Extreme rainfall in East Africa, October 2019–January 2020 and context under future climate change

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East Africa's 2019 short rains (October–December [OND]) were one of the wettest in recent decades. Floods and landslides occurred across the region, with initial estimates suggesting over 2.8 million people were adversely affected. Here we highlight some of the factors associated with this anomalously wet season and discuss the season in relation to the expected climate change signals over the region.

Figure 1 depicts the positive rainfall anomaly across East Africa; more than double the climatological rainfall was experienced at many locations. Rainfall started in early October 2019 (Figure 1b) and continued past the normal end of the short rains into January 2020, with flooding in Homa Bay, Kenya, at the end of January. Figure 1(c) shows that 2019 was one of the wettest short rains seasons since 1985, surpassed only by 1997, when large scale flooding was experienced across the region. The extremely high rainfall in 1997 was associated with the strong El Niño event (Black, 2005); there was no significant El Niño event during October–December 2019. Kenya Meteorological Department (KMD) report that all meteorological stations in Kenya recorded above 125% of their October–December long term means during OND 2019. At the coast, Mombasa recorded 942.1mm (over 300% of long-term mean) and in central Kenya, Meru recorded 1415.3mm (KMD, 2019).

October–December 2019 saw a strongly positive Indian Ocean Dipole (IOD, Box 1) event in the Indian Ocean (Saji *et al*., 1999; Webster *et al*., 1999), with anomalously warm SSTs in the western Indian Ocean, adjacent to East Africa, and anomalously cool SSTs in the eastern Indian Ocean. Figures 2(a–c) shows the SST anomalies in October–December 2019, and a time series of the IOD index; showing that this is one of the strongest events in the last 30 years. Positive IOD events tend to lead to enhanced rainfall over East Africa, with the positive IOD events in 1961 and 1997 leading to extremely wet conditions over East Africa (Saji *et al*., 1999); 1997 was also a strong El Niño year. Black *et al*. (2003) report that only IOD events where the Dipole Mode Index (DMI) is greater than 0.5°C for 3 contiguous months (when the zonal SST gradient is reversed for several months) lead to enhanced rainfall over East Africa. The positive IOD event in 2019 started in late summer, and persisted through to December (Figure 2b), thus falling within the 'extreme events' category as defined by Black *et al*. (2003) and influencing East African rainfall (Figures 1 and 2).

Climatologically, during OND westerly winds in the central equatorial Indian Ocean transport moisture away from East Africa (Figure 2g). During extreme positive IOD events strong low-level easterly wind anomalies (Figure 2f) are present in the north-central Indian Ocean, which weakens the westerly flow (Figures 2g,h) that normally transports moisture away from East Africa and leads to wetter conditions over East Africa and drier conditions in the central and eastern Indian Ocean basin (Black *et al*., 2003). Figure 2(e) shows that there were wetter conditions to the west and drier conditions over the central and eastern Indian Ocean in OND 2019. Figure 2(f) shows the 850hPa wind anomaly for OND 2019;

