

**A COMPREHENSIVE ANALYSIS OF TRENDS IN EXTREME  
PRECIPITATION OVER SOUTHEASTERN COAST OF BRAZIL**

**SHORT TITLE: EXTREME PRECIPITATION TRENDS OVER  
SOUTHEASTERN COAST OF BRAZIL**

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## ABSTRACT

Southeast Brazil (SE Brazil) is the most densely populated region in Brazil. Previous studies have shown evidence of positive trends in average precipitation and extreme events in a few locations, suggesting the increase in rainfall related hazards with potential impacts to urbanized areas of SE Brazil. This study provides a comprehensive analysis of the spatial variability of trends in extreme precipitation over SE Brazil focusing on regional and local scales. We examine two daily rainfall datasets with more than 70 years of data: individual stations and gridded observed precipitation data. Our results indicate that the frequency of both rainy days and extreme daily precipitation events have increased in Sao Paulo state. Conversely, precipitation has become more concentrated in fewer events in Rio de Janeiro and Espirito Santo states where both data sets indicate positive trends in the intensity of extreme daily rainfall. The increase in frequency and intensity of extreme events have both contributed to positive trends in total seasonal and average daily precipitation over Sao Paulo. Additionally, individual stations indicate negative trends in the number of light rainy days over large urbanized areas in the state of Sao Paulo. The spatial patterns of trends indicate that they are influenced by the proximity of large urban centers and topographic features, and also suggest variations and changes in the major climatic systems affecting precipitation regimes over SE.

**Keywords:** precipitation trends; extreme events; spatial variability of precipitation; observed precipitation; Southeast Brazil.

## 1. Introduction

Southeast Brazil (SE Brazil), with more than 85 million inhabitants, is the most populous region in the country and is responsible for about 55.2% of the gross national product (IBGE, 2012). The dominant climatic feature is the pronounced seasonal cycle in precipitation, moisture and circulation, controlled by the South American Monsoon System (SAMS) (Zhou and Lau, 2001). The South Atlantic Convergence Zone (SACZ), one of the main features of the SAMS, is characterized by a northwest-southeast rain band extending from the Amazon across SE Brazil toward the subtropical South Atlantic (Kodama, 1992) and is related to the occurrence of extreme precipitation events in SE Brazil (Liebmann *et al.*, 2001; Carvalho *et al.*, 2002; Carvalho *et al.*, 2004; Muza *et al.*, 2009; Cavalcanti, 2012). The economic and strategic position of SE Brazil brings forth concerns about environmental security, especially population exposure to precipitation-related disasters such as floods and landslides. This region exhibits one of the largest urban growth rates in Brazil (IBGE, 2012) and changes in precipitation regimes, particularly extremes, may dramatically increase population's vulnerability and negatively impact adaptation capability to projected future climate change scenarios by the middle and end of the 21<sup>st</sup> century (IPCC, 2013).

In 2013, the Intergovernmental Panel on Climate Change (IPCC) released its Fifth Assessment Report (AR5) showing that the increase in global temperature since the last century is certain both over land and ocean, with the last three decades being warmer than any other previous decades in instrumental records (Hartmann *et al.*, 2013). Although the warming of the troposphere is expected to increase the capacity of

the atmosphere to retain moisture following the Clausius-Clapeyron relation, implications for changes in rainfall are much more complex and spatially non-uniform (Held and Soden, 2006). Future scenarios of climate change for South America indicate an intensification of monsoonal circulation and precipitation south of 20°S (Kitoh *et al.*, 2013; Jones and Carvalho, 2013) and a southward displacement of the mean position of the SACZ (Seth *et al.*, 2010; Junquas *et al.*, 2012; Cavalcanti and Shimizu, 2012) by the end of the 21<sup>st</sup> century comparatively to the 20<sup>th</sup> century. However, these studies also indicate that large uncertainties still remain regarding the magnitude and signal of precipitation changes over SE Brazil (Kitoh *et al.*, 2013; Carvalho and Jones, 2013; Jones and Carvalho, 2013).

Previous observational studies have examined changes in precipitation regimes using rain gauge data at specific locations, most of them limited to a few decades. Over South America, they identified positive trends in precipitation mainly over Southeastern South America (SESA), including some locations in Southern Brazil (Haylock *et al.*, 2006; Marengo *et al.*, 2010). Over SESA, these positive trends were related to intensification of heavy rainfall rather than an increase in the frequency of wet days (Skansi *et al.*, 2013). Over SE Brazil (Figure 1), long-term trends in precipitation were less coherent and exhibited large spatial variability in trends. Despite the observed discrepancies, these studies detected positive trends in rainfall intensity in the states of Rio de Janeiro (RJ; Haylock *et al.*, 2006; Teixeira and Satyamurty, 2011, Dereczynski *et al.*, 2013) and São Paulo (SP; Liebmann *et al.*, 2004; Dufek and Ambrizzi, 2008; Marengo *et al.*, 2010, Marengo *et al.*, 2013; Teixeira and Satyamurty, 2011; Silva Dias

*et al.*, 2013, Valverde and Marengo, 2014). Silva Dias *et al.* (2013) observed that trends in heavy rainfall in the city of Sao Paulo were positively correlated to coupled modes of variability in the Pacific (Pacific Decadal Oscillation) and Atlantic (North Atlantic Oscillation) oceans, as well as with the South American Monsoon System (SAMS) and sea surface temperature anomalies along the southeastern coast of Brazil during the wet season.

In addition, some studies have shown an increase in the number of consecutive dry days and a decrease in the number of light rainy days (less than 5mm/day) in the city of Sao Paulo (Xavier *et al.*, 1994; Dufek and Ambrizzi, 2008; Silva Dias *et al.*, 2013; Marengo *et al.*, 2013). Raimundo *et al.* (2014) observed that stations with negative trends in light rainy days were located in more urbanized areas while those located in rural areas to the east, north, and northeast of the metropolitan area showed positive trends for the index.

Most studies that investigated trends in precipitation over SE Brazil were based on rain gauge data with low spatial density (Haylock *et al.*, 2006; Dufek and Ambrizzi, 2008; Marengo *et al.*, 2010; Teixeira and Satyamurty, 2011, Dereczynski *et al.*, 2013) or focused on specific locations such as the metropolitan area of Sao Paulo (Xavier *et al.*, 1994; Sugahara *et al.*, 2009; Silva Dias *et al.*, 2013; Marengo *et al.*, 2013; Raimundo *et al.*, 2014). The objective of this study is to provide a comprehensive analysis of the spatial variability of trends in extreme precipitation over SE Brazil using the longest and spatially densest set of observations available on the coast of Sao Paulo, Rio de Janeiro and Espirito Santo. Here we examined two datasets: rain gauge stations

and gridded data. While gridded precipitation offers an overview of regional and large-scale patterns of precipitation trends, individual stations provide local details and geographical features associated with the observed trends. The rain gauges selected for this study have more than 70 years of daily data with good quality and few missing days. The gridded precipitation dataset is based exclusively on observations, with a good spatial resolution ( $0.5^\circ$ ). The analyses of these data sets allow the detection of trends and respective patterns of spatial variability that have not been shown before for the study region.

We focus our analysis on the coast of SE Brazil because of its economic and social importance and also because of the high uncertainty in future projections of climate change, particularly concerning changes in precipitation regimes (Seth *et al.*, 2010; Kitoh *et al.*, 2013; Junquas *et al.*, 2012; Carvalho and Jones, 2013; Jones and Carvalho, 2013, Dereczynski *et al.*, 2013). This manuscript is organized as follows. Information about the datasets is provided in Section 2. Methodology is described in Section 3. Results are presented in Section 4 and final conclusions in Section 5.

## **2. Data**

We examine precipitation records from two datasets: a daily gridded precipitation dataset from the Physical Sciences Division (PSD), Earth System Research Laboratory (Figure 2; Liebmann and Allured, 2005) and data from individual stations, operated by different Brazilian agencies (Figure 1 and Table 1).

The PSD dataset provides daily precipitation grids from 1938 to 2012, with  $0.5^\circ$  latitude/longitude resolution, and is based on precipitation observed at stations located

over most of South America (Liebmann and Allured, 2005). The dataset is composed of daily totals over all valid stations located within a sample radius of  $0.5^\circ$  from the center of the grid point. This assures the inclusion of all stations in at least one grid point. The disadvantage of this method is that a few stations may be included in up to four different grid points, causing additional smoothing of the data and masking out extreme precipitation with a spatial scale smaller than the grid resolution (Liebmann and Allured, 2005). This dataset exhibits variable station density (Figure 2b) and data availability in space and time (Figure 2c). To avoid examining areas with relatively short time series that could misrepresent the extent of actual trends, we first remove all grid points with more than 40% of missing days over the entire period (Figure 2a). In addition, we considered only years with more than 95% of valid days along the wet season (October to March) and grid points with more than 50% of valid seasons (more than 38 years). With these criteria, the vast majority of grid points over SE Brazil have more than 60 years of data between 1938 and 2012 (dark shades in Figure 2c). This is the longest daily gridded precipitation available for the region.

To further understand trends in heavy precipitation and their spatial variation over the topographically complex and highly urbanized area of SE Brazil, we also analyze daily precipitation obtained from 36 rain gauges located on the coast of Sao Paulo (SP), Rio de Janeiro (RJ), Espirito Santo (ES), and southeastern Minas Gerais (MG) states (Figure 1). These stations are operated by different Brazilian agencies (Table 1), and are available from the Brazilian National Water Agency website (Agencia Nacional de Aguas – ANA; <http://hidroweb.ana.gov.br/>). All stations in this

data set have at least 70 years of observations, including the period between 1939 and 1999, with less than 5% missing days (Table 1). The quality control test carried out in this study checks for outliers based on neighboring stations, evaluates station metadata to detect changes in station location and days without readings, and adopts the Rodionov test (Rodionov, 2006) to detect steps and discontinuities in the time series.

