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Linking El Niño Southern Oscillation (ENSO) to Zimbabwe droughts

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Abstract
This study is aimed at establishing the link between El Niño Southern Oscillation (ENSO) and Zimbabwe droughts. The influence of ENSO on Zimbabwe droughts is investigated by looking at the relationship between ENSO and rainfall. Results suggest that during the rainy season following the beginning of an El Niño event, Zimbabwe usually experience dry conditions. Likewise, most of the negative Standardized Precipitation Index (SPI) values over the country correspond with El Niño events. Atmospheric anomalies which include westerly wind in the upper atmosphere, anomalously warm temperatures in the troposphere, weak vertical motion and high tropospheric pressure that occur during Zimbabwe droughts are also identified. Anomalously warm SSTs in the central and eastern tropical Pacific Ocean (El Niño events) have been related to changes in the upper – level wind and warm tropospheric temperatures which are associated with drought across Zimbabwe and southern Africa.
Key Words: *Zimbabwe; El Niño Southern Oscillation (ENSO); drought; Standardized Precipitation Index (SPI); correlation*

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I. Introduction

Although it has become the norm for southern Africa to experience droughts, it remains the dominant natural disaster over the region (Rouault and Richard, 2005; Shiferaw et al; 2014; Washington and Preston, 2006). Since most southern African economies depend mostly on rain fed agriculture (Seck et al, 2013; Waithaka et al, 2015), the significance of effective early warning information dissemination for informed decision making with regards to drought episodes is of paramount importance.

Some studies have indicated that natural variability particularly ENSO is the main cause of global drought events (Trenberth et al., 2014; Wang et al., 2014). Also many previous studies have established the influence of ENSO on southern Africa climate variability (Banu et al, 2015; Manatsa and Mukwada, 2012; Ratnam et al, 2014; Rouault and Richard, 2005). Zimbabwe has not been spared of the detrimental effects of the El Niño phenomenon; the 1991/92 drought which threatened the national food security and killed a lot of livestock and recently the 2015/16 poor growing season highlighted the negative impacts of the El Niño phenomenon to rainfall across the country (Maphosa, 1994; Hulme, 2005; Mamombe et al., 2016).

Although the persistence of the Botswana Upper High (Figure 1) results in drought episodes over Zimbabwe (Davis, 2011), the El Niño phenomenon has greater impacts since it affects the sea surface temperatures (SSTs) and air circulation in the Atlantic and Indian oceans which are regarded as the sources of moisture for southern Africa (Meyers et al., 2007).

This study is aimed at investigating the contribution of the El Niño phenomenon to droughts over Zimbabwe. We investigate the relationship between rainfall, sea surface temperatures (SSTs) and atmospheric variables that are linked to both the ENSO phenomenon and Zimbabwe rainfall. This is expected to make significant contributions to the country's early warning system.

II. Materials and Methods

In this study, we use monthly rainfall data from 102 stations dotted around Zimbabwe. The data was provided by the Meteorological Services Department of Zimbabwe. The station data was interpolated onto 0.5˚ x 0.5˚ regular grids. A seasonal subset was then created by averaging the monthly values into the following four groups; June, July and August (JJA); September, October and November (SON); December, January and February (DJF). Figure 2 shows the distribution of stations from which the data were obtained.

The sea surface temperatures used in this study are the National Oceanic and Atmospheric Administration (NOAA); NOAA_OI_SST_V2 data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, from their Web site at http://www.esrl.noaa.gov/psd/ (Reynolds et al., 2002). The analysis utilizes SSTs simulated by sea ice cover, in situ and satellite SSTs. For the ENSO time series, we used the anomaly index found on http://www.esrl.noaa.gov/psd/gcos_wgsp/Timeseries/Data/nino34.long.data (Kaplan et al., 1998).

For the relative humidity (RH), zonal wind (u), meridional wind (v), mean sea level pressure (MSLP), air temperature (T) and geopotential height at different levels the NCEP/NCAR reanalysis 2 derived data is used (Kalnay et al., 1996).

The Pearson's correlation coefficient (r) (Spiegel, 1988) is used in this study. Significance is estimated by the student's t statistic and a two tailed 5% significance level is applied in all cases unless specified otherwise.

III. Relationships between Zimbabwe rainfall and sea surface temperatures

The relationship between SSTs and rainfall is investigated by correlating summer rainfall with global SST anomalies in every 2.5° x 2.5° grid box. For the purposes of forecasting, we try to find the link between SSTs and rainfall, whereby SSTs will be leading rainfall. Thus, we used the seasonal (December, January, February (DJF); March, April, May (MAM); June, July, August (JJA); and September, October, November (SON)) SST anomaly data sets in this analysis. Seasonal rainfall is correlated with SST anomalies at 12 months lead (DJF SSTs), 9 months lead (MAM SSTs), 6 months lead (JJA SSTs), 3 months lead (SON SSTs) and at zero lag (DJF SSTs).

The results suggest that there is a strong connection between ENSO events and rainfall fluctuations in Zimbabwe. From the correlation field (Figure 3), there is a zone of negative correlations between Zimbabwe rainfall and SST anomalies across much of the tropical Pacific Ocean. The Niño 3.4 region is defined as the area bounded by (120°W-170°W) and (5°S-5°N) (Trenberth, 1997). Nine months before the rainy season, significant negative correlations between Zimbabwe rainfall and SSTs are realized over the Niño 3.4 region. The same correlation pattern is realized over the Atlantic, Indian and Pacific Oceans when the SSTs lead rainfall by six months (SON SSTs). However, a better defined correlation pattern and a notable zone of significant correlations (anomalously warm SSTs in drought years) are covering the tropical Pacific Ocean. From the simultaneous correlation field, DJF SSTs, the same pattern as that of SON is observed over the tropical Pacific Ocean. This implies that warmer than normal SSTs over the region (El Niño events) may result in drought episodes across Zimbabwe and cooler than normal SSTs (La Niña events) result in wet episodes across the country. This implies that there is a strong association between Zimbabwe rainfall fluctuations and the ENSO phenomenon such that anomalously warm SSTs over the tropical Pacific Ocean (El Niño) may lead to drought events over Zimbabwe and anomalously cool SSTs over the region (La Niña) result in wet events over Zimbabwe. This implies that El Niño events have a significant influence on the occurrence of drought events across the country.

IV. Relationships between rainfall and atmospheric variables

In this section, an analysis of the physical processes that are accountable for the differences in the rainfall distribution across Zimbabwe during El Niño events is performed. Basically, we investigate the type of the relationship between rainfall and SST through analyzing the atmospheric circulation conditions that are characteristic of dry summers.

