

ÁLVARO JAVIER ÁVILA DÍAZ

**EXTREME RAINFALL INDICES IN BRAZILIAN MOUNTAIN REGIONS
AND POTENTIALLY INDUCED HYDROLOGICAL HAZARDS**

Dissertação apresentada à Universidade Federal de Viçosa, como parte das exigências do Programa de Pós-Graduação em Meteorologia Aplicada, para obtenção do título de *Magister Scientiae*.

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Marcos Paulo Santos Pereira



Gilberto Chohaku Sedyama



Flávio Barbosa Justino
(Orientador)

*«Não perguntes o que a tua pátria pode fazer por ti.
pergunta o que tu podes fazer por ela»*

*«Ask not what your country can do for you,
ask what you can do for your country»*

John F. Kennedy, 1961.

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LIST OF ACRONYMS

PRCPTOT	Annual total precipitation in wet days mm
SDII	Annual total precipitation divides by the number of wet days in the year
RX1day	Annual maximum 1-day precipitation mm
RX5day	Annual maximum consecutive 5-day precipitation
R95	Annual precipitation due to very wet days when RR >95th percentile of 1978-2014 daily rainfall
R99	Annual precipitation due to very wet days when RR >99th percentile of 1978-2014 daily rainfall
NW	Annual count of days when $RR \geq 1$ mm
R10mm	Annual count of days when $RR \geq 10$ mm
R20mm	Annual count of days when $RR \geq 20$ mm
R30mm	Annual count of days when $RR \geq 30$ mm
CDD	Maximum number of consecutive days with $RR < 1$ mm
CWD	Maximum number of consecutive days with $RR \geq 1$ mm
RJMR	Mountain region of Rio de Janeiro
SCMR	Mountain region of Santa Catarina
P	Specific significance level
R	Pearson Correlation
β	Sen-Slope(s)

ABSTRACT

ÁVILA DÍAZ, Álvaro Javier, M.Sc., Universidade Federal de Viçosa, February, 2016. **Extreme rainfall indices in Brazilian mountain regions and potentially induced hydrological hazards.** Adviser: Flávio Barbosa Justino. Co-Advisers: Carlos Fernando Lemos and Marcelo Cid de Amorim

In order to understand the rising number of flash floods and mass movements in the densely populated region of southeastern Brazil, this study analyzes the spatial and temporal changes in precipitation from 1978 to 2014. We focus on the sensitivity of mountainous regions, specifically the Rio de Janeiro (RJMR) and Santa Catarina (SCMR) regions. Daily rainfall observations are aggregated into annual and seasonal indices, and RCLimindex is used to evaluate a suite of precipitation and extreme event indices. Results show positive annual and seasonal precipitation trends during all seasons except for the winter season in the RJMR. Diverse change points in their time series, spatial differences in the trends at individual stations, and trends associated with elevation suggest that despite the close proximity of these two regions, climate impacts are not uniform across all of southeastern Brazil. Climate mechanisms responsible for the observed precipitation trends are identified, but additional work is needed to isolate the causes. Statistically significant positive correlations are discovered between mass movements/flash floods events and annual maximum 1-day and 5-day consecutive precipitation, and these indices may be useful indicators of natural hazard events for this region.

RESUMO

ÁVILA DÍAZ, Álvaro Javier, M.Sc., Universidade Federal de Viçosa, fevereiro de 2016. **Índices extremos de precipitação nas regiões montanhosas de Brasil e seus potenciais riscos hidrológicos.** Orientador: Flávio Barbosa Justino. Coorientadores: Carlos Fernando Lemos e Marcelo Cid de Amorim

O recente aumento do número de inundações e movimentos de massa na região densamente povoada no sudeste do Brasil, o presente estudo analisa as alterações espaciais e temporais na precipitação durante o período de 1978-2014, nas regiões montanhosas dos estados brasileiros do Rio de Janeiro e Santa Catarina. Avaliou-se a presença de tendência nas series sazonais, anuais e do conjunto de índices extremos de precipitação onde foi usado o software Rclimdex. As series são calculados a partir das series precipitação diária. Com base nos resultados observou-se que nas escalas anuais e sazonais se tem um aumento de precipitação, exceto para a temporada de inverno na região montanhosa de Rio de Janeiro. Além disso, foram encontradas de mudanças abruptas em diferentes anos para as séries de tempo analisadas, diferenças espaciais nas tendências em estações individuais e tendências associadas com elevação sugerem que apesar da proximidade destas duas regiões, os impactos do clima não são uniformes em todo o sudeste do Brasil. Os mecanismos de clima responsáveis pelas tendências de precipitação observada são identificados, mas trabalho adicional é necessário para isolar as causas. Por outro lado, o número de desastres naturais de tipo hidrológico como os movimentos de massa/enchentes estão aumentando. Este tipo desastre mostrou correlações positivas significativas com os índices 1-day (máximo de precipitação anual em um dia) e o 5-dias (máximo de precipitação anual em cinco dias consecutivos), sendo assim índices que podem ser úteis indicadores de eventos de risco hidrológicos para estas regiões.

CHAPTER 1.0

GENERAL INTRODUCTION

Hydrological hazards such as flash floods, droughts, and mass movements cause significant losses to the agriculture and hinder economic development throughout the world (e.g., Devereux 2007, Middleton and Sternberg 2013). The resultant social, environmental, and economic effects created by these hazards in densely populated areas such as Brazil, Europe, and Asia have led government institutions to evaluate advanced and dynamic approaches to forecasting the severity of these events (Bof *et al.*, 2013; McCright e Dunlap, 2003).

In addition, statistical methods and on-site observations have been used to support decision makers in mitigating drought impacts (Anderson *et al.*, 2015; Chen, Chen e Yang, 2015; Qing, Zhu-guo e Liang, 2011; Zeng *et al.*, 2015; Zhang *et al.*, 2014). Insofar as flash floods are concerned, however, there is further need to understand the link between these events and precipitation variability (frequency and magnitude).

Globally, floods are the most frequent among all natural disasters (Kahn, 2005) . In particular, the number of reported extreme precipitation and related flood events has increased significantly over the last twenty years (Espinoza *et al.*, 2014; Silva Dias *et al.*, 2013). These hazards generate a significant financial and economic burden, signified by an increase in insured damages(Boers *et al.*, 2014; Cavallo *et al.*, 2013). Moreover, as King *et al* (2015) argue, precipitation extremes may differ dramatically in many locations in the near future, a remarkable threat to life and livelihoods of people.

Brief but often intense rainfall events in mountainous particularly pose a concern as these regions are susceptible to dangerous flash floods and mass movements. However, mountainous regions represent complex topography (Beniston, 2003); their characteristics (e.g., shape, extension, altitude, and vegetation cover) vary greatly among climate regimes both spatially and temporally

(Kohler e Masalli, 2009; Skansi *et al.*, 2013; Stephenson *et al.*, 2014; Tramblay, Adlouni, El e Servat, 2013; Valverde e Marengo, 2014; Wang e Li, 2015). Furthermore, localized extreme precipitation events occur within the context of changes in large-scale atmospheric flow. Recent studies on trends in sea surface

temperatures (SSTs) (e.g., Haylock *et al* 2006) and atmospheric circulation (e.g., Clem and Fogt 2015) near South America demonstrate that precipitation patterns in this region are dependent on remote tropical influences (Pereira *et al.*, 2014)

Therefore, fundamental questions may be posed related to the link between climate (and weather) and topographic features. One is whether the rate of warming within mountainous regions is changing at a different rate than the rest of the global land surface (Rangwala e Miller, 2012). Secondly, are short-term extreme precipitation events occurring more or less frequently as a function of topographic characteristics (Marengo *et al.*, 2009)?. These questions are specifically important for several tropical countries that are exceptionally vulnerable to shifts in precipitation patterns and related hydrological hazards, often affecting human life, health, food and water supplies, ecosystems, and infrastructure (Chadwick *et al.*, 2015).