These raingauge stations are included in the gridded dataset; however, as we will show next, individual stations are useful to identify local variations in trends, particularly near complex terrain and urban centers. Urban areas (Figure 1, cross hatching patterns) are delimited using the Global Rural-Urban Mapping Project Version 1 (GRUMPv1, available at <http://sedac.ciesin.columbia.edu/data/collection/grump-v1>; Balk *et al.*, 2006). This data set considers night light observations collected by a series of US Department of Defense meteorological satellites as one of the variables in the definition of the urban-extent grid. The major topographic feature of coastal SE Brazil is the Coastal Range, with average elevation below 1000m and some peaks above 2000m (Figure 1, shades).

This study focuses on the wet season (October to March) and thus most extreme precipitation events are related to the SACZ activity (Liebmann *et al.*, 2001; Carvalho *et al.*, 2002; Carvalho *et al.*, 2004; Cavalcanti, 2012). Mechanisms related to the observed trends are a subject of our current research but are not explored in this manuscript.

### **3. Detection and Characterization of Trends**

Trends in precipitation can be described as changes in intensity and/or frequency of rainfall events that may or may not alter the total annual or the mean daily



precipitation. To identify these changes, we derive various indices, based on daily precipitation observations for the wet season (October to March) from both gridded and station data (Table 2): total precipitation (*TotPR*), daily average (*DayPR*), percentage of rainy days (*%PRDay*), number of light rainy days (*NumbLightPR*), maximum seasonal precipitation (*MaxPR*), 95<sup>th</sup> percentile of daily precipitation (*95%*), frequency of extreme events (*NumbEx*) and intensity of extreme events (*IntEx*).

We define extreme events as days with precipitation equal or greater than the 95<sup>th</sup> percentile, calculated for each station (and grid point) and month separately and using all years of record. The intensity of the events is defined as the amount of rainfall exceeding the 95<sup>th</sup> percentile monthly climatological value, accumulated over the season. The frequency of extremes is estimated as the number of days per season that precipitation exceeds the monthly 95<sup>th</sup> percentile. If extremes occur in two or more consecutive days this sequence is considered as a single event.

For each derived index, we investigate the presence and magnitude of trends by applying the Mann-Kendall trend test (Wilks, 2011) and the Sen's slope test (Sen, 1968; Gocic and Trajkovic, 2013). The Mann-Kendall test identifies whether or not the index exhibits a trend whereas the Sen's slope test estimates the slope of the trend. Both are non-parametric tests and have been largely used in studies of tendency in atmospheric and hydrological variables (Dufek and Ambrizzi, 2008; Marengo *et al.*, 2010; Ghosh *et al.*, 2012; Gocic and Trajkovic, 2013). The Mann-Kendal statistic *S* is estimated as (Wilks, 2011):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (1)$$

where  $n$  is the number of data points;  $x$  is each of the measurements at different time steps  $i$  and  $j$ , with  $i \neq j$ ; and  $\text{sgn}(\cdot)$  is defined as:

$$\text{sgn} = \begin{cases} 1, & \text{if } (x_j - x_i) > 0 \\ 0, & \text{if } (x_j - x_i) = 0 \\ -1, & \text{if } (x_j - x_i) < 0 \end{cases} \quad (2)$$

The Mann-Kendall trend test checks the null hypothesis of no trend against the alternative hypothesis of the presence of a trend (Jain and Kumar, 2012); positive (negative)  $S$  indicates an increasing (decreasing) trend. If  $n > 10$ , the  $S$  statistics follows a Gaussian distribution with null average ( $E[S] = 0$ ) and variance:

$$\text{Var}[S] = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (3)$$

where  $m$  is the number of tied groups (zero difference between compared values) and  $t_i$  is the number of data points in each tied group (Wilks, 2011). The significance of this trend can be found using  $z$ -scores, estimated as:

$$z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}}, & S > 0 \\ \frac{S+1}{\sqrt{\text{Var}(S)}}, & S < 0 \end{cases} \quad (4)$$

If  $|z| > z_{\alpha/2}$ , the null hypothesis can be rejected at  $\alpha$  level of significance in a two-sided test (Jain and Kumar, 2012).

The Sen's slope estimator test (Gocic and Traijkovic, 2013; Adarsh and Janga Reddy, 2014), which considers the slopes between all data pairs in the time series, was also applied:

$$Q_i = \frac{x_j - x_k}{j - k} \text{ for } i = 1, 2, \dots, N \quad (5)$$

where  $N$  is the number of different pairs of observations so that  $N = \frac{n(n-1)}{2}$ ;  $x_j$  and  $x_k$  are data values at time  $j$  and  $k$ , with  $j > k$ . The slope estimator is computed by considering the median value of all ranked  $Q_{(i)}$ :

$$Q_{med} = \begin{cases} Q_{[(N+1)/2]} & , \text{ if } N \text{ is odd} \\ \frac{Q_{(N/2)} + Q_{[(N+2)/2]}}{2} & , \text{ if } N \text{ is even} \end{cases} \quad (6)$$

where  $Q_{med}$  represents the steepness of the trend, with positive (negative) values representing positive (negative) trends. The confidence interval for this test is estimated by  $C_\alpha = z_{1-\alpha/2} \sqrt{Var[S]}$ , where  $Var[S]$  is estimated by eq. 3, and  $z_{1-\alpha/2}$  is defined from the standard normal distribution. The confidence interval is:

$$Q_{min} = Q_{(M_1)} \text{ and } Q_{max} = Q_{(M_2+1)} \quad (7)$$

$$M_1 = \frac{N - C_\alpha}{2} \text{ and } M_2 = \frac{N + C_\alpha}{2} \quad (8)$$

where  $Q_{min}$  and  $Q_{max}$  are the lower and upper limits of the confidence interval. The slope  $Q_{med}$  is statistically different from zero if the two limits ( $Q_{min}$  and  $Q_{max}$ ) have similar sign.

Before applying these tests, we also check the autocorrelation of each time series. Whenever significance level of the lag-1 autocorrelation coefficient ( $r_1$ ) is above

0.95, the Mann-Kendall variance is adjusted by  $Var^*[S] = Var[S] \frac{1+r_1}{1-r_1}$ , as suggested by Wilks (2011).

Here, trends are considered statistically significant based on the statistic  $S$  for the Mann-Kendall test (Eq. 1) at 10% significance level. The confidence interval for the Sen's slope is also 10%.

## 4. Results

### 4.1. Climatology of the Indices

We first calculate the climatology of all indices evaluated in this paper (Figure 3) at those grid points with less than 40% missing data (Figure 2a), effectively restricting the analysis to eastern Brazil. Table 2 summarizes the indices investigated in this study and shows the climatological spatial average of each index over all grid points between 49°W to 40°W and 25°S to 20°S, representing SE Brazil. The average rainfall over SE Brazil during the wet season is 1122.7mm (*TotPR*; Figure 3a), and the mean wet day precipitation rate is about 9mm/day (*DayPR*; Figure 3b). *%PRDay* and *NumbLightPR* (Figures 3c and 3d) emphasize the large number of rainy days per season. Figure 3c shows that approximately 60% of the days (equivalent to 110 out of 182 days) have precipitation above 1mm/day. About 43% of the rainy days (i.e., 47 out of 110 rainy days; Figure 3d) are associated with precipitation rates between 1 and 5 mm/day.

The *MaxPR* and *95%* (Figures 3e and 3f) are also large over SE Brazil and both have spatial distribution similar to the *DayPR* spatial pattern, and all three indices are

consistent with the climatological position of the SACZ. Over SE Brazil, *MaxPR* is, on average, 52mm/day and 95% is 29.1mm/day. The average *NumbEx* is 7 events per season (Figure 3g), with *IntEx* larger than 90mm/season (Figure 3h).

Large *DayPR*, *MaxPR*, 95% and *IntEx* (Figures 3b, 3e, 3f and 3i) are also observed over Southern Brazil. Intense precipitation in this region results from the interplay of phenomena on a broad range of spatiotemporal scales and this discussion is beyond the scope of the present article.

#### 4.2. Trends in gridded dataset

The gridded dataset indicates a significant increase ( $p < 0.1$ ) in *TotPR* over SP and South Brazil (Figure 4a). Over SP, positive trends in *TotPR* are collocated with positive significant trends ( $p < 0.1$ ) in *DayPR*, *MaxPR*, 95%, *NumbEx*, and *IntEx* (Figures 4b, 4e, 4f, 4g and 4h, stippled areas). These positive trends suggest that extreme daily precipitation events are becoming more intense (increase in *IntEx*, *MaxPR* and 95%) and more frequent (increase in *NumbEx*), affecting the total seasonal precipitation (*TotPR*) and the daily average (*DayPR*). Conversely, there are significant negative trends ( $p < 0.1$ ) in *%PRDay* and *NumbLightPR* (Figures 4c and 4d) in the state, indicating a decrease in the number of rainy days (days with precipitation above 1mm) and light rain days (days with precipitation between 1 and 5 mm). Both results are in agreement with previous studies (Xavier *et al.*, 1994; Haylock *et al.*, 2006; Dufek and Ambrizzi, 2008; Sugahara *et al.*, 2009; Marengo *et al.*, 2010; Teixeira and Satyamurty,

2011; Silva Dias *et al.*, 2013; Skansi *et al.*, 2013; Raimundo *et al.*, 2014, Valverde and Marengo, 2014).

Interestingly, the area with positive trends in *TotPR*, *DayPR*, *MaxPR*, and *95%*, over SP is located south of the area of climatological maximum for each index (compare Figures 3 and 4). The climatological maximum for these indices is collocated with the average position of the SACZ (Figure 3), indicating that trends observed in the indices could be related to a progressive southwestward displacement of the SACZ. Previous studies that investigated multimodel projections of climate change in the wet season precipitation regimes using the Coupled Model Intercomparison Project (CMIP) phase-3 (Seth *et al.*, 2010) and more recently CMIP phase-5 dataset (Jones and Carvalho, 2013) and have indicated similar displacement of the SACZ, suggesting that the observed trends could be the signal of a regional response in precipitation caused by the radiative forcing due to global warming.

Over northern SE Brazil, negative trends in *TotPR*, *DayPR*, *MaxPR*, *95%*, *NumbEx* and *IntEx* (Figures 4a, 4b, 4e-4h) and positive trends in *%PRDay* and *NumbLightPR* (Figures 4c and 4d) are opposite to the observed trends over SP. We speculate that this drying tendency, which is associated with decrease in the intensity and frequency of extreme events, is related to the wetting tendency farther south, both a consequence of a southwestward displacement of the SACZ.