4.1 Air temperature

With the ever increasing risk of climate change, there is need to understand the connection between temperature and rainfall, and how the temperature relates to the ENSO phenomenon. Numerous studies have projected an increase in the frequency of El Niño events due to global warming (Ashok et al, 2009; Cai et al, 2014; Hansen et al, 2006; Timmermann et al, 1999). The relationship between Zimbabwe rainfall and air temperature is depicted in figure 4. At the surface (850hPa), there is a zone of negative correlations over southern Africa. Thus, an anomalously warm atmosphere results in suppressed rainfall and drought events. At 500hPa and 200hPa, the correlation field covers a much larger area. The El Niño phenomenon is associated with more solar radiation and diabatic heating in the tropical and subtropical regions of continental southern Africa (Trenberth et al, 2002). On the other hand, increased surface moisture and precipitation lead to increased evaporation and cooler surface temperatures (Dai et al, 1999). This implies that surface air temperature variations may be affected by variations in cloud cover.

4.2 Wind

As with temperature, correlations between Zimbabwe rainfall and the meridional wind component at 850hPa, 500hPa and 200hPa (V850, V500, V200) and the zonal wind component at 850hPa, 500hPa and 200hPa (U850, U500, U200) were computed. The correlation fields between rainfall and zonal and meridional winds are depicted in figures 5 and 6 respectively. At the surface (U850, V850), the correlations between rainfall and zonal wind are not significant and the low tropospheric meridional wind anomalies are south-easterly (negative correlations) over Zimbabwe. However, surface westerly wind anomalies over the tropical Indian Ocean have been observed to occur during El Niño events (Cadet, 1985).

At 200hPa, a well-defined pattern of significant negative correlations (westerly zonal wind anomalies during drought years) exist in Zimbabwe (15º-20ºS) and easterly wind anomalies (positive correlations) are realized in the middle levels (500hPa). Anomalously westerly airflow at 200hPa has been reported to occur over southern Africa during El Niño events (Lindesay, 1988b; Misra, 2003; Rocha and Simmonds, 1997). Also, westerly wind anomalies are detected at 200hPa across much of the tropical Indian, Atlantic and eastern Pacific Oceans. A weaker easterly airflow at 200hPa over southern Africa results in drought episodes because it reduces the formation of cloud bands and frequency of easterly waves over the region (Vecchi & Harrison, 2000).

4.3 Mean sea level pressure (MSLP)

The correlation field between Zimbabwe rainfall and mean sea level pressure is depicted in figure 7. For the purposes of forecasting, correlation analysis was performed for MSLP leading rainfall by six months (JJA MSLP), MSLP leading rainfall by three months (SON MSLP) and at zero lag (DJF MSLP). During drought episodes, the atmosphere over southern Africa, the Atlantic and Indian Oceans goes through significant changes as highlighted by the anomalously high MSLP (negative correlations) over the aforementioned regions. Six months before drought events (JJA MSLP), most of the Atlantic is covered by anomalously high pressures and the tropical eastern Pacific Ocean is dominated by anomalously low pressures (Figure 7). At three months lead, MSLP leading rainfall by three months (SON MSLP), a well defined correlation field extends from the tropical Atlantic Ocean to southern Africa. The same pattern is observed at zero lag (during DJF) but a zone of anomalously low pressures is observed over the tropical south eastern Atlantic, off the south west coast of South Africa during dry summers over Zimbabwe and southern Africa. Generally, pressures are expected to decrease over southern Africa during Austral summer because that is when the intertropical convergence zone (ITCZ) will be over the region. The ITCZ which is characterized by a band of low pressure systems is one of the major rainfall bearing systems for the tropical region. Climatic variations linked to the ENSO phenomenon have a significant influence on the seasonal movement of the ITCZ (Ambrizzi et al., 2004). This is the reason why pressures over southern Africa tend to be anomalously high during El Niño events which then leads to drought over Zimbabwe and southern Africa at large. This implies that El Niño inhibits the southward movement of the ITCZ over southern Africa by creating blocking high pressure systems over the region.

4.4 Geopotential Height

Results suggest an inverse proportionality between Zimbabwe rainfall and geopotential height as highlighted by the negative correlation field both at 850hPa and 500hPa levels (Figure 8). This implies that the higher the pressure at the surface and in the middle levels, the lower the rainfall. High pressure systems are usually associated with divergence and sinking air motion in the atmosphere. Thus high pressure in the middle levels inhibits rainfall. This implies that prolonged periods of anticyclonic circulation during the rainy season over Zimbabwe and southern Africa results in drought episodes over the country and the region at large. Middle level (500 hPa) positive geopotential height anomalies have been observed over southern Africa during El Niño events (Wang et al., 2014). Thus El Niño events result in pressure increases and this would in turn lead to dry conditions and hence, drought episodes across the country. At 200 hPa, there are negative correlations between Zimbabwe rainfall and geopotential height but the correlations are weaker than those at 850 hPa and 500 hPa (Figure 8c).

4.5 Vertical Velocity

Figure 9 shows the relationship between Zimbabwe rainfall and vertical velocity. Upward motion results in rainfall and downward motion results in sinking air and clear skies. From the results, there is negative correlation between Zimbabwe rainfall and vertical velocity over Zimbabwe because vertical pressure velocity in pressure coordinates is used to measure vertical motion. The relationship between vertical velocity and rainfall was evaluated at three pressure levels; 850hPa, 500hPa and 200hPa and maximum correlations were found at 200hPa. This implies that during a season where the vertical motion is weak, subdued amounts of rainfall will be realized across the country and therefore drought conditions would affect the country. ENSO has been reported to affect precipitation by causing changes in the vertical motions in the middle levels (Hoell et al., 2016).

4.6 Relative Humidity

The relationship between Zimbabwe rainfall and relative humidity at (a) 850 hPa and (b) 500 hPa pressure levels is displayed in figure 10. The correlation fields show that during drought episodes, the relative humidity at both the surface (850 hPa) and in the middle levels (500 hPa) will be anomalously low as indicated by the significant positive correlations across the country. Results suggest increased relative humidity over the Central Indian Ocean during drought events over Zimbabwe as shown by the negative correlations. Similarly, over the tropical Pacific, the relationship is negative (higher relative humidity during drought events) as depicted by a well defined area of significant negative correlations. It is worth noting that regions of low relative humidity (positive correlations) and regions of anomalously high mean sea level pressure (negative correlations) in figure 7(c) correspond particularly over southern Africa, tropical Pacific Ocean and south east Atlantic Ocean off the west coast of South Africa. During dry summers, continental high pressures over southern Africa weaken the thermal low pressures which are favorable for increased vertical motion and this implies that there will be decreased moisture condensation in the middle levels (500 hPa) and hence less rainfall which then results in drought conditions across the country.