Indeed, the understanding of precipitation patterns across distinct timescales is essential for the development of public policies, proper management of hydrological resources, and mitigation of their impacts on human activity and environment (Anderson *et al.*, 2015). In mountain regions, the causes of floods are complex and closely related to water conservancy facilities and soil structure (Wu *et al.*, 2015). In addition, coastal mountainous regions often experience a combination of high moisture content in the lower atmosphere and forced ascent that creates thermodynamically unstable conditions and may result in torrential precipitation (Seluchi e Chou, 2009)

Extreme weather events have severely impact Brazil in the last 3 decades (Dereczynski, Silva e Marengo, 2013; Silva Dias *et al.*, 2013). In particular, two events in southern Brazil are described as the region's worst weather tragedies in history. In January 2011, heavy rainfall sparked flash flooding and mudslides across the highlands of the state of Rio de Janeiro in southeastern Brazil. According to Brazilian official sources, the floods and mass movement claimed the lives of 916 people and left 35,000 people homeless (Marengo e Alves, 2012). The second event also occurred in southern Brazil, affecting 1.5 million people in the Santa Catarina State in November 2008. Flooding and deadly mudslides resulted in 120 casualties and left 69,000 people homeless (Fundação Brasileira para o Desenvolvimento Sustentável - FBDS, 2009).

This study focuses on trends in annual, seasonal, and extreme precipitation indices in order to address rising concerns of mass movements and flash floods in

southeastern Brazil. Section 2.1 describes our study regions and data. Section 2.2 demonstrates precipitation trends, illustrates the complex interaction between topographic features and the spatial weather/climate variability, and identifies key relationships between annual precipitation and extreme precipitation indices that may be used in advanced warning systems of natural hazards. Finally, chapter 3 summarizes the results and discusses the implications of these findings.

The results shown below are submitted for publication in the Journal Environmental Research Letters. The reference number for this article is ERL-102313. Authors of the article are Álvaro Ávila, Flávio Justino, Aaron Wilson, David Bromwich and Marcelo Amorim. First and second author of the Department of Agricultural Engineering of the Universidade Federal de Viçosa (Brazil), the third author from Polar Meteorology Group, Byrd Polar and Climate Research Center of The Ohio State University (USA). The fourth author works in the Atmospheric Sciences Program, Department of Geography, The Ohio State University (USA). The fifth author of the Universidade Federal Rural do Rio de Janeiro, Três Rios, Rio de Janeiro (Brazil).

CHAPTER 2.0

2.1. METHODOLOGY

2.1.1. Study region

The two areas evaluated in this study, the Rio de Janeiro Mountain Region (RJMR) and the Santa Catarina Mountain Region (SCMR) (figure 1), are located in a rock formation called the Serra do Mar. This mountain chain extends along the southeastern coastline of Brazil from Rio de Janeiro to Santa Catarina state, with some peaks exceeding 1000 m. Heavy rainfall with subsequent floods and mass movements (Seluchi, Chou e Gramani, 2011) frequent this region.

The RJMR (21.3–23.3 °S, 42.3°–43.3 °W) covers an area of 9.5 km² and occupies 21.8 % of the state (figure 1). With 108 people per km² in 2010 (Brazilian Institute of Geography and Statistics (IBGE), <http://www.ibge.gov.br/estadosat/>), this densely populated area is governed by a warm and rainy climate (figure2) in summer (October-March) and mild, dry weather in winter (April-September) (Dereczynski, Silva e Marengo, 2013). Based on a network of 35 rain gauges for the period 1978–2014, the annual mean precipitation is 1481 mm.

The SCMR (26.3–29.0 °S, 52.0°–49.0 °W) covers an area of 22.2 km² or 23.3% of the state's territory (figure1). According to the IBGE, the population density in 2010 was 18 people per km². The annual mean precipitation (1978–2014) is 1652 mm, distributed more equally throughout the year compared to the RJMR, with no specific dry period (figure2).

The main differences between these two mountainous regions are the larger amplitude of the seasonal cycle (figure2) and higher population density in RJMR as compared to SCMR. Nevertheless, both regions have experienced a number of mass movements and flashfloods in recent decades due to extreme precipitation events (Dereczynski, Silva e Marengo, 2013).

2.2.2. Data

The Brazilian National Water Authority (ANA; <http://hidroweb.aneel.gov.br>) provided daily precipitation data for 1978–2014. We calculated seasonal

precipitation totals based on the austral seasons of summer (DJF), autumn (MAM), winter (JJA), and spring (SON). The altitudes of the selected stations (figure1) range from 10 m to 1980 m in the RJMR and 80 m to 1200 m in the SCMR. In order to keep the record as complete as possible, we only analyzed stations with at least 90% of the data for the period. We used Multivariate Imputation by Chained Equations technique (Buuren e Groothuis-Oudshoorn, 2011; Costa *et al.*, 2012; Lopo *et al.*, 2014; Silva *et al.*, 2014) to process any remaining missing data.

Guided by the Expert Team on Climate Change Detection and Indices (ETCCDI; <http://etccdi.pacificclimate.org/>), 12 precipitation indices (table 1) and statistics were calculated using “R” software. RClindex was developed by the Environmental Canada in order to indicate extreme events (e.g., Zhang and Yang 2004, Wang and Li 2015). Quality control of the data was conducted using the RHtest V3 (Wang e Feng, 2010), which identifies step changes in a time series by comparing the goodness of fit of a two-phase regression model with that of a linear trend for the entire series (Wang *et al.*, 2010). The procedure detects shifts in the differences between the time series of the monthly mean precipitation anomalies of a candidate station and those of a three neighboring stations (Stephenson *et al.*, 2014). Testing indicated that the precipitation data used does not show significant biases, resulting in 35 and 27 stations in the RJMR and SCMR, respectively (figure 1).

We used the nonparametric Mann–Kendall (M-K) test (Kendall, 1975; Mann, 1945) for trend analysis. Additionally, the Sen Estimator was applied to estimate the linear trend (Sen, 1968). The combination of the M-K test and Sen Estimator has been successfully used in many climate studies (Dereczynski, Silva e Marengo, 2013; Skansi *et al.*, 2013; Trambly, Adlouni, El e Servat, 2013; You *et al.*, 2011). Long-term climate records may exhibit regimes shifts, as once dominant patterns are altered due to natural or anthropogenic causes (King *et al.*, 2015; Parmesan e Yohe, 2003). Therefore, we used the Pettitt test (Pettitt, 1979) to detect abrupt change points in the time series of precipitation and indices. A similar approach has been applied to identify regional trends and change points in Asia (Chen, Chen e Yang, 2015; Duan *et al.*, 2015; Wang e Li, 2015; Wu *et al.*, 2015). Finally, we used Pearson’s coefficients of correlation to identify statistical links between extreme precipitation indices and annual mean precipitation (AMP), elevation of stations, and hydrological hazards.

2.2. RESULTS AND ANALYSIS

2.2.1. Annual and Seasonal Precipitation

Figure 3 (left column) shows the seasonal precipitation trends for the RJMR. Positive trends are found for the annual ($30.67 \text{ mm decade}^{-1}$), summer ($4.95 \text{ mm decade}^{-1}$), autumn ($12.16 \text{ mm decade}^{-1}$), and spring ($12.20 \text{ mm decade}^{-1}$) time series, while a negative trend is found for winter ($-2.90 \text{ mm decade}^{-1}$). We argue that the positive trend in annual precipitation is the result of increasing autumn and spring precipitation. Although the M-K test reveals that none of these trends are statistically significant at $P < 0.10$, it is important to note that these trends implicate an enhanced amplitude of the seasonal cycle with wetter (drier) conditions in the rainy (dry) season (Da-Rocha *et al.*, 2014; Solman *et al.*, 2013). For the SCMR (figure 3; right column), the annual total precipitation increased at a rate of $72.05 \text{ mm decade}^{-1}$, the result of positive trends in all seasons (though not significant at $P < 0.10$). Discussion on the potential climate mechanisms related to the observed trends in precipitation is presented in the upcoming sections.

Box and whisker plots (figure 4a) further demonstrate the variability of linear trends for all 35 and 27 stations in the RJMR and SCMR during 1978–2014. Figure 4a shows annual precipitation trends in the RJMR region (1) vary widely with magnitudes between -161.68 and $370 \text{ mm decade}^{-1}$. Summer and autumn similarly show large variations in precipitation trends, while winter and spring (drier seasons) show smaller ranges in their trends. About 60% of stations show positive trends in annual precipitation with 17% of stations demonstrating significant positive trends (figure 4b).

