistent during the "long rains" and that La Niña can either enhance or suppress precipitation in eastern Africa.

Intuitively, these differences in IOD/ENSO-related seasonal precipitation might suggest that local winds differ between positive versus negative IOD and ENSO phases. However, minimal differences were found in wind vectors regardless of the IOD or ENSO phase (Figure 3). The combination of only subtle differences in wind vectors and large differences in precipitation across the phases implies that the IOD and ENSO may impact precipitation in coastal Tanzania to a greater extent by altering local stability than via moisture advection.

Evapotranspiration normals and anomalies by IOD/ENSO positive/negative phases during *kaskazi* and *kusi* are shown in Figure 5, with the patterns displaying many similarities to that for precipitation. *Kaskazi* has less mean evapotranspiration than *kusi*, with the positive (negative) IOD during *kaskazi* showing positive (negative) evapotranspiration anomalies. Also, the IOD in its positive/negative phase exerts more influence on evapotranspiration during *kaskazi* than in the *kusi* period. In both *kaskazi* and *kusi*, El

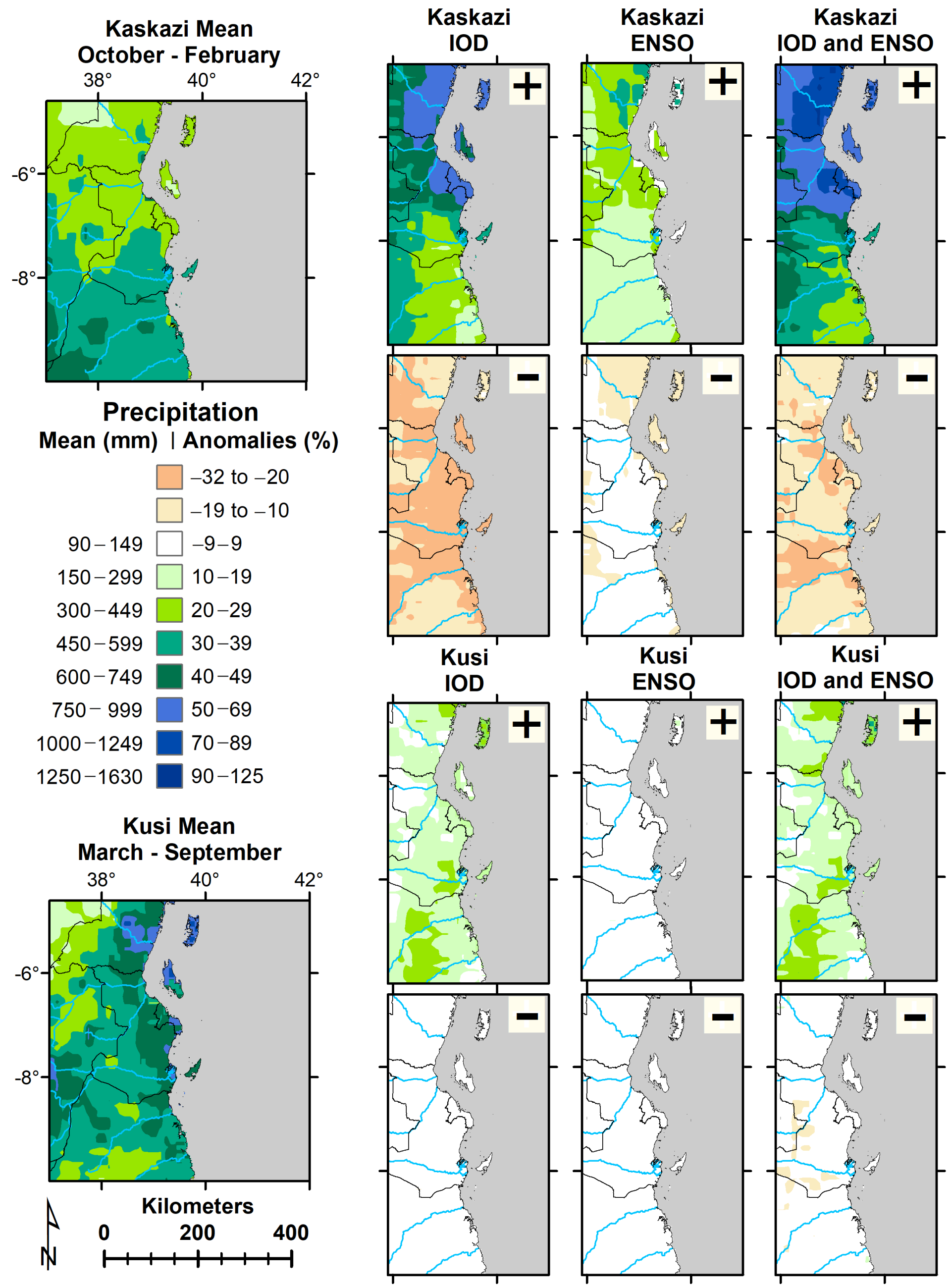

FIGURE 4 Mean precipitation (mm; left column) during *kaskazi* and *kusi*, and precipitation anomalies (%; second through fourth columns) in years having Indian Ocean Dipole index exceeding ±0.4°C, ENSO Niño3.4 index exceeding ±0.8°C (i.e., El Niño and La Niña, respectively), and simultaneous positive IOD and ENSO, and negative IOD and ENSO, during *kaskazi* and *kusi*; 1982–2010 [Colour figure can be viewed at wileyonlinelibrary.com]