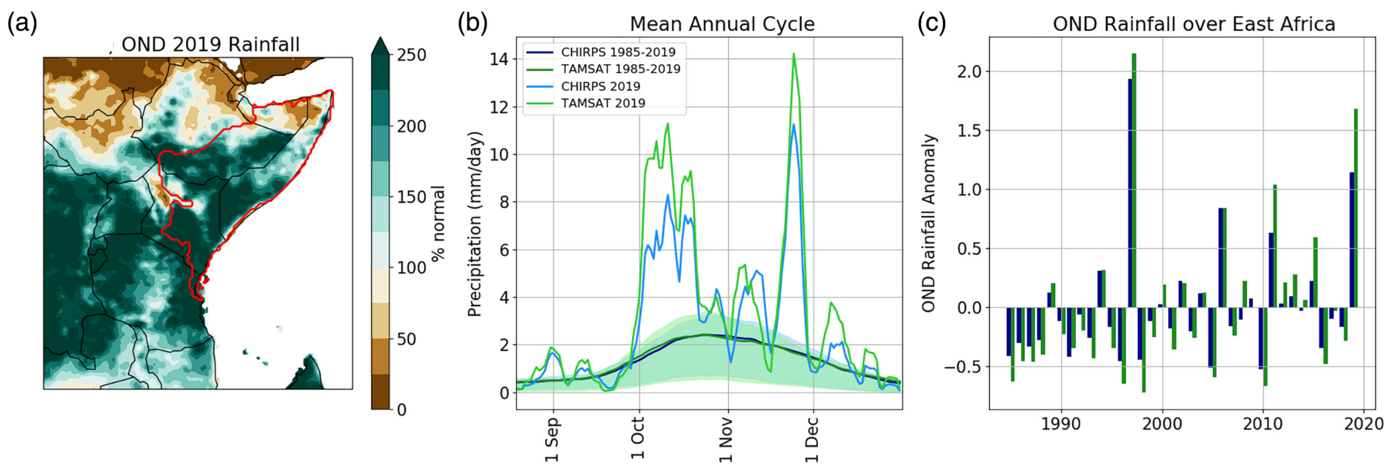

Figure 1. October-December (OND) rainfall across East Africa in 2019. (a) Shows the percentage of normal rainfall received over Eastern Africa in OND 2019 from TAMSATv3 (mean based on 1985–2019). (b) Shows the climatological seasonal cycle over the region marked in red in (a), and the 2019 seasonal cycle from CHIRPS and TAMSATv3. Shading shows the 25/75 percentile. (c) Shows the OND rainfall anomaly for 1985–2019 from CHIRPS and TAMSATv3.

