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Two summers of São Paulo drought: Origins in the western tropical Pacific

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Key Points:
- Large precipitation deficits seen in two consecutive summers, 2014 and 2015 in Sao Paulo region, Brazil
- Both years South Atlantic blocking highs are traced diagnostically to warm tropical W. Pacific SST
- Results highlight hemispheric symmetry in West Pacific origin of drought in Sao Paulo and California

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Abstract Two years of drought in Southeast Brazil have led to water shortages in São Paulo, the country's most populous city. We examine the observed drought during austral summers of 2013/2014 and 2014/2015 and the related large-scale dynamics. The 2013–2014 precipitation deficits were more concentrated in the state of São Paulo, while in 2014–2015 moderate deficits were seen throughout the region. We find that a persistent warm sea surface temperature (SST) anomaly in the western tropical Pacific Ocean was an important driver of drought via atmospheric teleconnection in the two December–February seasons. The warm SST and associated convective heating initiated a wave train across the South Pacific. The resulting anticyclonic geopotential height anomaly over the southwest Atlantic expanded the westward margin of the South Atlantic high and prevented low-pressure systems from entering southeast Brazil from midlatitudes. This mechanism suggests a hemispheric symmetry to that proposed for the recent California drought.

1. Introduction

In early 2015 the Brazilian megacity of São Paulo was dealing with unprecedented water shortages. The city's primary reservoir (Cantareira) levels were fluctuating around 5–15% of its capacity. While the reasons for the low levels of the reservoir are complex, they are partially due to the drought conditions that occurred in southeast Brazil in the austral summers of 2013–2014 and 2014–2015. Although by late summer (February and March) of 2015, precipitation in the region was above normal, the amount of rain was not sufficient to replenish the Cantareira reservoir to normal levels, and the situation remained critical [*Meghanck et al.*, 2015] through the 2015 dry season. The drought conditions affected not only São Paulo but also other large Brazilian cities in southeast Brazil including Rio de Janeiro and Belo Horizonte. Southeast Brazil has 44% of the Brazilian population and represents almost 50% of the country's Gross National Product.

Given the substantial impacts of these two years of drought in the region, e.g., in agriculture, hydropower production, and water shortages, it is fundamental to have a better understanding of the atmospheric conditions that led to these droughts. Recently, *Coelho et al.* [2015a] analyzed the drought in southeast Brazil with a focus on 2014. They showed that an important characteristic for the 2013/2014 drought was the persistence of a midatmosphere blocking high over SE Brazil. In addition, *Otto et al.* [2015] have found little connection of the drought conditions to anthropogenic warming. Our study is complementary to these, as we examine the drought in the two consecutive years, not only 2014, and analyze the differences and similarities in the two austral summer seasons. We restrict our analysis to the atmospheric and oceanic conditions in the two austral summers, not considering here the complex conditions of the rivers and reservoirs in the region.

The precipitation in southeast Brazil is under the influence of the South American Monsoon system [*Raia and Cavalcanti*, 2008] and has a strong influence of the El Niño–Southern Oscillation [ENSO; e.g., *Grimm et al.*, 2000] on interannual time scales. Precipitation varies intraseasonally in response to the Madden-Julian oscillation (MJO) with suppressed rainfall over eastern Brazil during the MJO phase where convection is enhanced over the maritime continent [*Carvalho et al.*, 2004]. Decadal variations in precipitation show some connection to SST although atmospheric drivers are also important [*Grimm and Saboia*, 2015]. The South American dipole is a dominant mode of precipitation variability in the region, with one center of action in southeast Brazil (in the region of the South Atlantic Convergence Zone, SACZ) and another over northeast Argentina, Uruguay, and southern Brazil. This dipole mode is associated with upper level anticyclonic wind anomaly across the subtropical east coast of South America (centered at 30S, 45W), with ascending motion and increased precipitation to the southwest and descent with suppressed convection to the northeast in the SACZ [*Robertson and Mechoso*, 2000]. *Bombardi et al.* [2014] showed that during neutral ENSO conditions, the South American dipole plays an important role in modulating the precipitation over eastern South America. It is noted that a dipole in sea surface temperature anomalies with centers over tropical and extratropical South Atlantic is often associated with this atmospheric variability [*Venegas et al.*, 1997]. However, *Robertson et al.* [2003] showed that this mode of SACZ variability is largely independent of the underlying SST. Rather, it can be excited by tropical heating and waves dispersing from the Pacific, and it has been shown to be active on interannual, intraseasonal, and decadal time scales [see, e.g., *Carvalho et al.*, 2004; *Robertson and Mechoso*, 2000; *Nogués-Paegle et al.*, 2002].