Niño/La Niña has somewhat less influence on evapotranspiration than IOD, with La Niña affecting evapotranspiration minimally (Figure 5).

The cumulative effects of positive (negative) IOD and El Niño (La Niña) on evapotranspiration are similar to those of precipitation (Figure 5). During *kaskazi*, coastal evapotranspiration is enhanced by El Niño during positive IOD years. These evapotranspiration anomalies are not apparent when *kaskazi* is subdivided into October–December and January–February sub-periods (not shown). During *kusi*, neither IOD phases nor coincident IOD + ENSO phases cause large evapotranspiration anomalies (Figure 5). This result coincides with the fact that *kusi* precipitation anomalies are also weak during the IOD and coincident IOD + ENSO phases. The “long rains” and dry season subdivisions of *kusi* also show little ENSO impact on evapotranspiration patterns during positive/negative IOD years (not shown).

Figure 6 shows the normals and anomalies for runoff. As was the case for precipitation and evapotranspiration, *kaskazi* has less average runoff than *kusi*, and a positive (negative) IOD phase during *kaskazi* is linked to positive (negative) runoff anomalies. During *kaskazi*, El Niño (La Niña) increases positive (negative) runoff anomalies, but little additional runoff during IOD phases is contributed by simultaneous El Niño/La Niña events (Figure 6). Again, subdividing the *kaskazi* into October–December and January–