For summer, autumn and spring, the majority of RJMR stations show positive trends with a small percentage of those trends being significant. Interestingly, during the winter season downward trends are present in roughly 70% of the stations with approximately 10% of those representing significant negative trends. This is well correlated with more frequent La Nina-like SST patterns in the Niño 3.4 region during JJA and increased blocking in the South Atlantic (Clem e Fogt, 2015).

The SCMR stations (2) reflect smaller spatial variation compared to RJMR, with annual precipitation trends between -49.08 and $+134.72 \text{ mm decade}^{-1}$ (figure 4a). However, more than 85% of stations have increasing annual trends with 33%

stations showing significant positive trends (figure 4c). The seasonal variability is similar to the annual variation insofar as the amplitude of the spatial distribution is concerned, with all seasons showing large percentages of positive trends (75–95%) (figure 4c). The greatest number of significant seasonal trends in the SCMR is found in spring (19%), the same season found to have significant correlations with the Oceanic Niño Index. Though many of the positive station trends are not significant during winter and spring, the overwhelming number of positive trends is still concerning, as recurrent precipitation in short intervals from September to March may be linked to mass movements and increased loss of life (Seluchi e Chou, 2009).

Interestingly, Pettitt tests reveal that despite the close proximity of these two regions, the RJMR and SCMR exhibit diverse change points in annual and seasonal precipitation time series. For instance, the seasonal time series reveal abrupt shifts in the RJMR (SCMR) in summer 2001 (1991), autumn 2003 (1982), winter 1990 (2010), and spring 1994 (1996). While some of these years correspond to ENSO events (1982, 2001, and 1996), additional climate/weather drivers such as South Atlantic SST variability must be considered (Barreiro, 2010; Cavalcanti *et al.*, 2015; Diaz, Studzinski e Mechoso, 1998).

2.2.2. Extreme Precipitation Indices and Regional Trends

Figure 5 shows that PRCPTOT (see table 1 for descriptions) is largely increasing in the RJMR (figure 5a) and the SCMR (figure 5b), with positive trends in ~60% and ~90% of the stations, respectively. Similar results are found for daily thresholds of RX1day, RX5day, and R95 indices, with positive trends in the majority of stations (more positive in the SCMR region). Light precipitation days (NW and R10mm) show more negative trends in the RJMR stations, with moderate (R20mm) and heavy (R30mm) days demonstrating no change or positive trends. On the other hand, all four annual count precipitation thresholds show positive trends in most stations for the SCMR.

Within the RJMR, there are only small changes in the trends in CDD as the percentage of stations with positive, negative and stationary trends out of the total stations are close to 50%, 40% and 10%, respectively. However, CWD shows a downward trend in most stations 57%. In the SCMR, both CDD and CWD show

more stations with negative trends. In summary, both regions have been experiencing greater rainfall, but this precipitation is occurring in heavier downpours and especially in the RJMR, with fewer consecutive wet days.

Figure 6 shows increasing trends in several precipitation indices (PRCPTOT, RX1day, RX5day, R95, R20mm, R30mm, and CDW) predominantly located in the southeastern part of the RJMR, while negative trends in CDD are noted in the west. In the SCMR (figure 7), many stations demonstrate significant ($p < 0.10$) positive trends in PRCPTOT, NW, R10mm, R20mm, and R30mm. This is particularly true for the NW and R20mm, both of which are strong indicators of soil water quantity, potential floods and mass movements (figures 7g and 7i). These results support the findings of Silva and Dereczynski (2014) who identified statistically significant increases in the annual total rainfall in the coastal lowland of the Rio de Janeiro municipality (between +40.0 and +320.0 mm decade⁻¹).

In our study, stations with the highest value of PRCTOT are also located at low elevation (Represa do Paraíso in RJMR (382.1 mm decade⁻¹) and Meleiro in SCMR (135.5 mm decade⁻¹)). This behavior is associated with the sea-breeze circulation coupled to the valley to mountain flow that penetrates inwards to the Rio the Janeiro plateau. This mesoscale circulation further interacts with the urban heat island frequently triggering convective storms (Dereczynski, Silva e Marengo, 2013; Freitas *et al.*, 2007; Silva Dias *et al.*, 2013).

Figure 8 shows trends in seasonal precipitation based on the elevations of our stations. In the RJMR, there is a tendency for decreasing (increasing) trends of precipitation in stations at higher (lower) elevations for all seasons. The strongest correlations are significant ($p < 0.10$) in autumn ($R = -0.38$) and winter ($R = -0.46$), but are weaker in spring ($R = -0.31$) and absent in summer ($R = -0.07$). This suggests that topography plays an interactive role with climate dynamics, particularly in autumn and winter in the RJMR (figures 8b and 8c). The correlation coefficients are close to zero and not significant for all seasons in the SCMR, revealing less importance of meso-scale processes in this region compared to the RJMR, where the land-sea breeze dominates during autumn and winter. In summer however, large-scale dynamics related to frontal systems and the presence of the South Atlantic Convergence Zone produce precipitation that is distributed throughout southeastern Brazil (Cavalcanti *et al.*, 2015).

Figure 9 illustrates the relationship between precipitation indices and elevation. With the exception of NW, both the RJMR and SCMR regions reflect negative correlations between increasing elevation in the various precipitation indices. However, the relationship is more robust in the RJMR as statistical significance ($P < 0.10$) is achieved for PRCPTOT, SDII, R10mm, and R20mm. Moreover, the regional trend demonstrated by RX1day, RX5day, R95, and R99 indicates that extreme precipitation events have occurred mainly at lower altitudes (table 2).

In the next elevation band (300–600m), negative values for SDII and CDD are found in the RJMR and CWD for the SCMR. As elevation increases, mean trends become weaker except for the highest elevations in the RJMR. In the SCMR, positive trends are found in almost all indices (except for CDW, table 2).

These results highlight the complexity of precipitation in mountainous regions with a high level of spatial distribution and temporal variability (Basist, Bell e Meentemeyer, 1994; Chen, Chen e Yang, 2015; Rangwala e Miller, 2012; Wang e Li, 2015; Zhang *et al.*, 2014). Furthermore, urbanization, deforestation, and other land-use aspects are likely to vary in the future, which may subsequently induce distinct change in the spatial distribution of precipitation extremes (Ghosh *et al.*, 2011; King *et al.*, 2015).

In order to verify whether the extreme precipitation indices have a connection with the change of annual total precipitation, Pearson's correlation coefficients between annual mean precipitation (AMP) and extreme precipitation indices are shown in table 3. AMP and extreme precipitation indices are correlated significantly ($P < 0.01$), with values between 0.53 and 0.98. However, AMP and CDD show a lower (non-significant) correlation ($R \leq -0.15$). These results agree with those obtained by Wang and Li (2015). More importantly, the correlation coefficients between AMP and the number of heavy precipitation days (R10 mm, R20 mm and R30mm) show significantly higher correlations, with values between 0.93 and 0.98.

This indicates that heavy, short interval precipitation is a more significant driver of annual precipitation, and highlights the susceptibility of this region to experience flash flooding and mass movements. Similarly, correlations in the SCMR are statistically significant at the 1% and 5% significance levels for practically all indices except for SDII and RX1day. Note the stronger correlation (0.82) in RX5day in the SCMR compared to RJMR suggests that although the precipitation is mainly occurring in heavier downpours, the events are of longer duration in the SCMR.

2.2.3. Potential Climate Mechanisms Related to Precipitation Changes

South America is influenced by numerous climate/weather mechanisms from daily to inter-annual timescales (e.g., Mechoso *et al* 2005, Raia and Cavalcanti 2008, Liebmann and Mechoso 2011). This includes the South American monsoon (Bombardi e Carvalho, 2009), mesoscale convective systems related to the South American low-level jet (Salio, Nicolini e Zipser, 2007), variability in the South American Convergence Zone (ZCAS; Silva Dias *et al* 2013), and recently to the atmospheric-oceanic coupling in the western tropical Pacific (Seth, Fernandes e Camargo, 2015). Mendes and Cavalcanti (2014) argue that increased atmospheric blocking in the South Atlantic, with persistent and stationary frontal systems, has led to an increase in precipitation in this region. Clem and Fogt (2015) link the recent positive trend in surface pressure in the South Atlantic to the influence of more La Niña-like conditions in the tropical Pacific.

