



Trend analysis of extreme thermal indices in south Brazil (1971 to 2014)

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Abstract

Southern Brazil has recently been the subject of many major natural hazards from weather and climatic origin, including violent floods in 2016 caused by very heavy rains. It has also experienced episodes of droughts and heat waves in recent years. The state of Paraná, located at the climatic transition zone, has densely populated urban areas, vast cultivation areas, and hydro-electric reservoirs (more than 20), so those extreme events are letting local populations vulnerable to the vagaries of the climate and their impacts on community, infrastructure, and ecosystem. This study analyzes climatic variability and trends of about ten climatic indices (with RCLimDex), calculated by using daily thermal data of ten stations spread mainly in two geographic regions of Paraná. The Mann-Kendall and Pettitt tests were applied for trends analysis and determine the presence of breakpoints in the time series (1971–2014). Our results showed that for the various thermal indices, there is a reduction of the cold days on all the stations, indicating a more pronounced increase of the indices based on the maximum temperatures (TX), especially in the north. On the other hand, the indexes based on minimum temperatures (TN) show a more modest and partial increase, varying accordingly to the location of the stations. Regionally, the trends calculated were similar, that is, North region presents a more expressive increase of the indices of heat whereas in the east predominates a reduction.

1 Introduction

Climatic conditions interfere, directly or indirectly, in most socioeconomic activities. Particularly in agricultural activities, the climate is seen as a conditioning factor, since the development of crops is compatible with the type of climate supply; which varies in time and space. Studying climate trends and variability allows us to identify the occurrence of climatic changes that, in the medium and long term, can affect forms of production, the availability of products, as well as matters related to agricultural policy, among others.

The Brazil economy and more specifically of Paraná state, located in the southern region of Brazil (Fig. 1), is highly dependent on agricultural activities, which are sensitive to the occurrence of extreme climatic events. The Paraná territory presents a complex pluvial variability due to an intricate atmospheric dynamics associated, mainly, to the phenomenon El Niño-Southern Oscillation (ENSO) that produces intense rains and prolonged droughts. Other extreme events, such as hot and cold waves, gusty winds, and tornadoes, have an impact on the territoriality of the state, which provokes constant analysis due to its direct impact on socioeconomic activities (Ely and Pereira 2011; Mangili and Ely 2016).

This paper presents analysis of the frequency and trends of thermal extremes in the context of the climatic transition zone with both tropical and subtropical climates. This ambivalence is what characterizes the climate of Paraná. Typically, studies analyzing variations and climatic extremes in South America cover large areas, such as large river basins or entire Brazilian regions, because of the availability of longer data series (Vincent et al. 2005; Marengo and Camargo 2008; Marengo et al. 2009; Mendonça 2006, 2014; Almeida et al. 2016; Alvares et al. 2017; Dubreuil et al. 2017). It is important to note that although

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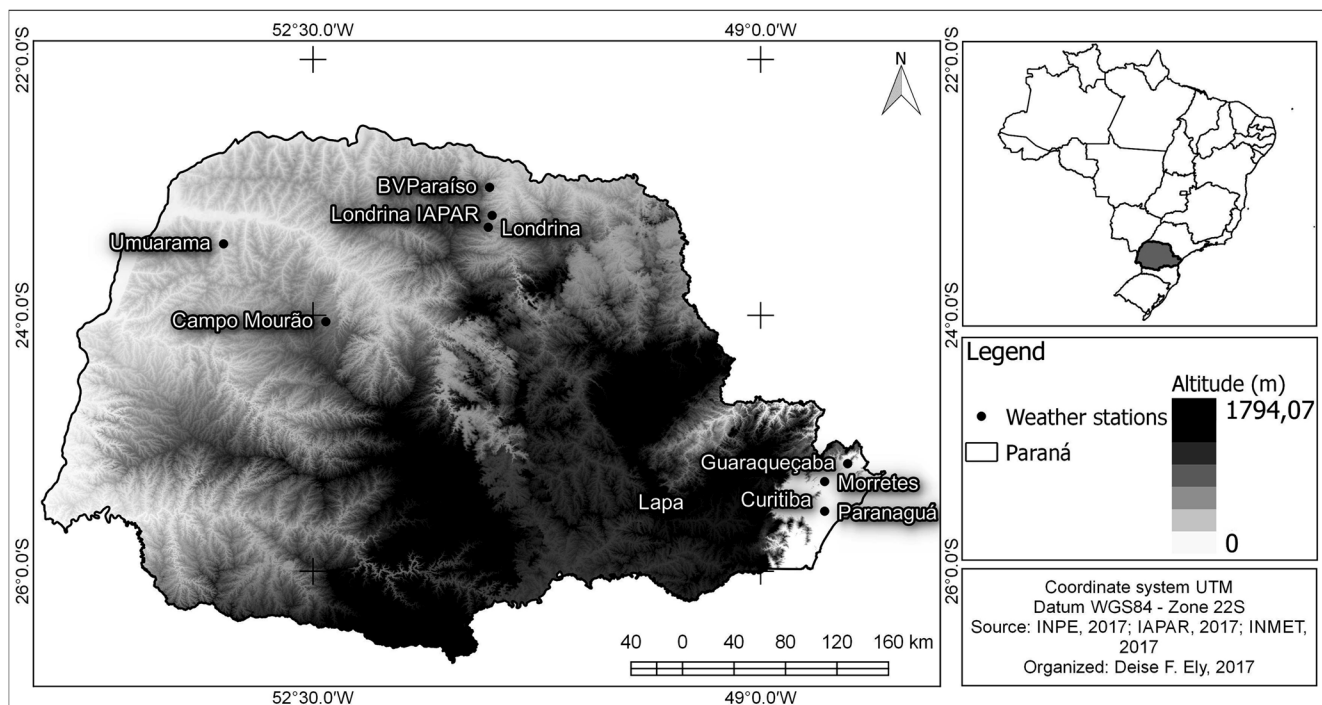