We also observe the presence of significant ( $p < 0.1$ ) positive trends over RJ for *TotPR*, *%PRDay*, *MaxPR*, *95%*, *NumbEx*, and *IntEx* indices (Figures 4a, 4c, 4e-h). The *DayPR* and *NumbLightPR* also show positive, but non-significant, trends in the region.

These trends are observed over the northern portion of the state and indicate that extreme events are becoming more frequent and intense over the region. Dereczynski *et al.* (2013) identified similar trends; however their study focused only on the city of Rio de Janeiro. Our analysis, based on gridded data with longer time series, detected that these trends are broader and extend over the northern portion of RJ.

#### 4.3. Trends at individual stations

To detail the spatial variability of trends over coastal areas of SE Brazil, we examined precipitation data from 36 individual stations with the longest available records in the region (Figure 1). Positive significant trends ( $p < 0.1$ ) in *TotPR* are identified in 5 stations whereas only 2 stations showed negative and significant ( $p < 0.1$ ) trends (Figure 5a). The *DayPR* also exhibits similar spatial variability of trends: 22 stations indicate positive trends although only 8 stations are statistically significant ( $p < 0.1$ ; Figure 5b). These trends in *DayPR* occur mostly in RJ, where the *%PRDay* and *NumbLightPR* (Figures 5c and 5d) show negative significant trends, indicating a tendency for fewer but more intense precipitation events over that area.

Further south, over SP, positive trends in *TotPR* and *DayPR* (Figures 5a and 5b) are observed along with positive trends in *%PRDay* (Figure 5c), in agreement with previous investigations based on individual stations (Dufek and Ambrizzi, 2008; Teixeira and Satyamurty, 2011). Trends in *NumbLightPR* (Figure 5d) are more complex, with negative significant trends observed over urbanized areas around the city of Sao Paulo as indicated in Xavier *et al.* (1994) and Marengo *et al.* (2013). Stations

over rural areas show positive significant trends for the number of light rainy days, as observed by Raimundo *et al.* (2014).

Trends in intense precipitation events are examined based on 4 indices: *MaxPR*, *95%*, *NumbEx* and *IntEx* (Figures 5e-5h). Positive trends in all four indices are observed in at least 24 out of the 36 stations for each index, and the trend in each index was statistically significant ( $p < 0.1$ ) in at least 6 stations. The majority of stations with significant trends are located over RJ and over urban areas of SP. These results reinforce the previous results (Figure 5) that the increase in *DayPR* over RJ is related to more intense and more frequent heavy precipitation days, with a decrease in *%PRDay* and *NumbLightPR*.

To compare our results with previous studies, we focus our analysis on two stations located in the Metropolitan Area of Sao Paulo (stations 30 and 31 in Figure 1 and Table 1). The precipitation record from station 31 has been examined in many previous studies due to its proximity to a large urban center, long record and excellent quality control of data (e.g., Xavier *et al.*, 1994; Sugahara *et al.*, 2009; Silva Dias *et al.*, 2013; Marengo *et al.*, 2013; Raimundo *et al.*, 2014). Our analysis indicate positive significant trends in *TotPR*, *DayPR*, *MaxPR*, *NumbEx*, and *IntEx* (Figures 5a, 5b, 5e, 5g and 5h), and negative trend in *NumbLightPR* (Figure 5d), in agreement with those previous studies.



#### 4.4. Comparison between gridded data and individual station trends

Overall, trends observed for the gridded dataset are similar to those for individual stations. This is not completely surprising as all stations used in this study were included in the gridded data. However, some local discrepancies do exist. The most noticeable differences are observed for *%PRDay* and *NumbLightPR* over the northern RJ. Gridded data indicate positive trends for both indices, significant for *%PRDay* (Figures 4c and 4d), while most stations over this area show significant negative trends for both indices (Figures 5c and 5d). These discrepancies are likely related to the averaging method utilized in the gridded dataset. In regions with complex topography, precipitation exhibits large spatial variability, with large amounts concentrated in small areas where orographic lifting may increase the probability of convective rainfall relative to neighboring stations. However, when averaging precipitation records into a  $0.5^\circ$  grid, these few stations likely contribute to the relative increase in the average number of rainy days. In these cases individual stations provide a more realistic characterization of spatial variability of rainfall trends.

Over SP, trends in *NumbLightPR* are also different between data sets, with the gridded dataset indicating a negative trend over the entire state (statistically significant over central SP; Figure 4d) while stations indicate negative trends only in two stations located in urbanized areas (Figure 5d). Other stations located in rural areas of SP show positive trends, indicating that  $0.5^\circ$  grid is not sufficient to resolve difference between urban and rural areas.

The analysis of both datasets also reveals a spatial pattern of trends over SP to RJ. While over SP there is an increase in total precipitation and daily rates (*TotPR* and *DayPR*, Figures 4a-b, 5a-b) caused by more intense and frequent extreme precipitation events (*MaxPR*, *95%*, *NumbEx* and *IntEX*; Figures 4e-4h and 5e-h), over RJ the intense events are becoming stronger and more frequent (*MaxPR*, *95%*, *NumbEx* and *IntEX*; Figures 4e-4h and 5e-5h), but the number of days with precipitation is decreasing (*NumbLightPR* and *%PRDay*, Figures 4c-d and 5c-d).

## 5. Discussion and Conclusions

Previous studies have shown compelling evidence that precipitation and its extremes have changed in the last decades in SE Brazil. These studies, however, were based on spatially averaged precipitation with relatively coarse resolution (Liebmann *et al.*, 2004; Teixeira and Satyamurty, 2011), or based on stations located in SP (Haylock *et al.*, 2006; Dufek and Ambrizzi, 2008; Sugahara *et al.*, 2009; Marengo *et al.*, 2010, Marengo *et al.*, 2013; Silva Dias *et al.*, 2013). The present study develops a comprehensive analysis of rainfall and its extremes using the most up to date and longest rainfall gauge records available in SP, RJ, ES and MG. Our major objective is to properly characterize patterns of changes in intensity and frequency of both light and extreme rainfall events. The trends detected using these observational precipitation dataset provide additional evidence that the projected changes for future scenarios of climate change are already occurring.

Although the gridded and gauge datasets used here are not independent, trend analysis using gridded precipitation identified regional patterns of changes in rainfall,

whereas station records improved the identification of local variations in these patterns, particularly near complex terrain and major urban centers. Mapping trends in SE Brazil has significant economic and social impacts for the country. High urban population density, inappropriate occupation of risk areas in RJ, SP and MG, and positive trends in extreme precipitation suggest an increasing exposure to rain-related disasters in these regions.

Table 3 summarizes the qualitative interpretation of the main results observed in this study. Over SP, both datasets indicate an increase in total seasonal and average daily precipitation and suggests that these changes are related to an increase in the frequency and intensity of extreme events, consistent with previous studies. Additionally, the gridded dataset indicates that the areas with significant trends for these indices are located southwest of the climatological maximum of rainfall. Since SACZ is the most important climatological phenomenon modulating precipitation in the region, a plausible explanation for the positive trend in total precipitation over SP is a southwestward displacement of the SACZ in recent decades, as previously speculated in Liebmann *et al.* (2004) and suggested in coupled climate model simulations of future scenarios of climate change in South America discussed in Seth *et al* (2010) and Jones and Carvalho (2013). Our results suggest that the poleward displacement of the SACZ is already detectable in historical data.

Farther north, in RJ and ES, both datasets agree that positive trends in the daily average are related to trends in intensity and frequency of extreme precipitation days (Table 3). Individual stations also reveal negative trends in the percentage of rainy days

and in the number of light rainy days. These trends, not evident in the gridded data, indicate changes in the frequency and intensity of precipitation events, with larger accumulation occurring in fewer rainy days. Dereczynski *et al.* (2013) identified similar trends in future scenarios of climate change for the city of Rio de Janeiro. Our results confirm that these trends are already detectable in historical data and show that these trends actually extend to larger areas north of the state.

Therefore, while over SP there is an increase in the number of rainy days and in the frequency and intensity of extreme events, over RJ and ES we observe a negative trend in the frequency of rainy days, with precipitation concentrated in fewer and more intense events. These results are consistent with the hypothesis of the southwestward displacement of the SACZ.

Tropical South America has undergone a rapid warming in the last 5 decades, a trend that is expected to continue and increase by the end of the 21<sup>st</sup> century (Carvalho and Jones, 2013). It has been argued that the reduction in the frequency of rainy days along the margin of the convective zones, such as the SACZ, is one of the consequences of the changes in moisture spatial variability in a warmer atmosphere (Chou and Neelin, 2004; Held and Soden, 2006; Lintner and Neelin, 2010; Ma *et al.*, 2011). According to previous studies, warmer temperatures would increase the saturation vapor pressure, increasing the moisture necessary to reach saturation. In the core of convective regions, there is always enough moisture to meet this higher threshold for precipitation. However, along the convective margins, the moisture availability might not be enough to reach the new level of saturation, since these areas receive most of their influx from

more stable areas, in this case the ocean. In addition, moisture in convective margins is also exported to the region of strong convection, reducing even more the moisture availability and, consequently, increasing stability and decreasing precipitation events in these regions. We speculate that the observed reduction in the number of rainy events over RJ and ES could be related to the warming and subsequent changes in saturation water vapor along the northern margin of the SACZ. The observed positive trends in extreme daily precipitation could be related to thermodynamic effects such as an increase in convective instability. Nevertheless, many other dynamic and thermodynamic mechanisms, combined with environmental changes such as the effect of rapid urbanization and land-use and change, could also have played a significant role in the observed trends in precipitation. Therefore, further investigation is necessary to properly recognize the underlying dynamical and physical mechanisms responsible for the observed trends in precipitation over SE Brazil.