The recent droughts in São Paulo were characterized by ENSO neutral conditions. Therefore, we examine beyond ENSO to understand the reasons for the drought conditions in these two years. Active MJO events occurred during the two austral summers, and while the net effect of the transient MJO response to seasonal precipitation depends on the timing and strength of the individual events, it has been suggested that the observed activity in 2013/2014 (and likely in 2014/2015) may have contributed to the deficit rainfall in the region [*Blunden and Arndt*, 2015]. While it is well known that warm ENSO events are followed by a warming of the tropical Atlantic [*Giannini et al.*, 2001; *Chang et al.*, 2006], in the absence of ENSO, the relationship of Atlantic SST with the Pacific is more complex [*Wu et al.*, 2007]. We explore the role of the South American dipole, SST (Pacific and Atlantic), and atmospheric circulation anomalies in driving precipitation deficits. We also discuss the parallels to recent drought in California which was characterized by anomalous ridging, in the northeast Pacific and inhibited the path of winter cyclones. It has been suggested that decadal variations in western Pacific SST have played a role in setting up drought conditions [*Seager et al.*, 2015].

In section 2 we will describe the data sets and methods used in our analysis. Section 3 gives a historical perspective of the recent drought. In sections 4 and 5 the large-scale conditions and drivers of the drought are discussed. A discussion and our conclusions are presented in section 6.

2. Data and Methods

The observed precipitation analysis employs monthly Global Precipitation Climatology Centre (GPCC) (version 6) rain gauge only data set at 1° spatial resolution from 1950 to 2010 [*Schneider et al.*, 2014]. The period through 2015 is complemented by GPCC First Guess product [*Schamm et al.*, 2014]. The spatial distribution of droughts is shown as standardized precipitation, i.e., with climatological December–February (DJF) mean removed and divided by DJF standard deviation. The time series of standardized precipitation is calculated for precipitation averaged over the southeast Brazil domain (25°S–14°S and 53°W–40°W), which is defined to represent a common area of the 2013/2014 and 2014/2015 droughts.

The observed large-scale setting in these two years is evaluated with the European Centre for Medium-Range Weather Forecast Interim reanalysis (ERA-Interim) [*Dee et al.*, 2011] using DJF seasonal mean anomalies of upper tropospheric (200 and 500 hPa) geopotential height, velocity potential, and winds. The climatological base period for all calculated anomalies is 1981–2010.

One common characteristic for the 2013/2014 and 2014/2015 droughts was the persistence of a mid atmosphere blocking high over SE Brazil (see *Coelho et al.* [2015a], and our analysis in section 3). To examine the potential role of wave dispersion from the Pacific on the anticyclonic anomaly in the South Atlantic, we apply an empirical orthogonal function (EOF) analysis on DJF anomalous 500 hPa geopotential heights using the ERA-Interim reanalysis [*Dee et al.*, 2011], which covers the period 1979–2015. Our choice for evaluating the period 1979 through early 2015 is due to the known issue of data reliability in the Southern Hemisphere prior to the satellite era [*Tennant*, 2004]. The constraints imposed by orthogonality in the EOF analysis make physical interpretation of modes unreliable [*Dommenget and Latif*, 2002]. Thus, we apply a varimax rotation to the first five modes, which correspond to 70% of total variance of unrotated EOFs over the Southern Hemisphere Pacific and Atlantic (120E–0E, 65S–0S). The rotated principal component (RPC) time series that represent features relevant to the SE Brazil droughts are correlated to standardized precipitation over South America and the Pacific and Atlantic sea surface temperature (SST). The correlation between RPC3 and SSTs is tested using a random phase method designed for serially correlated time series [*Ebisuzaki*, 1997], to account