Fig. 1 Location of meteorological stations selected for the study area

the area studied in this article has data collected over 30 years, the complexity of the responses that the region's transitional aspect can give in relation to climate change is still little discussed.

With respect to thermal extremes, these can be calculated by applying thresholds for minimum and maximum temperatures on a daily or monthly scale (Karl et al. 1999; Fortin et al. 2016; Vincent et al. 2005; Marengo et al. 2009; Almeida et al. 2016). The thermal indices allow a better description of the variability and trends of recent extreme conditions that may have an impact on society, affecting, for example, health, agriculture, and water resources.

Monteiro and Carvalho (2013) point out that projection of climate change for the twenty-first century shows an increase in the frequency and intensity of extreme climatic events of heat, but a reduction in the occurrence of extreme cold episodes for Europe. Vincent et al. (2005) claim that in the past 40 years, the frequency of cold days has declined in northern China as well as the number of hot days in the east has declined. In addition, since 1961, the frequency of hot days and nights has increased in Australia and New Zealand, while the frequency of extreme cold days and nights has decreased. In the period between 1910 and 1998, in the USA, the number of frozen days decreased, and a slight downward trend was also observed in the frequency of days with maximum temperature above the 90th percentile. While in southern Canada, the data show increasing trends in percentiles 5 and 95 of the minimum and maximum daily temperatures between 1900 and 1998. Marengo and

Camargo (2008) analyzed the trends of minimum and maximum air temperature and the diurnal thermal range (DTR) for southern Brazil from 1960 to 2002. A significant increase in nighttime temperatures (represented by the minimum temperature) compared to the smaller increases in daytime temperatures (represented by maximum temperature) was observed during the year and over the seasons in most of the weather stations studied. It has been found that warming trends are stronger during the winter compared to summer. Consequently, the annual and seasonal negative DTR trends observed in southern Brazil over the past 40 years are largely due to the greater increase in nighttime temperatures rather than daytime temperatures.

Mendonça (2006, 2014) points out that, in general terms, it is estimated that in the last 40 years, the average temperature in the southern region of Brazil has increased by about 1.3 °C, which would have been accompanied by an increase in average rainfall annual reports. However, this intensification of regional warming has been more pronounced in the northern part of the southern region of Brazil, as for example in the northern part of the state of Paraná where the tropical climate, without drought, dominates. In the last decades, it is verified a reinforcement of the tropical conditions through less cold winters and more concentrated rains in this region. Ely and Dubreuil (2014) analyzed the interannual variability of temperatures and precipitation on the southern part of the Paranapanema River basin, located in the state of Paraná, in order to identify a possible climatic variation. Daily temperature

and precipitation data were considered for the period from 1979 to 2010, submitted to the statistical tests of the linear regression, Mann-Kendall, and Pettitt, which indicated tendency to increase temperatures generally in the analyzed area. However, the results of the mentioned studies are based on the calculation of the maximum and minimum average temperatures for the annual and monthly cuts, not considering the daily thermal evolution and, therefore, justifying the development of the presented analysis.

Thus, the main objective of this study is to evaluate the frequency and trends of extreme temperatures from 1971 to 2014, applying ten thermal indices to ten meteorological stations located in distinct regions (north and east, Fig. 1). According to Marengo and Camargo (2008), in a region that depends heavily on agricultural production, changes in the frequency and intensity of extreme temperatures are important for ecosystem and societal responses.