RMetS Royal Meteorological Society

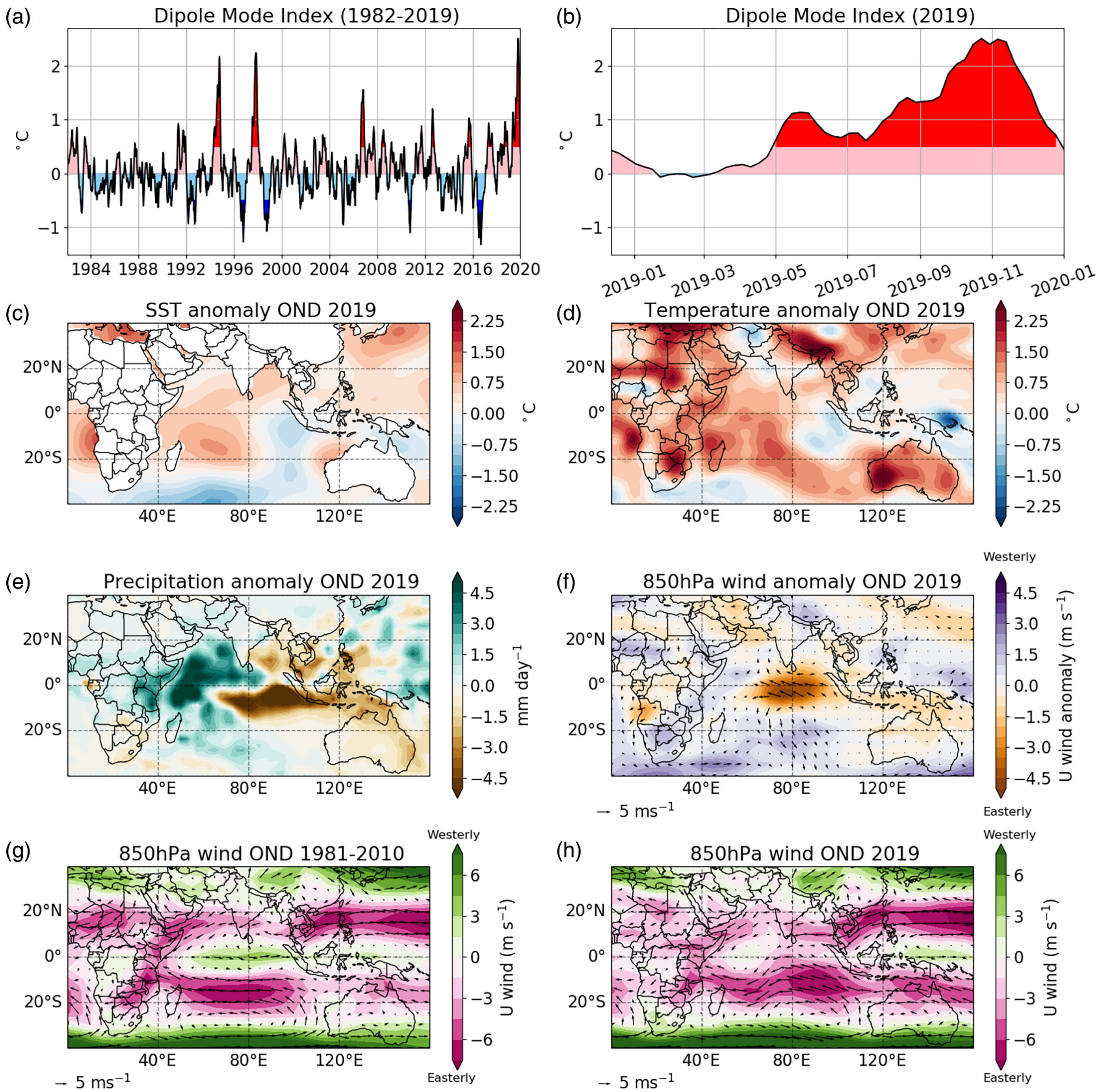

Figure 2. Timeseries of Dipole Mode Index (a, b) and SST anomaly (c), air temperature anomaly (d), precipitation anomaly (e) and 850hPa wind anomaly (f) for OND 2019. In (f) the colours show the zonal wind anomaly, and vectors show the total wind anomaly. (g, h) show the mean climatological 850hPa wind in OND, and the mean 850hPa wind in OND 2019; vectors show the total wind and colours show the zonal wind. DMI taken from https://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php. All anomalies are relative to 1981–2010 and are taken from NCEP reanalysis (temperature and wind), NOAA Extended SST V4 (SST) and GPCP precipitation (precipitation); https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.

this closely resembles the wind anomalies in extreme IOD events (figure 12 in Black *et al*., 2003), and Figure 2(h) shows that low-level winds over the central equatorial Indian Ocean (east of 70°E) were reversed in OND 2019, with strong easterly anomalies and easterly flow south of India (Figure 2f). This acts to reduce the advection of moisture away from, and enhances moisture transport towards, East Africa (Black *et al*., 2003).

Several other factors also contributed to the exceptionally wet season and the extremely heavy rainfall in October and December (Figure 1b). A sub-seasonal tropical atmospheric phenomenon within the atmosphere, which enhances convective activity, called the Madden-Julian Oscillation (MJO), was active over Africa and the Indian Ocean, especially during October. The presence of tropical cyclones in the western Indian Ocean also influenced rainfall over East Africa. In early December, there were four active tropical storms in the Indian Ocean Basin. While only one cyclone made landfall over East Africa (Cyclone *Pawan* made landfall over Somalia on 7th December), the presence of tropical cyclones influences wind patterns, and hence precipitation over the region. However, the interaction is complex; Cyclone *Idai* in March 2019 coincided with a delayed onset of the long rains season and lower rainfall over Kenya, while Cyclones Dumazile and Eliakim in March 2018 were associated with enhanced rainfall over Kenya. Finney *et al*. (2019) demonstrated that during the long rains (March–May [MAM]) the location of cyclones is key to determining their impact; cyclones to the east of Madagascar are associated with westerly winds around

Lake Victoria, which tend to enhance rainfall (Figure 3). In early December 2019, Cyclones Belna and Ambali were both located east of Madagascar and coincided with enhanced rainfall over Kenya. This suggests the results of Finney *et al.* (2019) may be applicable in seasons other than the long rains. Figure 3 shows the 700hPa wind anomaly and precipitation for 7 December 2019; this shows westerly wind anomalies over Kenya and heavy rainfall, particularly over western and southern Kenya. The cyclones north of the equator may have also impacted the flow and precipitation over East Africa.

An above average wet season was correctly forecast in advance (Figure 4). The 53rd Greater Horn of Africa Climate Outlook Forum (GHACOF), held in Tanzania in late August 2019, reported a 'higher chance of wetter conditions in most of the equatorial and southern sectors during October to December 2019' (Figure 4b), with greater than 50% probability of above average rainfall over some regions. This was strongly influenced by the evolving positive IOD event that was forecast to continue during the short rains. The IRI (International Research Institute for Climate and Society) seasonal forecast issued in September 2019 also indicated above normal rainfall for OND 2019 over Eastern Africa (Figure 4a). Given the strong forcing from the IOD it is possible that the GHACOF forecast was overly cautious in predicting increased rainfall; this cannot be evaluated based from a single prediction, but Walker *et al.* (2019) have recently shown to be the case in such situations where there is strong forcing from the IOD.

