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ORIGINAL PAPER

Changes of precipitation extremes indices in São Francisco River Basin, Brazil from 1947 to 2012

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Abstract

The São Francisco River is strategically important due to its hydroelectric potential and for bringing the largest water body of Brazilian Semiarid region, supplying water for irrigation, urban, and industrial activities. Thereby, for the purpose of characterizing changes on the precipitation patterns over São Francisco River basin, 11 extremes precipitation indices as defined by the joint WMO/CCI/ETCCDMI/CLIVAR project were calculated using daily observation from the 59 rain gauges during 1947–2012 period. The extreme climatic indices were calculated with the RClimDex software, which performs an exhaustive data quality control, intending to identify spurious errors and dataset inconsistencies. Weak and significant regional changes were observed in both CDD and SDII indices. Most precipitation extremes indices decreased but without statistical significance. The spatial analysis of indices did not show clearly regional changes due to the complexity of hydrometeorology of the region. In some cases, two rainfall stations exhibited opposite trends with the same significance level although they are separated by a few kilometers. This has occurred more frequently in Lower-Middle São Francisco, probably associated with intense land cover change over the last decades in this region.

1 Introduction

Climate change due to global warming is probably the most significant and far-reaching environmental threat of the present day; therefore, the most important climatic research topic of the last few decades (Dufek and Ambrizzi 2008; Croitoru et al. 2013). A consequence of global warming should be noted on the increase in both magnitude and frequency of extreme precipitation events, generated by increased atmospheric moisture levels, warmer air, thunderstorm activity, and/or large-scale storm activity (Sen Roy and Balling Jr. 2004; Oliveira et al. 2014). The increase on extreme precipitation event observations are associated to the occurrence of meteorological disasters such as droughts and floods, having catastrophic impacts on human socioeconomic development, being theme of scientific and societal interest during the last decade (Hanel and Buishand 2010; Xu et al. 2011; Liu et al. 2013).

Aiming to analyze climate extreme events, the World Meteorological Organization, Commission for Climatology and the Expert Team on Climate Change Detection, Monitoring Indices of the Climate Variability and Predictability (WMO/CCI/ETCCDMI/CLIVAR) has developed a set of indices representing a common guideline for regional analysis of the climate (Peterson et al., 2001). This indices has been used worldwide (e.g., Haylock et al. 2006; Alexander et al. 2006; Dufek and Ambrizzi 2008; Santos et al. 2011; Zongxing et al. 2012; Croitoru et al. 2013, 2016; Wang et al. 2013a, b; Ly et al. 2013; Liu et al. 2013; Zandonadi et al. 2015; Ruml et al. 2017). Concerning the studies over Brazil, scientific efforts to understanding hydrometeorological aspects on the São Francisco basin has been performed due to the relevant role of São Francisco river in Brazil semiarid region, because this river is the largest basin wholly within Brazilian territory (Maneta et al. 2009; Chan et al. 2012), supplying water for urban and industrial activities for example navigation, fisheries, hydropower production, and irrigation which are economically strategic for the semiarid region of

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Northeast Brazil (Sato and Godinho 2004; Maneta et al. 2009; Torres et al. 2011).

The irrigation of cultivated areas can strengthen the economic activities and, consequently, promoting social development. However, some studies (e.g., Maneta et al. 2009) indicate a strong and harmful water consuming activity in the basin. According to Chan et al. (2012) more than 6.4 billion m^3 $year^{-1}$, corresponding to 68% of the total water withdrawals, are used for irrigation projects in São Francisco River Basin, and the authors projected an increase of 250% until 2025 on water consumption on the basin, where irrigation uses more than 75% of the river's water.

Much of the predicted increase in water consumption will be for the water supply of the semiarid regions (Brazilian States of Ceará, Pernambuco, Paraíba and Rio Grande do Norte) by transposition from 2016. The Transposition Project, which basically, consisting of artificial drainage channels constructed to divert the water flux supplying nearby dams (Chan et al. 2012; Stolf et al. 2012). This flux should be divided in two regions: North Axis, near to Cabrobó municipality (Pernambuco State) with a total flux of 42.4 m^3 s^{-1}; and East Axis located in Floresta municipality (Pernambuco State), with a total flux of 21.1 m^3 s^{-1}. Furthermore, by using natural canals, water will be transferred to the chutes of the region's rivers, perpetuating them (Stolf et al. 2012). For the North Axis, 42.4 m^3 s^{-1} will be destined to the Basins of Jaguaribe (Ceará State), Apodi, and Piranhas-Açu (Rio Grande do Norte and Paraíba States). For the East Axis, a total of 21.1 m^3 s^{-1} will be destined to the States of Pernambuco and Paraíba River Basin. Chan et al. (2012) describes that the Transposition Project is a large effort to balance the availability and use of water across the drought-prone Northeast. The final objective is to ensure the supply of northeast big cities, including Fortaleza, Juazeiro do Norte, Crato, Mossoró, Campina Grande, Caruaru, and João Pessoa.

The actual scenario observed on São Francisco River region covers different aspects such as the following: increase of water demand of the São Francisco River in coming years due to expansion of irrigated areas, increase of population, the implementation of Transposition Project, absence of action policies to optimize water use. Thus, a possible influence of climate change has created an environment of relevant concern. A possible scenario increasing in magnitude and frequency of extreme precipitation events are expected according to the Intergovernmental Panel on Climate Change (IPCC) and features of extreme weather and climate events are likely to change in the twenty-first century owing to anthropogenic climate changes (IPCC 2007, 2012; Santos and Fragoso 2013). This scenario can affect negatively the sustainability of several activities on São Francisco River Basin, because changes in the climatology of precipitation, evapotranspiration, soil moisture content, runoff, and stream flow (Arora and Boer 2001).

Analyzing the changes in the precipitation extremes will hopefully provide a scientific basis and content for environmental education, water management, forecast, and prevention of natural hazards in the Basin. Thus, the aim of this present paper is to provide a comprehensive analysis of observed precipitation changes over the São Francisco River Basin during 1947 to 2012 period, using 11 extreme precipitation indices calculated from the WMO/CCI/ETCCDMI/CLIVAR algorithms (Peterson et al. 2001), focusing on daily precipitation trends analysis in a regional context.

2 Material and methods

2.1 Study area

The São Francisco River Basin is located on Brazil between geographical coordinates of 7.0°–21.0°S and 35.0°–47.7°W (Fig. 1), covering 638,576 km^2, which correspond around 8% of the Brazilian territory (Fig. 1). The flow average annual of 2850 m^3 s^{-1}, ranging from 1,077 to 5290 m^3 s^{-1}. Along 2860 km, the river crosses five Brazilian states: Minas Gerais (MG), Bahia (BA), Pernambuco (PE), Alagoas (AL), and Sergipe (SE) (Maneta et al. 2009; Torres et al. 2011; Santos et al. 2012; ANA 2013).

The river's headwaters are located in Serra da Canastra National Park (state of Minas Gerais, Southeast Brazil region) and its outfall on Atlantic Ocean, between Alagoas and Sergipe states (Coastland of the Northeast Brazil). The São Francisco River Basin can be divided into four hydrographic regions (Upper, Middle, Lower-Middle, and Lower São Francisco) (Fig. 1) according to features of prevailing ecosystem and climates. Thus, São Francisco River enclose four different climates types: dry subhumid with dry season that coincides with winter in the southern hemisphere (Upper São Francisco), semiarid (Middle São Francisco), semiarid and arid (Lower-Middle São Francisco), and subhumid (Lower Francisco). Areas of different ecosystems were observed along region: Atlantic Forest (headwaters), Cerrado (Upper and Middle São Francisco), Caatinga (Middle and Lower-Middle São Francisco), Caatinga, Atlantic Forest, and native formations (mangrove and coastal vegetation) (Lower São Francisco). Furthermore, the basin cover areas of transition between the Cerrado and Caatinga, deciduous seasonal forests and semi-deciduous (CBHSF 2004; Filogonio et al. 2010; Chan et al. 2012). The São Francisco River Basin climatology is characterized by high spatiotemporal variability due to the action of different large, meso and local scale meteorological systems (Oliveira et al., 2017). The mean annual precipitation ranges from 1500 mm (Upper São Francisco in Minas Gerais) to 350 mm (Lower-Middle São Francisco).