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## Figures and Table

**Fig. 1** Inset: Location of SE Brazil (shaded) and study area (dashed line) in Brazil. Main map: Location of the study area (dashed line) at SE Brazil; stations analyzed (•); shades: local topography (1km resolution DEM from SRTM; USGS 2004); cross hatching: urban area (GRUMPv1 dataset, Balk et al. 2006). Information about stations is provided in Table 1. This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Fig. 2** Gridded dataset: % of missing days (a); average number of stations per grid point (b); and number of valid years per grid point (c). (b) and (c): only grid points with less than 40% missing days. Dashed line: study area. Gray contour: states of SE

Brazil. Stars: Sao Paulo (23.6°S, 46.6°W) and Rio de Janeiro (22.9°S, 43.2°W).

This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Fig. 3** Wet season climatology for gridded data: *TotPR* (a), *DayPR* (b), *%PRDay* (c), *NumbLightPR* (d), *MaxPR* (e), *95%* (f); *NumbEx* (g) and *IntEx* (h). Dashed line: study area. Gray contour: states of SE Brazil. Stars: Sao Paulo (23.6°S, 46.6°W) and Rio de Janeiro (22.9°S, 43.2°W). This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Fig. 4** Trends in gridded dataset for wet season: *TotPR* (a), *DayPR* (b), *%PRDay* (c), *NumbLightPR* (d), *MaxPR* (e), *95%* (f); *NumbEx* (g) and *IntEx* (h). Blue (red) areas: positive (negative) trends (Sen's slope); stippled areas: significant trends ( $p < 0.1$ ). Gray contour: states of SE Brazil. Stars: Sao Paulo (23.6°S, 46.6°W) and Rio de Janeiro (22.9°S, 43.2°W). This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Fig. 5** Trends in station data for wet season: *TotPR* (a), *DayPR* (b), *%PRDay* (c), *NumbLightPR* (d), *MaxPR* (e), *95%* (f); *NumbEx* (g) and *IntEx* (h). "+" ("−"): positive (negative) trends; blue (red) symbols: positive (negative) significant trends ( $p < 0.1$ ); shades: local topography; dashed line: study area. In (d) cross hatching: urban areas (source: GRUMPv1 dataset, Balk et al. 2006). This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Table 1** Stations analyzed, latitude, longitude, height, city where located, time range, percentage of missing, and source institution. The location of these stations is in Figure 1

**Table 2** Precipitation indices, acronyms, their definition, and mean value for the wet season (based on the gridded data averaged over the entire period for all grid points over coastal SE Brazil - 49°W to 40°W and 25°S to 20°S)

**Table 3** Trends in each index considering both dataset, for the states of RJ and ES, SP, and the Metropolitan Area of Sao Paulo (MASP). Symbols: positive (↗), negative (↘) or no significant (▬) trends.

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# **A COMPREHENSIVE ANALYSIS OF TRENDS IN EXTREME PRECIPITATION OVER SOUTHEASTERN COAST OF BRAZIL**

## **SHORT TITLE: EXTREME PRECIPITATION TRENDS OVER SOUTHEASTERN COAST OF BRAZIL**

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## ABSTRACT

Southeast Brazil (SE Brazil) is the most densely populated region in Brazil. Previous studies have shown evidence of positive trends in average precipitation and extreme events in a few locations, suggesting the increase in rainfall related hazards with potential impacts to urbanized areas of SE Brazil. This study provides a comprehensive analysis of the spatial variability of trends in extreme precipitation over SE Brazil focusing on regional and local scales. We examine two daily rainfall datasets with more than 70 years of data: individual stations and gridded observed precipitation data. Our results indicate that the frequency of both rainy days and extreme daily precipitation events have increased in Sao Paulo state. Conversely, precipitation has become more concentrated in fewer events in Rio de Janeiro and Espirito Santo states where both data sets indicate positive trends in the intensity of extreme daily rainfall. The increase in frequency and intensity of extreme events have both contributed to positive trends in total seasonal and average daily precipitation over Sao Paulo. Additionally, individual stations indicate negative trends in the number of light rainy days over large urbanized areas in the state of Sao Paulo. The spatial patterns of trends indicate that they are influenced by the proximity of large urban centers and topographic features, and also suggest variations and changes in the major climatic systems affecting precipitation regimes over SE.

**Keywords:** precipitation trends; extreme events; spatial variability of precipitation; observed precipitation; Southeast Brazil.



## 1. Introduction

Southeast Brazil (SE Brazil), with more than 85 million inhabitants, is the most populous region in the country and is responsible for about 55.2% of the gross national product (IBGE, 2012). The dominant climatic feature is the pronounced seasonal cycle in precipitation, moisture and circulation, controlled by the South American Monsoon System (SAMS) (Zhou and Lau, 2001). The South Atlantic Convergence Zone (SACZ), one of the main features of the SAMS, is characterized by a northwest-southeast rain band extending from the Amazon across SE Brazil toward the subtropical South Atlantic (Kodama, 1992) and is related to the occurrence of extreme precipitation events in SE Brazil (Liebmann *et al.*, 2001; Carvalho *et al.*, 2002; Carvalho *et al.*, 2004; Muza *et al.*, 2009; Cavalcanti, 2012). The economic and strategic position of SE Brazil brings forth concerns about environmental security, especially population exposure to precipitation-related disasters such as floods and landslides. This region exhibits one of the largest urban growth rates in Brazil (IBGE, 2012) and changes in precipitation regimes, particularly extremes, may dramatically increase population's vulnerability and negatively impact adaptation capability to projected future climate change scenarios by the middle and end of the 21<sup>st</sup> century (IPCC, 2013).

In 2013, the Intergovernmental Panel on Climate Change (IPCC) released its Fifth Assessment Report (AR5) showing that the increase in global temperature since the last century is certain both over land and ocean, with the last three decades being warmer than any other previous decades in instrumental records (Hartmann *et al.*, 2013). Although the warming of the troposphere is expected to increase the capacity of the atmosphere to retain moisture following the Clausius-Clapeyron relation, implications for changes in rainfall are much more complex and spatially non-uniform (Held and Soden, 2006). Future scenarios of climate change for South America indicate an intensification of monsoonal circulation and precipitation south of 20°S (Kitoh *et al.*, 2013; Jones and Carvalho, 2013) and a southward displacement of the mean position of the SACZ (Seth *et al.*, 2010; Junquas *et al.*, 2012; Cavalcanti and Shimizu, 2012) by the end of the 21<sup>st</sup> century comparatively to the 20<sup>th</sup> century. However, these studies also indicate that large uncertainties still remain regarding the magnitude and signal of precipitation changes over SE Brazil (Kitoh *et al.*, 2013; Carvalho and Jones, 2013; Jones and Carvalho, 2013).

Previous observational studies have examined changes in precipitation regimes using rain gauge data at specific locations, most of them limited to a few decades. Over South America, they identified

positive trends in precipitation mainly over Southeastern South America (SESA), including some locations in Southern Brazil (Haylock *et al.*, 2006; Marengo *et al.*, 2010). Over SESA, these positive trends were related to intensification of heavy rainfall rather than an increase in the frequency of wet days (Skansi *et al.*, 2013). Over SE Brazil (Figure 1), long-term trends in precipitation were less coherent and exhibited large spatial variability in trends. Despite the observed discrepancies, these studies detected positive trends in rainfall intensity in the states of Rio de Janeiro (RJ; Haylock *et al.*, 2006; Teixeira and Satyamurty, 2011, Dereczynski *et al.*, 2013) and São Paulo (SP; Liebmann *et al.*, 2004; Dufek and Ambrizzi, 2008; Marengo *et al.*, 2010, Marengo *et al.*, 2013; Teixeira and Satyamurty, 2011; Silva Dias *et al.*, 2013, Valverde and Marengo, 2014). Silva Dias *et al.* (2013) observed that trends in heavy rainfall in the city of Sao Paulo were positively correlated to coupled modes of variability in the Pacific (Pacific Decadal Oscillation) and Atlantic (North Atlantic Oscillation) oceans, as well as with the South American Monsoon System (SAMS) and sea surface temperature anomalies along the southeastern coast of Brazil during the wet season.

In addition, some studies have shown an increase in the number of consecutive dry days and a decrease in the number of light rainy days (less than 5mm/day) in the city of Sao Paulo (Xavier *et al.*, 1994; Dufek and Ambrizzi, 2008; Silva Dias *et al.*, 2013; Marengo *et al.*, 2013). Raimundo *et al.* (2014) observed that stations with negative trends in light rainy days were located in more urbanized areas while those located in rural areas to the east, north, and northeast of the metropolitan area showed positive trends for the index.

Most studies that investigated trends in precipitation over SE Brazil were based on rain gauge data with low spatial density (Haylock *et al.*, 2006; Dufek and Ambrizzi, 2008; Marengo *et al.*, 2010; Teixeira and Satyamurty, 2011, Dereczynski *et al.*, 2013) or focused on specific locations such as the metropolitan area of Sao Paulo (Xavier *et al.*, 1994; Sugahara *et al.*, 2009; Silva Dias *et al.*, 2013; Marengo *et al.*, 2013; Raimundo *et al.*, 2014). The objective of this study is to provide a comprehensive analysis of the spatial variability of trends in extreme precipitation over SE Brazil using the longest and spatially densest set of observations available on the coast of Sao Paulo, Rio de Janeiro and Espirito Santo. Here we examined two datasets: rain gauge stations and gridded data. While gridded precipitation offers an overview of regional and large-scale patterns of precipitation trends, individual stations provide local details and geographical features associated with the observed trends. The rain gauges selected for

this study have more than 70 years of daily data with good quality and few missing days. The gridded precipitation dataset is based exclusively on observations, with a good spatial resolution ( $0.5^\circ$ ). The analyses of these data sets allow the detection of trends and respective patterns of spatial variability that have not been shown before for the study region.

We focus our analysis on the coast of SE Brazil because of its economic and social importance and also because of the high uncertainty in future projections of climate change, particularly concerning changes in precipitation regimes (Seth *et al.*, 2010; Kitoh *et al.*, 2013; Junquas *et al.*, 2012; Carvalho and Jones, 2013; Jones and Carvalho, 2013, Dereczynski *et al.*, 2013). This manuscript is organized as follows. Information about the datasets is provided in Section 2. Methodology is described in Section 3. Results are presented in Section 4 and final conclusions in Section 5.

## 2. Data

We examine precipitation records from two datasets: a daily gridded precipitation dataset from the Physical Sciences Division (PSD), Earth System Research Laboratory (Figure 2; Liebmann and Allured, 2005) and data from individual stations, operated by different Brazilian agencies (Figure 1 and Table 1).