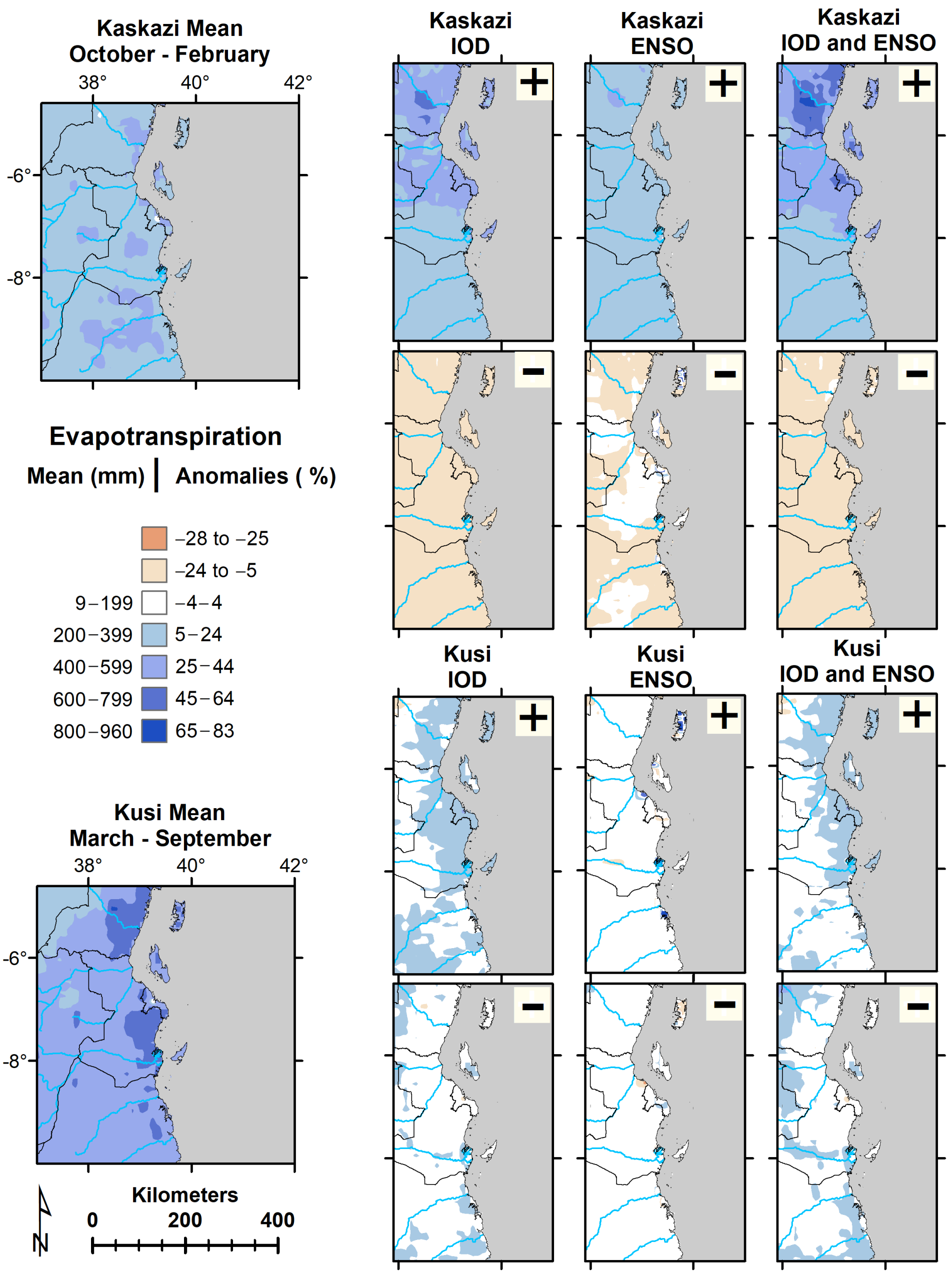

FIGURE 5 As in Figure 4, but for evapotranspiration [Colour figure can be viewed at wileyonlinelibrary.com]

February sub-periods reveals the same general runoff patterns as in the October–February *kaskazi* (not shown).

Kusi runoff anomalies are difficult to assess due to relatively small totals and sharp differences between sub-periods of *kusi*. As in the precipitation analysis, the positive IOD is associated with positive (near-normal) runoff anomalies in the southern (northern) part of study. El Niño/La Niña tends to have minor influences on runoff, resulting in IOD being the dominant driver (Figure 6). However, in contrast to the IOD-related precipitation and evapotranspiration anomalies during *kusi*, the negative IOD is linked to anomalously large *kusi* runoff in northern Tanzania, again with minimal contribution by a simultaneous La Niña event.

Subdivision of the *kusi* runoff into the "long rains" and dry periods (not shown) suggests that the March–May "long rains" period is driving the patterns shown in Figure 6. The IOD seems to have a different influence during the June–September dry period. Specifically, above (below) average runoff occurs during a positive (negative) IOD. Like the March–May and overall pattern, however, ENSO appears to exert little additional influence on the IOD pattern during the dry season.