2 Data and methods

The meteorological stations considered in this study are part of two distinct collection networks—National Institute of Meteorology (INMET) and Agricultural Institute of Paraná (IAPAR). Table 1 shows the historical averages (1971 to 2014) calculated for each station. The climatic normals from the INMET network for average temperatures during the reference period from 1961 to 1990 are 20.5 °C at Campo Mourão, 21.1 °C at Londrina, 16.8 °C at Curitiba, and 21.2 °C at Paranaguá while IAPAR does not have the climatic temperature normals for its network of stations.

The orography and flow orientation of the river systems (Fig. 1) delimit varying natural landscapes in Paraná and contribute to regional climate being characterized differently. For

Table 1 Thermal normals (annual average values) from 1971 to 2014 and weather types of meteorological stations used in this study

Meteorological stations	T_{\max} (°C)	T_{mean} (°C)	T_{\min} (°C)	Köppen climatic types
Curitiba	23.4	17.3	13.2	Cfb
Lapa	23.1	17.0	13.1	Cfb
Morretes	26.2	20.7	17.3	Cfa
Guaraqueçaba	26.2	20.8	17.3	Cfa
Paranaguá	26.0	21.4	18.0	Cfa
Bela Vista do Paraíso	27.1	21.3	17.0	Cfa
Londrina	28.0	22.9	16.2	Cfa
LondrinaIAPAR	27.3	21.0	16.0	Cfa
Campo Mourão	26.9	20.4	15.1	Cfa
Umuarama	27.8	22.1	17.8	Cfa

example, Lapa and Curitiba stations generally have relatively low average temperatures (Table 1), the result of the dominant influence of cold-air systems (Atlantic polar air mass and cold fronts); while stations located further inland have higher average values due to the presence of hot and humid air systems (equatorial and tropical continental air masses and Atlantic tropical air mass).

Monteiro and Carvalho (2013) emphasize that many papers have been dedicated to investigate ways to evaluate the frequency, duration, and intensity of extreme events through the use of indices. The calculation of such indices varies and can be classified into simple or relative climatic indices and bioclimatic indices.

“Climate indices are usually based on the isolated use of climate elements, aiming to understand the variability, climatic rhythms and exceptional events” (Monteiro and Carvalho 2013, p 118). In this paper, frequency and trends of extreme temperatures will be evaluated through the use of ten thermal indices (Table 2).

According to Fortin et al. (2016), the recent warming observed on a global scale may be difficult to detect on a regional or local scale, especially where geographical features (mountains) or large bodies of water are located nearby. Other considerations could also affect the ability to detect climate trends at regional or local scales, for example, if the meteorological network is scarce over the territory or if stations relocation or instrument replacement happens, or when the time series is too short (less than 30 years) or incomplete (more than 20% of missing data). The countryside of Paraná was developed by the implantation of agricultural activities in the 1930s, and thereafter it was only in the 1970s that an official network was established for collection of meteorological data. Nevertheless, about ten stations cover a period of more than 30 years and they have few missing data.

The data used for this study come from IAPAR and INMET, which have daily data of maximum and minimum temperatures for more than 30 years (the duration varies according to the stations). The Paraná state has other climate data networks, such as the Brazilian Agricultural Research Corporation (EMBRAPA) and the Technological Institute SIMEPAR. As our study aims to analyze trends over at least 30 years, we chose not to use EMBRAPA and SIMEPAR data since their series began only in the 1990s. But some author as Alvares et al. (2017) integrated the IAPAR, SIMEPAR, and INMET data with the networks of other states to analyze the frost days climatology in the Center-South of Brazil considering at least 18 consecutive years of data from 1961 to 2014, and this is sufficient to ensure adequate climate modeling and reach their research objectives.

Thermal data from ten stations (Fig. 1 and Table 3) were located in two distinct regions: five in the north of the state, where the characteristics of the tropical climate of central Brazil predominate, with a mean temperature in the coldest

Table 2 Description of the thermal indices used in the present study (TX and TN are daily maximum and minimum temperature, respectively)

Element	Index	Indicator name	Definitions	Units
TX	SU25, SU30, SU35	Summer days	Annual count when TX (daily maximum) > 25 °C; > 30 °C; > 35 °C	Days
	WSDI	Warm spell duration indicator	Annual count of days with at least 6 consecutive days when TX > 90th percentile	Days
	TXx	Maximum temperature	Maximum daily value recorded in a month	°C
	TX95t	Very warm day threshold	Value of 95th percentile of TX	°C
TN	FD	Frost days	Annual count when TN (daily minimum) < 0 °C	Days
	CSDI2, CSDI6	Cold spell duration indicator	Annual count of days with at least 2 (CSDI2) or 6 (CSDI6) consecutive days when TN < 10th percentile	Days
	TNn	Minimum temperature	Minimum daily value recorded in a month	°C
Both	DTR	Diurnal temperature range	Monthly mean difference between TX and TN	°C

month below 18 °C and in the hottest month hotter than 22 °C, with no defined dry season. The other five stations in the east and coast, where the humid subtropical climate prevails with cool or cold winter.