The precipitation of Upper and portions of Middle São Francisco (located on Southeastern region and southwest of the Bahia state, respectively) are mainly influenced by South America Convergence Zone (SACZ), acting on Southeastern

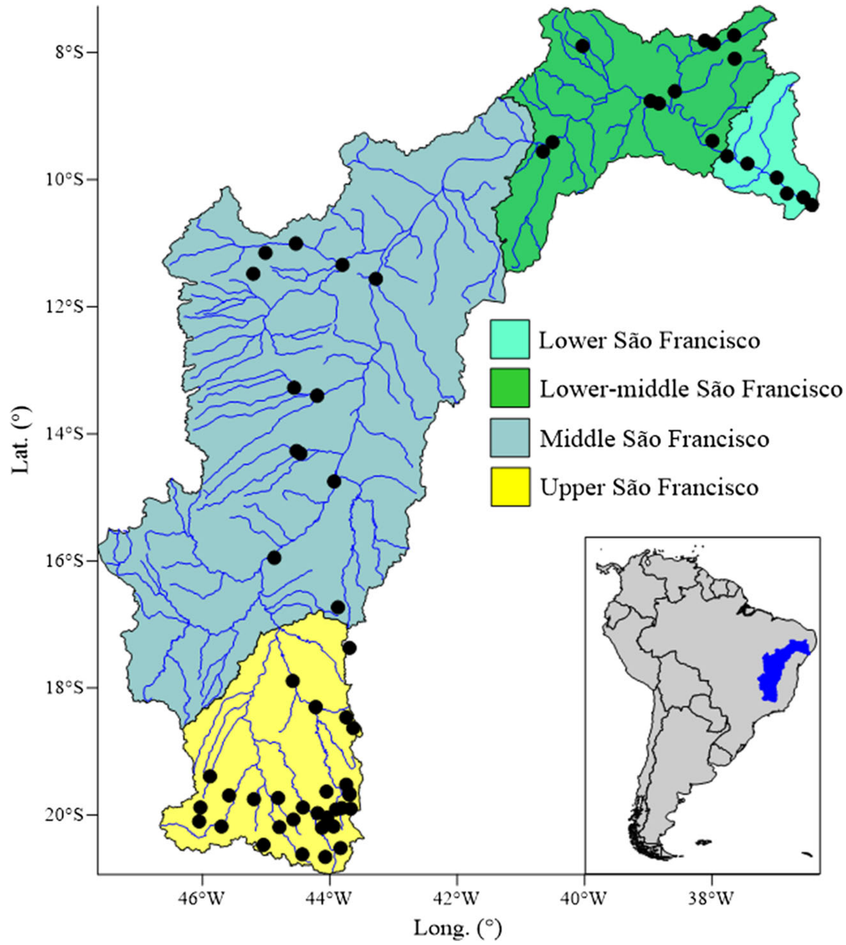

Fig. 1 The region marked in blue on the South America map (smaller figure, bottom right corner) is the São Francisco River Basin for which the location of the 59 rainfall stations is shown on the greatest figure

region of Brazil during summer (Cavalcanti 2012). The Lower-Middle (west of Bahia and Pernambuco) has a short rainy season, concentrated during March and April. The most persistent large scale meteorological feature related to the rainy season is the intertropical convergence zone (ITCZ) (Hastenrath and Heller 1977; Souza and Cavalcanti 2009; Cavalcanti, 2012). The rainy season occurs when the interhemispheric southward gradient of sea surface temperature (SST) is weakest and the ITCZ reaches its southern position, generally during April (Hastenrath 2006). The Lower-Middle São Francisco is vulnerable to occurrence of severe droughts, which is generally associated with strong El Niño events. The Lower São Francisco is located in the coastland of Northeast and the seasonality of precipitation modulated mainly by Easterly Wave Disturbances (EWD), frequently from May to August and causing heavy rainfall event (Chan et al. 2012; Oliveira et al. 2013a).

2.2 Dataset

2.2.1 Data description

Changes in the extremes precipitation indices were identified by using daily precipitation times series recorded in 59 rainfall stations across São Francisco River Basin from 1947 to 2012 period. The set of rainfall stations present a reasonable spatial coverage, consequently appropriated to characterize the regional behavior and variability of the precipitation extremes on the São Francisco River Basin (Fig. 1). The period of 66 year was chosen due to characterize a long-term dataset for each station. The dataset are management by National Water Agency of Brazil (ANA).

2.2.2 Quality control

A data quality control was performed due to the calculations of extreme indices, which are sensitive to spurious errors associated to changes in station location, exposure, equipment, and observational practice (Haylock et al. 2006; Santos et al. 2011). This procedure is needed to identify errors during the processing of the data and avoid the use of inconsistent data (Dufek and Ambrizzi 2008; Croitoru et al. 2013). The RClimDex quality control is performed as follows: (i) replaces all missing values (currently coded as −99.9) into an internal format that the software recognizes (i.e., NA, not available) and (ii) replaces all unreasonable values into NA.

2.3 Method

2.3.1 Indices calculations

The RClimDex 1.0 software developed by Canadian Meteorological Service (Zhang and Yang 2004) was used in this study, obtaining 11 climatic extremes precipitation indices as described in the Table 1. They were chosen from the list established by the WMO/CCI/ETCCDMI/CLIVAR (Santos et al. 2011; Croitoru et al. 2013).

2.3.2 Trends detection

Linear trends for extreme precipitation indices were calculated using the nonparametric approach Sen's slope estimator based on Kendall (Sen 1968). Sen's slope estimator has been applied in studies of annual temperature and precipitation in Canada (Zhang et al. 2000) and Loess Plateau, China (Yan et al. 2015) and for extremes wave heights over Northern Hemisphere oceans (Wang and Swail 2001). This method does not assume a specific distribution for the data, being non-sensitive to outliers (Yan et al. 2015). Therefore, possible time series autocorrelation can influence on statistical significance of a trend (Nalley et al. 2013; Yan et al. 2015). Here, the presence of possible autocorrelations was detected by using the autocorrelation coefficient ρ_k of the discrete time series for a$lag-k$ (Mondal et al., 2012). The hypothesis of serial independence was tested by the $lag-1$ autocorrelation as $H_0:\rho_1$ against $H_1:|\rho_1|>0$ (Mondal et al. 2012). No autocorrelation in the time series was detected and original Mann-Kendal test (Nalley et al. 2013) was applied. The regional precipitation series were converted into trends per decade and the linear trends was considered statistically credible if it was significant at the 0.05 and 0.10 levels.

2.3.3 Regional analysis

Regionally averaged anomaly series for each index was calculated by using Eq. (1), as previously used worldwide (New et al. 2006; Keggenhoff et al. 2014; Li et al. 2014; Yan et al. 2015):

$$x_{r,t} = \sum_{i=1}^{n_t}\left(x_{i,t}-x'_i\right)/n_t \quad (1)$$

where $x_{r,\ t}$ is the regionally averaged index at year t; $x_{i,\ t}$ is the index for station i at year t;x_i is the 1947–2012 index mean at station i; $n_t$is the number of stations with data in year t. For all indices, the regionally averaged series are expressed in the index units. To avoid the average series being dominated by those stations with a high value, $x_{i,\ t}$ and x_i were standardized by dividing. Them by the station standard deviation. A similar procedure was adopted by Keggenhoff et al. (2014), and Yan et al. (2015).