The hydroclimatic anomalies described above, in addition to other ocean processes, such as upwelling/downwelling, upper ocean mixing, advection by the East African Coastal Current, and inshore flows (Manyilizu *et al.*, 2014; 2016), are inversely related to variability in salinity in the adjacent Indian Ocean, to some extent in the inter-annual time series

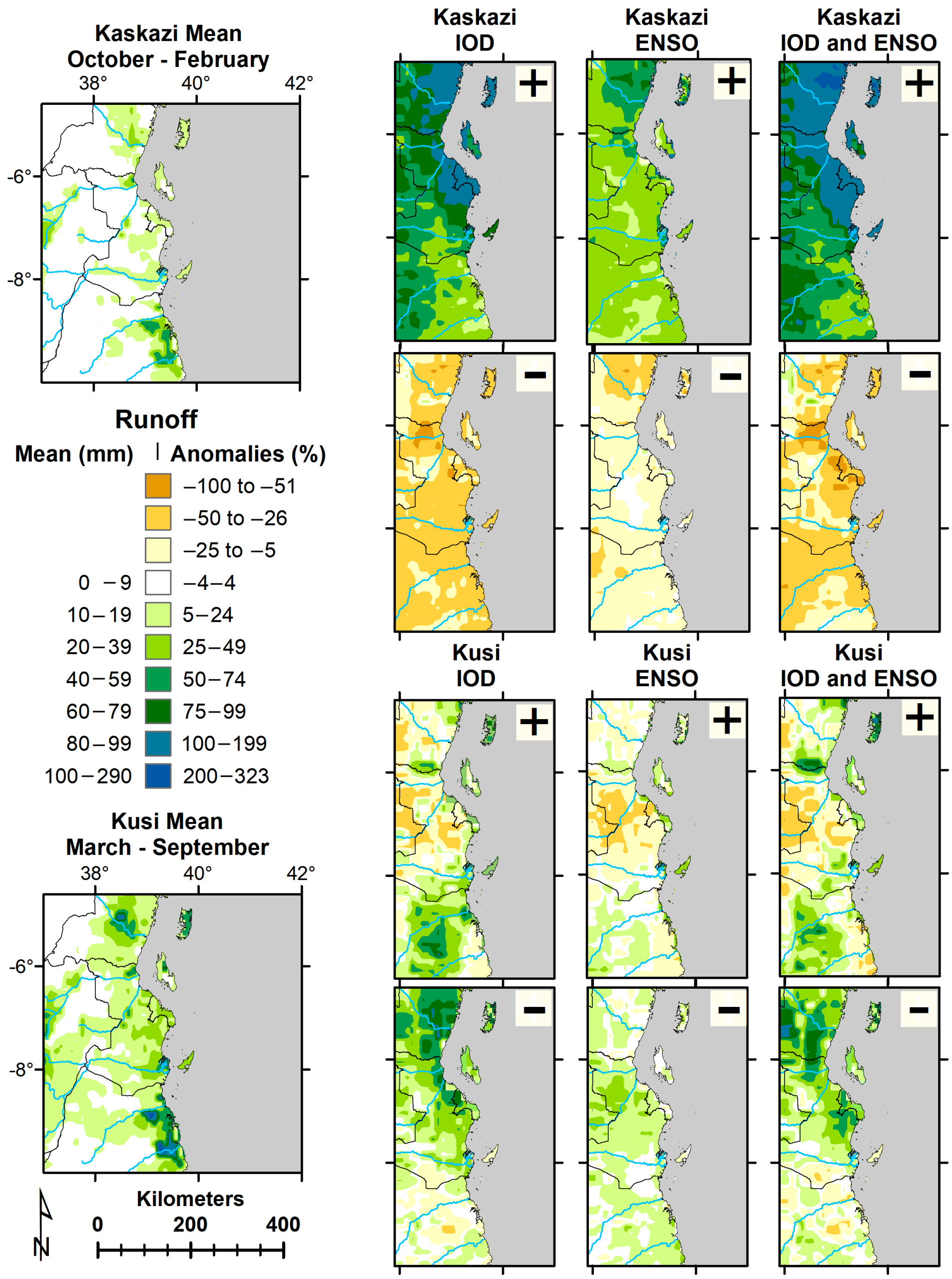

FIGURE 6 As in Figure 4, but for runoff [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 7a) but especially in the monthly cycle (Figure 7b). The range of near-surface salinity adjacent to the Tanzanian coast is less than 2.0 practical salinity units (PSU) across *kaskazi* and *kusi*, even during the modes of the IOD and ENSO (Figure 8). However, these differences may be important for key environmental processes and ecosystem services, such as those involving mangrove vegetation.