We analyzed the correlations between precipitation over the RJMR and SCMR and several climate indices. These included the Caribbean SST Index (CAB; Penland and Matrosova 1998), the Atlantic Meridional Mode (AMM; Chiang and Vimont 2004), the Niño 3.4 SST index and its 3-month running mean (Oceanic Niño Index (ONI)), and the spatially averaged mean sea level pressure over two centers of action in South America and the South Atlantic (Mechoso *et al.*, 2005). SCMR precipitation is well correlated with the ONI and AMM, but a weak relationship is found with CAB and the pressure dipole in South America and South Atlantic. ONI is correlated with precipitation in the SCMR most of the annual cycle, whereas the AMM is a stronger driver from June to December. Thus, trends in precipitation seem not to be related to variations in the monsoon intensity.

A similar evaluation for the RJMR reveals that the AMM, CAB and the ONI are likely to play a substantial role in driving the precipitation variability. SST changes in the Caribbean, which are significantly correlated with the AMM, are associated with the modification of the northeast trade winds such that precipitation in South America is severely limited when the trade winds are weak (Marengo *et al.*, 2008). Weak trade winds reduce the amount of water vapor that is advected into the region. With limited moisture advection, the intensification of cold fronts near the RJMR and the formation of the ZCAS is tempered (Raia e Cavalcanti, 2008).

2.2.4. Precipitation Indices and Hydrological Hazards (H.H)

Mass movements and flash flood events were compiled based on data from the Brazilian Atlas of Natural Disasters (Atlas Brasileiro de Desastres Naturais 1991–2012; <http://150.162.127.14:8080/atlas/atlas.html>). Figure 10 shows that 49 mass movements and 97 flash floods were reported in the RJMR; 2 mass movements, 179 flash floods, and 143 droughts occurred in the SCMR from 1991 to 2012. Flooding caused by local sewerage systems and drought was not included in this analysis.

The time series are characterized by low frequency events prior to 2000 in the RJMR, with a substantial increase in flashfloods and an upward trend in mass movements thereafter (figure 10a). In the SCMR, flashfloods shows remarkable increases in frequency (figure 10b), with changes more severe since 2003. The correlations over the RJMR ($R \geq 0.78$) are significant at the $p < 0.01$, but this is not the case for the SCMR. The temporal evolution of H.H is not clear because the correlation coefficients ($R < 0.3$) and slopes are not statistically significant.

Pearson`s correlations between flash floods and precipitation indices, including RX1day and RX5day exceed 0.36 over the RJMR (table 4) which demonstrates that these indices, if predicted in advance, may be a good candidate for the natural hazards forecast. Similarly over the SCMR, Pearson`s correlation varies between 0.49 and 0.70 ($P < 0.05$) for all precipitation indices, except for CDD.

As demonstrated above, a significant increase in mass movements (2.2 events decade⁻¹) is observed in the RJMR. Figure 10 shows that mass movements and flash floods events exhibited positive correlations and showed statistical significance with the RX1day and RX5day. The most important mass movements occurred in 2007 (events = 13; Rx1day = 102 mm; Rx5day = 229 mm), 2009 (events = 6; RX1day = 121 mm; Rx5day = 221 mm), 2010 (events = 6; RX1day = 97 mm; RX5day = 193 mm), and 2012 (events = 9; Rx1day = 96 mm; Rx5day = 192 mm).

Nunes and Silva (2013) analyzed the occurrences of extreme rainfall events in the eastern and northern regions of Santa Catarina State for the last 60 years (1951–2010). They found a positive linear trend in most of regions indicating greater frequency of flash flooding events in recent decades. Figure 10 shows severe flood events in 1993, 1997, 1998, 2001, 2009, 2010 and 2011. In this study, AMP, PRCPTOT, RX1day, RX5day, R95, R99, NW, R10, R20, R30 and CWD also captured these extreme years (1997, 1998, 2001, 2010 and 2011). The 2011 and 2001

years recorded the higher values of AMP, PRCPTOT, RX1day, R95, R99 and the highest frequency of NW, R10, R20 and R30.

CHAPTER 3.0

GENERAL CONCLUSIONS

One of the major problems in mountainous regions such as the Andes, Asia, Northern America and Europe, are damages caused by floods and mass movements that are directly related to very intense rainfall and can be responsible for substantial socioeconomic impacts (Aristizábal *et al.*, 2011; Diakakis, 2012; Gaume *et al.*, 2009; Zandonadi *et al.*, 2015). These events in Brazil have been responsible for loss of life and have seriously affected the livelihoods of survivors (Silva Dias *et al.*, 2013; Valverde e Marengo, 2014; Zandonadi *et al.*, 2015).

In this study, the majority of precipitation-related indices present positive trends, especially in the extreme precipitation indices (PRCPTOT, RX1day, Rx5day, R95 and R30mm). Similar to previous studies across South America (Alexander *et al.*, 2006; Haylock *et al.*, 2006; Skansi *et al.*, 2013), it has been demonstrated that precipitation intensity has increased in most recent years. Regional averages of the annual precipitation in the RJMR and SCMR exhibit positive trends as well. Furthermore, we found an increasing trend in seasonal time scales in the SCMR. In the RJMR, a downward precipitation trend is found only for winter.

We have suggested a number of mechanisms that may be responsible for trends in precipitation in this region including changes in atmospheric circulation (Clem e Fogt, 2015; Mendes e Cavalcanti, 2014), the South American monsoon (Bombardi e Carvalho, 2009), and others (Salio, Nicolini e Zipser, 2007; Silva Dias *et al.*, 2013). Further investigation on the atmospheric dynamics involved will likely demand modeling simulations and will be addressed in future work.

In both regions, higher values of RX1day and RX5day are currently associated with and are likely to lead to future severe flash floods and mass movements. It should be noted that although several extreme indices have been correlated with hydrological hazards, there may be other non-linear interactions and causes as well. Thus, precipitation indices should be analyzed under distinct time intervals such as between 1-5 days, and in larger periods (e.g 30 days), because in most cases the soil water capacity is not achieved by a single precipitation event. This approach increases the ability for indicating potential formation of mass movements, flash floods, and drought.

The RJMR and SCMR are typical longitudinal mountains that are influenced by topographic differences. Rainfall distributions have not only lateral differences but also variations with altitude. Comparisons between precipitation indices in these regions reveal distinct elevation characteristics with upward (downward) trends are most significant at low (high) altitudes. This indicates enhanced moisture availability at the lower troposphere allowing increased precipitation. On the other hand, in mountain peaks, precipitation events (in some cases snowfall) should become less frequent affecting human life by inducing changes in the production of crops, water availability that can result in food insecurity.

Thus, natural disaster early warning, improvement of disaster prevention, and mitigation capability should be urgently posed in order to reduce the impact of these natural disasters on civilians. In this sense, results presented can be utilized by decision makers to establish initial thresholds for preventive measures.

Importantly, this work demonstrates that although the annual and seasonal trends in precipitation do not reach certain statistical thresholds, their impacts on the environment are severe with increased trends in mass movements and flash flooding events. Thus, recent positive trends in precipitation in general and in heavier events specifically pose tangible, dangerous threats to human life despite the lack of statistical significance.

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CHAPTER 4.0

TABLES AND FIGURES

4.1. Tables

Table 1. Definitions of the 12 selected extreme precipitation indices

Indices	Description	Units
PRCPTOT	Annual total precipitation in wet days	mm
SDII	Annual total precipitation in divided by the number of wet days in the year	mm/day
RX1day	Annual maximum 1-day precipitation	mm
RX5day	Annual maximum consecutive 5-day precipitation	mm
R95	Annual precipitation due to every wet days when RR>95th percentile of 1978-2014 daily rainfall	mm
R99	Annual precipitation due to extremely wet days when RR>99th percentile of 1978-2014 daily rainfall	mm
NW	Annual count of day when $RR \geq 1$ mm	Days
R10mm	Annual count of day when $RR \geq 10$ mm	Days
R20mm	Annual count of day when $RR \geq 20$ mm	Days
R30mm	Annual count of day when $RR \geq 30$ mm	Days
CDD	Maximum number of consecutive days with $RR < 1$ mm	Days
CDW	Maximum number of consecutive days with $RR \geq 1$ mm	Days

Table 2. Spatially averaged trend of precipitation indices in categorized elevation