3 Results and discussion

Annual trends of the precipitation-related extreme indices over the São Francisco River Basin for 59 sites during the 1947 to 2012 period as shown in Table 2. The bold and highlighted values, which presented statistics significance at 0.05 level, and values highlighted significance 0.10 level. Table 3 shows the frequency of the extreme precipitation indices trends type. The percentage of the data of each precipitation-related extreme index in each group that were created according to the following criteria: trend (increasing and decreasing), statistically significant (at the 0.05 and 0.10 level) and not significant. The results presented in Tables 2 and 3 indicate linear trends of the daily precipitation extremes

Table 1 ETCCDMI Precipitation-related extreme indices used for this study

No.	Acronym	Nome of the index	Description	Unit
1	R10mm	Number of heavy precipitation days	Annual number of days with more than 10 mm day^{-1}	Days
2	R20mm	Number of very heavy precipitation days	Annual number of days with more than 20 mm day^{-1}	Days
3	R50mm	Number of extremely heavy precipitation days	Annual number of days when PRCP > 50 mm*	Days
4	CDD	Consecutive dry days	Annual maximum number of consecutive days with RR < 1 mm	Days
5	CWD	Consecutive wet days	Annual maximum number of consecutive days with RR > 1 mm	Days
6	R95p	Very wet days	Annual total PRCP when RR > 95th percentile	mm
7	R99p	Extremely wet days	Annual total PRCP when RR > 99th percentile	mm
8	Rx1day	Max 1-day precipitation amount	Monthly maximum 1-day precipitation	mm
9	Rx5day	Max 5-day precipitation amount	Monthly maximum consecutive 5-day precipitation	mm
10	SDII	simple daily intensity index	Annual total precipitation divided by the number of wet days in the year	mm
11	PRCPTOT	Annual total wet-day precipitation	Annual total amount of precipitation cumulated in wet days	mm

*50 mm was the threshold defined by the authors

Table 2 Slopes of linear trends of precipitation extremes indices observed on each rainfall station per year

Rainfall Station	PRCPTOT	RX1day	RX5day	R10mm	R20mm	R50mm	SDII	CDD	CWD	R95p	R99p
Afogados da Ingazeira	**6.424**	0.239	**0.812**	**0.26**	**0.117**	0.018	**0.076**	**-0.869**	-0.001	1.543	**0.91**
Bambuí	-0.838	0.399	0.581	-0.092	-0.009	0.006	0.025	-0.01	0.003	1.232	2.147
Barreiras	-0.454	-0.199	-0.151	-0.001	-0.018	-0.008	-0.03	-0.034	-0.005	-0.838	-0.866
Belém de São Francisco	**3.907**	0.296	0.482	**0.096**	**0.061**	0.021	0.015	**-1.197**	0.023	1.303	0.169
Belo Horizonte	-4.318	0.348	-0.153	**-0.364**	**-0.121**	-0.001	-0.058	**-0.525**	**-0.149**	-0.031	0.107
Betim	0.862	0.104	0.455	-0.043	0.005	0.016	0.017	-0.337	-0.024	1.723	**1.274**
Bom Despacho	-0.886	0.248	0.28	-0.015	-0.057	**-0.084**	**-0.11**	**-0.68**	**0.088**	**-4.193**	-0.703
Brumadinho	2.76	0.051	0.271	0.029	0.006	0.009	**-0.073**	**-0.537**	0.025	0.716	0.179
Caeté	2.937	0.191	0.769	-0.019	0.037	0.013	**-0.047**	-0.46	0.046	1.362	0.668
Carmo do Cajuru	-3.146	0.185	0.259	**-0.147**	**-0.085**	-0.003	**-0.124**	-0.22	**0.069**	0.02	0.47
Cocos	-2.349	0.007	-0.325	-0.095	-0.08	-0.004	**-0.058**	0.079	0.031	-0.417	-0.363
Congonhas	-2.403	0.056	-0.125	-0.074	-0.032	-0.003	0.005	**-0.328**	-0.043	-0.358	0.681
Custódia	**-9.066**	-0.345	**-1.065**	**-0.393**	**-0.144**	**-0.03**	-0.006	**1.121**	**-0.034**	**-2.076**	-0.814
Delmiro Gouveia	0.146	0.191	0.122	-0.038	-0.027	-0.004	**-0.057**	-0.178	-0.013	-0.255	0.526
Entre Rio de Minas	-1.104	-0.047	0.418	-0.093	**-0.085**	-0.021	-0.073	**-0.581**	**0.053**	-0.638	-0.287
Flores	-0.764	-0.231	-0.2	-0.052	**-0.064**	-0.013	**-0.153**	**-0.705**	0.024	-1.055	-0.327
Floresta	0.663	-0.217	-0.282	0.024	0.019	-0.006	-0.005	-0.005	-0.013	-0.319	-0.727
Florestal	3.945	**0.479**	**1.009**	0.072	0.085	0.03	0.028	-0.513	-0.023	2.322	1.526
Formosado Rio Preto	0.263	0.232	0.257	-0.058	0.002	0.024	-0.004	**-0.562**	-0.026	1.71	0.551
Gouveia	-1.291	-0.13	-0.577	-0.061	-0.013	0.001	0.006	0.126	-0.022	-0.292	-0.956
Ibirité	-0.048	**0.581**	0.458	-0.015	-0.021	-0.016	0.006	-0.134	-0.018	0.536	**2.422**
Iguatama	**4.384**	0.095	0.342	0.088	**0.123**	0.012	**0.05**	**-0.368**	-0.009	**1.998**	0.681
Itapecerica	0.212	-0.106	0.307	0.004	0.018	0.008	0.018	-0.154	-0.018	0.655	-0.086
Itaúna	3.787	-0.172	0.078	0.097	0.039	-0.006	0	-0.257	0.008	-0.8	-1.071
Jaboticatubas	-0.613	0.162	**0.797**	-0.036	0	-0.002	**0.038**	-0.039	**-0.069**	0.153	0.298
Juatuba	0.247	0.181	0.525	-0.068	-0.059	0.01	-0.03	-0.161	0.064	0.914	0.243
Juazeiro	0.251	-0.301	-0.077	0.012	0.018	-0.01	-0.021	0.268	-0.006	-0.758	-0.419
Lassance	-0.659	-0.195	-0.147	-0.09	-0.013	0.015	-0.011	-0.073	0.023	0.776	-0.474
Manga	-0.241	**0.312**	-0.166	-0.027	-0.025	-0.006	**-0.056**	-0.377	0.023	-0.313	0.419
Mansidão	-2.302	-0.049	**-1.049**	-0.041	-0.05	-0.025	**-0.062**	-0.345	-0.004	-1.271	-0.454
Montalvânia	1.882	0.196	0.283	0.003	0.006	0.008	**-0.07**	-0.415	**0.065**	0.9	0.91
Montes Claros	**-11.966**	**-0.879**	**-3.097**	-0.015	**-0.186**	**-0.214**	**-0.234**	**-0.807**	-0.059	**-11.047**	**-3.929**
Morpará	-0.83	-0.144	-0.563	-0.012	-0.026	-0.011	-0.031	-0.547	-0.022	-0.43	-0.079
Nova Lima	3.53	-0.157	-0.246	**0.157**	0.068	0.012	0.002	**-0.596**	0.017	1.317	-0.802
Onça Pintada	3.033	0.232	0.304	0.077	0.1	0.007	0.035	-0.337	-0.026	0.908	0.579
Ouricuri	2.673	0.156	0.215	0.019	-0.014	0.003	**-0.142**	-0.557	**0.033**	1.18	0.398
Pão de Açúcar	**4.804**	0.35	0.439	0.113	0.03	0.01	0.004	-0.414	**0.036**	1.132	0.67
Passa Tempo	-0.504	0.024	0.449	**-0.119**	0.013	0.001	0.03	-0.365	-0.04	0.429	0.345
Pedro Leopoldo	1.119	0.164	0.436	-0.029	0.012	0.007	-0.029	**-0.77**	-0.035	0.612	0.207
Penedo	-3.027	-0.031	-0.559	-0.078	-0.021	-0.022	0.016	**0.285**	**-0.089**	-1.041	0.507
Piaçabuçu	**-8.291**	0.174	-0.684	**-0.29**	**-0.278**	-0.037	**-0.14**	-0.037	0.014	**-4.547**	0.157
Piranhas	0.028	-0.022	0.155	-0.008	-0.002	-0.004	-0.006	0.242	-0.015	0.127	-0.198
Poço do Cavalo	0.316	-0.025	-0.289	-0.031	-0.01	0.013	-0.104	**-1.583**	0.023	0.351	-0.339
Presidente Juscelino	-3.412	-0.235	-0.548	-0.073	-0.083	**-0.03**	0.007	-0.219	**-0.055**	**-2.149**	-0.454
Propriá	1.899	0.104	0.194	0.053	0.026	0.007	0.03	0.177	-0.012	1.402	0.412
Sabará	-1.742	0.009	-0.076	-0.104	-0.021	-0.009	0.023	0.029	-0.042	0.167	0.07
Santa Maria da Boa Vista	**-19.189**	**-0.467**	**-1.529**	**-0.628**	**-0.342**	**-0.041**	**0.096**	**0.901**	**-0.118**	**-2.827**	**-1.175**
Santa Maria da Vitória I	-0.573	-0.4	-0.48	-0.035	-0.006	-0.006	-0.017	-0.359	-0.033	-0.424	-0.638
Santa Maria da Vitória II	0.697	**0.783**	0.528	-0.077	-0.182	**0.042**	-0.014	**-0.556**	-0.023	**2.803**	**1.098**
Santa Rita de Cássia	**-4.084**	**-0.354**	**-0.608**	-0.058	**-0.089**	**-0.053**	**-0.039**	-0.145	-0.036	**-3.659**	-0.787
Santo Hipólito	0.055	-0.205	-0.376	-0.009	-0.051	-0.019	**-0.077**	**-0.587**	0.04	-1.448	-0.435
São Francisco	-1.875	-0.008	-0.05	-0.057	-0.028	**-0.028**	-0.018	-0.118	-0.029	-1.77	-0.21
Serra da Saudade	2.864	0.118	0.125	0.013	0.015	0.029	0.008	**-0.441**	0.06	2.034	0.367
Tapiraí	0.635	0.112	-0.178	0.069	-0.017	-0.011	0.002	-0.244	-0.015	-0.222	-0.59
Taquaraçu de Minas	-2.201	-0.112	0.1	-0.071	-0.035	-0.005	**0.037**	0.046	-0.038	-0.502	-0.251
Traipú	-0.856	-0.256	-0.358	-0.086	-0.024	-0.008	**-0.057**	0.085	-0.009	-0.723	-0.54
Triunfo	-3.972	**-0.51**	-0.57	-0.049	-0.062	**-0.047**	-0.012	**0.457**	**-0.078**	**-3.792**	**-1.859**
Várzea da Palma	**-16.369**	**-0.582**	**-1.925**	**-0.456**	**-0.277**	**-0.128**	**-0.147**	0.319	**-0.085**	**-8.155**	**-2.494**
Vespasiano	3.26	0.327	**0.803**	0.062	0.072	**0.037**	**0.039**	-0.031	-0.003	**2.482**	0.909