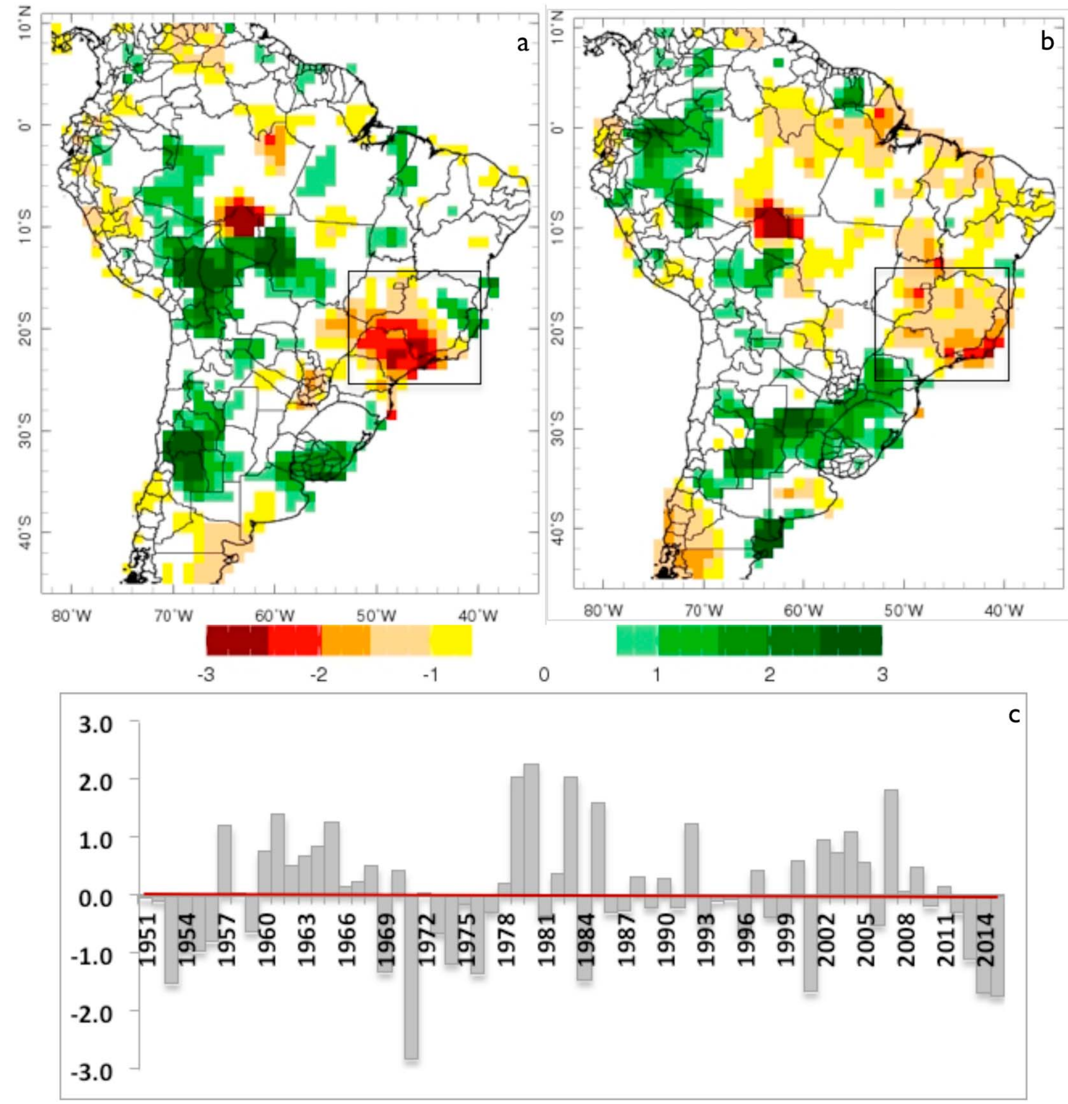

Figure 1. Standardized December–February (DJF) precipitation in (a) 2013–2014 and (b) 2014–2015. (c) Time series of domain averaged DJF standardized precipitation (baseline period: 1981–2010) and corresponding linear trend (red line) in the southeastern (SE) region of Brazil. The *x* axis shows the year. The box in Figures 1a and 1b represents the SE Brazil domain. Standardized units.

for autocorrelation common to SST time series and correlations significant at the $p<0.1$ (90%) level that are indicated by dots. Gridded SST data are obtained from the National Oceanic and Atmospheric Administration (NOAA) Extended Reconstructed SST version 4 [*Huang et al.*, 2015].