		Altitude (m)	10-300	300-600	600-900	900-1200	1620-1980
RJMR	Percentage of stations (%)		37	23	23	11	6
SCMR			11	30	22	37	-
RJMR	PRCPTOT		44.56	59.44	-2.92	-12.29	37.60
SCMR	(mm/decade)		129.08	59.49	63.10	64.14	-
RJMR	SDII		0.41	-0.18	0.12	-0.24	1.06
SCMR	(mm/d/decade)		0.90	0.29	0.01	-0.14	-
RJMR	RX1day		3.76	0.37	2.40	1.63	-2.67
SCMR	(mm/decade)		2.57	0.49	1.88	1.04	-
RJMR	RX5day		3.60	0.57	2.80	0.72	2.80
SCMR	(mm/decade)		9.66	1.75	3.27	0.07	-
RJMR	R95		14.37	4.62	14.35	11.17	-27.70
SCMR	(mm/decade)		50.66	18.80	17.00	16.99	-
RJMR	R99		6.89	0.08	12.78	1.97	-4.03
SCMR	(mm/decade)		26.32	6.75	7.23	3.05	-
RJMR	NW		-0.69	2.24	-1.38	1.06	-6.04
SCMR	(days/decade)		0.95	1.72	2.24	4.70	-
RJMR	R10mm		0.97	0.93	-1.40	-2.20	4.63
SCMR	(days/decade)		2.25	1.33	1.13	1.10	-
RJMR	R20mm		0.51	0.74	-0.14	-0.74	2.02
SCMR	(days/decade)		2.26	1.17	1.05	1.11	-
RJMR	R30mm		0.47	0.51	0.17	0.16	0.69
SCMR	(day/decade)		1.67	0.68	0.52	0.88	-
RJMR	CDD		0.14	-1.25	-0.33	-1.38	1.23
SCMR	(days/decade)		0.36	0.01	0.01	-0.59	-
RJMR	CWD		0.44	0.33	-0.17	-0.42	0.01
SCMR	(days/decade)		0.00	-0.07	-0.06	-0.22	-

The elevation band with maximum magnitude is highlighted in light gray cells; Trends marked in bold are statistically significant at the 0.1 level.

Table 3. Pearson's correlation coefficients of precipitation indices

		PRCPTOT	SDII	RX1day	RX5day	R95	R99	NW	R10	R20	R30	CDD	CWD
RJMR	AMP	1.00	0.61	0.53	0.58	0.76	0.54	0.90	0.95	0.97	0.93	-0.15	0.80
SCMR		1.00	0.82	0.63	0.82	0.89	0.78	0.89	0.96	0.98	0.96	-0.44	0.55

Correlation marked in bold are statistically significant at the 0.01 level.

Table 4. Pearson's correlations coefficients between precipitation indices and hydrology hazards during 1991-2012 in the RJMR and SCMR.

		Mass movements	Flash Floods
RJMR	AMP	0.18	0.22
SCMR		-	0.73
RJMR	PRCPTOT	0.18	0.22
SCMR		-	0.73
RJMR	SDII	0.27	0.24
SCMR		-	0.52*
RJMR	RX1day	0.42**	0.36**
SCMR		-	0.63*
RJMR	RX5day	0.58*	0.39**
SCMR		-	0.55*
RJMR	R95	0.23	0.14
SCMR		-	0.70
RJMR	R99	0.35	0.22
SCMR		-	0.63
RJMR	NW	0.03	0.09
SCMR		-	0.58*
RJMR	R10mm	0.13	0.23
SCMR		-	0.60*
RJMR	R20mm	0.15	0.23
SCMR		-	0.65*
RJMR	R30mm	0.20	0.15
SCMR		-	0.70
RJMR	CDD	-0.01	-0.07
SCMR		-	-0.25
RJMR	CWD	0.37**	0.35
SCMR		-	0.49*

Correlation marked in bold are statistically significant at the 0.01 level. *Significant at the 0.05 level; ** Significant at the 0.1 level.

4.2. Figures

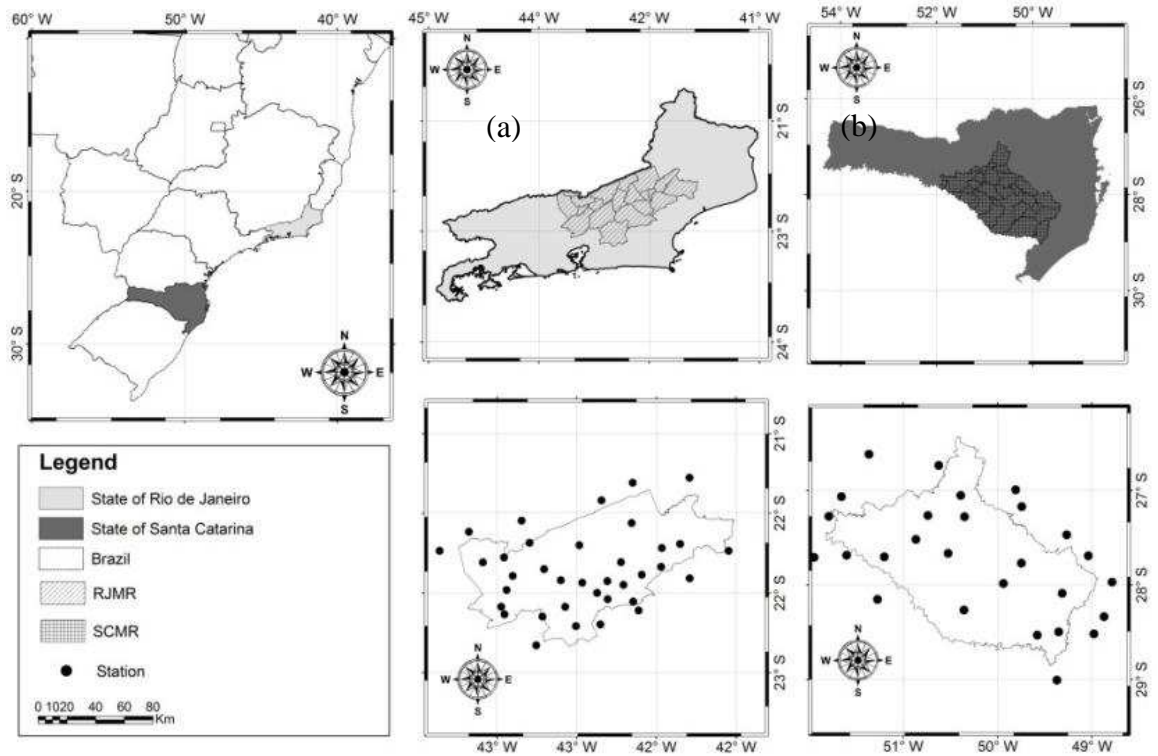


Figure 1. Geographical location of the RJMR (a) and SCMR (b) and the distributions of meteorological stations currently used.

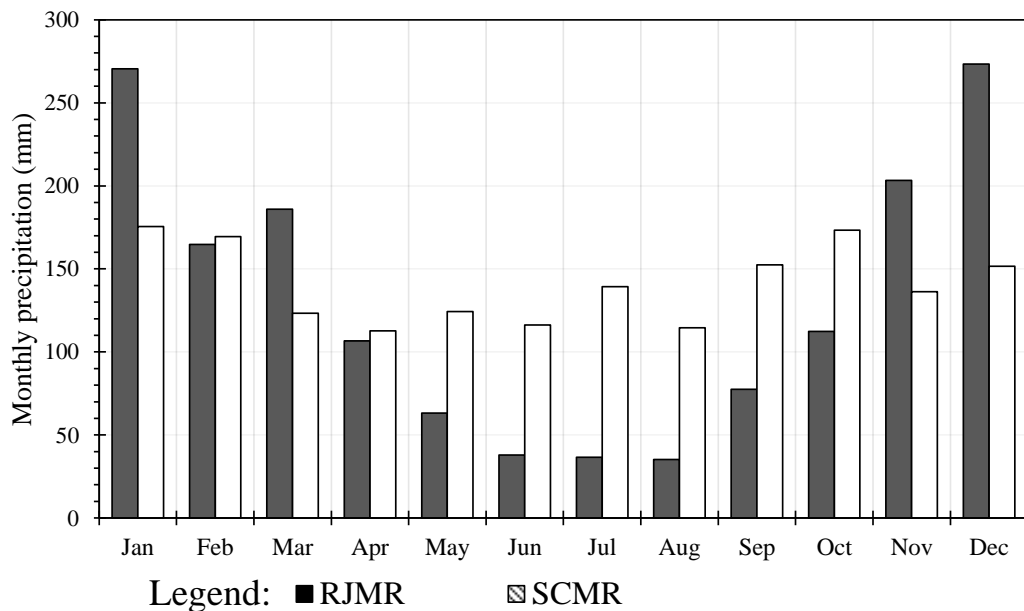


Figure 2. Annual cycle of monthly precipitation over RJMR and SCMR during 1978-2014.