The next step of the analysis consists in making a quality control of the data, and then fill in the missing data in the time series. Two methods were tested, first the approach of the nearest neighbor and the NIPALS (Non Linear Iterative Partial Least Squares) method (Wold 1973). The NIPALS method was applied to the data set, which is in fact a principal component analysis (PCA) model that is obtained and used to calculate the missing values. We only keep stations with less than 20% missing data (Table 3) for our analyses.

The homogenization of the data was performed using the software RHtestsV4 (Wang and Feng 2013) to detect the problems of data homogeneity. The main objective of this quality control procedure is to identify outliers that are data-processing errors, such as errors introduced by users or

relations among stations. The series values were checked to see if they were outside a defined range of values that corresponds to four standard deviations from the daily average values. If values exceeded these thresholds, they were identified as erroneous and checked manually by the authors on a case-by-case basis. In most cases, we corrected these values, but in a few instances, we considered them to be plausible extreme values and kept them. Where it was necessary, adjustments were made, for example, when we detected a jump in time series caused by station relocation rather than by climatic variation. The model used is based on the maximum penalized t and the F tests (Wang et al. 2007; Wang 2008a), which are integrated into a recursive test algorithm (Wang 2008b). To calculate the adjustments on the series, RHtestsV4 uses a QM (quantile-matching) algorithm (Fortin et al. 2016).

Once the data quality control was completed, the climatic indices were calculated from the modified series using the ClimPACT software (similar to RClmDex which was

Table 3 Geographical coordinates of stations used and proportion of missing

Stations (code)	Latitude S	Longitude W	Altitude (m)	Missing data (%)	
				Tmax	Tmin
Bela Vista do Paraíso (2251027)	-22.57	-51.12	600	2.9	2.9
Londrina (2351003)	-23.22	-51.10	585	11.6	11.6
Londrina (83766)	-23.31	-51.10	566	16.3	15.0
Campo Mourão (83783)	-24.05	-52.36	616	10.1	3.7
Umuarama (2353008)	-23.44	-53.17	480	3.8	3.8
Morretes (2548038)	-25.30	-48.49	59	-	-
Lapa (2549091)	-25.47	-49.46	910	17.8	17.8
Curitiba (83842)	-25.43	-49.26	923	5.8	5.8
Paranaguá (83844)	-25.53	-48.51	4.5	21.3*	10.1
Guaraqueçaba (2548039)	-26.16	-48.51	40	16.2	16.2

*The Paranaguá station is an exception, as it has more than 20% of missing data and we consider it in our analyses so that we could have the same number of stations in the north and east of the state with a long series of data

Table 4 Trends in indices calculated for temperatures

Indices	BVParaiso	Londrina IAPAR	Londrina	CMourão	Umuarama	Morretes	Lapa	Curitiba	Paranaguá	Guaraqueçaba
SU25	<i>0.22</i>	0.18	<i>0.33</i>	0.00	<i>0.39</i>	0.07	<i>0.24</i>	<i>0.30</i>	0.10	-0.15
SU30	<i>0.35</i>	<i>0.29</i>	<i>0.45</i>	0.05	<i>0.58</i>	0.16	-0.06	0.11	0.08	-0.06
SU35	<i>0.38</i>	<i>0.29</i>	<i>0.32</i>	0.08	<i>0.42</i>	0.13	-0.26	-0.05	-0.08	0.16
WSDI	0.13	0.01	0.16	0.03	<i>0.37</i>	<i>0.20</i>	0.05	0.18	0.06	-0.22
TXx	<i>0.34</i>	<i>0.32</i>	<i>0.26</i>	0.11	<i>0.36</i>	0.06	-0.36	0.05	-0.03	0.15
TX95t	0.15	0.15	<i>0.54</i>	0.12	0.09	-0.12	-0.03	-0.01	-0.18	-0.15
FD	-0.08	-0.17	-0.18	-0.05	-0.05	-0.34	-0.07	-0.43	-0.21	-0.15
CSDI2	-0.31	-0.41	-0.24	0.07	-0.37	-0.53	-0.04	-0.56	-0.52	-0.35
CSDI6	-0.29	-0.28	0.01	<i>0.27</i>	-0.21	-0.45	-0.08	-0.37	-0.37	-0.20
TNn	<i>0.20</i>	0.17	<i>0.20</i>	0.00	0.14	<i>0.34</i>	-0.01	<i>0.41</i>	0.25	0.11
DTR	<i>0.29</i>	<i>0.26</i>	<i>0.38</i>	0.17	<i>0.53</i>	0.12	0.10	<i>0.44</i>	0.16	0.11

The values in italic indicate the occurrence of trends (positive, not null, or negative) for a level of significance $\alpha = 0.05$

developed by the team of experts for the detection of climate change). Indices are based on various thresholds to calculate the frequency, intensity, and duration of thermal extremes from the daily data series (Table 2).