The bold and highlighted values represent significance at 5% level ($p < 0.05$), and values only highlighted represent significance at 10% level ($0.05 < p < 0.1$)

Table 3 The percentage of stations showing significant at the 5% and at the 10%, and *n* significant trends for the precipitation-related extreme indices over São Francisco River Basin

Index	Mean	Range	Percentage of stations with increasing trends				Percentage of stations with decreasing trends			
			Sig. at 5%	Sig. at 10%	No sig.	All	Sig. at 5%	Sig. at 10%	No sig.	All
PRCPTOT	− 0.88	− 19.19 to 6.44	6.8	5.1	35.6	47.5	10.2	1.7	40.6	52.5
RX1day	0.01	− 0.88 to 0.79	6.8	6.8	40.7	54.2	8.5	5.1	32.2	45.8
RX5day	− 0.07	− 3.1 to 1.01	6.8	3.4	40.7	50.9	10.2	6.8	32.2	49.1
R10mm	− 0.05	− 0.63 to 0.26	5.1	1.7	23.7	30.5	11.9	5.1	52.5	69.5
R20mm	− 0.03	− 0.34 to 0.12	5.1	5.1	27.1	37.3	15.3	5.1	42.3	62.7
R50mm	− 0.01	− 0.21 to − 0.04	3.4	8.5	30.5	42.3	15.3	5.1	37.3	57.7
SDII	− 0.03	− 0.23 to 0.10	10.2	3.4	28.8	42.4	28.8	5.1	23.7	57.6
CDD	− 0.25	− 1.58 to 1.12	6.8	0.0	15.3	22.1	28.8	11.8	37.3	77.9
CWD	− 0.01	− 0.15 to 0.09	10.2	5.1	20.3	35.6	13.6	3.4	47.4	64.4
R95p	− 0.40	− 11.05 to 2.80	5.1	6.8	37.3	49.1	15.3	1.7	33.9	50.9
R99p	− 0.04	− 3.93 to 2.42	6.8	5.1	39.0	50.9	6.8	3.4	39.0	49.1

indices that are not statistically significant in majority of the studied sites. This behavior has been common in different region around the world, for example Santos et al. (2011) in Utah, USA, Croitoru et al. (2013), in Black Sea western coast, Keggenhoff et al. (2014) in Georgia, Zhao et al. (2014), in Pearl River Basin, southern China, Yan et al. (2015) in Loess Plateau, and Croitoru et al. (2016) in Romania. According to Santos et al. (2011) and Stephenson et al. (2014), the number of precipitation indices trends with statistical significance is reduced because precipitation has large temporal variability. This variability occurs mainly in regions subject to intraseasonal and/or interseasonal extreme events (storms and heavy rainfall interspersed with long dry spells, wet or dry years). Thus, the trends of long-term precipitation changes will have statistical significance if the occurrence of extreme events (dry or wet years) were frequent.

According to Table 2, from 59 studied rainfall stations, only 6 (Afogados da Ingazeira, Custódia, Santa Maria da Boa Vista, Santa Rita de Cássia, Montes Claros, and Várzea da Palma) were observed statistically significance in extreme precipitation indices. Interestingly, three sites are located on the Lower-Middle São Francisco basin: Afogados da Ingazeira, Custódia, and Santa Maria da Boa Vista. Santa Rita de Cássia and Montes Claros are located in the Middle, while Várzea da Palma is located in the Upper São Francisco. The Lower-Middle São Francisco basin is quite vulnerable to the occurrence of precipitation extreme events, and the rainy season is mainly influenced by ITCZ. Anomalous ITCZ behavior and occurrence of intense El Niño and La Niña events can produce precipitation extremes (wet or dry years) overall Northeast Brazil region (Cavalcanti 2012; Oliveira et al. 2013b). However, relatively near rainfall station (such as Afogados da Ingazeira, Custódia and Santa Maria da Boa Vista) have shown opposite significant trends signal, suggesting local effects influence. On the other hand, linear trends of most indices in Afogados da Ingazeira are positive with statistical significance level $p < 0.05$, Custódia extreme precipitation indices have opposite trends (decreasing) with same statistical significance level, given that distance between them is about 50 km. The probable causes of these opposing trends detected in the Lower-Middle and Lower São Francisco will be discussed subsequently.

Analyzing the regionally averaged anomaly series (Fig. 2) is noted that the changes in precipitation extremes over São Francisco River Basin during 1947–2012 were low, and only the SDII and CDD had statistically significant trends at the 0.05 and 0.10 levels, respectively (Fig. 2g, h). Still, according to Fig. 2 is noted that all precipitation-related extremes indices had decreasing trends, except Rx1day (Fig. 2b). The PRCPTOT had a weak decreasing trend and the regional trend for this index was − 7.9 mm/decade, but no-significant at 0.05 level (Fig. 2a). The Rx1day was unique index that had increasing trend, but very weak (0.02 mm/decade, no-significant at the 0.05 level), while RX5day, in turn, has a decreasing trend (− 0.73 mm/decade, no-significant at the 0.05 level) (Fig. 2b, c). R10mm, R20mm, and R50mm indices had decreasing trends no-significant at the 0.05 level, whose values was − 0.33, − 0.29, and − 0.07 days/decade, respectively (Fig. 2d–f). The slowly regional trends of PRCPTOT, RX1day, RX5day, R10mm, R20mm, and R50mm are due to changes of these precipitation-related extremes indices has been predominantly no-significant, beyond balance between percentage of rainfall stations with opposite trends (Table 3). Trends no-significant of these indices (PRCPTOT, Rx1day, Rx5day, R10mm, R20mm, and R50mm) has been recurrent in several studies carried out over different regions around the world, over different time series length, such as Europe (Keggenhoff et al.

