Linkage between Malawi Rainfall and Global Sea Surface Temperature

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Abstract: Correlations between summer rainfall in Malawi and global sea surface temperature (SST) were studied to elucidate the linkage between SST and rainfall. We used SSTs for the period 1979–2011 and rainfall data for 1981–2012 from nine stations, which were grouped into two zones on the basis of inter-station rainfall correlations. The Pearson correlation coefficient was used to test the hypothesis that the main influence on summer rainfall in Malawi was the Indian Ocean SST rather than the Pacific or Atlantic SST. We found that summer rainfall was more strongly correlated with the Indian Ocean SST compared to the Atlantic and Pacific Ocean SSTs. The correlations were more significant for northern stations than for central and southern stations. These results agree with other findings, suggesting that different climatic drivers influence the climate of different parts of Malawi. Northern areas are strongly influenced by the SST Indian Ocean dipole, whereas central and southern areas are strongly linked to the SST in the subtropical Indian Ocean. The results reveal that SST in the Atlantic Ocean off South Africa also affects Malawi rainfall. We conclude that the Indian Ocean SST, including in particular the SST dipole strongly influences Malawi rainfall.

Keywords: Atmospheric circulation; Indian Ocean dipole; Pearson correlation coefficient; SST; Linkage

1 Introduction
The climate of southern Africa is influenced by the position of the subcontinent in relation to the major circulation features of the atmosphere of the southern hemisphere (Torrance, 1972). Southern Africa (SA) is under the influence of a sub-tropical anticyclone throughout the year and experiences a unimodal rainy season from October to April and the distribution of rainfall is erratic both temporally and spatially (Mwafulirwa, 1999). According to Lindesay and Harrison (1986), the Intertropical Convergence Zone (ITCZ), Southern Oscillation, El Niño Southern Oscillation (ENSO), SST and Walker Circulation strongly influence rainfall variability over SA. Generally, rainfall is below normal over southern Africa during El Niño years and above normal during La Niña years (Nicholson and Entekhabi, 1986; Lindesay, 1988).

Many studies have related African rainfall variability to SST over the Atlantic, Indian, and Pacific Oceans. Decreasing SST in central south Atlantic and increasing SST off the coast of southwestern African can lead to a demonstrable increase in daily rainfall and rainfall extremes over SA (Williams et al., 2008). According to Misra (2003), patterns of regional linkage between dominant mode of SA precipitation variability and SST anomalies over eastern Indian Ocean is influenced by variations of Pacific Ocean SST. The nature of the linkage between SA precipitation and eastern Indian Ocean SST is apparent only when the Pacific Ocean SST variability is excluded. Other researchers who have done work on the influence of SST on SA rainfall include Mason and Tyson (1992), Enfield and Mayer (1997).

The literature on linkage between SST and summer rainfall in Malawi is sparse. Notable previous studies have been in the area of climate variability and have included Ngongondo et al. (2011), Jury and Nkosi (2000), Mason (1997), and Nkhokwe (1996). Jury and Mwafulirwa (2002) studied the climate variability in Malawi, statistical associations and predictability. They found negative correlations between dry summers and SSTs in the West Indian Ocean and positive correlations between dry summers and SSTs in the East Atlantic and Agulhas region. A north–south gradient of SST was apparent in the sub-tropical West Indian Ocean. The goal of this study was to clarify the relationships between summer rainfall in Malawi and global SSTs.

2 Materials and methods

2.1 Study area
Malawi is located within tropical southeastern Africa (lat 9–15°S, long 32–36°E). Malawi has an area of 118,000 km² and is dominated on its eastern side by Lake Malawi, which is part of the Great African Rift valley (Kumbuyo et al. 2014). Malawi experiences a savanna climate which is tropical wet and dry. A cool, dry season is experienced from May to August; hot, dry season from September to October; and rainy season from November to April, with annual rainfall averaging 725–2500 mm as reported on www.metmalawi.com/climate web page. The Intertropical Convergence Zone (ITCZ) which migrates from North to South dominates the country and strongly influences rainfall together with topography (Torrance 1972). The ITCZ works in collaboration with the Congo air boundary, northwest monsoon, which consists of redirected tropical...
Atlantic air that reaches Malawi through the Congo basin, and tropical cyclones from the West Indian Ocean (Ngongondo et al., 2011)

2.2 Materials and methods
Rainfall data for the period 1981–2011 from nine rainfall stations in Malawi was obtained from the Department of Climate Change and Meteorological Services (Table 1). Sea surface temperature data for the period 1979–2011 were obtained from the British Atmospheric Data Centre (BADC).