The PSD dataset provides daily precipitation grids from 1938 to 2012, with  $0.5^\circ$  latitude/longitude resolution, and is based on precipitation observed at stations located over most of South America (Liebmann and Allured, 2005). The dataset is composed of daily totals over all valid stations located within a sample radius of  $0.5^\circ$  from the center of the grid point. This assures the inclusion of all stations in at least one grid point. The disadvantage of this method is that a few stations may be included in up to four different grid points, causing additional smoothing of the data and masking out extreme precipitation with a spatial scale smaller than the grid resolution (Liebmann and Allured, 2005). This dataset exhibits variable station density (Figure 2b) and data availability in space and time (Figure 2c). To avoid examining areas with relatively short time series that could misrepresent the extent of actual trends, we first remove all grid points with more than 40% of missing days over the entire period (Figure 2a). In addition, we considered only years with more than 95% of valid days along the wet season (October to March) and grid points with more than 50% of valid seasons (more than 38 years). With these criteria, the

vast majority of grid points over SE Brazil have more than 60 years of data between 1938 and 2012 (dark shades in Figure 2c). This is the longest daily gridded precipitation available for the region.

To further understand trends in heavy precipitation and their spatial variation over the topographically complex and highly urbanized area of SE Brazil, we also analyze daily precipitation obtained from 36 rain gauges located on the coast of Sao Paulo (SP), Rio de Janeiro (RJ), Espirito Santo (ES), and southeastern Minas Gerais (MG) states (Figure 1). These stations are operated by different Brazilian agencies (Table 1), and are available from the Brazilian National Water Agency website (Agencia Nacional de Aguas – ANA; <http://hidroweb.ana.gov.br/>). All stations in this data set have at least 70 years of observations, including the period between 1939 and 1999, with less than 5% missing days (Table 1). The quality control test carried out in this study checks for outliers based on neighboring stations, evaluates station metadata to detect changes in station location and days without readings, and adopts the Rodionov test (Rodionov, 2006) to detect steps and discontinuities in the time series.

These rain gauge stations are included in the gridded dataset; however, as we will show next, individual stations are useful to identify local variations in trends, particularly near complex terrain and urban centers. Urban areas (Figure 1, cross hatching patterns) are delimited using the Global Rural-Urban Mapping Project Version 1 (GRUMPv1, available at <http://sedac.ciesin.columbia.edu/data/collection/grump-v1>; Balk *et al.*, 2006). This data set considers night light observations collected by a series of US Department of Defense meteorological satellites as one of the variables in the definition of the urban-extent grid. The major topographic feature of coastal SE Brazil is the Coastal Range, with average elevation below 1000m and some peaks above 2000m (Figure 1, shades).

This study focuses on the wet season (October to March) and thus most extreme precipitation events are related to the SACZ activity (Liebmann *et al.*, 2001; Carvalho *et al.*, 2002; Carvalho *et al.*, 2004; Cavalcanti, 2012). Mechanisms related to the observed trends are a subject of our current research but are not explored in this manuscript.

### 3. Detection and Characterization of Trends

Trends in precipitation can be described as changes in intensity and/or frequency of rainfall events that may or may not alter the total annual or the mean daily precipitation. To identify these changes, we derive various indices, based on daily precipitation observations for the wet season (October

to March) from both gridded and station data (Table 2): total precipitation (*TotPR*), daily average (*DayPR*), percentage of rainy days (*%PRDay*), number of light rainy days (*NumbLightPR*), maximum seasonal precipitation (*MaxPR*), 95<sup>th</sup> percentile of daily precipitation (*95%*), frequency of extreme events (*NumbEx*) and intensity of extreme events (*IntEx*).

We define extreme events as days with precipitation equal or greater than the 95<sup>th</sup> percentile, calculated for each station (and grid point) and month separately and using all years of record. The intensity of the events is defined as the amount of rainfall exceeding the 95<sup>th</sup> percentile monthly climatological value, accumulated over the season. The frequency of extremes is estimated as the number of days per season that precipitation exceeds the monthly 95<sup>th</sup> percentile. If extremes occur in two or more consecutive days this sequence is considered as a single event.

For each derived index, we investigate the presence and magnitude of trends by applying the Mann-Kendall trend test (Wilks, 2011) and the Sen's slope test (Sen, 1968; Gocic and Trajkovic, 2013). The Mann-Kendall test identifies whether or not the index exhibits a trend whereas the Sen's slope test estimates the slope of the trend. Both are non-parametric tests and have been largely used in studies of tendency in atmospheric and hydrological variables (Dufek and Ambrizzi, 2008; Marengo *et al.*, 2010; Ghosh *et al.*, 2012; Gocic and Trajkovic, 2013). The Mann-Kendal statistic  $S$  is estimated as (Wilks, 2011):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sgn}(x_j - x_i) \quad (1)$$

where  $n$  is the number of data points;  $x$  is each of the measurements at different time steps  $i$  and  $j$ , with  $i \neq j$ ; and  $\text{sgn}(\cdot)$  is defined as:

$$\text{sgn} = \begin{cases} 1, & \text{if } (x_j - x_i) > 0 \\ 0, & \text{if } (x_j - x_i) = 0 \\ -1, & \text{if } (x_j - x_i) < 0 \end{cases} \quad (2)$$

The Mann-Kendall trend test checks the null hypothesis of no trend against the alternative hypothesis of the presence of a trend (Jain and Kumar, 2012); positive (negative)  $S$  indicates an increasing (decreasing) trend. If  $n > 10$ , the  $S$  statistics follows a Gaussian distribution with null average ( $E[S] = 0$ ) and variance:

$$Var[S] = \frac{n(n-1)(2n+5) - \sum_{i=1}^m t_i(t_i-1)(2t_i+5)}{18} \quad (3)$$

where  $m$  is the number of tied groups (zero difference between compared values) and  $t_i$  is the number of data points in each tied group (Wilks, 2011). The significance of this trend can be found using  $z$ -scores, estimated as:

$$z = \begin{cases} \frac{S-1}{\sqrt{Var(S)}}, & S > 0 \\ \frac{S+1}{\sqrt{Var(S)}}, & S < 0 \end{cases} \quad (4)$$

If  $|z| > z_{\alpha/2}$ , the null hypothesis can be rejected at  $\alpha$  level of significance in a two-sided test (Jain and Kumar, 2012).

The Sen's slope estimator test (Gocic and Traijkovic, 2013; Adarsh and Janga Reddy, 2014), which considers the slopes between all data pairs in the time series, was also applied:

$$Q_i = \frac{x_j - x_k}{j - k} \text{ for } i = 1, 2, \dots, N \quad (5)$$

where  $N$  is the number of different pairs of observations so that  $N = \frac{n(n-1)}{2}$ ;  $x_j$  and  $x_k$  are data values at time  $j$  and  $k$ , with  $j > k$ . The slope estimator is computed by considering the median value of all ranked  $Q_{(i)}$ :

$$Q_{med} = \begin{cases} Q_{[(N+1)/2]} & , \text{ if } N \text{ is odd} \\ \frac{Q_{(N/2)} + Q_{[(N+2)/2]}}{2} & , \text{ if } N \text{ is even} \end{cases} \quad (6)$$

where  $Q_{med}$  represents the steepness of the trend, with positive (negative) values representing positive (negative) trends. The confidence interval for this test is estimated by  $C_\alpha = z_{1-\alpha/2} \sqrt{Var[S]}$ , where  $Var[S]$  is estimated by eq. 3, and  $z_{1-\alpha/2}$  is defined from the standard normal distribution. The confidence interval is:

$$Q_{min} = Q_{(M_1)} \text{ and } Q_{max} = Q_{(M_2+1)} \quad (7)$$

$$M_1 = \frac{N - C_\alpha}{2} \text{ and } M_2 = \frac{N + C_\alpha}{2} \quad (8)$$

where  $Q_{min}$  and  $Q_{max}$  are the lower and upper limits of the confidence interval. The slope  $Q_{med}$  is statistically different from zero if the two limits ( $Q_{min}$  and  $Q_{max}$ ) have similar sign.

Before applying these tests, we also check the autocorrelation of each time series. Whenever significance level of the lag-1 autocorrelation coefficient ( $r_1$ ) is above 0.95, the Mann-Kendall variance is adjusted by  $Var^*[S] = Var[S] \frac{1+r_1}{1-r_1}$ , as suggested by Wilks (2011).

Here, trends are considered statistically significant based on the statistic  $S$  for the Mann-Kendall test (Eq. 1) at 10% significance level. The confidence interval for the Sen's slope is also 10%.

## 4. Results

### 4.1. Climatology of the Indices

We first calculate the climatology of all indices evaluated in this paper (Figure 3) at those grid points with less than 40% missing data (Figure 2a), effectively restricting the analysis to eastern Brazil. Table 2 summarizes the indices investigated in this study and shows the climatological spatial average of each index over all grid points between 49°W to 40°W and 25°S to 20°S, representing SE Brazil. The average rainfall over SE Brazil during the wet season is 1122.7mm (*TotPR*; Figure 3a), and the mean wet day precipitation rate is about 9mm/day (*DayPR*; Figure 3b). *%PRDay* and *NumbLightPR* (Figures 3c and 3d) emphasize the large number of rainy days per season. Figure 3c shows that approximately 60% of the days (equivalent to 110 out of 182 days) have precipitation above 1mm/day. About 43% of the rainy days (i.e., 47 out of 110 rainy days; Figure 3d) are associated with precipitation rates between 1 and 5 mm/day.

The *MaxPR* and *95%* (Figures 3e and 3f) are also large over SE Brazil and both have spatial distribution similar to the *DayPR* spatial pattern, and all three indices are consistent with the climatological position of the SACZ. Over SE Brazil, *MaxPR* is, on average, 52mm/day and *95%* is 29.1mm/day. The average *NumbEx* is 7 events per season (Figure 3g), with *IntEx* larger than 90mm/season (Figure 3h).

Large *DayPR*, *MaxPR*, *95%* and *IntEx* (Figures 3b, 3e, 3f and 3i) are also observed over Southern Brazil. Intense precipitation in this region results from the interplay of phenomena on a broad range of spatiotemporal scales and this discussion is beyond the scope of the present article.