3. Observed Drought

The months from December to February represent the peak of the wet season in southeastern (SE) Brazil with average precipitation around 640 mm as estimated from GPCC [*Schneider et al.*, 2014]. Total precipitation in DJF 2013–2014 and 2014–2015 totaled 490 mm and 478 mm, respectively, which corresponds to standardized anomalies of −1.68 and −1.74 (Figure 1c). The intensity of standardized anomalies (σ) can be assessed by the probability of occurrence of a certain value determined by a Gaussian distribution. Drought events of magnitude $\sigma \leq -1.5$ ($p < 0.07$) have occurred previously in 2000–2001, 1983–1984, 1952–1953, and most markedly in 1970–1971, but none was followed or preceded by another drought event of similar intensity as in the case of 2013–2014 and 2014–2015. Despite the similar magnitudes averaged over the Brazil's SE, the spatial distribution of the anomalies (Figures 1a and 1b) shows a distinct pattern. While much of the focus

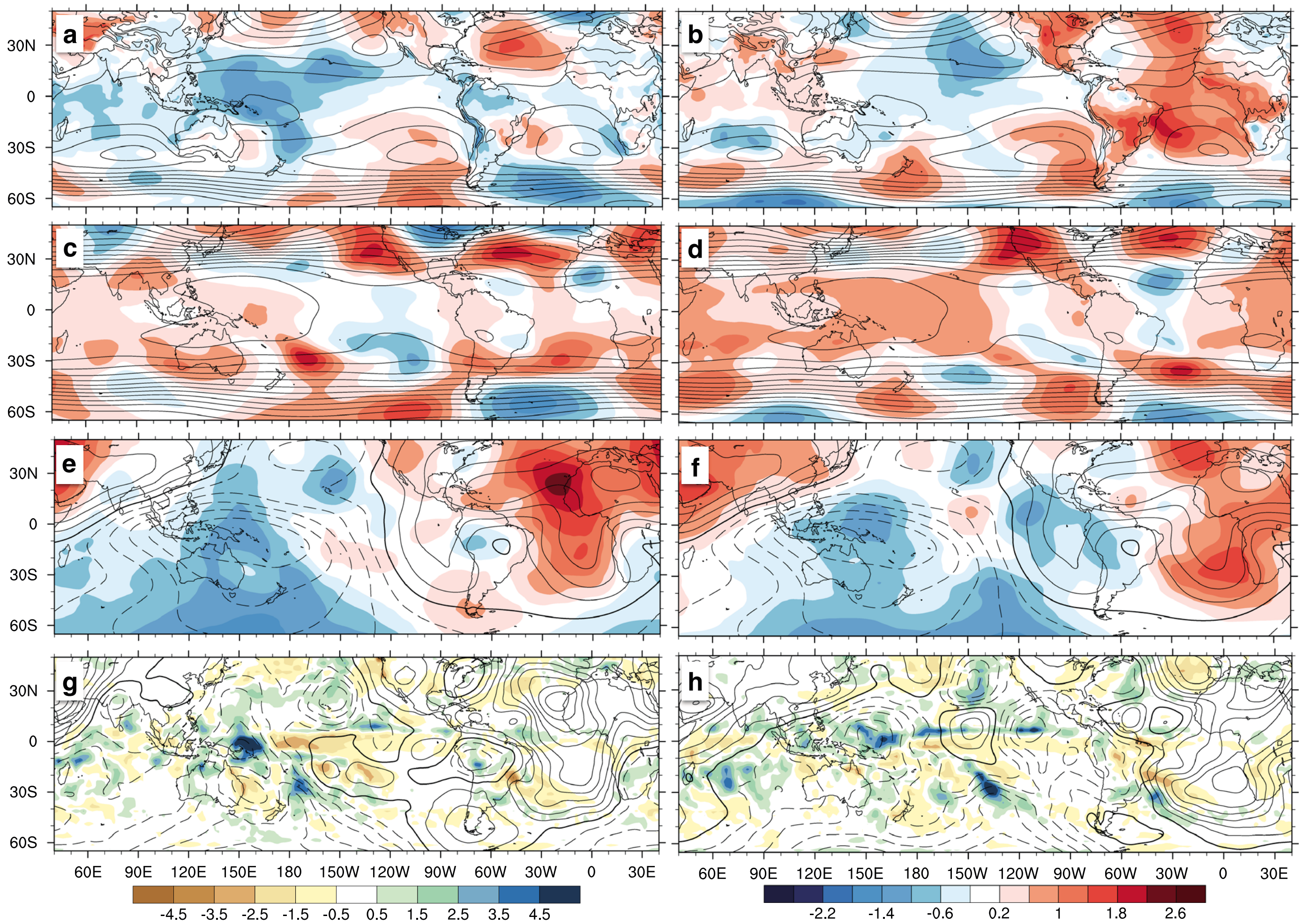

Figure 2. Observations in December–February of (a, c, e, and g) 2014 and (b, d, f, and h) 2015: (Figures 2a and 2b) standardized sea level pressure anomaly (colors) and climatology (contours with intervals from 984 to 1032 by 400 hPa), (Figures 2c and 2d) standardized 200 hPa geopotential height anomaly (colors) and climatology (contours with intervals from 10,500 to 12,500 by 100 m), (Figures 2e and 2f) standardized 200 hPa velocity potential anomaly (colors) and climatology (contours with intervals from -100 to 100 by 20×10^{-5} m^2/s), and (Figures 2g and 2h) precipitation anomaly (colors, mm/day) and 200 hPa velocity potential anomaly (contours with intervals from -3 to 3 by $.25 \times 10^{-5}$ m^2/s).

has been on the metropolitan area of São Paulo, the drought was a regional phenomenon in both years. The DJF 2013–2014 drought was more concentrated and locally severe in the state of São Paulo and Minas Gerais, whereas in DJF 2014–2015 more moderate values were seen throughout eastern Brazil. No precipitation trend is found during the DJF season in southeastern Brazil over the period 1950–2015 (Figure 1c). Note that while southeast Brazil was experiencing drought, the region to the southwest (referred to as southeastern South America) saw excess precipitation in both years.

4. Large-Scale Setting

The common features of large-scale circulation anomalies associated with these two drought years can be seen in Figure 2. Standardized geopotential height anomalies in the upper troposphere (Figures 2c and 2d) indicate a wave train with centers of action around the tip of South America resulting in positive height anomalies just poleward of 30S. In addition, both years were characterized by anomalous upper tropospheric convergence across much of the South Atlantic and east coast of South America indicating large-scale subsidence (Figures 2e and 2f) which was associated with a westward expansion of the Atlantic subtropical anticyclone in both years (Figures 2a and 2b). More remotely, anomalous divergence was seen in the western equatorial and south Pacific and in 2015 also in the east Pacific and western South America. ENSO conditions

