IMPACT OF OBSERVED CIRCULATION CHANGES IN PRECIPITATION OCCURRENCE IN SOUTHEASTERN BRAZIL

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1. Background

The focus of my PhD research is to investigate how changes in circulation and available moisture have been affecting precipitation occurrence over Southeast Brazil (SE Brazil). Even though a warmer troposphere is expected to have its capacity of retaining moisture increased according to the Clausius-Clapeyron relation, precipitation response for these changes are much more complex and spatially non-uniform (e.g. Held and Soden, 2006). Previous studies evaluated various precipitation indices over South America and identified positive trends in different areas, including SE Brazil and São Paulo state (Haylock et al., 2006; Marengo et al., 2010). These positive trends were related to an intensification of the heavy rainfall rather than an increase in duration or frequency of wet days (Skansi et al., 2013). In addition to uptrends in extreme precipitation, some studies have shown an increase in the number of consecutive dry days and a decrease in the number of light rainy days (days with less than 5mm/day) in São Paulo state, indicating that precipitation is getting concentrated in fewer rainy days (Dufek and Ambrizzi, 2008). There is also evidence that the South American Monsoon System (SAMS) in getting longer, with earlier onset and later demise (Jones and Carvalho, 2013).

Zilli et al (2016), evaluating only observational data, identified an increase in total precipitation during the rainy season over the southern coastal of Southeast Brazil (between 20°S and 25°S) as a result of more rainy days (days with precipitation above 1mm/day) and more frequent and intense extreme events. Further north along the coast (between 20°S and 23°S), extreme events are also becoming more intense and frequent but the number of rainy days is decreasing. Such changes in the spatial-temporal distribution of precipitation could be related to changes in SAMS and the South Atlantic Convergence Zone (SACZ) intensity and location.

During the austral summer (DJF), South America is under the influence of a monsoonal circulation, responsible for the largest part of precipitation on SE Brazil (Kodama, 1992, 1992; Zhou and Lau, 1998, 2001, Liebmann et al., 2001; Jones and Carvalho, 2002). The monsoonal upper level circulation over South America is dominated by the Bolivian High, located over the Andean altiplano, and the Nordeste trough, over tropical Atlantic (Chen et al., 1999; Lenters and Cook, 1999). On lower levels, the main circulation features are the subtropical high pressure areas over both Pacific and Atlantic oceans, straddling the continent. Over the continent, the development of a heating low, centered over northern Argentina (Chaco low), increases the land-ocean temperature contrasts and favors the poleward flow along the tropical eastern coast of South America (Kodama, 1993; Zhou and Lau, 1998). The increased thermal contrast also favors the penetration of the trade winds deeper into the Amazon region that are deflected southward along the eastern slope of the Andes forming the Low Level Jet (LLJ). This jet favors the moisture transport from the Amazon toward subtropical latitudes (Liebmann et al, 2004).
The southward extension of the convective activity toward SE Brazil and subtropical South Atlantic Ocean is denominated South Atlantic Convergence Zone and is one of the main features of the SAMS (Zhou and Lau 1998, Liebmann et al. 2001, Carvalho et al. 2002, 2004, Marengo et al. 2012). Kodama (1992, 1993) described the SACZ as a baroclinic structure located eastward of a trough in the subtropical and it is formed by moisture converging from two different regions: northeasterly inflows originated in the southwestern periphery of the South Atlantic Subtropical High and westerly flows along the convergence zone, becoming more intense with height and forming part of the subtropical jet in upper levels. These two components are essential for the development and strengthening of the convergence zone, intensifying the frontogenesis and generating convective instability (Kodama 1993).

By investigating changes in summer climatology since 1979, our previous studies (Zilli et al, in preparation) identified an increase in atmospheric thermodynamic forcing during the summer, with warmer, moister and more unstable conditions over tropical South America, including SE Brazil. However, the dynamic forcing related to the occurrence of precipitation is getting weaker, with reduced land-ocean pressure gradient slowing down the northerly flow along Brazilian east coast and weakening the moisture convergence over the area. These changes in circulation can affect the location and intensity of the SACZ. The present investigation evaluates the influence of observed changes in circulation on SACZ location and related precipitation.