The standardized precipitation index (SPI) scatter plot in figure 11 shows how different phases of ENSO affect rainfall over Zimbabwe. Different colors represent different phases of the ENSO phenomenon. Generally, during El Niño years the country receives less rainfall as indicated by the number of negative SPI values during the El Niño events. It is interesting to note that all the El Niño events which occurred after the year 1989 resulted in negative Zimbabwe SPI. The 1991/92 season is the driest season for the period under investigation. This could be attributed to the increase in the intensity of the El Niño events because of global warming (Ashok and Yamagata, 2009; Lee and McPhaden, 2010).The meanings of the SPI values are shown in table 1. Most of the El Niño events resulted in negative SPI values for Zimbabwe rainfall. Although most of the rainfall seasons may be classified as near normal, the majority of these events resulted in agricultural drought across the country. This implies that El Niño events result in subdued rainfall amounts over Zimbabwe.

Table 2 shows the different phases of the ENSO and the resultant rainfall over Zimbabwe for the period 1951 to 2010. Above normal rainfall is received when mean rainfall exceeding 125% of the long term average is received and below normal rainfall is received when the seasonal mean rainfall amount is less than 75% of the long term average. Results indicate that most of the drought events occurred during El Niño episodes as highlighted by the higher percentage of below normal rainfall during El Niño events. This implies that El Niño events usually lead to drought events across the country. Results suggest that ENSO influences seasonal rainfall by affecting the prevalence of a number of tropical and mid latitude atmospheric systems.

V. Conclusions

This study was aimed at investigating the influence of the ENSO phenomenon to the frequency of occurrence of droughts across Zimbabwe. This was achieved by correlating Zimbabwe rainfall with SSTs and the atmospheric variables that respond to variations in the phases of the ENSO. The relationship between rainfall and ENSO is such that during El Niño (warm phase) dry conditions usually associated with lower than average rainfall are usually realized and during La Niña (cold phase) rainfall will be mostly within the average to above average range. Therefore, anomalously high SSTs over the tropical Pacific Ocean usually correspond to drought conditions across the country. Results also show that most El Niño events are associated with negative SPI over Zimbabwe.

Rainfall correlates significantly with the zonal wind at 200hPa. During drought episodes, an anomalously westerly airflow prevails across the country and southern Africa. Also during drought episodes, the atmosphere over Zimbabwe and southern Africa goes through significant changes as highlighted by the anomalously high MSLP, anomalously high temperatures in the troposphere, decreased relative humidity over the country, weak vertical motion and high pressures in the middle levels. The above changes to the atmospheric conditions usually occur during El Niño events. This implies that El Niño contributes significantly to droughts over Zimbabwe. Hence the option of growing drought tolerant crops particularly small grains and short season varieties would be encouraged during El Niño years and farmers should also be encouraged to retain their harvests from the previous season in order to avert hunger. It is also recommended that the country be adequately prepared for cloud seeding before the commencement of the rainy season during the warm phase of ENSO and awareness programmes on the prudent use of water in both rural and urban areas should be increased during dry years. .

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Table 1. Standardized Precipitation Index values and their interpretation

Standardised Precipitation Index value	Atmospheric conditions
2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to -1.49	Moderately dry
-1.5 to -1.99	Severely dry
≤ -2	Extremely dry

Table 2. Different phases of ENSO and the resultant rainfall over Zimbabwe for the period from 1951 to 2010

ENSO Phase	Received rainfall				Total
	Number of years with above normal rainfall	Percentage	Number of years with below normal rainfall	Percentage	
El Niño	8	38	13	62	21
La Niña	10	67	5	33	15
Neutral	13	54	11	46	24

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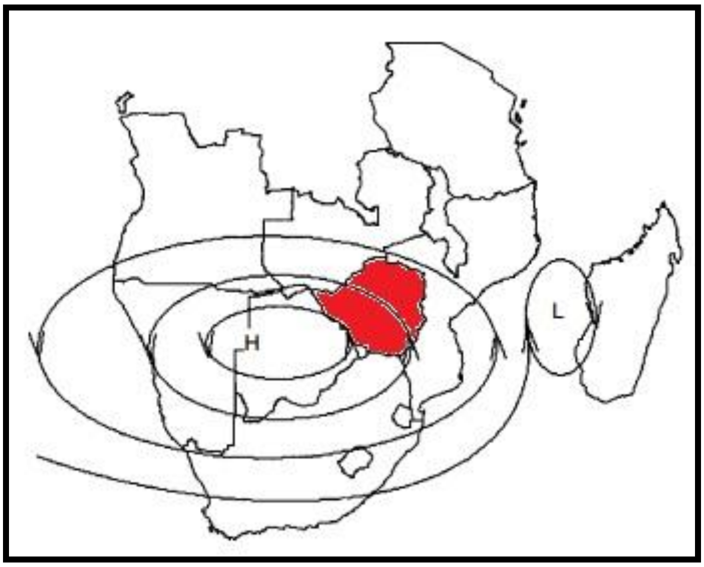

Figure 1: The map of Southern Africa showing the position of the Botswana Upper High with respect to Zimbabwe. Zimbabwe is indicated by the red colour.

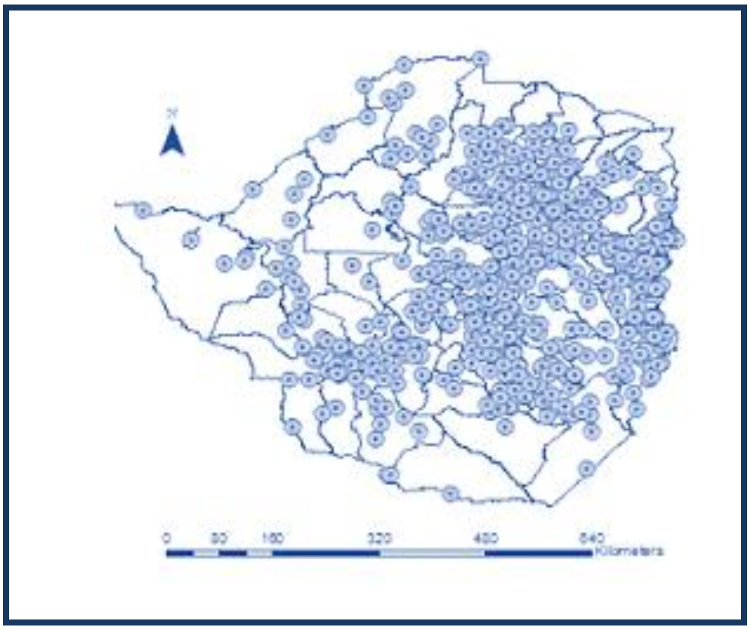

Figure 2: The distribution of the rainfall stations from which the data were obtained.