The final step was to calculate trends on the series of indices for the entire study period. For trend analysis, we used the

non-parametric Mann-Kendall or MK test (Mann 1945; Kendall 1975). The MK test allowed us to calculate the τ (tau) which varies between -1 and +1 in our study (or between -4 and +4 according to Sneyers 1990), where the positive values indicate an upward trend and negative values, a downward trend (Almeida et al. 2016).

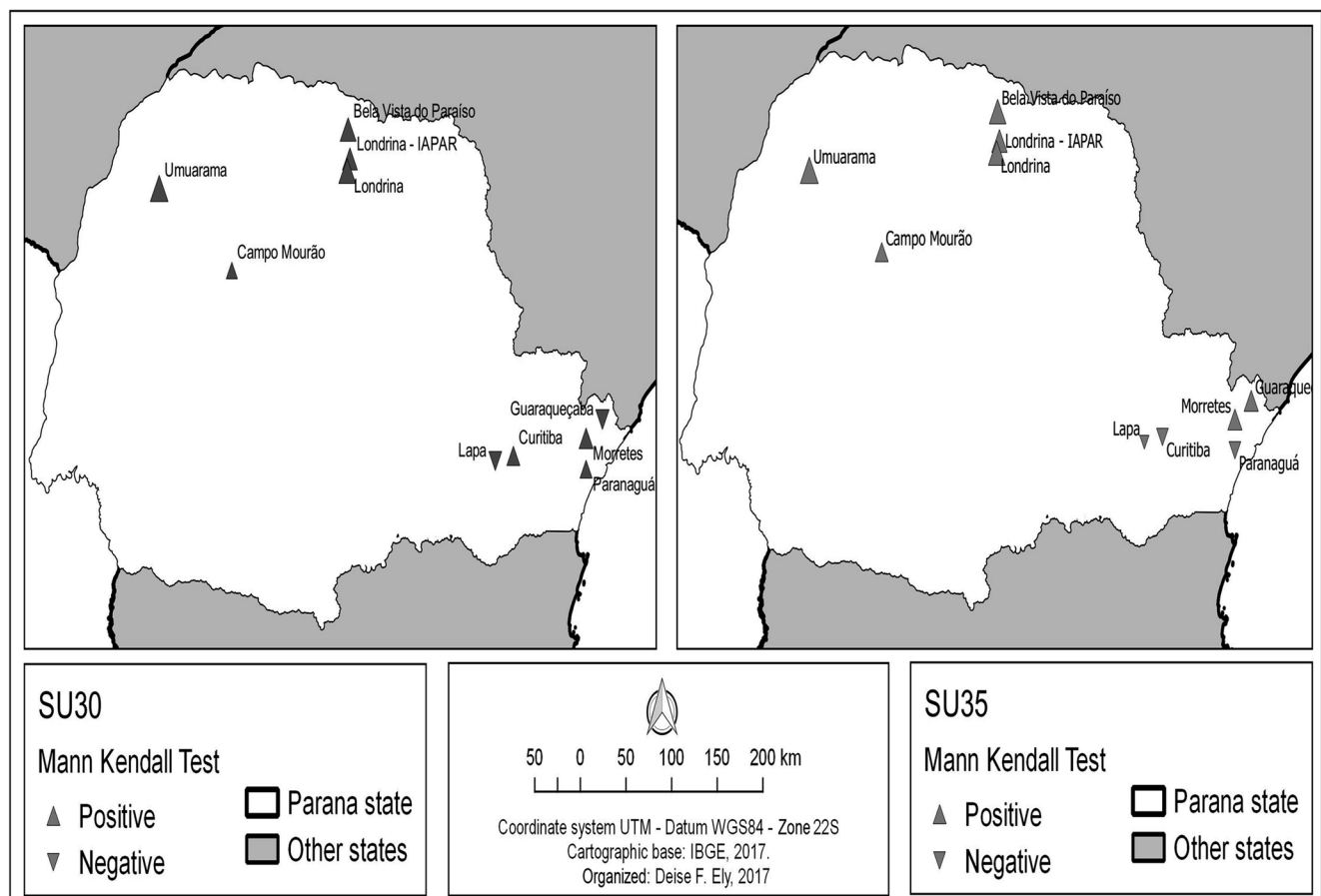


Fig. 2 Trends calculated for the number of days with temperatures over 30 and 35 °C