2. Dataset and Methods

Changes in the precipitation associated with the SACZ were investigated using precipitation data from two different reanalyses and one merged satellite and rain gauge product. The reanalyses utilized are the National Center for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR; Saha et al 2010) and the National Aeronautics and Space Administration (NASA) Modern-Era Retrospective Analysis for Research and Applications (MERRA; Rienecker et al 2011) version 1. Both datasets are based on data from various sources assimilated into atmospheric models, which provide a complete description of different variables in daily basis at a regular grid space (0.5° of latitude and longitude for both cases). Since the datasets are a product of atmospheric models, the outputs are subject to different parametrization schema and other limitations relative to numerical integration. CFSR has data from 1979 until 2014 while MERRA has data from 1979 until 2013.

To validate the precipitation changes observed in the reanalyses, we utilized Global Precipitation Climatology Project (GPCP), based on multiple satellite measurements merged with rain gauge data where it is available (Huffman et al. 2001). In this study, we focused on monthly averages of daily precipitation rates with 2.5° spatial resolution, from 1979 until 2014.

To isolate summer precipitation related to SACZ events, we performed an Empirical Orthogonal Function (EOF) analysis of the seasonal anomalies of precipitation rate of all datasets, similar to the description in Silva and Carvalho (2007). Precipitation rates were averaged over austral summer (DJF), considering a reduced domain: -50°S and -60°W to -10°S and 15°W. We opted for reducing the domain to remove the influence of the Amazon region and the Andes and focus on the SACZ influence on the precipitation. To avoid interference from ENSO events, we removed the seasons associated with strong events (1982-83, 1988-89, 1991-92, 1997-98, 1998-99, and 1999-2000). The EOF analysis was performed over the correlation matrix, using a T-mode (Wilks, 2011).

The EOF modes associated with the SACZ were used to reconstruct the average summer precipitation rate and to evaluate its evolution during the period considered. The SACZ region was defined as the region with
precipitation above 6mm/day, equivalent to the average plus one standard deviation precipitation over the considered domain for all datasets. We also evaluated the location of the north margin of the oceanic SACZ by tracking the position of 2.5mm/day isohyets over tropical South Atlantic.

2.1. Climatology Comparison

Since both MERRA and CFSR precipitation products are not entirely based on observational data, we first compared their seasonal climatology with GPCP's climatology (Fig. 1).

GPCP summer average (Fig 1a) has large precipitation rates over the ITCZ and the Amazon, extending southeastward to form the SACZ. There is also a local maximum precipitation over the subtropical southwest Atlantic, corresponding to the oceanic extent of the SACZ. Over eastern South Atlantic and South Pacific, the average precipitation rate is very low (<1mm/day), corresponding to the location of the subtropical anticyclonic circulation.

Fig. 1: Austral summer average (DJF) of daily precipitation rates (in mm/day) for the three dataset considered: (a) GPCP; (b) CFSR; and (c) MERRA. Contours interval: 1mm/day.
Both MERRA and CFSR correctly place the three main precipitation areas: ITCZ, Amazon, and SACZ. However, MERRA underestimates the average precipitation over central Amazon, shifting it northward, and along the ITCZ (Fig 1c). It also underestimates the average precipitation along the continental and oceanic SACZ extent. CFSR has all three precipitation areas correctly place, even though it overestimates the average precipitation over central Amazon and Atlantic ITCZ (Fig 1b).

2.2. EOF analysis

The next step is to evaluate the principal components of each dataset produced by the EOF analysis. Since the analysis is limited to the domain from -50°S, -60°W to -10°S, 15°W, it does not considers the areas with the largest discrepancies between GPCP and the reanalyses.

GPCP’s first mode (EOF1, Fig 2a, top) explains 22.4% of the summer precipitation variability and depicts the dipolar structure, with one center over eastern Brazil and other, with opposite signal, over southern Brazil and northeastern Argentina, as described in previous studies (e.g. Nogues-Paegle and Mo, 2001; Carvalho et al 2004; Grimm and Zilli, 2009). The EOF time series shows an interannual oscillation with a slight increasing trend after 2008 (Fig 2a, graphic on bottom left). This mode is considered statistically separated from lower order modes, according to North rule (Hannachi et al 2007; Fig 2a, graphic on bottom right).