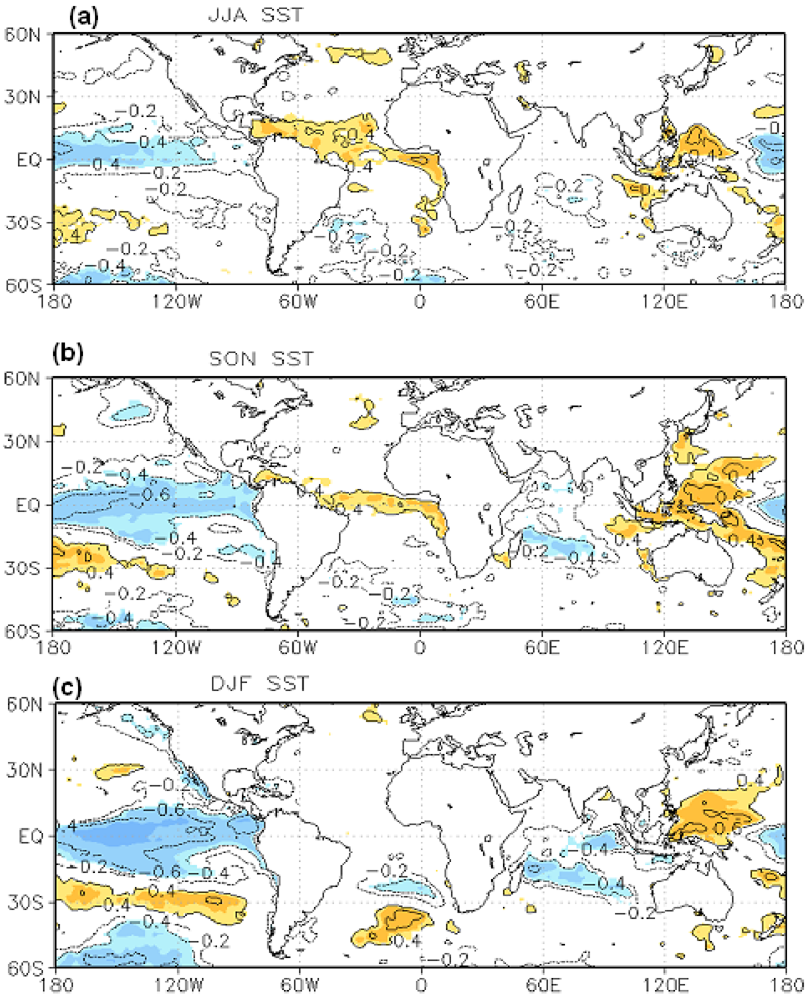

Figure 3: Correlation field between global sea surface temperatures and Zimbabwe rainfall for (a) June, July and August, (b) September, October and November and (c) December, January and February SSTs