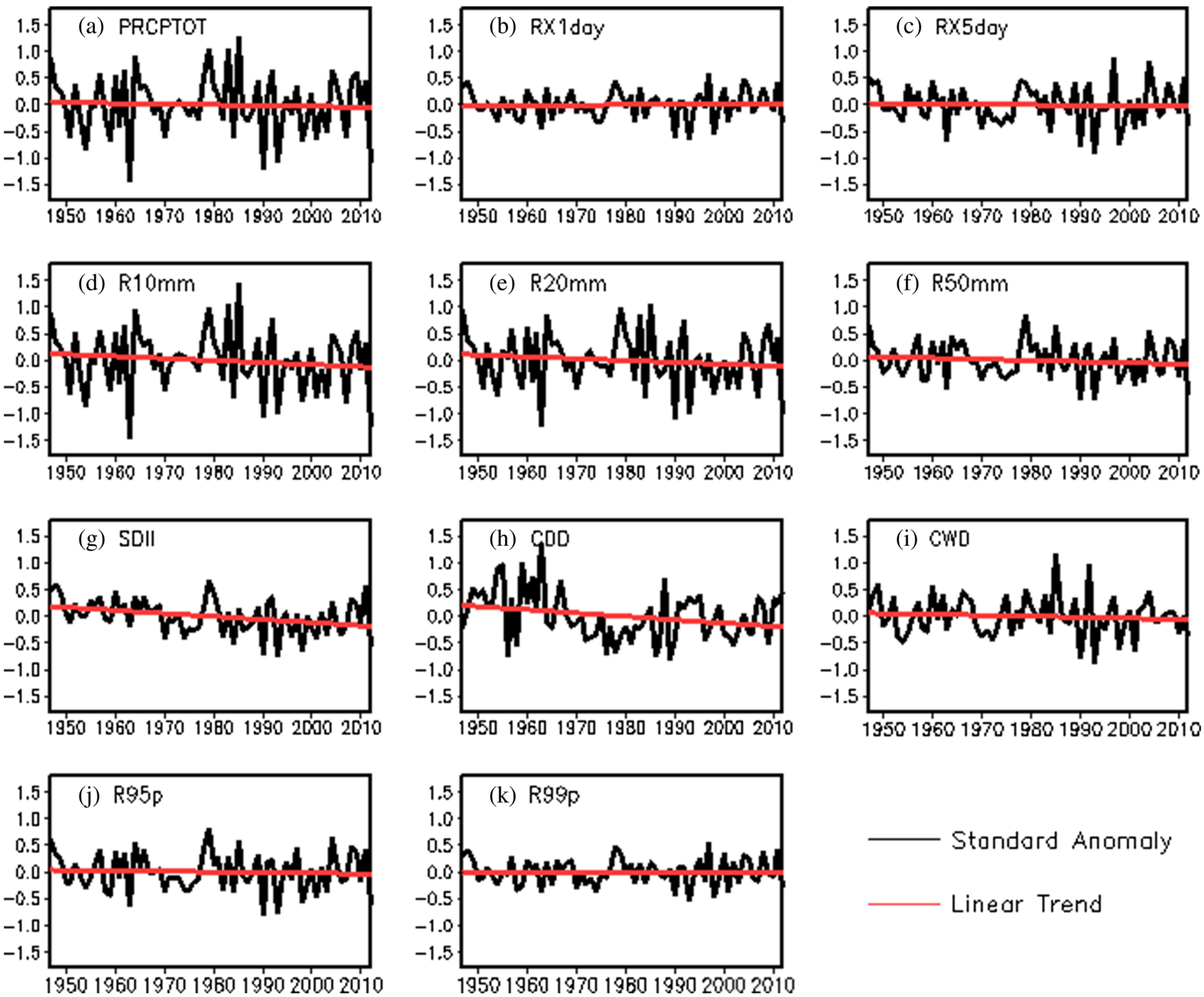

Fig. 2 Regional annual anomaly series, 1947–2012, for indices of precipitation extremes

2014; Boccolari and Malmusi 2013), Asia (Yan et al. 2015; Song et al. 2015), Southeastern United States (Powell and Keim 2015), and Caribbean region (Stephenson et al. 2014).

The average precipitation on wet days (SDII) had a significant decreasing trend at the 0.05 level (Fig. 2g). The regional trend was − 0.28 mm/decade. According to Table 2, about 60% of rainfall station exhibited decreasing trends, but 28% were significant at the 0.05 level and 5.1% were significant at the 0.10 level. Peterson et al. (2001) affirm that SDII would summarize the wet part of the year. The significant decreasing trend implies that wet part of the year is decreasing, i.e., the rainfall season is shortening. This is a concern relevant, especially for the region of the Middle São Francisco, where all the rainfall stations had negative trends for this index. The Middle São Francisco is a region with intensive agricultural production, mainly soybeans, and the decrease in wet part of the year will involve an increase in the demand for water to irrigation supply.

The regional average of consecutive dry days (CDD) has significant decreasing trends at the 0.10 level and had a rate of − 2.26 days/decade (Fig. 2h). Rainfall stations with decreasing trend were predominant (almost 80%, Table 3). According to Fig. 4d, the rainfall station which had CDD with decreasing trends are predominantly located on Upper and Middle São Francisco, while the rainfall stations with significant increasing trends are on Lower-Middle and Lower São Francisco. On the other hand the changes in consecutive wet day (CWD) was weak, only − 0.71 days/decade, and decreasing trend no-significant (Fig. 2i). According to Table 2, the percentage of rainfall stations that had decreasing trends was 65%, but about 47% was non-significant.

The very wet day precipitation (R95p) has shown decreasing trend, whose regional intensity was − 3.35 days/decade no-significant (Fig. 2j) and extremely wet day precipitation (R99p) (Fig. 2k) presented decrease trends of − 2.67 days/decade, this results agreement with other studies around the globe (Brown et al. 2010; Keggenhoff et al. 2014; Yan et al. 2015; Zhao et al. 2014; Cao and Pan 2014; Song et al. 2015).

Otherwise, Figs. 3 and 4 have shown spatial patterns of trends for the precipitation-related extreme indices based on daily data. These figures provide a spatial view of the positive and negative trends in each rainfall station, as well as their intensity through the size of the symbols, beyond significance (closed symbol) and not significant (open symbols). Figure 3 shows the results of the precipitation indices (mm), while Fig. 4 shows results of the precipitation indices with units of days. According to these analyses, there is not regional coherence concerning the geographical distribution of increasing and decreasing trends of precipitation-related extremes indices. Surrounding rainfall stations have opposite trends, making it difficult to detect regional trends. According to Stephenson et al. (2014) the reduced spatial coherence found in precipitation indices is due to high spatial and temporal