The anomalously wet conditions continued after the normal end of the short rains in December into January 2020; Figure 5(b) shows the precipitation anomaly over East Africa in January 2020. Following the heavy rainfall in OND 2019, and the saturated soil conditions, this has led to further flooding and adverse consequences. This may be related to the persistence of the warm SST anomaly in the western Indian Ocean (Figure 6). While the IOD index was less than 0.5°C after early January 2020 (Figure 2b), this was due to a weakening of the cool anomaly in the eastern Indian Ocean; the warm SST anomaly in the western Indian Ocean persisted throughout January 2020. Figures 6(a) and (b) shows the interannual correlation between January SSTs and January rainfall over East Africa (region shown on map); this shows that years with warm SSTs in the western Indian Ocean in January are associated with higher rainfall over East Africa in January. Above average January rainfall was also found in 1998 (following the strong IOD event in 1997: Figures 2a, 5a). Figure 6(c) shows that SSTs were also above average in the western Indian Ocean in January 1998. Thus, this persistence of the warm SSTs in the western Indian Ocean may be linked to above average January rainfall over East Africa; further analysis is required to determine the precise mechanisms.

January 2020 has also seen a potentially unprecedented locust outbreak across East Africa, damaging crops and raising concerns around food security. This is related to the extreme weather; wet conditions and above average temperatures (Figures 2d,e and 7b), which have led to favourable climate and vegetation characteristics for the locusts. Again, the same conditions were found in January 1998; although in that case the locust outbreak was restricted to Ethiopia, and did not affect Kenya, perhaps because it experienced a negative temperature anomaly in January 1998 (Figure 7a).

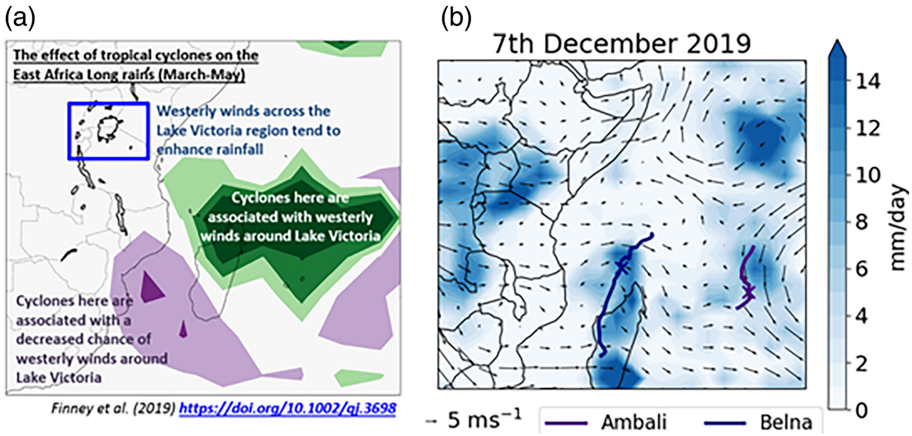

Figure 3. (a) Schematic showing the impact of Indian Ocean cyclones on rainfall around Lake Victoria during MAM, with green/purple colours showing where cyclones are associated with increased/decreased chance of westerly winds over the Lake Victoria region (blue box) (based on analysis in Finney et al., 2019). (b) Figure showing the cyclone tracks (IBTrACS), mean precipitation and 700hPa wind anomalies (NCEP/NCAR reanalysis) on 7th December when Cyclones Ambali and Belna were active in the western Indian Ocean; the cross on the tracks shows the position at 1200 UTC on 7 December 2019.