## 4.2. Trends in gridded dataset

The gridded dataset indicates a significant increase ( $p < 0.1$ ) in *TotPR* over SP and South Brazil (Figure 4a). Over SP, positive trends in *TotPR* are collocated with positive significant trends ( $p < 0.1$ ) in *DayPR*, *MaxPR*, *95%*, *NumbEx*, and *IntEx* (Figures 4b, 4e, 4f, 4g and 4h, stippled areas). These positive trends suggest that extreme daily precipitation events are becoming more intense (increase in *IntEx*, *MaxPR* and *95%*) and more frequent (increase in *NumbEx*), affecting the total seasonal precipitation (*TotPR*) and the daily average (*DayPR*). Conversely, there are significant negative trends ( $p < 0.1$ ) in *%PRDay* and *NumbLightPR* (Figures 4c and 4d) in the state, indicating a decrease in the number of rainy days (days with precipitation above 1mm) and light rain days (days with precipitation between 1 and 5 mm). Both results are in agreement with previous studies (Xavier *et al.*, 1994; Haylock *et al.*, 2006; Dufek and Ambrizzi, 2008; Sugahara *et al.*, 2009; Marengo *et al.*, 2010; Teixeira and Satyamurty, 2011; Silva Dias *et al.*, 2013; Skansi *et al.*, 2013; Raimundo *et al.*, 2014, Valverde and Marengo, 2014).

Interestingly, the area with positive trends in *TotPR*, *DayPR*, *MaxPR*, and *95%*, over SP is located south of the area of climatological maximum for each index (compare Figures 3 and 4). The climatological maximum for these indices is collocated with the average position of the SACZ (Figure 3), indicating that trends observed in the indices could be related to a progressive southwestward displacement of the SACZ. Previous studies that investigated multimodel projections of climate change in the wet season precipitation regimes using the Coupled Model Intercomparison Project (CMIP) phase-3 (Seth *et al.*, 2010) and more recently CMIP phase-5 dataset (Jones and Carvalho, 2013) and have indicated similar displacement of the SACZ, suggesting that the observed trends could be the signal of a regional response in precipitation caused by the radiative forcing due to global warming.

Over northern SE Brazil, negative trends in *TotPR*, *DayPR*, *MaxPR*, *95%*, *NumbEx* and *IntEx* (Figures 4a, 4b, 4e-4h) and positive trends in *%PRDay* and *NumbLightPR* (Figures 4c and 4d) are opposite to the observed trends over SP. We speculate that this drying tendency, which is associated with decrease in the intensity and frequency of extreme events, is related to the wetting tendency farther south, both a consequence of a southwestward displacement of the SACZ.

We also observe the presence of significant ( $p < 0.1$ ) positive trends over RJ for *TotPR*, *%PRDay*, *MaxPR*, *95%*, *NumbEx*, and *IntEx* indices (Figures 4a, 4c, 4e-h). The *DayPR* and *NumbLightPR* also show positive, but non-significant, trends in the region. These trends are observed over the northern



portion of the state and indicate that extreme events are becoming more frequent and intense over the region. Dereczynski *et al.* (2013) identified similar trends; however their study focused only on the city of Rio de Janeiro. Our analysis, based on gridded data with longer time series, detected that these trends are broader and extend over the northern portion of RJ.

### 4.3. Trends at individual stations

To detail the spatial variability of trends over coastal areas of SE Brazil, we examined precipitation data from 36 individual stations with the longest available records in the region (Figure 1). Positive significant trends ( $p < 0.1$ ) in *TotPR* are identified in 5 stations whereas only 2 stations showed negative and significant ( $p < 0.1$ ) trends (Figure 5a). The *DayPR* also exhibits similar spatial variability of trends: 22 stations indicate positive trends although only 8 stations are statistically significant ( $p < 0.1$ ; Figure 5b). These trends in *DayPR* occur mostly in RJ, where the *%PRDay* and *NumbLightPR* (Figures 5c and 5d) show negative significant trends, indicating a tendency for fewer but more intense precipitation events over that area.

Further south, over SP, positive trends in *TotPR* and *DayPR* (Figures 5a and 5b) are observed along with positive trends in *%PRDay* (Figure 5c), in agreement with previous investigations based on individual stations (Dufek and Ambrizzi, 2008; Teixeira and Satyamurty, 2011). Trends in *NumbLightPR* (Figure 5d) are more complex, with negative significant trends observed over urbanized areas around the city of Sao Paulo as indicated in Xavier *et al.* (1994) and Marengo *et al.* (2013). Stations over rural areas show positive significant trends for the number of light rainy days, as observed by Raimundo *et al.* (2014).

Trends in intense precipitation events are examined based on 4 indices: *MaxPR*, *95%*, *NumbEx* and *IntEx* (Figures 5e-5h). Positive trends in all four indices are observed in at least 24 out of the 36 stations for each index, and the trend in each index was statistically significant ( $p < 0.1$ ) in at least 6 stations. The majority of stations with significant trends are located over RJ and over urban areas of SP. These results reinforce the previous results (Figure 5) that the increase in *DayPR* over RJ is related to more intense and more frequent heavy precipitation days, with a decrease in *%PRDay* and *NumbLightPR*.

To compare our results with previous studies, we focus our analysis on two stations located in the Metropolitan Area of Sao Paulo (stations 30 and 31 in Figure 1 and Table 1). The precipitation record

from station 31 has been examined in many previous studies due to its proximity to a large urban center, long record and excellent quality control of data (e.g., Xavier *et al.*, 1994; Sugahara *et al.*, 2009; Silva Dias *et al.*, 2013; Marengo *et al.*, 2013; Raimundo *et al.*, 2014). Our analysis indicate positive significant trends in *TotPR*, *DayPR*, *MaxPR*, *NumbEx*, and *IntEx* (Figures 5a, 5b, 5e, 5g and 5h), and negative trend in *NumbLightPR* (Figure 5d), in agreement with those previous studies.

#### 4.4. Comparison between gridded data and individual station trends

Overall, trends observed for the gridded dataset are similar to those for individual stations. This is not completely surprising as all stations used in this study were included in the gridded data. However, some local discrepancies do exist. The most noticeable differences are observed for *%PRDay* and *NumbLightPR* over the northern RJ. Gridded data indicate positive trends for both indices, significant for *%PRDay* (Figures 4c and 4d), while most stations over this area show significant negative trends for both indices (Figures 5c and 5d). These discrepancies are likely related to the averaging method utilized in the gridded dataset. In regions with complex topography, precipitation exhibits large spatial variability, with large amounts concentrated in small areas where orographic lifting may increase the probability of convective rainfall relative to neighboring stations. However, when averaging precipitation records into a 0.5° grid, these few stations likely contribute to the relative increase in the average number of rainy days. In these cases individual stations provide a more realistic characterization of spatial variability of rainfall trends.

Over SP, trends in *NumbLightPR* are also different between data sets, with the gridded dataset indicating a negative trend over the entire state (statistically significant over central SP; Figure 4d) while stations indicate negative trends only in two stations located in urbanized areas (Figure 5d). Other stations located in rural areas of SP show positive trends, indicating that 0.5° grid is not sufficient to resolve difference between urban and rural areas.

The analysis of both datasets also reveals a spatial pattern of trends over SP to RJ. While over SP there is an increase in total precipitation and daily rates (*TotPR* and *DayPR*, Figures 4a-b, 5a-b) caused by more intense and frequent extreme precipitation events (*MaxPR*, *95%*, *NumbEx* and *IntEX*; Figures 4e-4h and 5e-h), over RJ the intense events are becoming stronger and more frequent (*MaxPR*, *95%*, *NumbEx*

and *IntEX*; Figures 4e-4h and 5e-5h), but the number of days with precipitation is decreasing (*NumbLightPR* and *%PRDay*, Figures 4c-d and 5c-d).

## 5. Discussion and Conclusions

Previous studies have shown compelling evidence that precipitation and its extremes have changed in the last decades in SE Brazil. These studies, however, were based on spatially averaged precipitation with relatively coarse resolution (Liebmann *et al.*, 2004; Teixeira and Satyamurty, 2011), or based on stations located in SP (Haylock *et al.*, 2006; Dufek and Ambrizzi, 2008; Sugahara *et al.*, 2009; Marengo *et al.*, 2010, Marengo *et al.*, 2013; Silva Dias *et al.*, 2013). The present study develops a comprehensive analysis of rainfall and its extremes using the most up to date and longest rainfall gauge records available in SP, RJ, ES and MG. Our major objective is to properly characterize patterns of changes in intensity and frequency of both light and extreme rainfall events. The trends detected using these observational precipitation dataset provide additional evidence that the projected changes for future scenarios of climate change are already occurring.

Although the gridded and gauge datasets used here are not independent, trend analysis using gridded precipitation identified regional patterns of changes in rainfall, whereas station records improved the identification of local variations in these patterns, particularly near complex terrain and major urban centers. Mapping trends in SE Brazil has significant economic and social impacts for the country. High urban population density, inappropriate occupation of risk areas in RJ, SP and MG, and positive trends in extreme precipitation suggest an increasing exposure to rain-related disasters in these regions.

Table 3 summarizes the qualitative interpretation of the main results observed in this study. Over SP, both datasets indicate an increase in total seasonal and average daily precipitation and suggests that these changes are related to an increase in the frequency and intensity of extreme events, consistent with previous studies. Additionally, the gridded dataset indicates that the areas with significant trends for these indices are located southwest of the climatological maximum of rainfall. Since SACZ is the most important climatological phenomenon modulating precipitation in the region, a plausible explanation for the positive trend in total precipitation over SP is a southwestward displacement of the SACZ in recent decades, as previously speculated in Liebmann *et al.* (2004) and suggested in coupled climate model simulations of future scenarios of climate change in South America discussed in Seth *et al* (2010) and

Jones and Carvalho (2013). Our results suggest that the poleward displacement of the SACZ is already detectable in historical data.