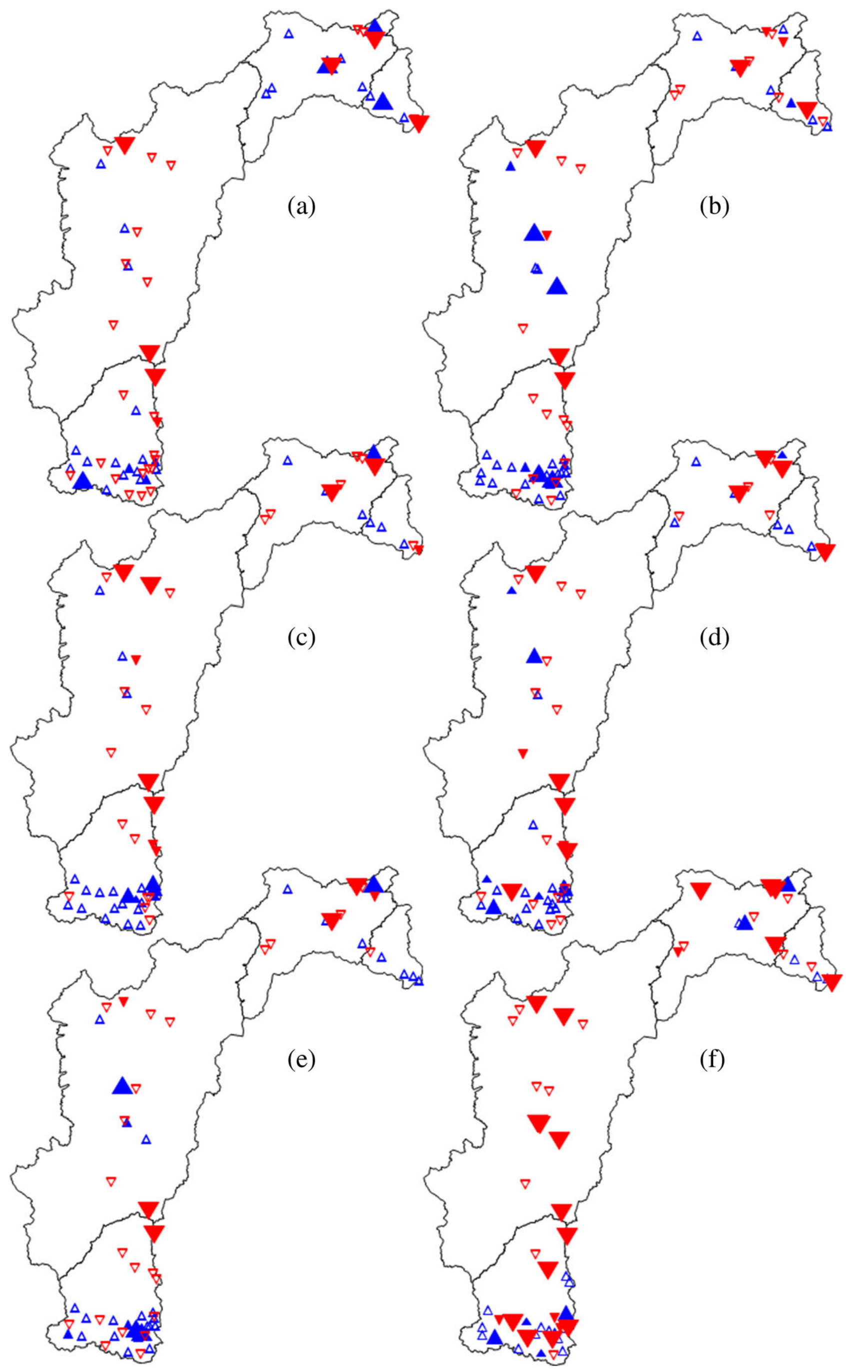

Fig. 3 Spatial distribution of precipitation extreme indices **a** PRCPTOT, **b** RX1day, **c** RX5day, **d** R95p, **e** R99p, and **f** SDII over São Francisco River Basin. The closed biggest triangle blue (red) indicated increasing (decreasing) trends significant at 5% level, the closed smaller triangle blue (red) indicated increasing (decreasing) trends significant at 10% level. The open smaller triangle blue (red) indicated increasing (decreasing) trends no-significant

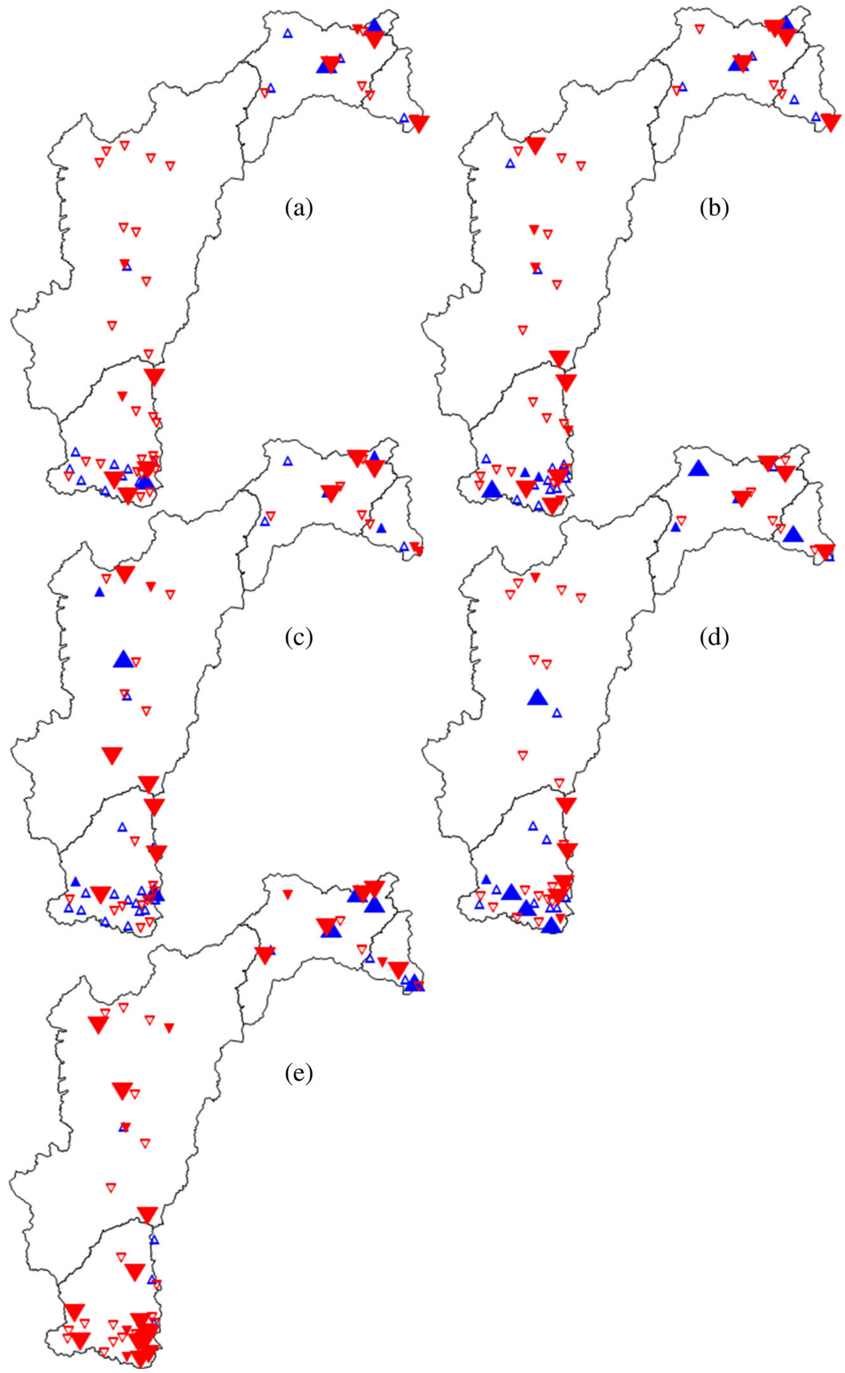

Fig. 4 Spatial distribution of precipitation extreme indices **a** R10mm, **b** R20mm, **c** R50mm, **d** CDD, and **e** CWD over São Francisco River Basin. The closed biggest triangle blue (red) indicated increasing (decreasing) trends significant at 5% level, the closed smaller triangle blue (red) indicated increasing (decreasing) trends significant at 10% level. The open smaller triangle blue (red) indicated increasing (decreasing) trends no-significant

variability; unlike to temperature whose changes have been found better regional coherence. The absence of regional/spatial coherence of precipitation-related extremes indices has been recurrent in studies carried out on different regions around the world (Frich et al. 2002; Alexander et al. 2006; Croitoru et al. 2013; Keggenhoff et al. 2014; Stephenson et al. 2014; Yan et al. 2015; Powell and Keim 2015).

We observed an absence of regional coherence of change in climatic extreme indices, mainly on Lower-Middle and Lower São Francisco. The clearest example of these contrasting trends was found in rainfall stations of the Afogados da Ingazeira and Custódia. While the trends of PRCPTOT, RX5day (Fig. 3a, c), R10mm, and R20mm (Fig. 4a, b) in Afogados da Ingazeira was increasing with the statistical significance level $p < 0.05$, Custódia has trends decreasing with same statistical significance level. However, the distance between these two cities is only 52.7 km. Also showed opposite trends of the PRCPTOT the rainfall stations of Santa Maria da Boa Vista and Belém de São

Francisco (Lower-Middle São Francisco), beyond Pão de Açúcar and Piaçabuçu (Lower São Francisco).

These opposing trends observed on Lower-Middle and Lower São Francisco are probably associated to local scale events, regional circulation induced by the changes in land use over the regions from the 1950s. For example, the construction of the Paulo Afonso Dam for hydropower generation at 1954. According to Avissar and Pan (2000) and Correia et al. (2006a), the insertion of large water bodies in a region can modify the energy budget and its hydrological cycle, affecting rain distribution, rain quantity, maximum and minimum temperatures, and atmospheric moisture. In the subsequent decades, three new dams for hydropower generation were constructed: Sobradinho, built during 1979 year, Itaparica (currently Luiz Gonzaga Dam) during 1980s, and Xingó early 1990s, forming a lake greater than 5000 km^2. The dams insertion modified temperature and humidity regional pattern, since there was replacement of natural vegetation (specifically the caatinga, deciduous vegetation, typically low evapotranspiration rate) by free water and with high rate of evaporation. Studies using regional climate models has been showed the influence of Sobradinho dam in mesoscale circulation associated with the lake of 4214 km^2 (Correia et al. 2006a, b). According to Correia et al. (2006a), the alterations were observed to be more significant in the atmospheric humidity and wind speed. The wind speed alterations occur because the temperature gradient is less intense over water bodies. These changes in the wind speed patterns possibly altered the distribution of rainfall in the region, favoring increase rainfall in some areas and decrease in other areas, rising occurrence of opposing trends in very close rainfall stations (less than 60 km). In addition to the construction of the dams, there was also a high expansion of irrigated districts such as Bebedouro, established during 1968 year, Tourão, established during 1979 Maniçoba and Curaçá, established during 1980 year, Senador Nilo Coelho, stablished from 1984 year, all in Lower-Middle São Francisco, totalizing more than 40,000 ha.