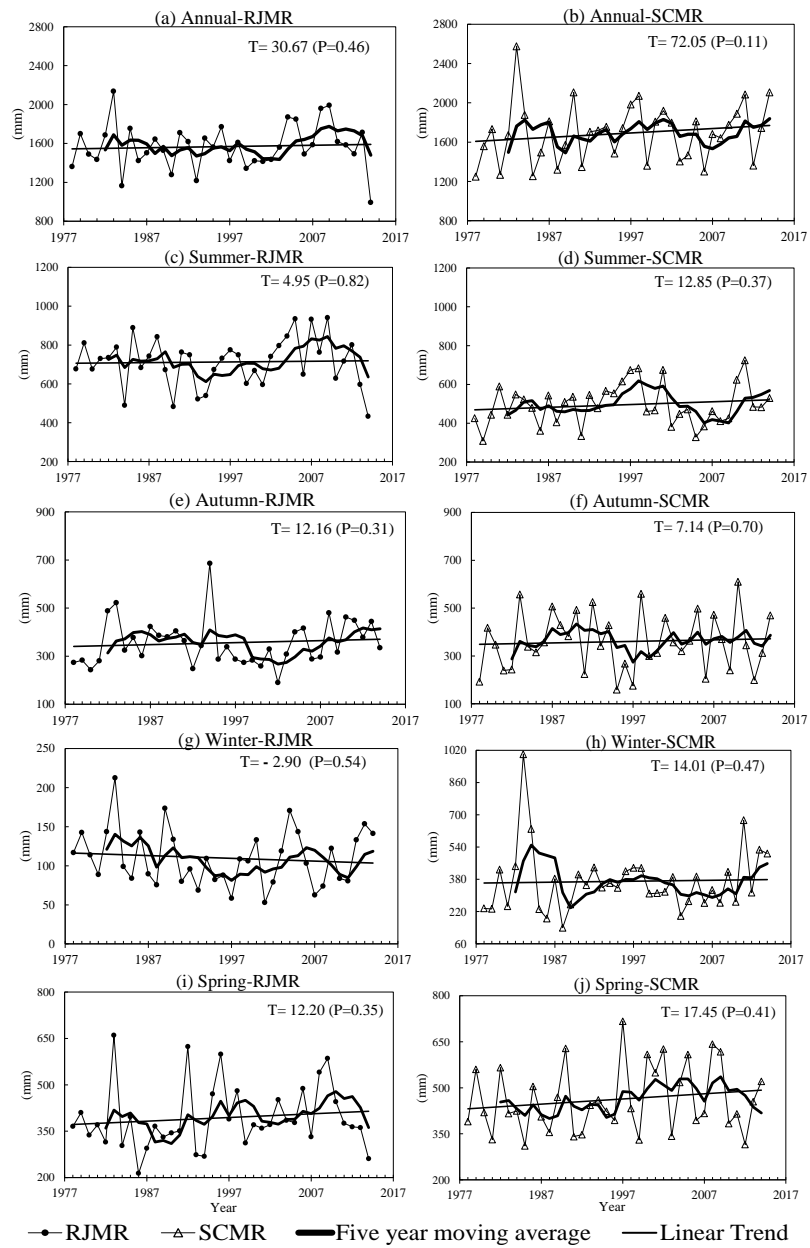


Figure 3. Inter-annual variation of seasonal precipitation over RJMR and SCMR from 1978-2014, T and P show magnitude trends and statistically significance.

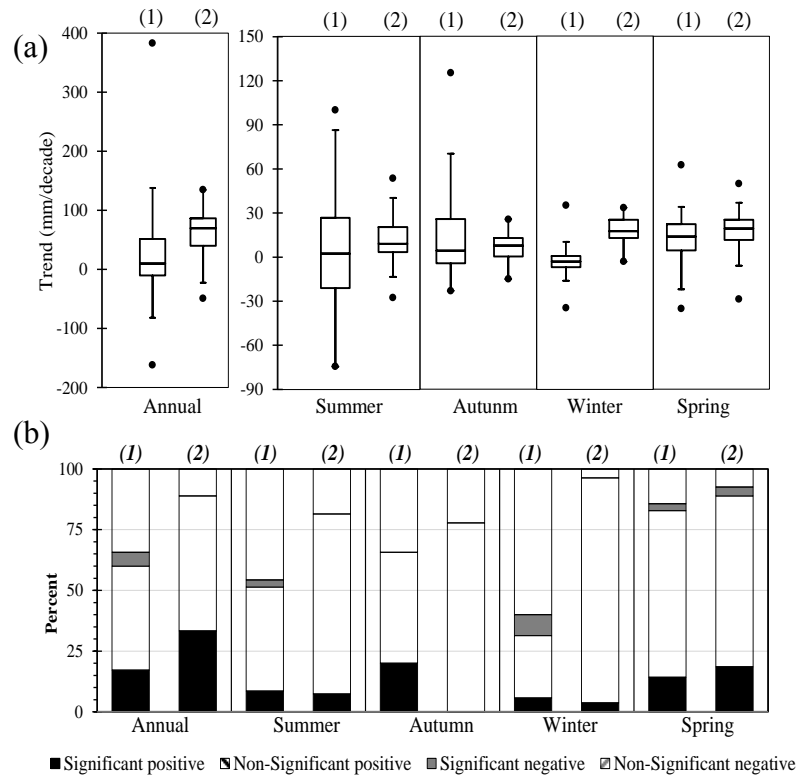


Figure 4. (a) Annual and seasonal variability of precipitation linear trends over the RJMR (1) and SCMR (2). (b) Percentage of stations with positive and negative trends out of the total examined stations.

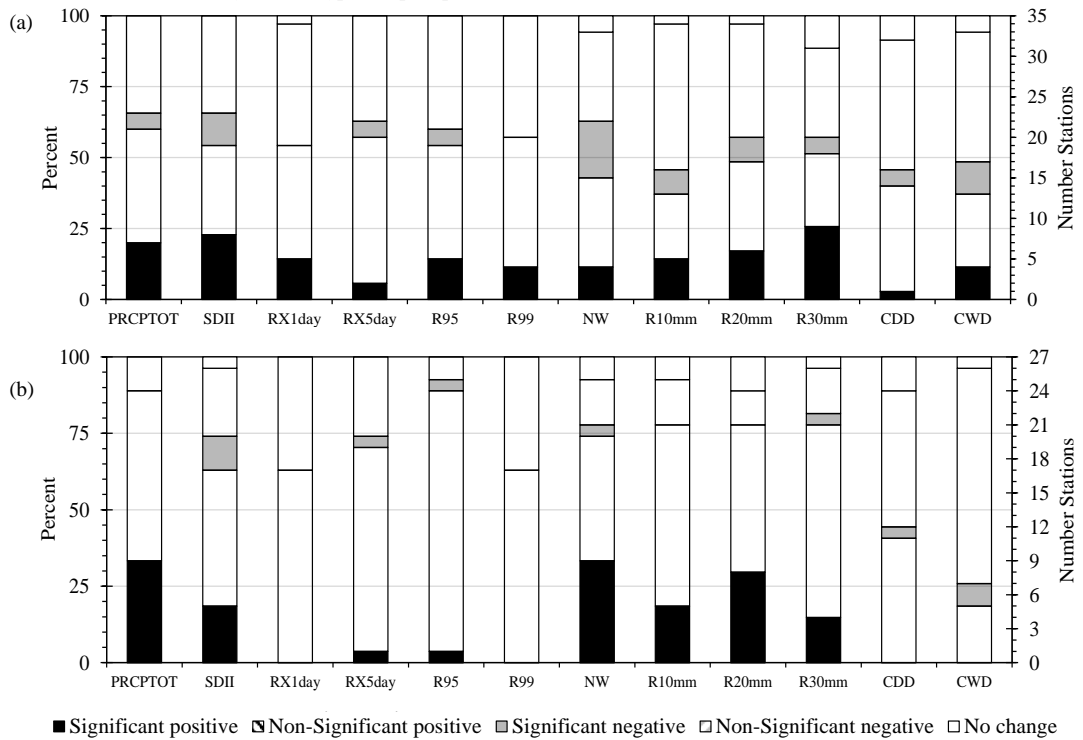


Figure 5. Precipitation indices-based percentage of stations with positive, negative and stationary trends out of the total stations examined over RJMR (a) and SCMR (b) during 1978-2014.