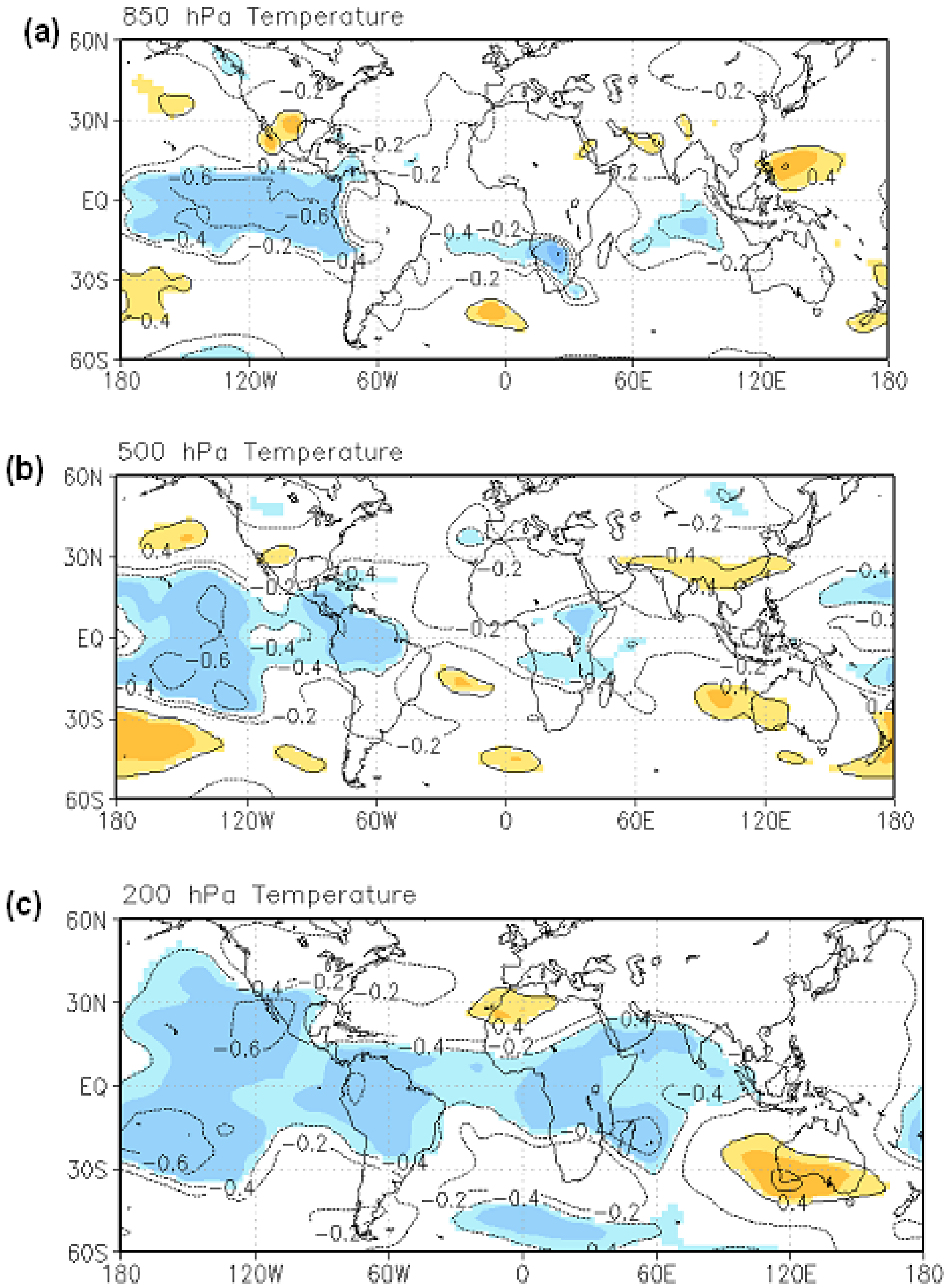

Figure 4: Correlation between Zimbabwe rainfall and air temperature at (a) 850 hPa, (b) 500 hPa and (c) 200 hPa pressure levels

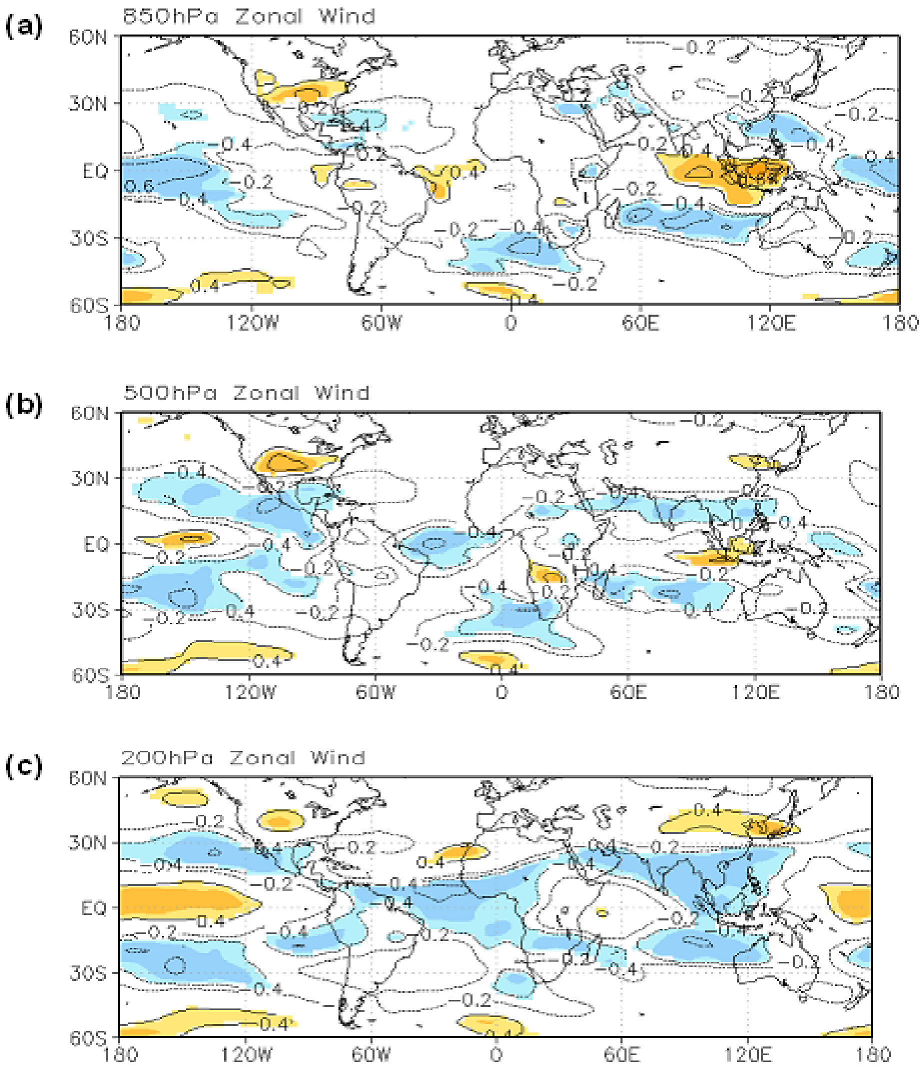

Figure 5: Correlation field for Zimbabwe rainfall and zonal wind at (a) 850 hPa (b) 500 hPa and (c) 200 hPa pressure levels