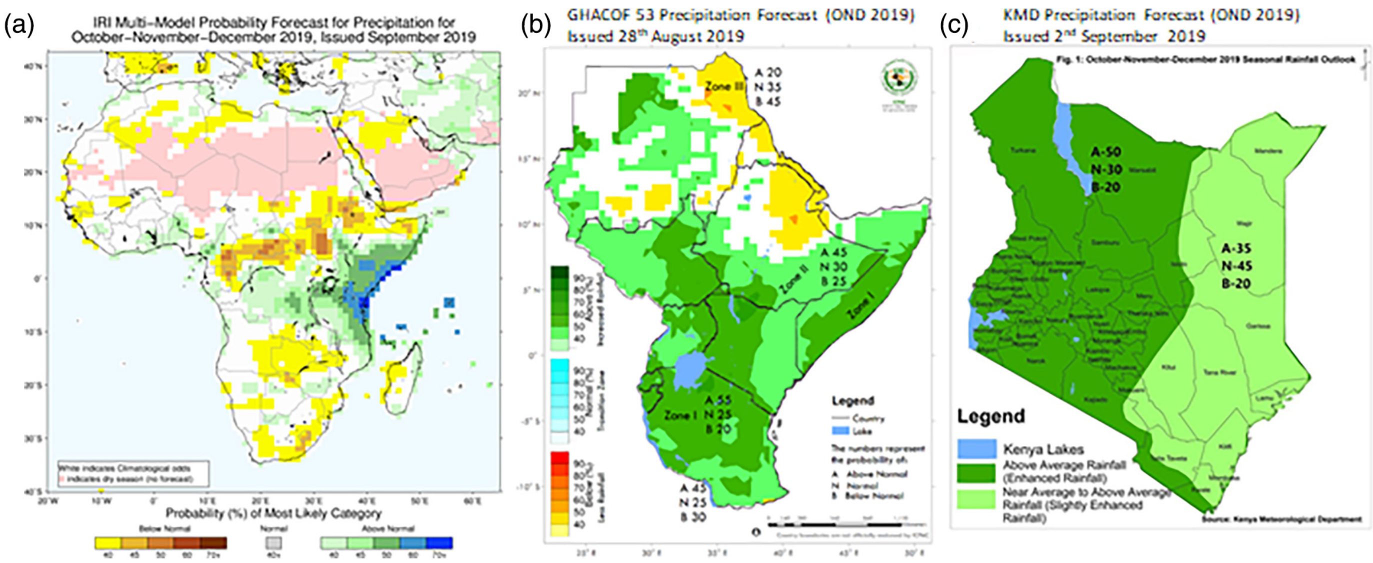

Figure 4. Forecasts for OND 2019 from IRI (a) and GHACOF (b) and Kenya Met Department (c). IRI forecast image credit: International Research Institute for Climate and Society, Columbia University. GHACOF forecast from the GHACOF 53 statement.

Future projections from climate models indicate increasing rainfall during the short rains under future climate change (Rowell *et al.*, 2015; Dunning *et al.*, 2018), suggesting that events such as the increased rainfall during the 2019 short rains could become more frequent under climate change. IPCC projections also show an increase in December–January rainfall over the Horn of Africa, with at least 90% of models agreeing on the sign of change (Collins *et al.*, 2013). Furthermore, recent work has shown that climate change can also increase the intensity of rain in storms over Africa because global warming increases the saturation vapour pressure and so potentially the total column water and storm intensities (Kendon *et al.*, 2019; Finney *et al.*, 2020). Therefore, for any given strength of positive IOD events, more intense rainfall events are expected in the future.

Cai *et al.* (2018) explored the relationship between strongly positive IOD events and climate change; they concluded that under a global average warming of 1.5 degC (above pre-industrial levels) strongly positive IOD events may occur twice as often. Furthermore, the rate of recent warming of the western Indian Ocean is one of the fastest of any tropical ocean over the last century (Roxy *et al.*, 2014), and climate models project that continuation of these higher rates of warming should be expected under climate change (Zheng *et al.*, 2013; Chu *et al.*, 2014). There is strong agreement across climate models regarding these changes in Indian Ocean SSTs, therefore increasing our confidence in increased occurrence of very wet short rains and January rainfall over East Africa under future climate change.

The season had many adverse impacts on society, including severe flooding that led to the destruction of property, loss of lives (both human and livestock) and crops, and displacement of people. In cereal growing regions, farmers were unable to harvest their crops; landslides and mud slides destroyed homes in West Pokot and led to loss of life, and roads and bridges were washed away in some areas, disrupting transport systems (Kenya Meteorological Department, 2019). Furthermore, the season made a major contribution to a rapid rise in Lake Victoria's water level, and combined with above average rainfall during the 2020 long rains led to record breaking water levels there (Marsham, 2020). With future projections suggesting that such seasons could become more frequent under climate change, societies should prepare and adapt for more events similar to the short rains of 2019 and January rainfall of 2020. It will be increasingly important to use forecasts in risk management to help adapt to such events, especially for the short rains, where seasonal forecasts have been shown to have higher skill (Walker *et al.*, 2019).