Fig. 2: (a)-(c): First EOF (maps, shades), their respective time series (bottom left graphics) and value of the four first eigenvalues and their error (bottom right graphics) for (a) GPCP; (b) CFSR; and (c) MERRA. On the maps, the blue contours indicate the average daily precipitation rate (each 1mm/day). The significance explained by each mode is on the bottom right of the time series graphic. (d) Same as (a), for the second EOF using GPCP data.
Both CFSR and MERRA explain more than 25% of their respective summer precipitation variability (25.7% for CFSR and 32.5% for MERRA) and reproduce the dipolar structure, however in MERRA the north center is almost absent (Fig 2c, top). In both reanalyses, the south center is displaced northwestward and the north center is mostly over the northern margin of the SACZ. Both time series are consistent with the GPCP time series, although with less interannual fluctuation (Fig 2b and 2c, graphic on bottom left). They also indicate a positive trend after 2005, with more precipitation over central South America and drying along the northern margin of the SACZ. These modes can be considered statistically separated from their respective second modes, according to the North’s rule (Hannachi et al, 2007; Fig 2b and 2c, graphic at the bottom right).

It is worth examining GPCP’s EOF2 since it can be considered statistically separated from the third mode (Fig 2a, graphic at bottom right). GPCP’s EOF2 explains 13.6% of the total summer variability and also shows a dipolar structure with opposite centers over both margins of the SACZ (Fig 2d, top), similar to the oceanic SACZ mode observed in Carvalho et al (2004). During its positive phase, GPCP EOF2 indicates a wetting (drying) of the northern (southern) margin. The location of the northern center is very similar to the location of the northern centers on MERRA’s and CFSR’s EOF1. The GPCP’s EOF2 time series also shows a strong interannual fluctuation with remarking decreasing trend after 2008. Note that, during the negative phase of this mode, there is a wetting of the southern margin and a drying of the northern, indicating a southwestward shift of the average SACZ position.

Since CFSR’s and MERRA’s second modes are not statistically independent from higher order modes, we will not consider them in our analyses.

Visual inspection of the spatial modes of variability indicate that both CFSR’s and MERRA’s EOF1 are a combination of GPCP’s first and second modes, with GPCP EOF2 being more similar to reanalyses EOF1 (with opposite signal) than the GPCP EOF1. Correlation analysis indicates that GPCP EOF1 is positively and significantly correlated with CFSR EOF1 (\(\rho=0.34\), p-value=0.027), but only marginally correlated with MERRA EOF1 (\(\rho=0.18\), p-value=0.18). GPCP EOF2 is strongly negatively correlated with CFSR EOF1 (\(\rho=-0.5\) and p-value=0.0007) and MERRA EOF1 (\(\rho=-0.32\) and p-value=0.041).

### 2.3. Reconstructed Precipitation Analysis

Our objective with the EOF analysis was to isolate precipitation modes related with SACZ events to further investigate their temporal trends. According to the EOF analysis, both CFSR and MERRA average summer precipitation is well explained by their EOF1. Additionally, CFSR and MERRA EOF1 are correlated with GPCP EOF1 and EOF2. Thus, our next step is to reconstruct the summer average precipitation rate using EOF1 for MERRA and CFSR, and EOF1+EOF2 for GPCP.

GPCP reconstructed precipitation (RecPrecip) depicts the spatial extension of SACZ (Fig 3a, shades), with most of its variability (standard deviation, contours in Fig 3a) located along the northern margin of the convergence zone. There is also local maximum variability over southern Brazil and northeastern Argentina. CFSR RecPrecip (Fig 3b, shades) has a spatial distribution very similar to GPCP RecPrecip, with the continental and oceanic maxima located at similar positions. Its variability (Fig 3b, contours) is also similar to GPCP’s, especially along the northern margin of the SACZ. The local maximum variability along the southern continental margin is displaced northwestward in the CFSR RecPrecip, and is stronger than the local maximum for the GPCP RecPrecip. MERRA RecPrecip underestimates local precipitation (Fig 3c, shades), with a maximum along the coast over the continent. Even though it places a second maximum over the oceanic SACZ, it is also underestimated. The variability follows the precipitation distribution (Fig 3c, contours), with a maximum along
southeastern Brazilian coast. As MERRA cannot capture the precipitation distribution associated with SACZ, we will focus the remainder of the analysis on CFSR and GPCP datasets.