The BADC HadISST 1.1 dataset (http://badc.nerc.ac.uk

| Station No. | Station Name | Zone | Latitude (°S) | Longitude (°E) | Elevation (m) | Mean annual rainfall (mm) | CV |
|-------------|--------------|------|---------------|---------------|---------------|--------------------------|----|
| 1           | Karonga      | 1    | 9.88          | 33.95         | 529           | 942                       | 0.23|
| 2           | Nkhatabay    | 1    | 11.60         | 34.30         | 500           | 1570                      | 0.21|
| 3           | Bolero       | 2    | 11.02         | 33.78         | 1100          | 626                       | 0.22|
| 4           | Kasungu      | 2    | 13.03         | 33.46         | 1036          | 784                       | 0.22|
| 5           | Salima       | 2    | 13.75         | 34.58         | 512           | 1207                      | 0.26|
| 6           | Dedza        | 2    | 14.32         | 34.27         | 1632          | 947                       | 0.16|
| 7           | Mangochi     | 2    | 14.43         | 35.25         | 482           | 805                       | 0.31|
| 8           | Makoka       | 2    | 15.52         | 35.22         | 1029          | 1003                      | 0.21|
| 9           | Ngabu        | 2    | 16.50         | 34.95         | 102           | 826                       | 0.29|

Figure 1: Map of Malawi showing location of study areas

Figure 2: Mean monthly rainfall for Zone 1 and Zone 2

Figure 3: Time series for March–April average rainfall for Zone 1 and December–February average rainfall for Zone 2
relationship between rainfall and SST. Two-month averages of monthly SST were computed to gauge the statistical significance of the correlations observed. The main hypotheses of the study were as follows:

1. Indian Ocean SST is the main factor that influences summer rainfall in Malawi.
2. There is a strong statistical relationship between Atlantic and Pacific Ocean SST and summer rainfall in Malawi.

3 Results and discussion

3.1 Relationship between Zone 1 rainfall and SST

In the South Atlantic Ocean, significant positive correlations between SST and summer rainfall in Malawi were observed off the southwest coast of South Africa at lags 1–4 months (Figure 4). The correlations were more pronounced at lag 4 months. Decreasing SST in the central South Atlantic (lag 1 – 2 months) and increasing SST off the coast of southwestern Africa (lag 3–4 months) have been found to lead to a demonstrable increase of daily rainfall and rainfall extremes over SA (Williams et al., 2008).

Furthermore, they reported that these relationships reflect local effects, such as a change in Walker cell circulation. We believe that Malawi, being in SA, is affected by these phenomena, and that these effects explain the positive correlations observed (Figure 4). Also, Rouault et al. (2003), noted that the occurrence of warm events in the tropical SE Atlantic during the late austral summer can amplify local atmospheric instability, evaporation, and rainfall; leading to above-average rainfall, the effects of which extend further than usual into SA. In the South Atlantic Ocean off the coast of Brazil, SSTs were positively correlated with Malawi rainfall at lags of 4–5 months, and 7–8 months (Figure 4). According to Nicholson (1997), the ENSO signal in African rainfall variability is a result of the influence of the ENSO on SST in the Atlantic and Indian Oceans, which, in turn, influences rainfall. He reported that cold (La Niña) and warm (El Niño) phases of the ENSO cycle relate correspond to improved and decreased rainfall over the African continent. However, the onset of the warming and cooling in the south and equatorial Atlantic occurs progressively later from south to north; thus the signal “propagates” northward.

At lags of 5–8 months, negative correlations between SST and rainfall were observed in the Indian Ocean, southeast of Madagascar (Figure 4). The correlations were more pronounced at lags of 7 and 8 months. A region of significant positive correlation was observed in the north, east and northeast of Australia in the Pacific Ocean and the area between Indonesia and Australia in the Indian Ocean at lags of 5–11 months (Figure 4). From lags of 8 months, the area of positive correlation moving towards the Indian subcontinent and finally reaching east Africa at Lag 11 months (Figure 4) in the region bounded by 50–125°E and 30ºN–30ºS. The correlations were associated with type I error rates of 1–5%. Reason (2001a), Behera and Yamagata (2001) in their study of subtropical Indian Ocean SST dipole events and southern African rainfall reported that when the SST is warm (cold) to the south of Madagascar and cool (warm) off Western Australia, increased (decreased) summer rains occur over large areas of southeastern Africa. This SST pattern leads to increased (decreased) rainfall via enhanced convergence of air with above-average moisture content over the region. These events produce above-normal rainfall over many parts in south-central Africa. Likewise, Xie and Arkin (1996) have suggested that when warm SST anomalies occur to the south of Madagascar and cool anomalies occur off Western Australia, summer rains over southeastern Africa are enhanced. Furthermore, these authors suggest that the impact on rainfall is related to a weakening of the maritime ITCZ over the Indian Ocean and enhanced moisture transport towards southeastern Africa by stronger Southeasterlies.

In the North Atlantic Ocean, a region of significant positive correlation between SST and summer rainfall in Malawi was apparent at lags of 5–8 months. The region extends from the Caribbean Sea, North America, coasts of Portugal and West Africa (Figure 4). Enfield and Mayer (1997) reported that the SST in the tropical Atlantic differed independently on an inter-annual basis in the zones north and south of the ITCZ. They further reported that these events appear to be associated with a northward shift in the latitude of the ITCZ, with consequent warming immediately north of the mean ITCZ position and weak cooling to the south. The shift in ITCZ northward can have an effect on rainfall
amounts and distribution in Malawi as Malawi rainfall is dependent on ITCZ.