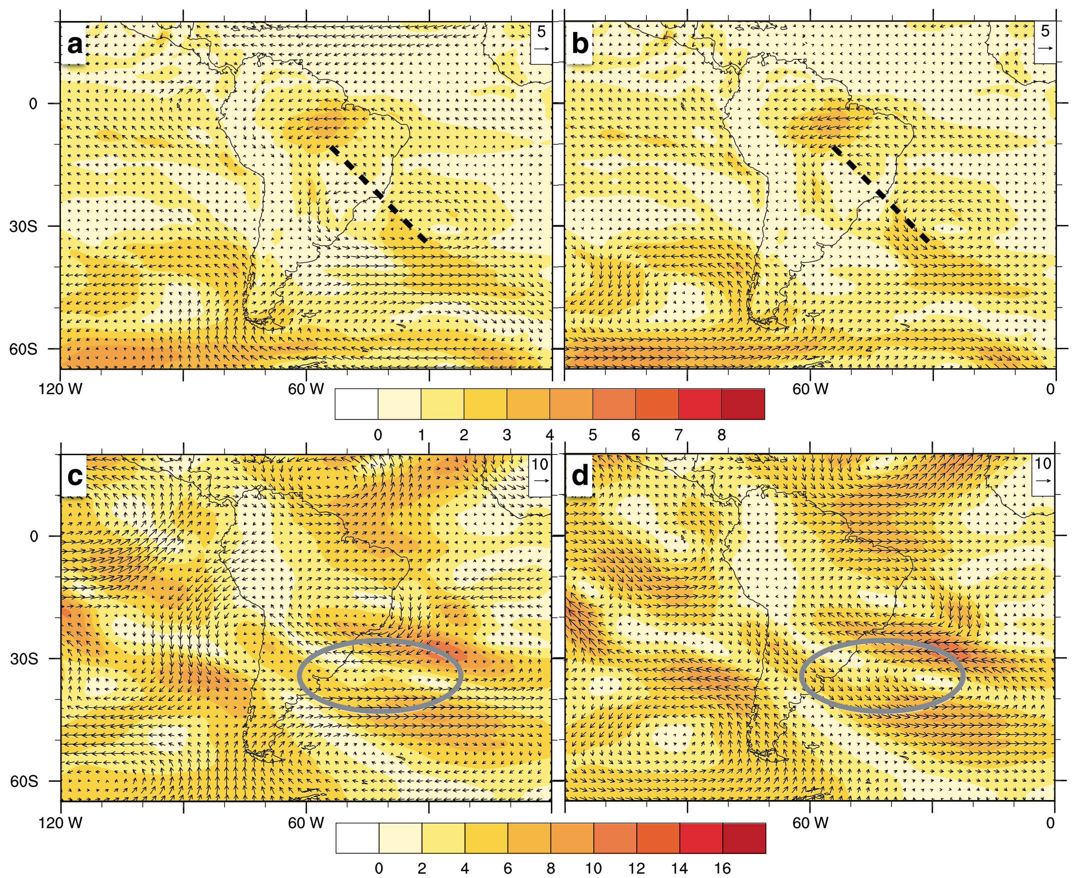

Figure 3. Observations in December–February of (left) 2014 and (right) 2015: (Figures 3a and 3b) 850 hPa with SACZ (black dashes) and (Figures 3c and 3d) 200 hPa vector wind anomalies with wind speed anomalies (colors, m/s). Upper level anticyclonic anomaly is shown in gray.

in both years were effectively neutral; however, a negative Interdecadal Pacific Oscillation [IPO; *Meehl and Hu*, 2006]—like precipitation pattern—was evident in the tropical Pacific with excess precipitation in the western warm pool and relatively dry conditions in the remainder of the tropical Pacific Ocean. In South America, east central Brazil experienced deficit rainfall, while excess precipitation was observed in the southeastern region of the continent, including Uruguay and Argentina and southern Brazil. The observed precipitation dipole was associated with a weakening of the South Atlantic Convergence Zone (SACZ) (Figures 2g and 2h).

The observed northeast-southwest dipole in precipitation, evident in both drought years, is associated with a dominant mode of variability in the South American monsoon and the South Atlantic Convergence Zone. The upper (c and d) tropospheric winds (Figure 3) show anticyclonic anomalies across the subtropical east coast of South America and southwest Atlantic Ocean, shifted by a few degrees poleward and eastward compared with the circulation described by *Robertson and Mechoso* [2000]. These wind anomalies lead to ascending motion and increased rainfall to the southwest and descent associated with suppressed rainfall to the northeast, weakening the SACZ. Low level wind anomalies (Figures 3a and 3b) indicate anticyclonic anomalies in the oceanic region of the SACZ, while over the continent-strengthened easterlies are deflected poleward by the Andes and result in stronger winds in the region of the low level jet important for moisture transport to Southeastern South America [e.g., *Rickenbach et al.*, 2002; *Muza et al.*, 2009]. These results are consistent with a positive-phased dipole event which displaces the storm track poleward and yields a warm SST anomaly in the subtropical Atlantic and cold anomaly in the extratropics [*Bombardi et al.*, 2014]. This dipole mode of variability has been shown to be important for intraseasonal, interannual, and decadal time scales and can be a response to midlatitude wave forcing or shifts in the tropical (i.e., Walker) circulation [*Carvalho et al.*, 2004; *Robertson and Mechoso*, 2000; *Nogués-Paegle and Mo*, 1997; *Grimm and Saboia*, 2015].