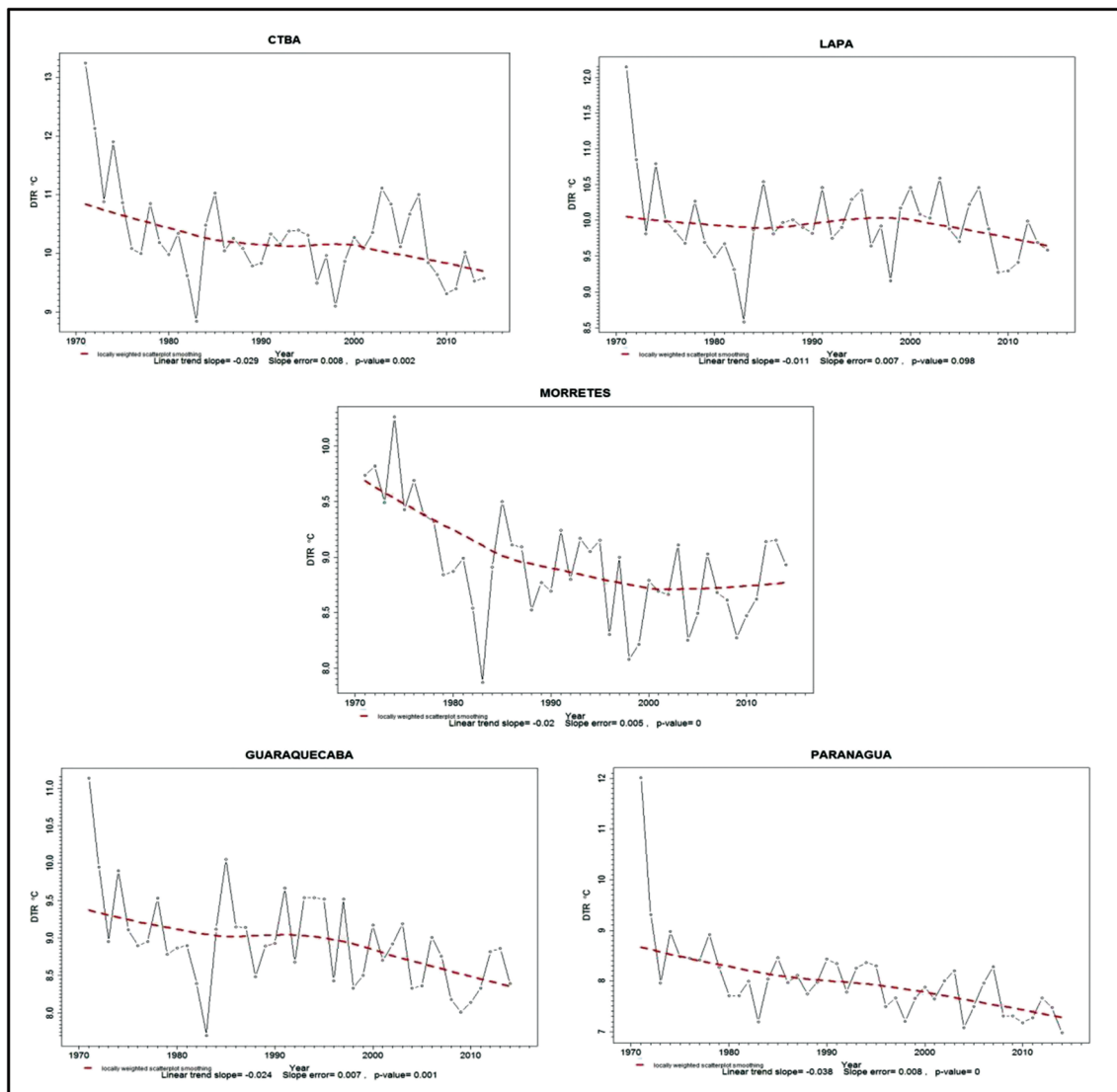


Fig. 3 Trends of the diurnal temperature range (DTR) for the eastern stations

3 Results and discussion

Trend analysis of air temperature data from the University of Delaware (available on the CDC/NOAA website) shows an increase in temperature and confirms the presence of a temperature gradient over the Paraná, ranging from 25 °C in the north to 15 °C in the eastern part of the state. It is possible to identify positive anomalies (0.1) only in the west and negative anomalies only in the east (0.1), which coincides with significant positive trends in extreme temperatures that were observed along the coasts of South America, as identified by Vincent et al. (2005). Moreover, no significant trend was detected in the interior of the continent. This lack of a significant trend underlines the need for more work on the continent, especially at a finer scale.

Geographical location of each station helps us to distinguish certain similarities between the stations situated in the northern part and those in the eastern part of the state; we will come back to this later. Another finding is that no station has significant trends for all the indices, which is not surprising because of the large variability of the thresholds used to calculate them. Nevertheless, these two general observations highlight the climatic disparity that exists between certain stations (as presented in Table 4).