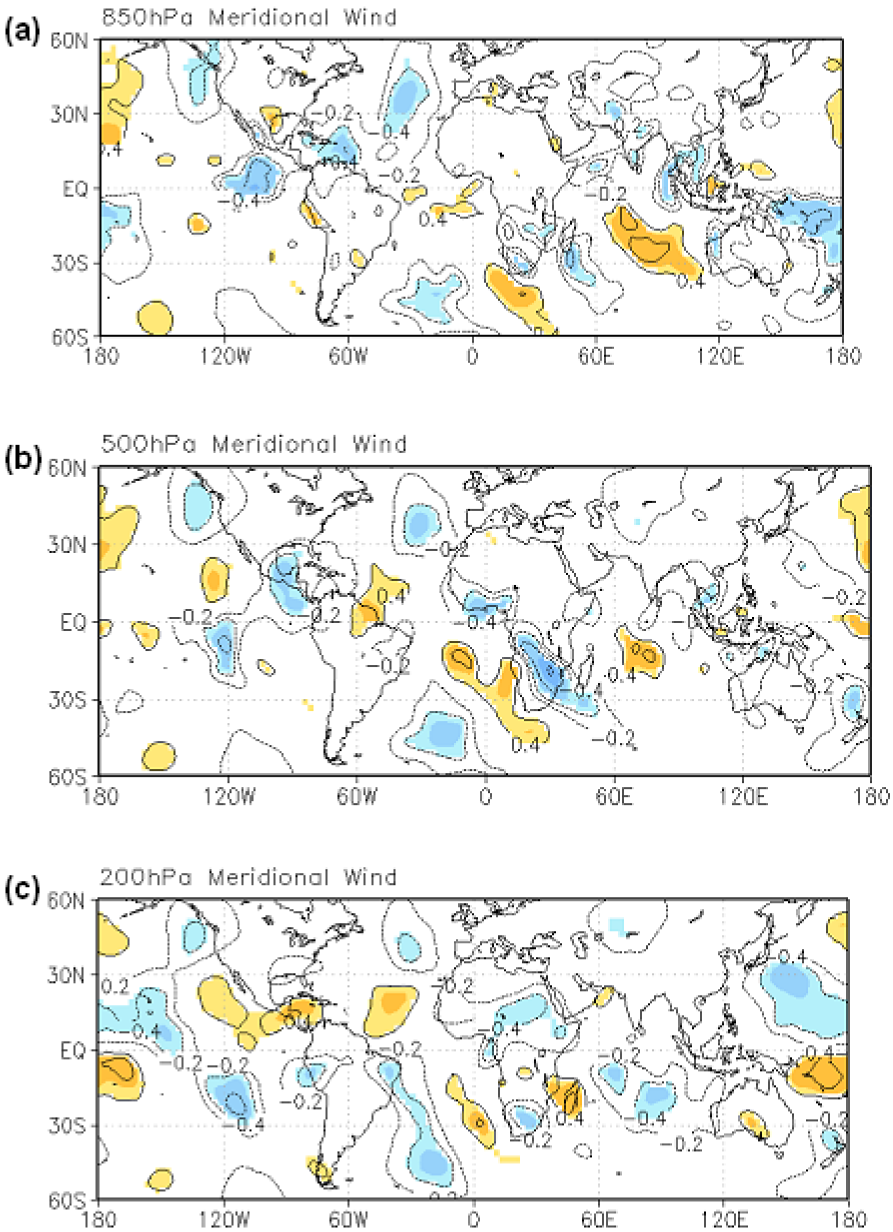

Figure 6: Correlation between Zimbabwe rainfall and meridional wind at (a) 850 hPa (b) 500 hPa and (c) 200 hPa pressure levels

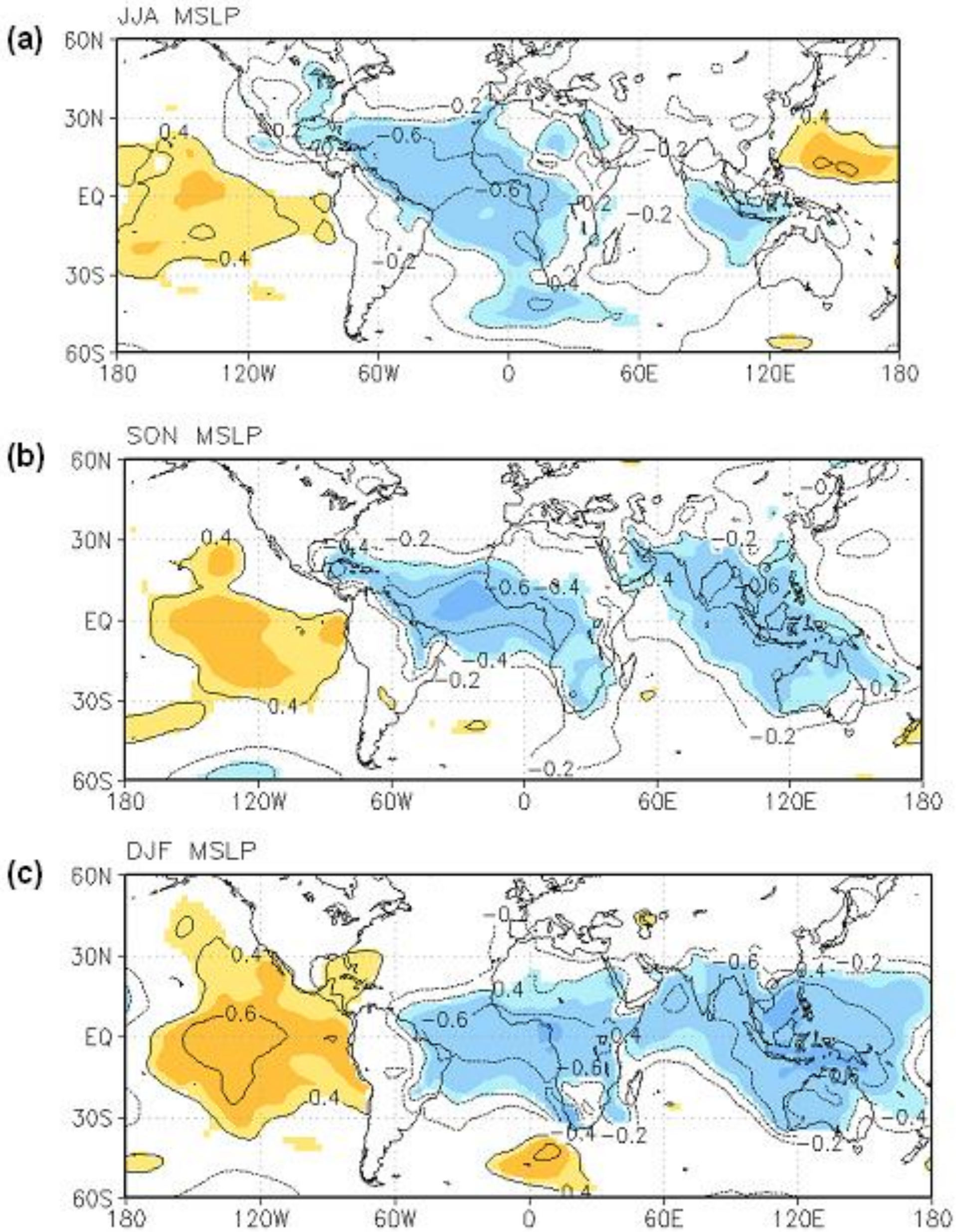

Figure 7: Correlation field between Zimbabwe rainfall and mean sea level pressure for (a) JJA (b) SON and (c) DJF