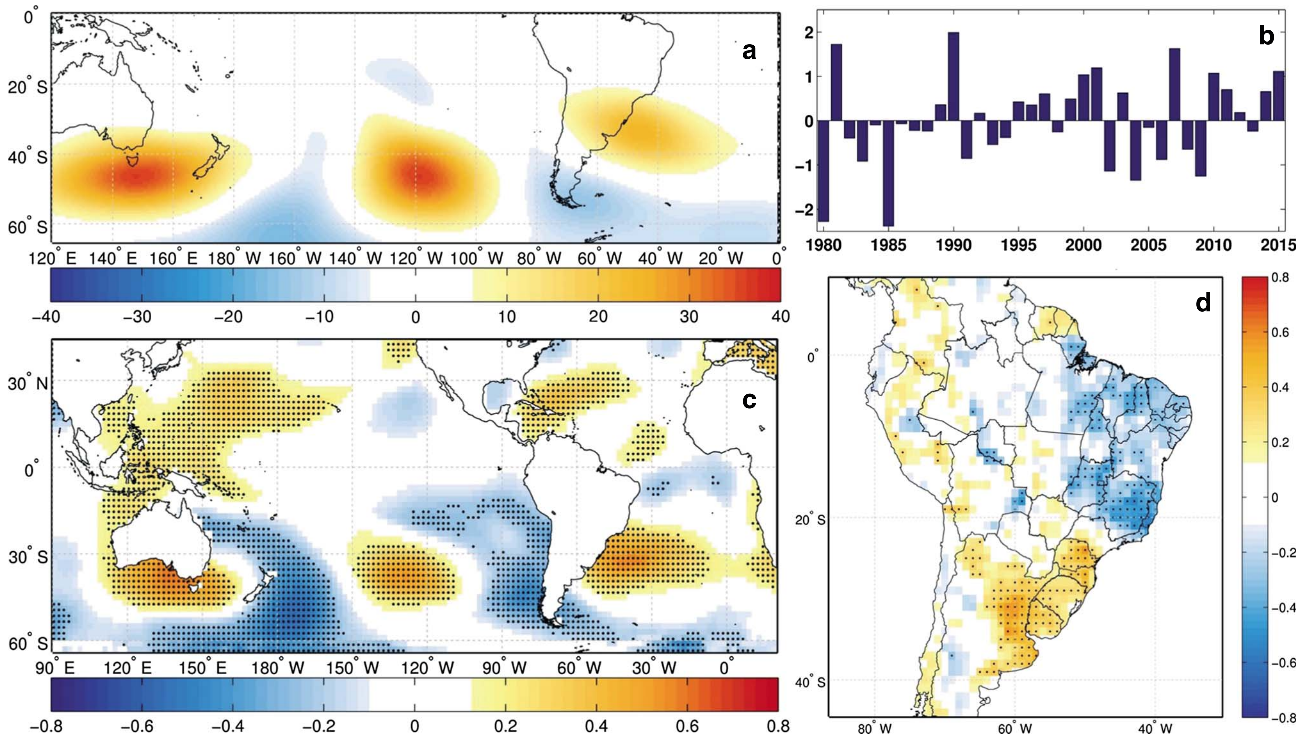

Figure 4. (a) REOF3 and (b) RPC3 of 500 hPa geopotential heights from ERA-Interim, (c) correlation of RPC3 with SST, and (d) correlation of RPC3 with Precipitation. Dots indicate significant correlation at the $p < 0.1$, using the *Ebisuzaki* [1997] method for correlation with SST and two-tailed *t* test for precipitation.