3.2 Relationship between Zone 2 rainfall and SST
Positive correlations between the SST southwest and southeast of Madagascar and Malawi rainfall are apparent at lags of 2–5 months (Figure 5). At lags of 8–11 months (Figure 5), a significant positive correlation is apparent in the Indian Ocean, the duration of the lag shifting from the Indonesian coast toward Australia. This region is bounded by 90–120ºE and 0–30ºS.

Negative correlations between SST and summer rainfall in Malawi at lags of 3–4 are apparent in a region of the Indian Ocean bounded by 60–90ºE and 20–40ºS. The

Figure 4: Correlation map for SST and rainfall for Zone 1 at 0-11 months lag. The legend shows the scale of the correlation
correlations in this region are associated with type I error rates of 1–5%. According to Rocha and Simmonds (1997), anomalously warm SSTs in the tropical Pacific and Indian Oceans, related to ENSO events, produce dry conditions over much of southeastern Africa. They further stated that rainfall in southeastern Africa is greatly affected by SSTs in the central Indian Ocean, which are partially independent of ENSO. Reason and Mulenga (1999) noted that there appears to be a mixed influence of El Niño and La Niña on wet and dry years and SST anomalies in the tropical Indian Ocean, as well as in the Pacific Ocean. This influence is reminiscent of the ENSO effect on dry and wet conditions over southeastern Africa. It can be deduced that the negative correlation is due to the opposite of this phenomenon. There is a significant negative correlation (p = 1–5%) between SST and summer rainfall in Malawi in the region bounded by 30–60°W and 20–35°N in the North Atlantic Ocean at lags of 5 and 6 months, as shown in Figure 5. Fauchereau et al. (2003) revealed that in the tropical Atlantic, the influence of SST in the southern basin overshadows the influence of SST and upper-air dynamics in the northern basin.

Figure 5: Correlation map for SST and rainfall for Zone 2 at 0-11 months lag. The legend shows the scale of the correlation
Table 2: Cross correlation for differenced time series for Zone 1

| Location     | Lags   | Positive SST correlation | Negative SST correlation | Differenced time series |
|--------------|--------|--------------------------|--------------------------|-------------------------|
| Indian Ocean | 4 – 5  | 0.60                     | -0.43                    | 0.62                    |
| Pacific Ocean| 2 – 3  | 0.54                     | -0.62                    | 0.63                    |
| Pacific Ocean| 4 – 5  | 0.57                     | -0.48                    | 0.57                    |

The study further reported that a warm South Atlantic reduces the thermal gradient with the African continent, the result being a southward shift of the ITCZ. Rainfall not directly associated with ITCZ activity and falling in areas bordering the South Atlantic Basin is by contrast positively correlated with SST (high rainfall in years of warm South Atlantic waters); that is the case from Angola to Gabon in April–May, and then further north as the season proceeds.

3.3 Differenced time series
Malawi rainfall showed both positive and negative correlation with Atlantic, Indian and Pacific SST. According to Yasuda et al., (2009) taking the difference between the positive and negative time series \( r \geq 0.36 \) gives a dipole effect in the resulting differenced time series. Using this approach, the differenced time series were calculated and the results showed increased correlations (Table 2). For example the positive correlation value for Indian Ocean SST at lags 4 and 5 months was 0.59 and for negative correlation was -0.43 but the correlation for differenced time series was 0.62 for Zone 1. This means that a dipole effect was created and agrees with literature that the Indian Ocean dipole has an effect on Malawi rainfall.

4 Conclusions
We found that summer rainfall in Malawi was more strongly correlated with SSTs in the Indian Ocean compared to those in the Atlantic and Pacific. The correlation was more significant for Zone 1 (northern stations) than Zone 2 (central and southern stations). The rainfall in Zone 2 appears to be influenced more by SST in the subtropical Indian Ocean than by ENSO or the tropical Indian Ocean dipole. These findings are consistent with those from other studies, such as by Wood and Mornierie (2013). Malawi straddles both equatorial east Africa (north of 10°S) and subtropical southern Africa (south of 15°S), and given its geographic location, this study concluded that the northern and southern regions of Malawi are likely influenced by different climate drivers.

The present study also revealed that the Atlantic SST influences summer rainfall in Malawi. The areas of influence are the southwest of SA and off the coast of Brazil, but the influence was significant for Zone 1 only. We can speculate that the Agulhas current, which flows off the southwest coast of Africa, has an influence on air-sea interactions and intensification of weather systems, including modification of regional atmospheric circulation and modulation of climate mode impacts (e.g., the Benguela Niño and the subtropical Indian Ocean dipole). The SSTs in the Pacific Ocean were more strongly correlated with summer rainfall in Zone 2 than Zone 1. These correlations reflect the influence of ENSO signals and circulation patterns, as previous studies have revealed. The SSTs in the Persian Gulf, Red Sea, and Mediterranean Sea were significantly and negatively correlated with summer rainfall in Malawi. Further investigations are needed to establish whether there is some atmospheric circulation anomaly that is forcing the significant correlations between SST and rainfall in these cases.

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