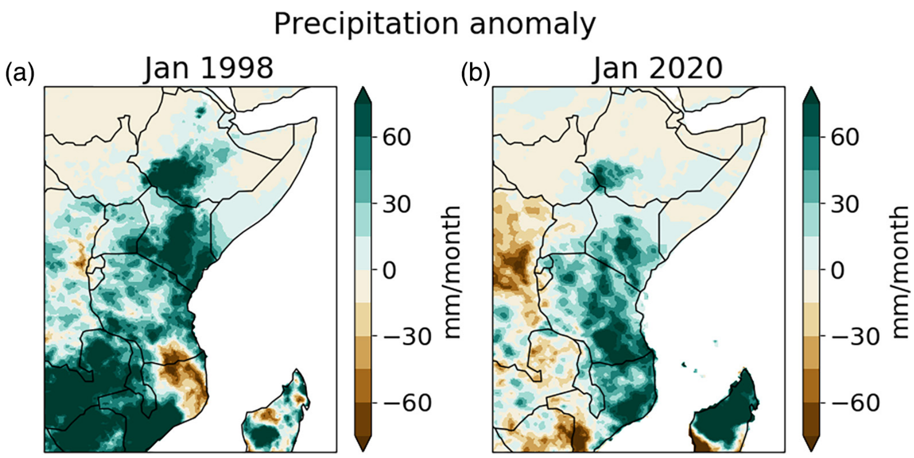

Figure 5. Precipitation (TAMSATv3, relative to 1985–2020) anomalies in January 1998 and January 2020.