4 Summary and conclusions

The present study aims to identify linear trends of climatic indices based on precipitation observations over the São Francisco river basin, Brazil, from 1947 to 2012 by using 11 extreme precipitation indices generated by the joint WMO/CCI/ETCCDMI/CLIVAR. Data were carefully examined for quality and an exhaustive data quality control was conducted in order to identify spurious errors and inconsistencies on dataset. The significance of changes in precipitation extremes was weak and only the regional trends in CDD and SDII were significant. The trends of the most precipitation extremes indices were decreasing, but the most changes were not statistically significant. Spatial changes of precipitation extremes are complex. In other words, it is difficult to define a regional pattern of changes in precipitation extremes, since they occurred randomly. It is common two rainfall stations to exhibit opposite trends signals with the same significance level although they are separated by a few kilometers. The low spatial coherence of the trends found are similar to those identified in other regions in different continents (Croitoru et al. 2013; Stephenson et al. 2014; Yan et al. 2015). However, the low spatial coherence is clearer in Lower-Middle São Francisco and it is probably associated with intense land cover change over the last decades in this region (Correia et al., 2006a, b). The changes in precipitation extreme were more intense in six rainfall stations (Afogados da Ingazeira, Custódia, Santa Maria da Boa Vista, Santa Rita de Cássia, Montes Claros, and Várzea da Palma). Where three of them are located in the Lower-Middle São Francisco. In these rainfall stations changes of almost all precipitation extreme indices was statistically significant.

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References

Alexander LV, Zhang X, Peterson TC, Caesar J, Gleason B, Tank AMGK, Haylock M, Collins D, Trewin B, Rahimzadeh F, Tagipour A, Kumar R, Revadekar J, Griffiths G, Vincent L, Stephenson DB, Burn J, Aguilar E, Brunet M, Taylor M, New M, Zhai P, Rusticucci M, Vazquez-Aguirre JL (2006) Global observed changes in daily climate extremes of temperature and precipitation. J Geophys Res 111:D05109

ANA, 2013. Região Hidrográfica do São Francisco. Accessed at: http://www.ibge.gov.br/home/geociencias/cartografia-/default_territ_area.shtm

Arora VK, Boer GJ (2001) Effects of simulated climate change on the hydrology of major river basins. J Geophys Res 106(D4):3335–3348. https://doi.org/10.1029/2000JD900620

Avissar R, Pan H (2000) Simulations of the summer hydrometeorological processes of Lake Kinneret. J Hydrometeorol 1(1):95–109. https://doi.org/10.1175/1525-7541(2000)001<0095:SOTSHP>2.0.CO;2

Boccolari M, Malmusi S (2013) Changes in temperature and precipitation extremes observed in Modena, Italy. Atmos Res 122:16–31. https://doi.org/10.1016/j.atmosres.2012.10.022

Brown PJ, Bradlwy RS, Keimig FT (2010) Changes in extreme climate indices for the northeastern United States, 1870-2005. J Clim 23(24):6555–6572. https://doi.org/10.1175/2010JCLI3363.1

Cao L, Pan S (2014) Changes in precipitation extremes over the "Three-River headwaters" region, hinterland of the Tibetan Plateau, during 1960-2012. Quat Int 321:105–115. https://doi.org/10.1016/j.quaint.2013.12.041

Cavalcanti IFA (2012) Large scale and synoptic features with extreme precipitation over South America: a review and case studies for the first decade of the 21st century. Atmos Res 118:27–40. https://doi.org/10.1016/j.atmosres.2012.06.012

CBHSF (2004) Plano Decenal de Recursos Hídricos da Bacia Hidrográfica do Rio São Francisco–PBHSF (2004-2013) – Resumo Executivo

Chan Z, Graylee K, Kajenthira A, Lee H, Martínez D, Roman A (2012) São Francisco River basin background paper. Water Federalism Conference Proceedings. Accessed at: http://watersecurityinitiative.seas.harvard.edu/conference-papers-and-presentations

Correia MF, Silva Dias MAF, Aragão MRS (2006a) Soil occupation and atmospheric variations over Sobradinho Lake area. Part one: an observation analysis. Meteorog Atmos Phys 94(1-4):103–113. https://doi.org/10.1007/s00703-005-0173-4

Correia MF, Silva Dias MAF, Aragão MRS (2006b) Soil occupation and atmospheric variations over Sobradinho Lake area. Part two: a regional modelling study. Meteorog Atmos Phys 94(1-4):115–128. https://doi.org/10.1007/s00703-005-0174-3

Croitoru A-E, Piticar A, Burada DC (2016) Changes in precipitation extremes in Romania. Quat Int 415:325–335

Croitoru A-E, Chiotoroiu B-C, Todorova VI, Torică V (2013) Changes in precipitation extremes indices on the Black Sea western coast. Glob Planet Change 102:10–19. https://doi.org/10.1016/j.gloplacha.2013.01.004

Dufek AS, Ambrizzi T (2008) Precipitation variability in São Paulo State, Brazil. Theor Appl Climatol 93(3-4):167–178. https://doi.org/10.1007/s00704-007-0348-7

Filogonio R, Assis VB, Passos LF, Coutinho ME (2010) Distribution of populations of broad-snouted caiman (Caiman latirostris I Daudin 1802, Alligatoridae) in the São Francisco River basin, Brazil. Braz J Biol 70(4):961–968. https://doi.org/10.1590/S1519-69842010000500007

Frich P, Alexander LV, Della-Marta P, Gelason B, Haylock M, Tank AMGK, Peterson T (2002) Observed coherent change in climatic extremes during the second half of the twentieth century. Clim Res 19:193–212. https://doi.org/10.3354/cr019193

Hanel M, Buishand TA (2010) On the value of hourly precipitation extremes in regional climate model simulations. J Hydrol 393(3-4):265–273. https://doi.org/10.1016/j.jhydrol.2010.08.024

Hastenrath S (2006) Circulation and teleconnection mechanisms of Northeast Brazil droughts. Prog Oceanogr 70(2-4):407–415. https://doi.org/10.1016/j.pocean.2005.07.004

Hastenrath S, Heller L (1977) Dynamics of climatic hazards in northeast Brazil. Quart J R Meteorol Soc 103(435):77–92. https://doi.org/10.1002/qj.49710343505

Haylock MR, Peterson TC, Alves LM, Ambrizzi T, Anunciação YMT, Baez J, Barros VR, Berlato MA, Bidegain M, Coronel G, Corradi V, Garcuia VJ, Grimm AM, Karoly D, Marengo JA, Marino MB, Moncunill DF, Nechet D, Quintana J, Rebello E, Rusticucci M, Santos JL, Trebejo I, Vincent LA (2006) Trends in total and extreme south American rainfall in 1960-2000 and links with sea surface temperature. J Clim 19(8):1490–1512. https://doi.org/10.1175/JCLI3695.1

IPCC (2007) Climate change 2007: the physical science basis. Cambridge, U.K.