![Fig. 3: Reconstructed average summer precipitation rate (in mm/day, shades) and its standard deviation (contours, each 0.2mm/day in (a) and 0.4mm/day in (b) and (c)). Reconstructed precipitation for (a) GPCP, using EOF1+EOF2; (b) CFSR, using EOF1; and (c) MERRA, using EOF1.](image)

After reconstructing the precipitation using the EOF modes associated with the SACZ, we were able to evaluate changes in the spatial distribution of precipitation since 1979. Since we are interested in changes on the positioning of the SACZ, we defined two parameters to analyze it: the 6mm/day isohyet (~average + standard deviation for both dataset), encompassing the maxima in precipitation over the SACZ, and the 2.5mm/day isohyet over tropical Atlantic, indicating the position of the SACZ northern margin.

GPCP RecPrecip is shifting southwestward over the continent, with both north and southern margins of the maximum precipitation shifting after 2009 (Fig 4a, solid red contour over the continent). Note that, except for the period of 2003-2008 (Fig 4a, solid orange contour over the continent), the area with precipitation above 6mm/day is consistently moving southwestward in more recent years, compared to its position in 1979-1984 (Fig 4a, solid black contour over the continent) and 1985-1990 (Fig 4a, solid purple contour over the continent) over the continent. It is important to remember that ENSO years were not included in this analysis. The position of the northern margin of the oceanic SACZ (Fig 4a, dashed contours, equivalent to the 2.5mm/day isohyet) is also shifting southwestward after 2009 (red dashed contour), with similar behavior as observed over the continent.

CFSR RecPrecip indicates an oscillation on the position of the southern margin of the continental maximum precipitation, but no change along the northern margin (Fig 4b, solid contours over the continent). Note that, for this dataset, the smallest spatial extent of the area with average precipitation above 6mm/day occurs in 1997-2002 period (Fig 4b, green solid contour over the continent). After that, the margin is consistently shifting southwestward. The behavior is similar for the northern margin of the oceanic SACZ, with 1997-2002 period (Fig 4b, green dashed contour) representing the northernmost position of the margin and 2009-2014 (Fig 4b, red dashed contour) its southernmost position.

Despite the differences along the northern portion of the continental maximum, both dataset represented a southwestward shift along the southern margin of the continental SACZ and a drying trend along is northern oceanic margin. Differences in the northern portion of the continental margin can be attributed to differences in local variability associated with GPCP EOF1, which has a strong activity center over the region, not represented in the CFSR EOF1.
Fig. 4: Reconstructed average summer precipitation (mm/day) over 6 year periods, according the key on the upper right corner. Solid contours: 6mm/day isohyet along the SACZ; Dashed contour: 2.5mm/day isohyet, restricted to areas above tropical Atlantic Ocean. (a) GPCP (EOF1+EOF2); and (b) CFSR (EOF1)
3. Final Remarks and Future Work

Kodama (1992) identified the northerly wind along eastern Brazilian coast and the position of the subtropical jet over South America as the main mechanisms producing the SACZ. Our previous results (Zilli et al, in preparation) identified a weakening of the northerly winds along eastern Brazilian coast. Our objective here was to verify if the changes observed in the wind is affecting the position and strength of the SACZ. The southward shift of the oceanic margin observed for GPCP and CFSR precipitation associated with the SACZ reinforce this hypothesis.

Furthermore, our previous results (Zilli et al, in preparation) also an intensification of the westerly flow from the Amazon toward southeastern Brazil, increasing the moisture transport from the Amazon to the region. Such increased moisture availability could favor the occurrence of precipitation along the southern margin of the maximum convection region over the continent, as shown in Fig 4.

Our next steps are to identify mechanism associated with the observed circulation changes and investigate whether climate models are able to identify such trends on their present climate scenarios.

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5. References

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