6 | SUMMARY AND CONCLUSIONS

This research has identified distinct hydroclimatological patterns of coastal Tanzania, using the most recent climate normals (1982–2010), to advance understanding of how climatic variables drive mangrove and nearby fisheries ecosystem productivity and spatial distribution in this coastal region. In general, along coastal Tanzania, substantially less seasonal precipitation occurs during the time of northeast monsoon (*kaskazi*; ≈October–February) than during the southeast monsoon (*kusi*; ≈March–September). During the *kaskazi*, the positive (negative) phase of the IOD produces positive (negative) anomalies of precipitation, evapotranspiration, and runoff exceeding 50, 25, and 100%, respectively, and reduced (enhanced) salinity in the nearby Indian Ocean by 0.5 practical salinity units, with the positive IOD having a stronger signature. These positive-IOD-related anomalies generally exceed those during *kusi*, when positive precipitation, evapotranspiration, and runoff are only about 20, 30,

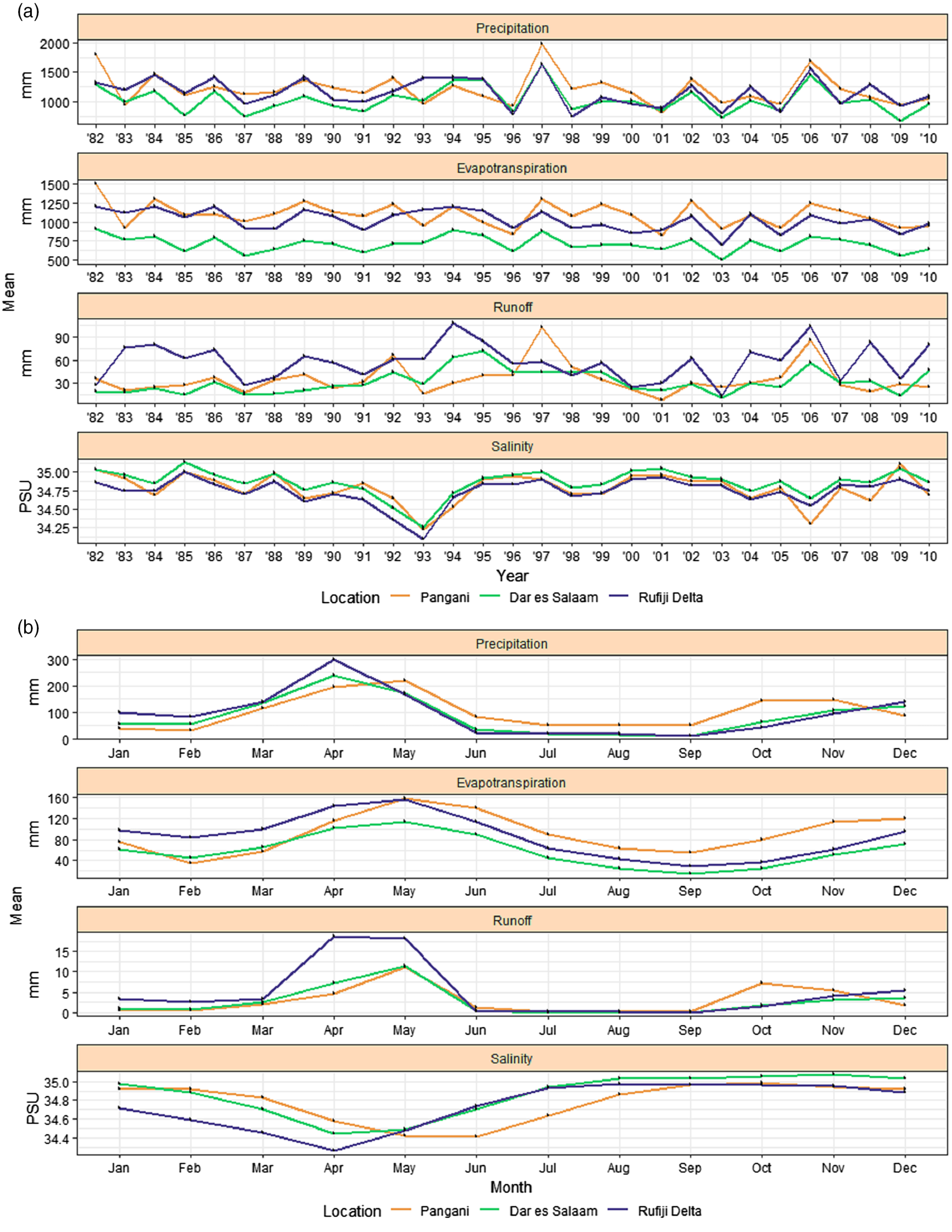

FIGURE 7 Time series of precipitation, evapotranspiration, runoff, and salinity at Pangani, Dar es Salaam, and Rufiji Delta, 1982–2010: (a) annual; (b) monthly [Colour figure can be viewed at wileyonlinelibrary.com]