For thermal indices calculated from maximum temperatures, we found that summer days (SU25) show a significant increase for five stations analyzed but no significant increase for the other stations. In addition, a slight decrease for the Guaraqueçaba station was observed (−0.15) but it is not statistically significant. For the SU30 and SU35 indices, the results are more or less similar especially for the northern

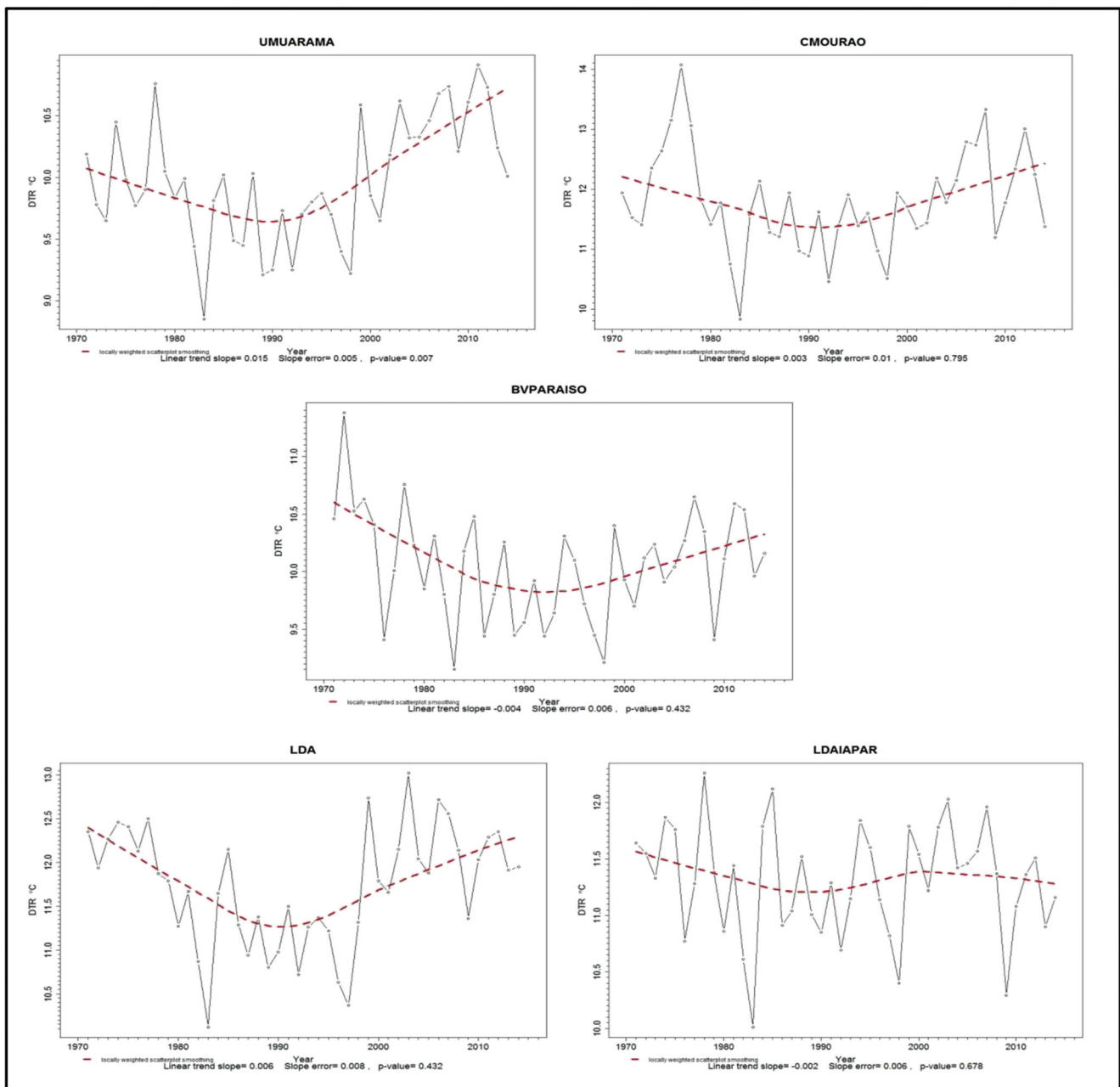


Fig. 4 Trends of the diurnal temperature range (DTR) for the northern stations

stations (BVParaiso, Londrina IAPAR, and Londrina) where a significant increase in the number of days with temperature above 30 °C (SU30) and 35 °C (SU35) was observed over the study period (as shown in Fig. 2).