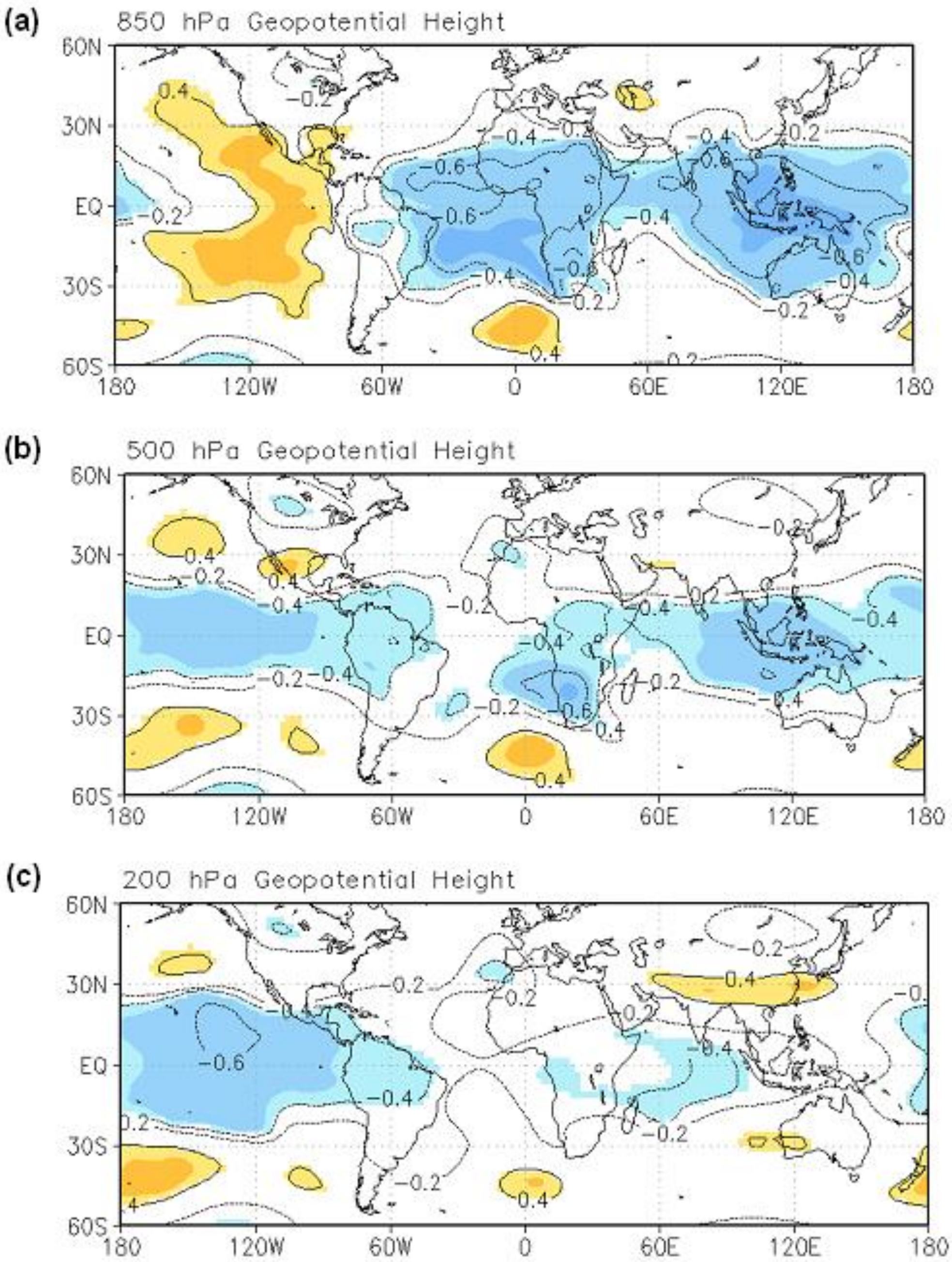

Figure 8: Correlation field between Zimbabwe rainfall and geopotential height at (a) 850 hPa (b) 500 hPa and (c) 200 hPa

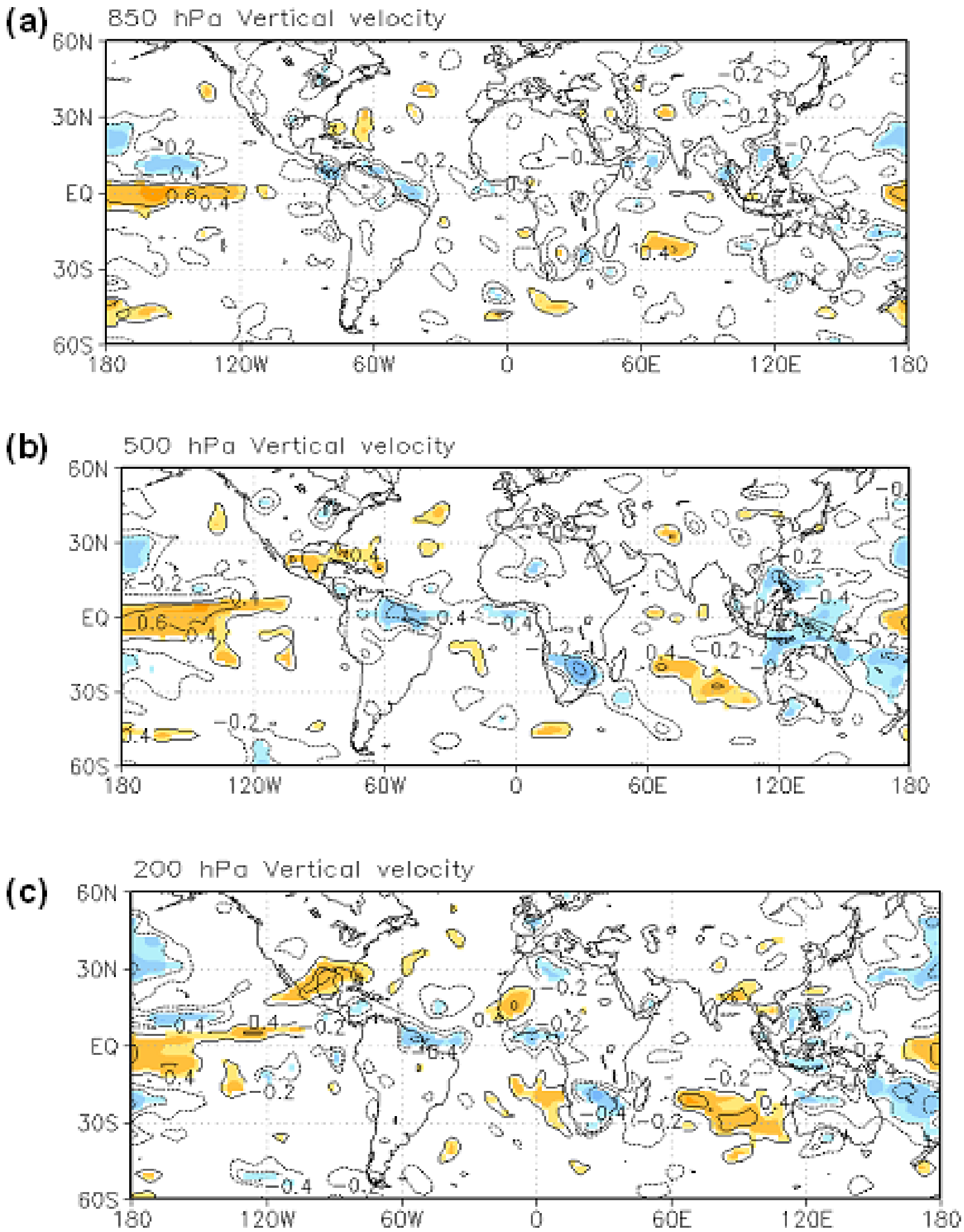

Figure 9: Correlation field between Zimbabwe rainfall and vertical velocity at (a) 850 hPa (b) 500 hPa and (c) 200 hPa pressure levels