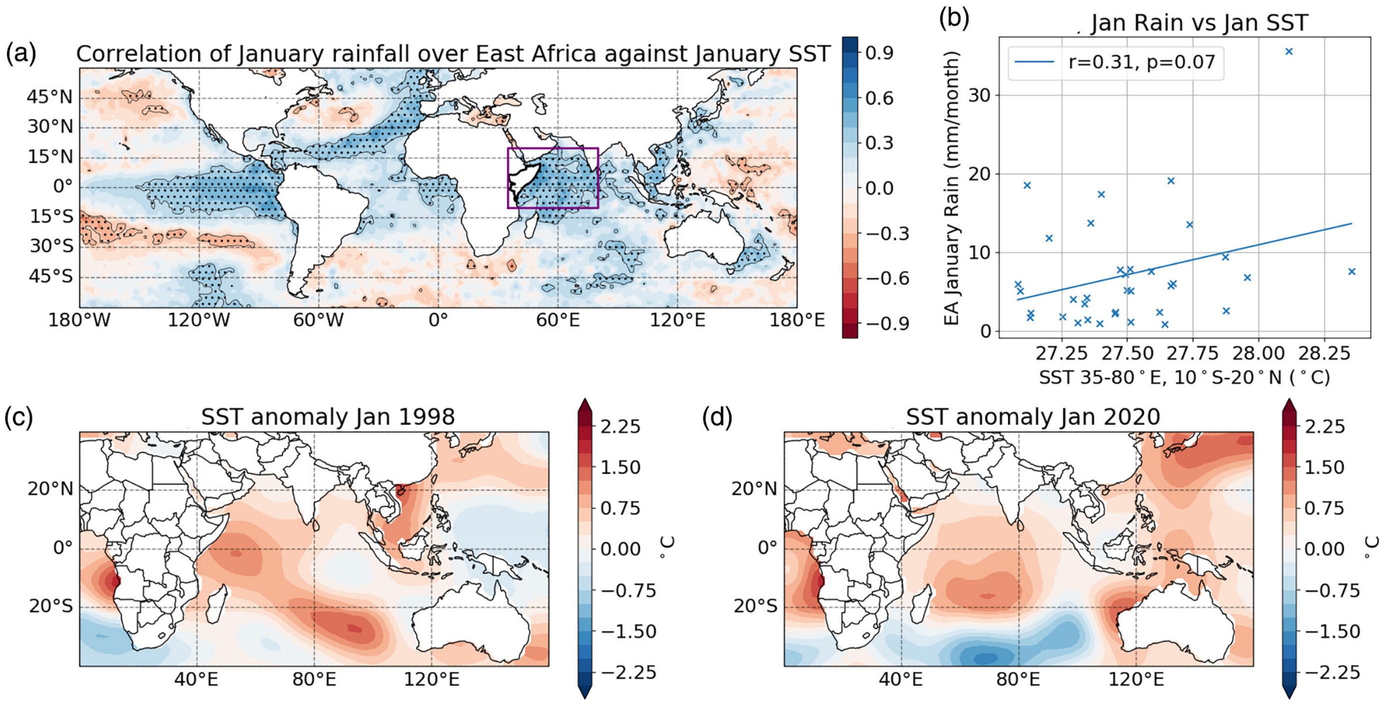

Figure 6. Correlation of January rainfall over Eastern Africa (region in black, TAMSATv3) against HadISST SST over 1985–2019; stippling indicates where the correlation is significant at the 90% level (a). (b) shows the scatter plot of mean January rainfall over East Africa (black region, TAMSATv3) against mean January SST (HadISST) over the purple box shown in (a) for 1985–2019. (c, d) show the SST anomaly in January 1998 and January 2020. For (c and d) SST anomalies are relative to 1981–2010 and are taken from NOAA Extended SST V4 (SST); https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.

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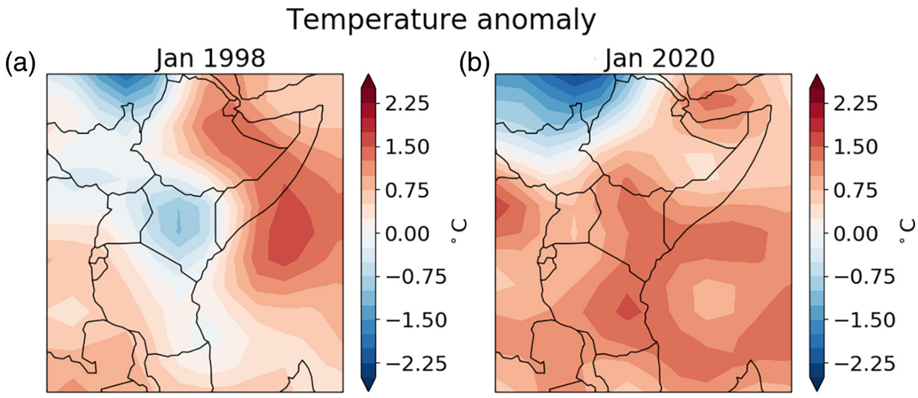
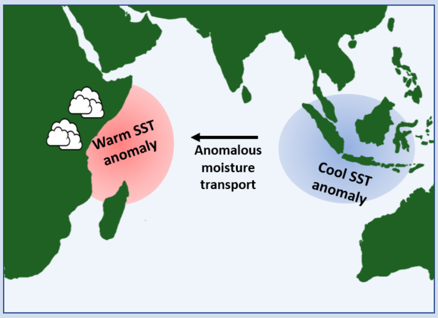


Figure 7. Temperature (NCEP reanalysis, relative to 1981–2010) anomalies in January 1998 and January 2020.

Box 1. Indian Ocean Dipole

The Indian Ocean Dipole (IOD) describes the difference in sea surface temperatures (SSTs) between the east and west Indian Ocean. On average in October–December the eastern Indian Ocean is warmer than the western Indian Ocean. During positive IOD events warm SST anomalies in the west and cool SST anomalies in the east lead to a reversal of the zonal SST gradient, which impacts the weather, particularly rainfall, over the Indian Ocean and surrounding continents. Over East Africa, positive IOD events are associated with enhanced rainfall, whereas over the Maritime Continent and Indonesia positive IOD events are associated with suppressed rainfall.

Often positive IOD events occur during El Niño events, for example 1982 and 1997. But in other years such as 1961 and 2019 strong IOD events can occur during neutral ENSO conditions.



Schematic of a positive Indian Ocean Dipole event.

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TAMSATv3 data is available from http://www.tamsat.org.uk/. CHIRPS data is available from https://data.chc.ucsb.edu/products/CHIRPS-2.0/. DMI Index from https://stateoftheocean.osmc.noaa.gov/sur/ind/dmi.php. IBTrACS data from https://www.ncdc.noaa.gov/ibtracs/. HadISST data from https://www.metoffice.gov.uk/hadobs/hadisst/. Forecast data was obtained from IRI, ICPAC and KMD. All other fields were obtained from https://www.esrl.noaa.gov/psd/cgi-bin/data/composites/printpage.pl.

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