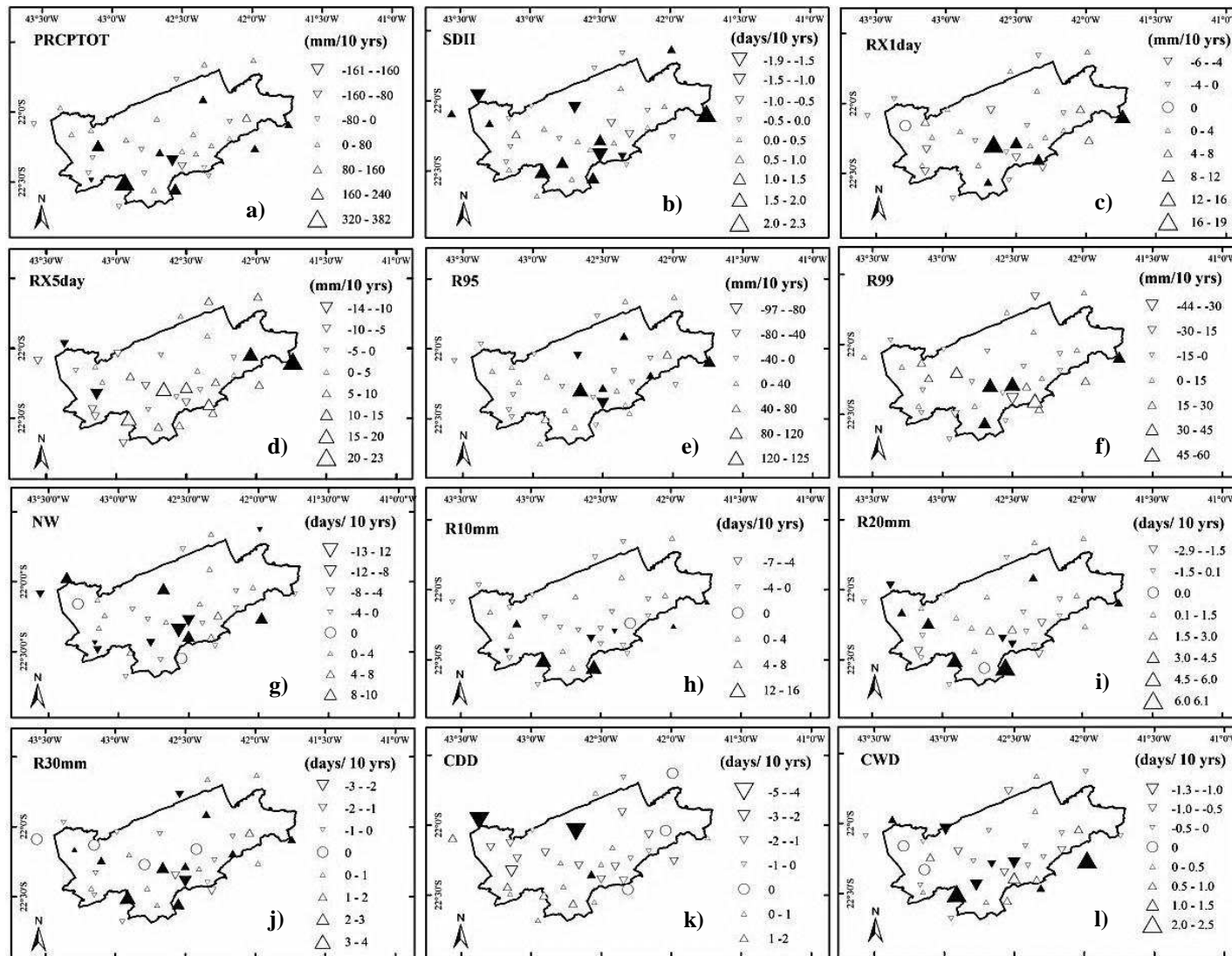


Figure 6. Spatial distribution of M-K trends of precipitation indices over the RJMR (Figures a-l), for the 1978-2014 interval. Positive/negative trends are shown as up/down triangles; the filled triangles are related to statistically significant trends (significant at the 10% level) and circle indicated no change trends.

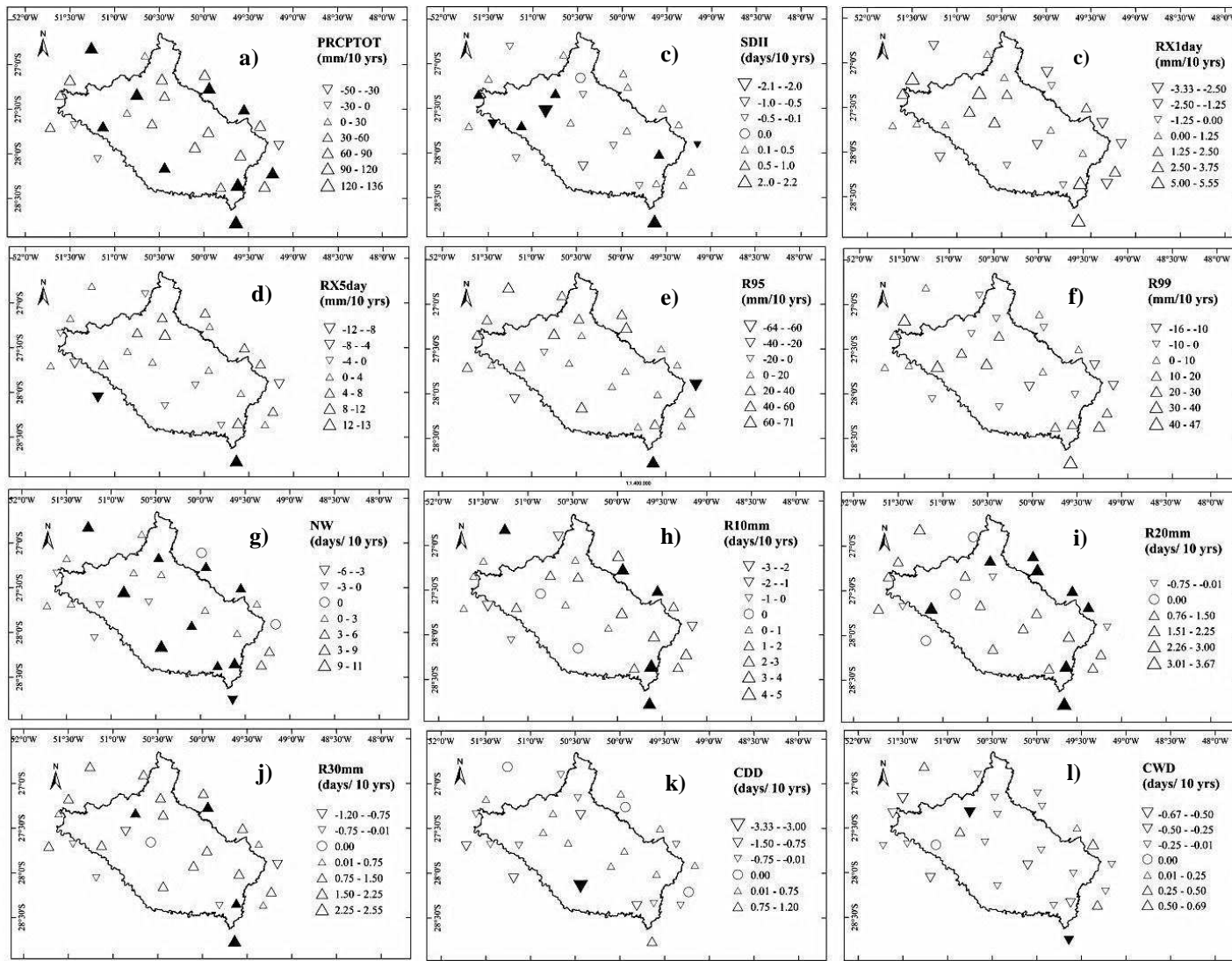


Figure 7. Spatial distribution for M-K trends of precipitation indices in the SCMR (Figures a-l), during 1978 to 2014. Positive/negative trends are shown as up/down triangles; the filled triangles are related to statistically significant trends (significant at the 10% level) and circle indicated no change trends.