Farther north, in RJ and ES, both datasets agree that positive trends in the daily average are related to trends in intensity and frequency of extreme precipitation days (Table 3). Individual stations also reveal negative trends in the percentage of rainy days and in the number of light rainy days. These trends, not evident in the gridded data, indicate changes in the frequency and intensity of precipitation events, with larger accumulation occurring in fewer rainy days. Dereczynski *et al.* (2013) identified similar trends in future scenarios of climate change for the city of Rio de Janeiro. Our results confirm that these trends are already detectable in historical data and show that these trends actually extend to larger areas north of the state.

Therefore, while over SP there is an increase in the number of rainy days and in the frequency and intensity of extreme events, over RJ and ES we observe a negative trend in the frequency of rainy days, with precipitation concentrated in fewer and more intense events. These results are consistent with the hypothesis of the southwestward displacement of the SACZ.

Tropical South America has undergone a rapid warming in the last 5 decades, a trend that is expected to continue and increase by the end of the 21<sup>st</sup> century (Carvalho and Jones, 2013). It has been argued that the reduction in the frequency of rainy days along the margin of the convective zones, such as the SACZ, is one of the consequences of the changes in moisture spatial variability in a warmer atmosphere (Chou and Neelin, 2004; Held and Soden, 2006; Lintner and Neelin, 2010; Ma *et al.*, 2011). According to previous studies, warmer temperatures would increase the saturation vapor pressure, increasing the moisture necessary to reach saturation. In the core of convective regions, there is always enough moisture to meet this higher threshold for precipitation. However, along the convective margins, the moisture availability might not be enough to reach the new level of saturation, since these areas receive most of their influx from more stable areas, in this case the ocean. In addition, moisture in convective margins is also exported to the region of strong convection, reducing even more the moisture availability and, consequently, increasing stability and decreasing precipitation events in these regions. We speculate that the observed reduction in the number of rainy events over RJ and ES could be related to the warming and subsequent changes in saturation water vapor along the northern margin of the SACZ. The observed positive trends in extreme daily precipitation could be related to thermodynamic effects

such as an increase in convective instability. Nevertheless, many other dynamic and thermodynamic mechanisms, combined with environmental changes such as the effect of rapid urbanization and land-use and change, could also have played a significant role in the observed trends in precipitation. Therefore, further investigation is necessary to properly recognize the underlying dynamical and physical mechanisms responsible for the observed trends in precipitation over SE Brazil.

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## Figures and Table

**Fig. 1** Inset: Location of SE Brazil (shaded) and study area (dashed line) in Brazil. Main map: Location of the study area (dashed line) at SE Brazil; stations analyzed (“I”); shades: local topography (1km resolution DEM from SRTM; USGS 2004); cross hatching: urban area (GRUMPv1 dataset, Balk et al. 2006). Information about stations is provided in Table 1. This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Fig. 2** Gridded dataset: % of missing days (a); average number of stations per grid point (b); and number of valid years per grid point (c). (b) and (c): only grid points with less than 40% missing days. Dashed line: study area. Gray contour: states of SE Brazil. Stars: Sao Paulo (23.6°S, 46.6°W) and Rio de Janeiro (22.9°S, 43.2°W). This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Fig. 3** Wet season climatology for gridded data: *TotPR* (a), *DayPR* (b), *%PRDay* (c), *NumbLightPR* (d), *MaxPR* (e), *95%* (f); *NumbEx* (g) and *IntEx* (h). Dashed line: study area. Gray contour: states of SE Brazil. Stars: Sao Paulo (23.6°S, 46.6°W) and Rio de Janeiro (22.9°S, 43.2°W). This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Fig. 4** Trends in gridded dataset for wet season: *TotPR* (a), *DayPR* (b), *%PRDay* (c), *NumbLightPR* (d), *MaxPR* (e), *95%* (f); *NumbEx* (g) and *IntEx* (h). Blue (red) areas: positive (negative) trends (Sen’s slope); stippled areas: significant trends ( $p < 0.1$ ). Gray contour: states of SE Brazil. Stars: Sao Paulo (23.6°S, 46.6°W) and Rio de Janeiro (22.9°S, 43.2°W). This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Fig. 5** Trends in station data for wet season: *TotPR* (a), *DayPR* (b), *%PRDay* (c), *NumbLightPR* (d), *MaxPR* (e), *95%* (f); *NumbEx* (g) and *IntEx* (h). “+” (“-”): positive (negative) trends; blue (red) symbols: positive (negative) significant trends ( $p < 0.1$ ); shades: local topography; dashed line: study area. In (d) cross hatching: urban areas (source: GRUMPv1 dataset, Balk et al. 2006). This figure is available in color online at [wileyonlinelibrary.com/journal/joc](http://wileyonlinelibrary.com/journal/joc)

**Table 1** Stations analyzed, latitude, longitude, height, city where located, time range, percentage of missing, and source institution. The location of these stations is in Figure 1

**Table 2** Precipitation indices, acronyms, their definition, and mean value for the wet season (based on the gridded data averaged over the entire period for all grid points over coastal SE Brazil - 49°W to 40°W and 25°S to 20°S)



**Table 3** Trends in each index considering both dataset, for the states of RJ and ES, SP, and the Metropolitan Area of Sao Paulo (MASP). Symbols: positive (▲), negative (▼) or no significant (■) trends.

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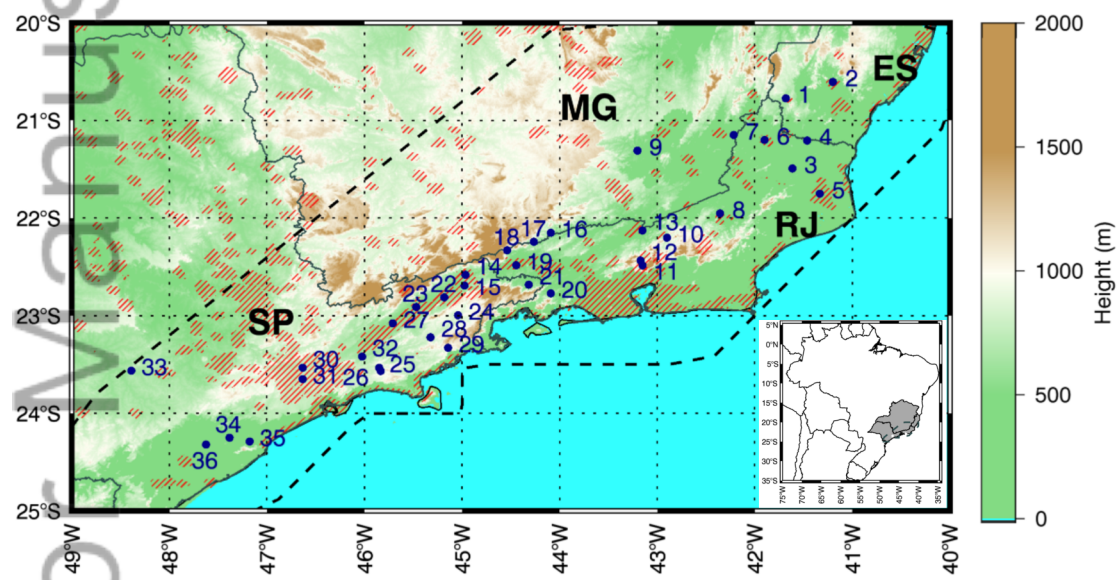