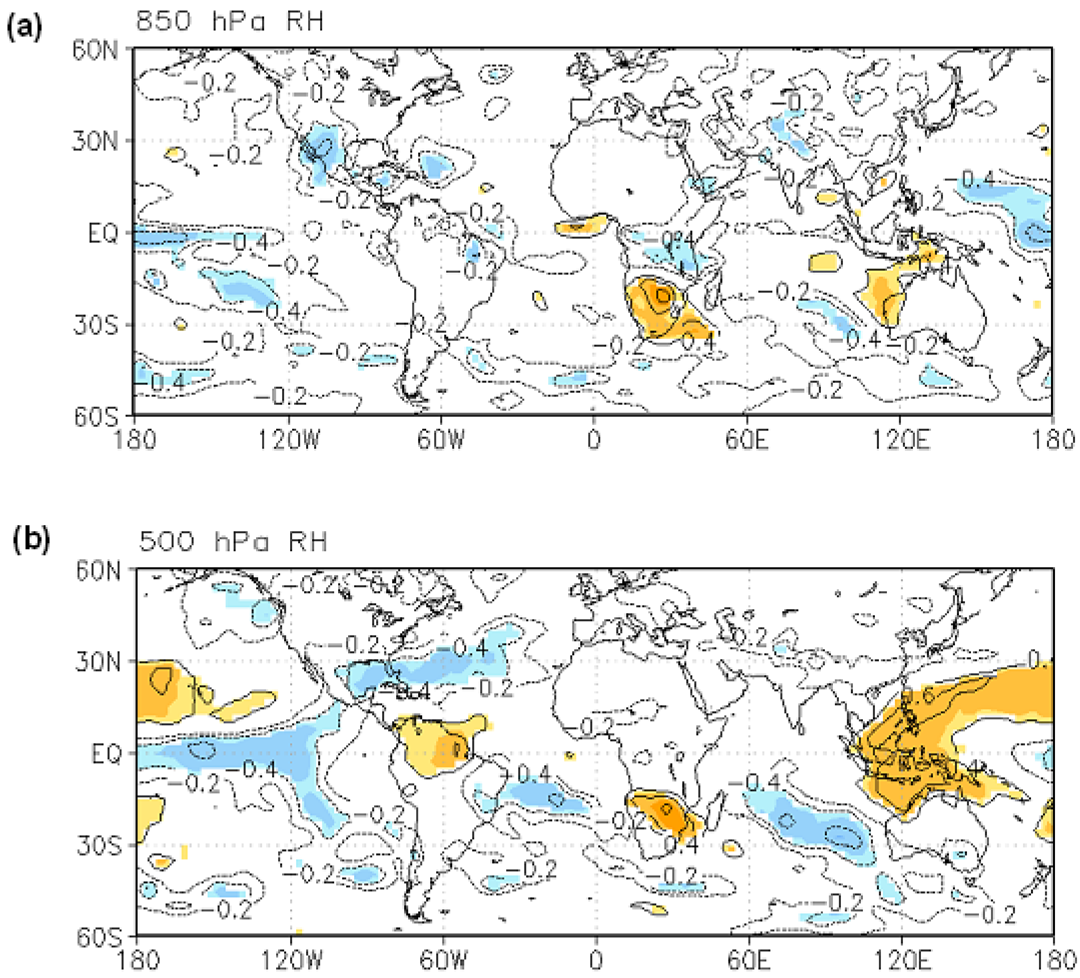

Figure 10: Correlation between Zimbabwe rainfall and relative humidity at (a) 850 hPa and (b) 500 hPa pressure levels

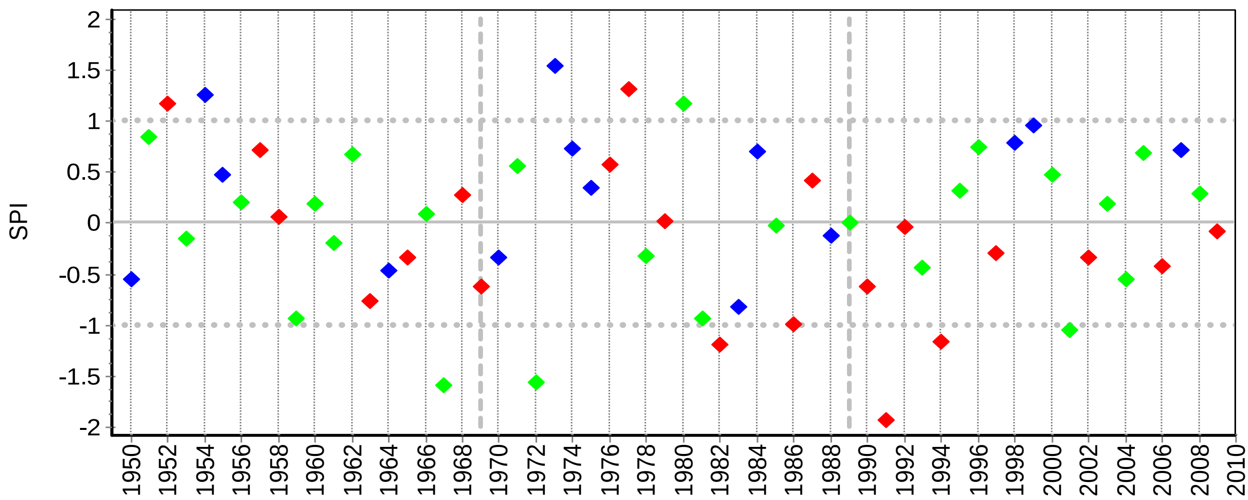

Figure 11: Zimbabwe Standardized Precipitation Index (SPI) scatter plot. The red squares correspond with El Niño years, the blue squares correspond with La Niña years and the green squares correspond with neutral years.