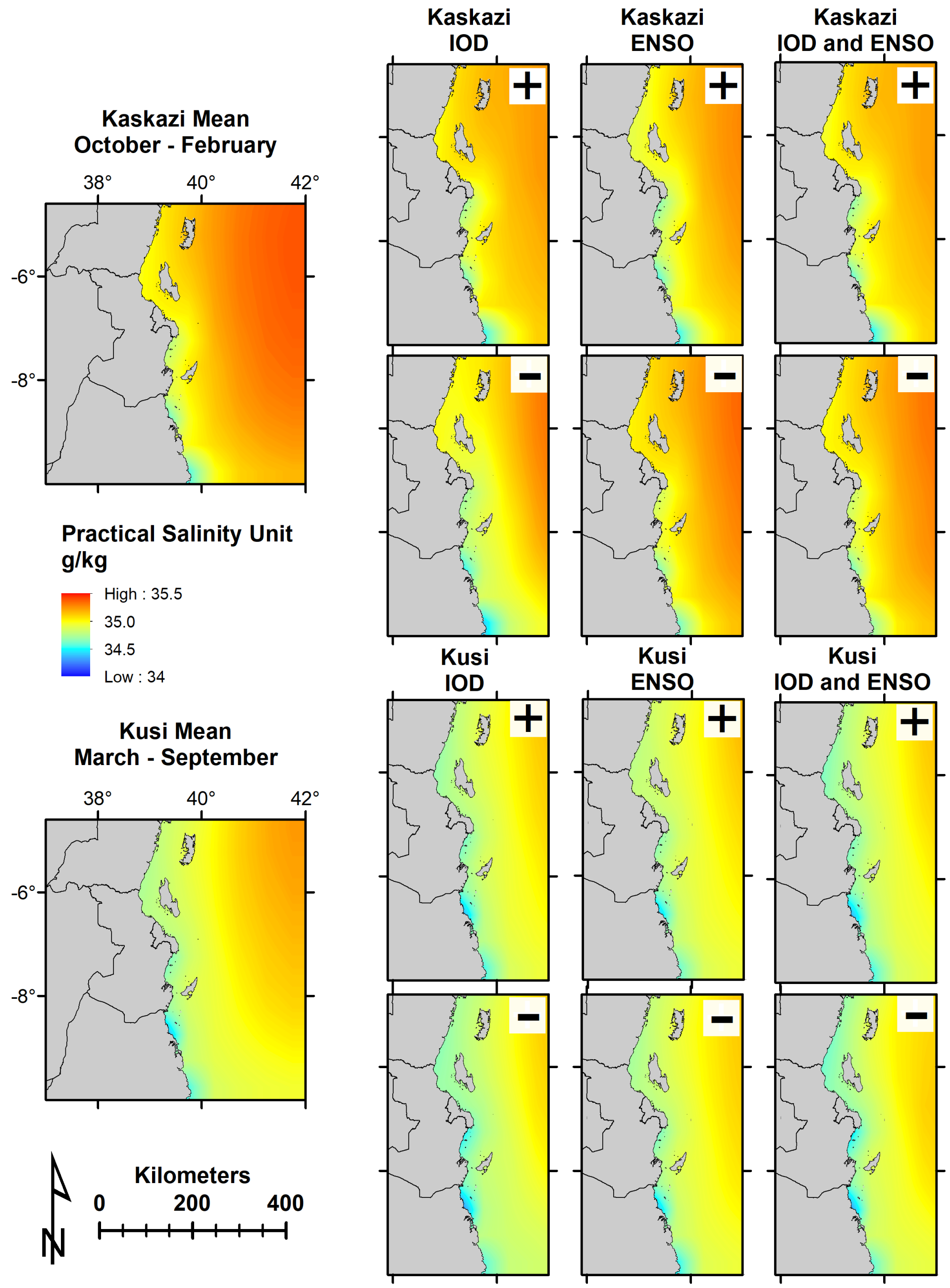

FIGURE 8 As in Figure 4, but for means (rather than anomalies) of practical salinity units [Colour figure can be viewed at wileyonlinelibrary.com]

and 30, respectively. The negative phase of the IOD generates near-normal precipitation and evapotranspiration, but much above-normal runoff during *kusi.* While ENSO effects in general are less prominent than those of the IOD, El Niño enhances precipitation, evapotranspiration, and runoff anomalies during the positive phase of IOD to a greater extent during *kaskazi* (by approximately 25, 20, and 30%, respectively) than during *kusi* (when little anomaly of the consistently minimal precipitation and evaporation occurs). La Niña generally contributes less to these hydroclimatic anomalies than does El Niño. Finally, unlike the patterns observed for precipitation and evapotranspiration, runoff during *kusi* is greater during the negative IOD (and especially during negative IOD + La Niña). However, this *kusi* runoff pattern is driven by the "long rains" of March–May rather than the dry June–September period, potentially affecting stream discharge in the coastal zone.

Results from this study support the notion that low-frequency modes of variability in the form of the IOD and ENSO can have synergistic impacts on the hydroclimatic regime in the region, particularly during the October–February period. Because positive IOD events may become more frequent in the future (Cai *et al*., 2014) and because of the possibility for increased moisture variability associated with El Niño events in the future (Christensen *et al*., 2013), there is a potential for a wetter "short rains" season from a hydroclimatic perspective. As long-lead IOD/ENSO outlooks continue to improve, such seasonal changes to the hydrologic cycle in