fig1

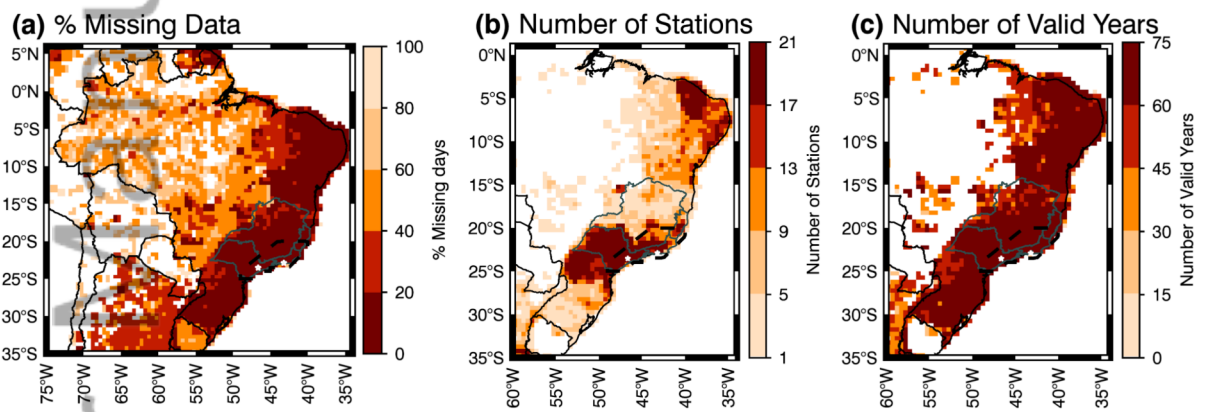


fig2

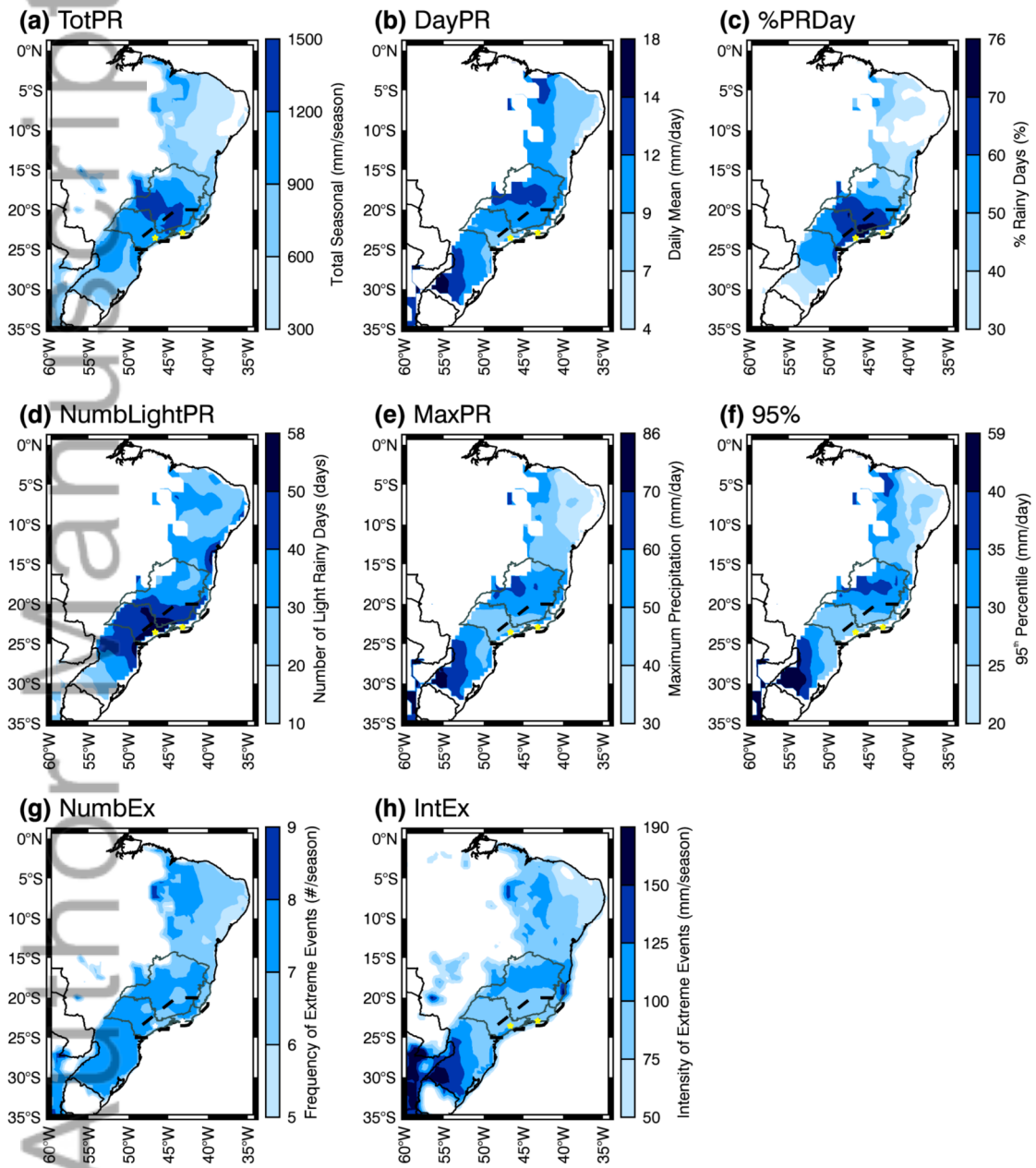


fig3

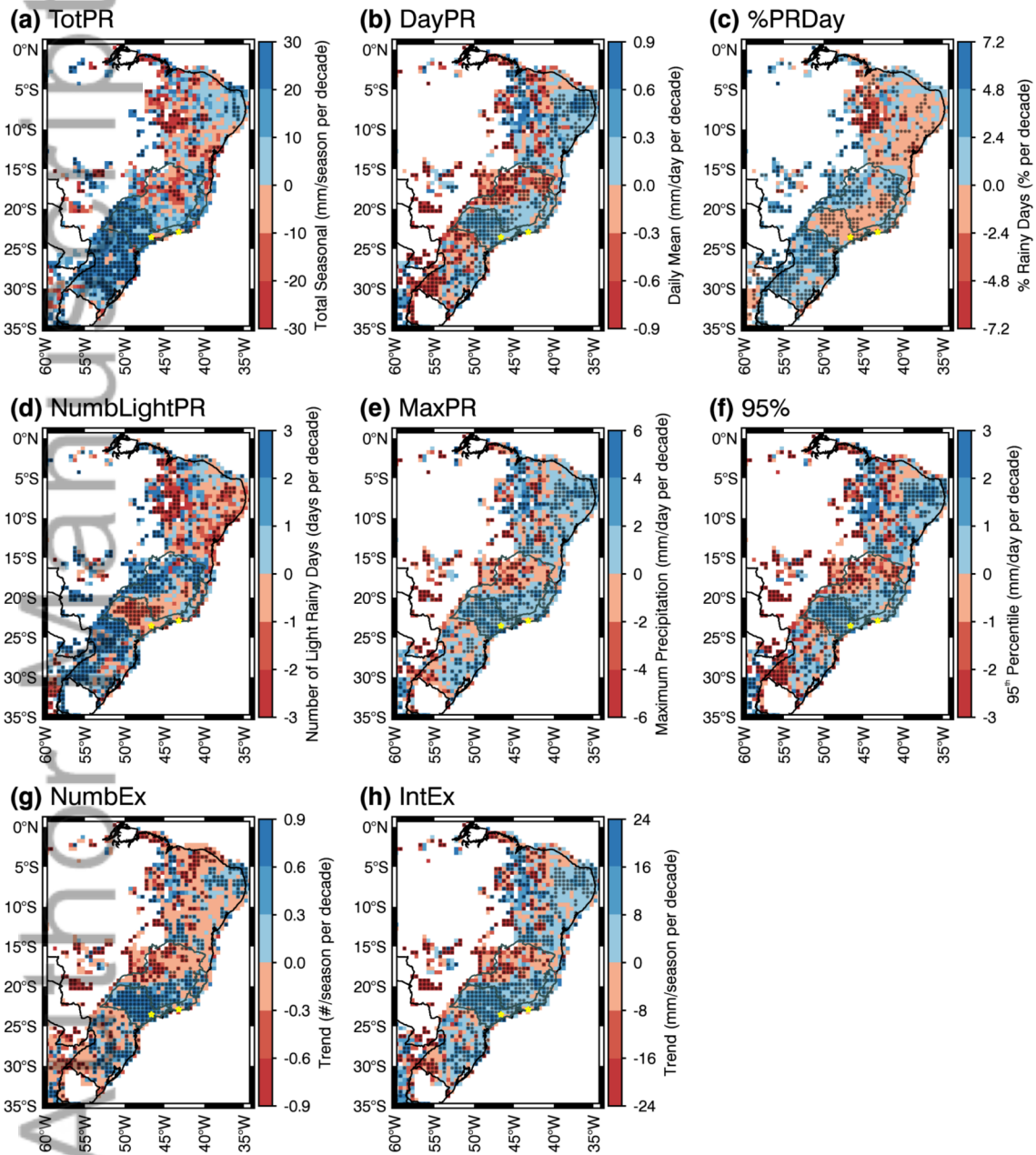


fig4

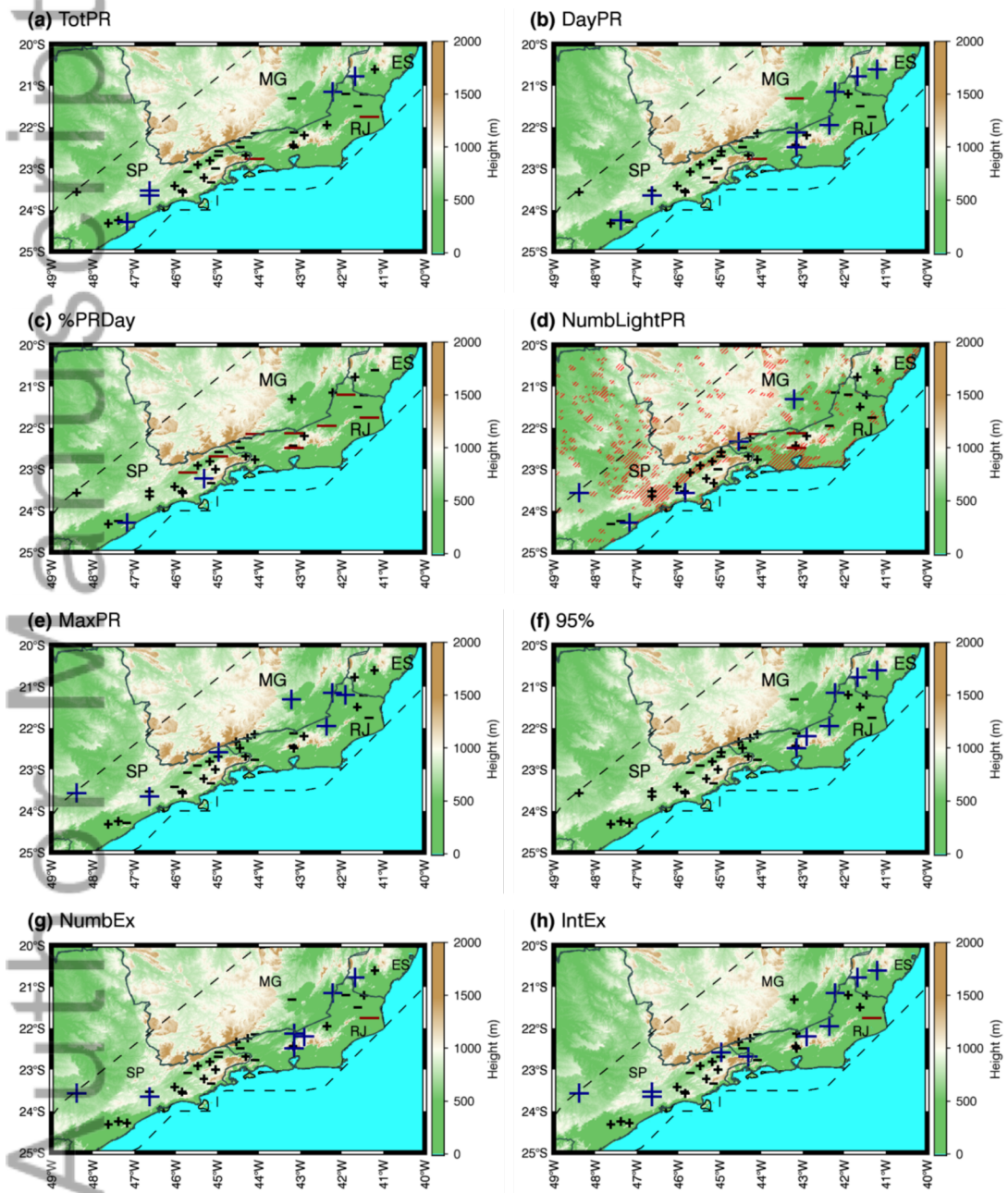


fig5