5. A Combination of Drivers

It is evident from the observed geopotential height anomalies that midlatitude waves played a role in creating a blocking high in the South Atlantic in these two consecutive years. A rotated EOF (REOF) analysis performed on 500 hPa height anomalies (DJF 1979–2015) yielded EOFs 1 and 2 (not shown) which describe variability associated with ENSO (REOF1, 36% of variance explained) and a large-scale warming trend (REOF2, 22%). In Figures 4a and 4b the third REOF (12%) shows a curved wave train crossing the south Pacific and southern South America that results in a positive geopotential height anomaly over the southwest Atlantic and southeastern South America. This anomaly is associated with a westward expansion of the Atlantic subtropical anticyclone and the principal component time series (RPC3) indicates large amplitude anomalies in the past two years. A correlation of this mode against SST exhibits a relationship to the tropical Pacific with a pattern similar to the IPO. There is also an extratropical wave train in SST anomalies, including the warm subtropical South Atlantic, which is driven by the atmospheric circulation anomalies [e.g., *Hartmann*, 2015; *Grimm and Saboia*, 2015]. Precipitation anomalies correlated with RPC3 indicate drier conditions in northeast of South America and wetter in the southeast of the continent with São Paulo located at the central node of this variability. Thus, it appears that atmospheric heating in the western Pacific warm pool may have been a driver of the recent droughts in the São Paulo region. Note that this mechanism is similar to one suggested to factor in the recent California drought, i.e., initiated by convective heating from decadal variations in western tropical Pacific SST [*Seager et al.*, 2015]. In addition, recent observational analysis of decadal variations in South American precipitation shows a precipitation dipole as the first REOF in summer and a similar relationship to SST anomalies (including the west tropical Pacific and the subtropical South Atlantic) [*Grimm and Saboia*, 2015].

6. Discussion and Conclusions

Here we have examined the recent two years of observed drought in the São Paulo region.

We find that a warm SST anomaly in the western tropical Pacific Ocean has been an important driver of drought via atmospheric teleconnection in the two DJF seasons. Results suggest that the warm SST and atmospheric heating from convection initiated a wave train in the geopotential height field across the South Pacific that excited a mode of variability known as the South American dipole. The upper tropospheric anticyclonic wind anomaly over southeast amplified the westward margin of the South Atlantic anticyclone and inhibited the equator ward progress of low-pressure systems into southeastern Brazil from midlatitudes while at the same time yielding excess precipitation poleward of the region, consistent with the dipole mode of variability. The warm west Pacific SST is in part a decadal variation [*Seager et al.*, 2015], and it is notable that the relationship between the precipitation dipole and west Pacific SST anomalies on decadal time scales has also been seen by *Grimm and Saboia* [2015]. While the proposed mechanism plays a role in the two years of drought, additional factors are at work in generating differences between the two years in the regional extent of precipitation deficits.

Recently, *Coelho et al.* [2015a, 2015b] analyzed the drought in southeastern Brazil with a focus on 2014. They showed that an important characteristic for the 2013/2014 drought was the persistence of a midatmosphere blocking high over SE Brazil and emphasized a relationship to the lack of convective heating in the central Pacific Ocean. Our study is complementary in that we examine the drought in the two consecutive years, not only 2014, and link the geopotential height anomaly and the South American dipole mode over southeastern Brazil to the heating in the western Pacific. This suggests parallels between the São Paulo drought and the forcing of recent drought in California.

The California drought was also characterized by anomalous ridging, a blocking high, in the northeast Pacific which prevented winter cyclones from reaching California. There is some agreement that SST forcing may have played a role in driving the anomalous ridge [*Wang et al.*, 2014; *Wang and Schubert*, 2014; *Seager et al.*, 2015], but there remains a disagreement regarding the mechanisms. Results presented here are in agreement with the mechanism presented by *Seager et al.* [2015] in a model study of the 2011–2014 drought: the convective heating response to warm SST anomalies in the western tropical Pacific (associated with negative PDO) initiates a north Pacific wave train in geopotential heights that lead to a blocking high along the U.S. West Coast. It has been previously suggested that heating anomalies in the tropical Pacific (e.g., El Niño) can drive hemispherically and zonally symmetric climate anomalies via eddy-driven mean meridional circulation [*Seager et al.*, 2003]. Additional work and model experiments will be needed to further investigate if west Pacific SST anomalies played a role creating the drought conditions in both hemispheres and to clarify the underlying mechanism. Our results suggest there is hemispheric symmetry in these droughts and support the need for further study.

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