eastern Africa may become more predictable. Decisions involving human activities in the area, including the use of mangrove wetlands and changes in areal extent due to land use, must consider this likely possibility to align conservation and management policies to support environmental, economic, and social sustainability. This outlook is particularly significant given that mangrove wetlands hold a potential role for mitigation of greenhouse gas emissions (Ringius, 2002; Rovai *et al*., 2016).

Additional analysis of the response of water balance components to IOD/ENSO at a subseasonal scale would be useful for water resource planning purposes in coastal Tanzania. The hydroclimatology of the region has already been noted to be of importance for natural and human systems (Vaidya, 2005), including mangrove wetlands, which depend on an optimal range of freshwater (and associated nutrient) input and salinity regimes (Fatoyinbo and Simard, 2013). More detailed impacts of IOD-related variability on the mangrove and human systems should also be investigated, because IOD/ENSO phases may elicit different seasonal and inter-annual hydroclimatic response. For example, changing patterns within the year and long-term trends in IOD/ENSO may lead to changes in mangrove ecosystem productivity (perhaps through litterfall production and tree growth rates), while impacting households through their drinking water sources, agriculture, and other livelihoods. Furthermore, the effect of extreme events should be examined for their role in mangrove ecosystem disturbance amid the "slow motion" attributes of a changing climate. All such changes, natural and anthropogenic, are likely to influence human livelihood in this ecologically and economically vulnerable coastal region.

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