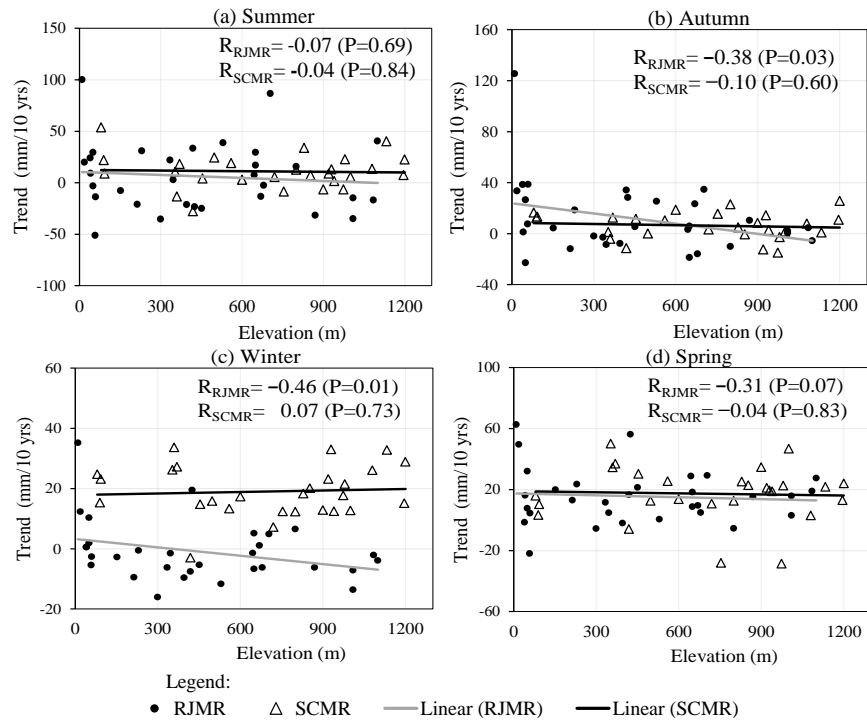


Figure 8. Magnitude trend of the seasonal precipitation amount (mm/10 years) related to elevation. R stands for correlation coefficients and p for statistical significance. The filled circles and triangles indicated trends in each station for RJMR and SCMR, respectively.

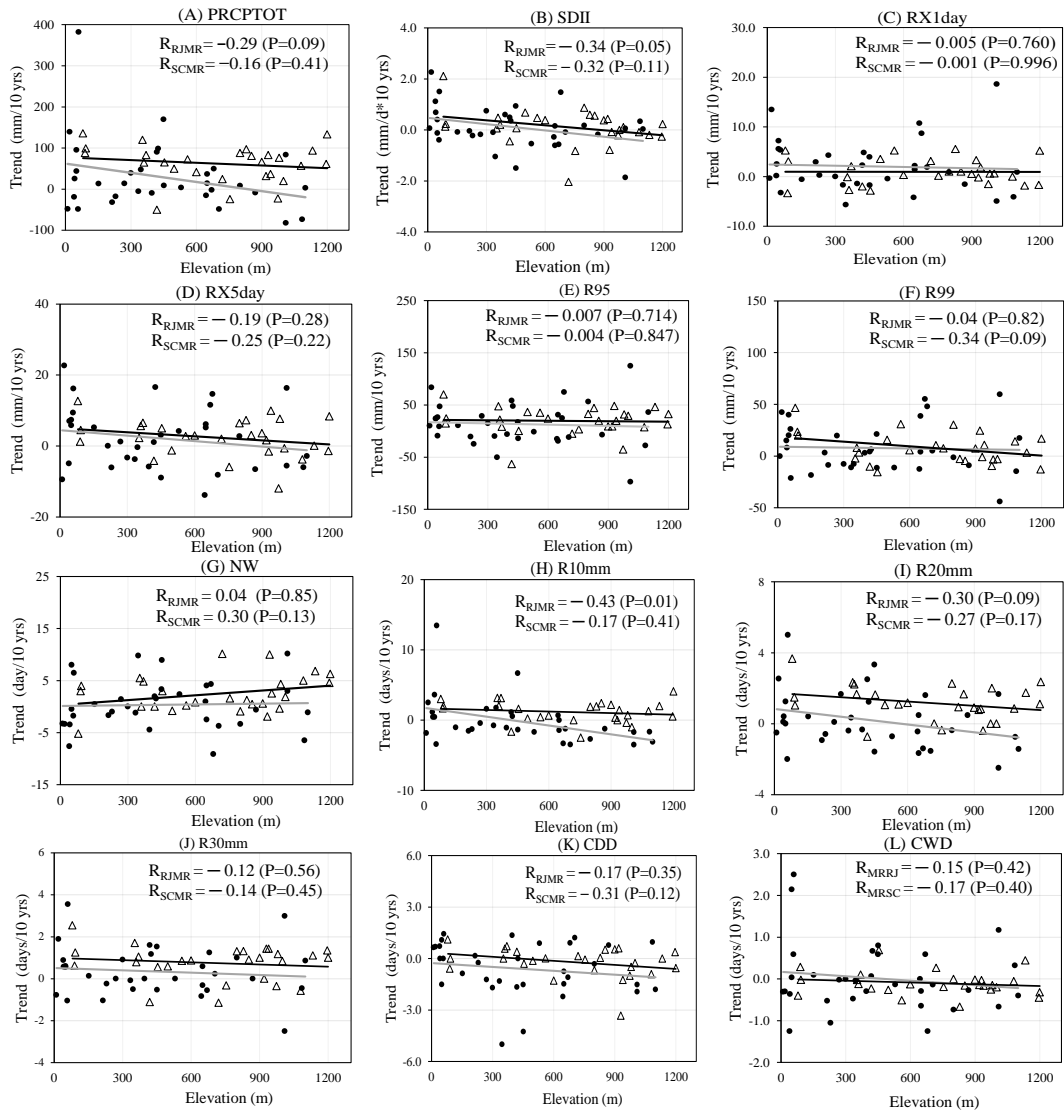


Figure 9. Magnitude trends of precipitation based indices related to elevation. R stands for correlation coefficients and p for statistical significance. The filled circles and triangles indicated trends in each station for RJMR and SCMR, respectively.

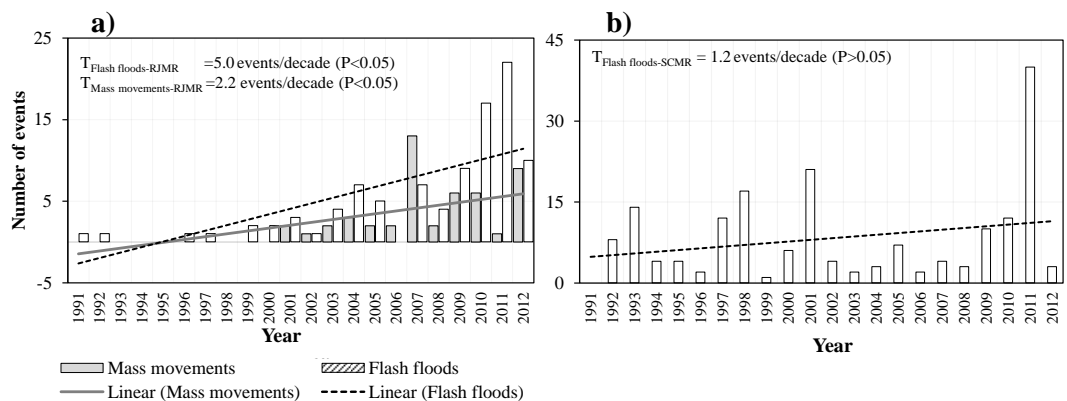


Figure 10. Annual changes of hydrological hazards in the RJMR (a) and SCMR (b) during 1991 to 2012.

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