IPCC (2012) Summary for policymakers. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) Managing the risks of extreme events and disasters to advance climate change adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York, pp 3–21

Keggenhoff I, Elizbarashvili M, Amiri-Farahani A, King L (2014) Trends in daily temperature and precipitation extremes over Georgia, 1971-2010. Weather Clim Extremes 4:75–85. https://doi.org/10.1016/j.wace.2014.05.001

Li ZX, Feng Q, Liu W, Wang TT, Gao Y, Wang YM, Cheng AF, Li JG, Liu L (2014) Spatial and temporal trend of potential evapotranspiration and related driving forces in Southwestern China, during 1961-2009. Quat Int 336: 127–144 https://doi.org/10.1016/j.quaint.2013.12.045

Liu W, Zhang M, Wang S, Wang B, Li F, Che Y (2013) Changes in precipitation extremes over Shaanxi Province, northwestern China, during 1960-2011. Quat Int 313-314:118–119. https://doi.org/10.1016/j.quaint.2013.06.033

Ly M, Traore SB, Alhanssane A, Sarr B (2013) Evolution of some observed climate extremes in the West African Sahel. Weather Clim Extremes 1:19–25

Maneta MP, Torres M, Wallender WW, Vosti S, Kirby M, Bassoi LH, Rodrigues LN (2009) Water demand and flows in the São Francisco River basin (Brazil) with increased irrigation. Agric Water Manag 96(8):1191–1200. https://doi.org/10.1016/j.agwat.2009.03.008

Mondal A, Kundu S, Mukhopadhyay A (2012) Rainfall trend analysis by Mann-Kendall test: a case study of north-eastern part of Cuttack District, Orissa. Int J Geol Earth Environ Sci 2:70–78

Nalley D, Adamowski J, Ozga-Zielinski B (2013) Trend detection in surface air temperature in Ontario and Quebec, Canada during 1967-2006 using discrete wavelet transform. Atmos Res 132-133:375–398. https://doi.org/10.1016/j.atmosres.2013.06.011

New M, Hewitson B, Stephenson DB, Tsiga A, Kruge A, Manhique A, Gomez B, Coelho CAS, Masisi DN, Kululanga E, Mbambalala E, Adesina F, Saleh H, Kanyanga J, Adosi J, Bulanr L, Fortunaga L, Mdoka ML, Lajoie R (2006) Evidence of trends in daily climate extremes over southern and west Africa. J Geophys Res 111(D14):D14102. https://doi.org/10.1029/2005JD006289

Oliveira PT, Lima KC, Santos e Silva CM (2013a) Synoptic environment associated with heavy rainfall events on the coastland of Northeast Brazil. Adv Geosci 35:73–78. https://doi.org/10.5194/adgeo-35-73-2013

Oliveira PT, Santos e Silva CM, Lima KC (2013b) Linear trend of occurrence and intensity of heavy rainfall events on Northeast Brazil. Atmos Sci Lett 15:172–177

Oliveira PT, Santos E, Silva CM, Lima KC (2017) Climatology and trend analysis of extreme precipitation in sub regions of Northeast Brazil. Theor Appl Climatol 120:77–90. https://doi.org/10.1007/s00704-016-1865-z

Oliveira PT, Santos e Silva CM, Lima KC (2014) Linear trend of occurrence and intensity of heavy rainfall events on Northeast Brazil. Atmos Sci Lett 5: 172–177. https://doi.org/10.1002/asl2.484

Peterson TC, Folland C, Gruza G, Hogg W, Mokssit A, Plummer N. 2001. Report on the activities of the Working Group on Climate Change Detection and Related Rapporteurs 1998–2001.World Meteorological Organization Rep., Geneva, Switzerland p.1071 (WCDMP-47, WMO-TD).

Powell EJ, Keim BD (2015) Trends in daily temperature and precipitation extremes for the southeastern United States: 1948–2012. J Clim 28(4):1592–1612. https://doi.org/10.1175/JCLI-D-14-00410.1

Ruml M, Gregorić E, Vujadinović M, Radovanović S, Matović G, Vuković A, Počuča V, Sojičić D (2017) Observed changes of temperature extremes in Serbia over the period 1961-2010. Atmos Res 183:26–41. https://doi.org/10.1016/j.atmosres.2016.08.013

Santos CAC, Neale CMU, Rao TVR, Silva BB (2011) Trends in indices for extremes in daily temperature and precipitation over Utah, USA. Int J Climatol 31(12):1813–1822. https://doi.org/10.1002/joc.2205

Santos HA, Pompeu PS, Kenji DOL (2012) Changes in the flood regime of São Francisco River (Brazil) from 1940 to 2006. Reg Environ Chang 12(1):123–132. https://doi.org/10.1007/s10113-011-0240-y

Santos M, Fragoso M (2013) Precipitation variability in northern Portugal: data homogeneity assessment and trends in extreme precipitation indices. Atmos Res 131:34–45. https://doi.org/10.1016/j.atmosres.2013.04.008

Sato Y, Godinho HP (2004) Migratory fishes of the São Francisco river. In: Carolsfeld J, Harvey B, Ross C, Baer A (eds) Migratory fishes of South America: biology, fisheries, and conservation status. World Fisheries Trust/Word Bank/International Development Research Centre, Washington, DC, pp 195–232

Sen PK (1968) Estimates of regression coefficient based on Kendall's tau. J Am Stat Assoc 63(324):1379–1389. https://doi.org/10.1080/01621459.1968.10480934

Sen Roy S, Balling Jr. RC (2004) Trends in extreme daily precipitation indices in India. Int J Climatol 24: 457–466. https://doi.org/10.1002/joc.99

Song X, Song S, Sun W, Mu X, Wang S, Li J, Li Y (2015) Recent changes in extreme precipitation and drought over the Songhua River basin, China, during 1960-2013. Atmos Res 157:137–152. https://doi.org/10.1016/j.atmosres.2015.01.022

Souza P, Cavalcanti IFA (2009) Atmospheric centres of action associated with the Atlantic ITCZ position. Int J Climatol 29(14):2091–2015. https://doi.org/10.1002/joc.1823

Stephenson TS, Vincent LA, Allen T, Van Meerbeeck CJ, McLean N, Peterson TC, Taylor MA, Aaron-Morrison AP, Auguste T, Bernard D, Boekoudt JRI, Blenman RC, Braithwaite GV, Brown G, Butler M, Cumberbatch CJM, Etienne-Leblanc S, Lake DE, Martin DE, McDonald JL, Zaruela MO, Porter AO, Ramirez MS, Tamar GA, Roberts BA, Mitro SS, Shaw A, Spence JM, Winter A, Trotman AR (2014) Changes in extreme temperature and precipitation in the Caribbean region, 1961-2010. Int J Climatol 34:2957–2971

Stolf R, Piedade SMS, Silva JR, Silva LCF, Maniero MA (2012) Water transfer from São Francisco River to semiarid northeast of Brazil: technical data, environmental impacts, Survery of opinion about the amount to be transferred. Eng Agric 32:998–1010

Torres MO, Maneta M, Howitt R, Vosti SA (2011) Economic impacts of regional water scarcity in the São Francisco River basin, Brazil: an application of a linked hydro-economic model. Environ Dev Econ 17:227–248

Wang S, Zhang M, Sun M, Wang B, Li X (2013a) Changes in precipitation extremes in alpine areas of Chinese Tianshan Mountains, central Asia, 1961-2011. Quat Int 311:97–107. https://doi.org/10.1016/j.quaint.2013.07.008

Wang S, Zhang M, Wang B, Sun M, Li X (2013b) Recent changes in daily extremes of temperature and precipitation over the western Tibetan Plateau, 1973-2011. Quat Int 313-314:110–117. https://doi.org/10.1016/j.quaint.2013.03.037

Wang XL, Swail VR (2001) Changes of extremes wave heights in northern hemisphere oceans and related atmospheric regimes. J Clim 14(10):2204–2221. https://doi.org/10.1175/1520-0442(2001)014<2204:COEWHI>2.0.CO;2

Xu X, Du Y, Tang J, Wang Y (2011) Variations of temperature and precipitation extremes in recent two decades over China. Atmos Res 101(1-2):143–154. https://doi.org/10.1016/j.atmosres.2011.02.003

Yan G, Qi F, Wei L, Aigang L, Yu W, Jing Y, Aifang C, Yamin W, Yubo S, Li L, Qianqian M (2015) Changes of daily climate extremes in Loess Plateau during 1960-2013. Quat Int 371:5–21. https://doi.org/10.1016/j.quaint.2014.08.052

Zandonadi L, Acquaotta F, Fratianni S, Zavattini JA (2015) Changes in precipitation extremes in Brazil (Paraná River basin). Theor Appl Climatol 123:741–756

Zhang X, Yang F (2004) RClimDex (1.0) user guide. Climate Research Branch Environment Canada, Downsview

Zhang XB, Vincent LA, Hogg WD, Niitsoo A (2000) Temperature and precipitation trends over Canada during 20th century. Atmos-Ocean 38(3):395–429. https://doi.org/10.1080/07055900.2000.9649654

Zhao Y, Zou X, Cao L, Xu X (2014) Changes in precipitation extremes over the Pearl River basin, southern China, during 1960-2012. Quat Int 333:26–39. https://doi.org/10.1016/j.quaint.2014.03.060

Zongxing L, He Y, Wang P, Theakstone WH, An W, Wang X, Lu A, Zhang W, Cao W (2012) Changes of daily climate extremes in southwestern China during 1961-2008. Glob Planet Change 80-81:255–272. https://doi.org/10.1016/j.gloplacha.2011.06.008