The warm spell duration indicator (WSDI), which considers the annual count of 6 consecutive days in which the maximum temperature is above the 90th percentile, presents a significant increase in Umuarama and Morretes stations but a reduction in Guaraqueçaba. The maximum temperature daily value recorded on a monthly basis (TXx) shows a statistically significant increase for the Bela Vista do Paraíso, LondrinaIAPAR, Londrina, and

Umuarama stations. On the other hand, the Paranaguá and Lapa stations show decreasing trends over the study period (Table 4). For the threshold of very warm days (TX95t), only Londrina recorded a statistically significant increase, whereas the other stations show no change over the same period. Stations located either to the east or near the coast recorded a slight decreasing trend.

For the indices that use the minimum temperatures (TN) rather than the maximum temperatures (TX), our observations do not present very polarized trends either. Alvares et al. (2017) developed a model of the number of frost days to better characterize the spatial and

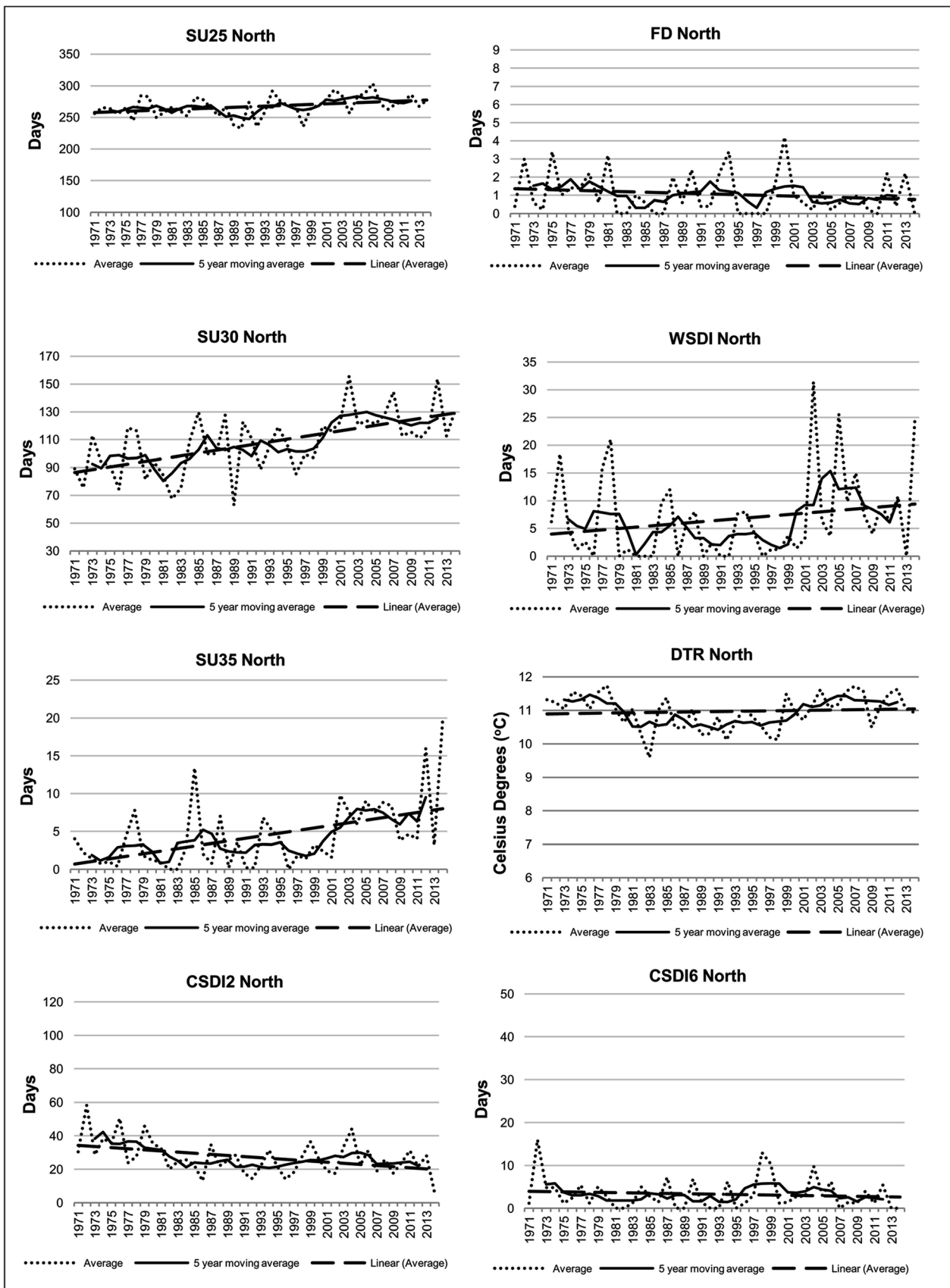


Fig. 5 Regional indices calculated based on the average values from the northern stations

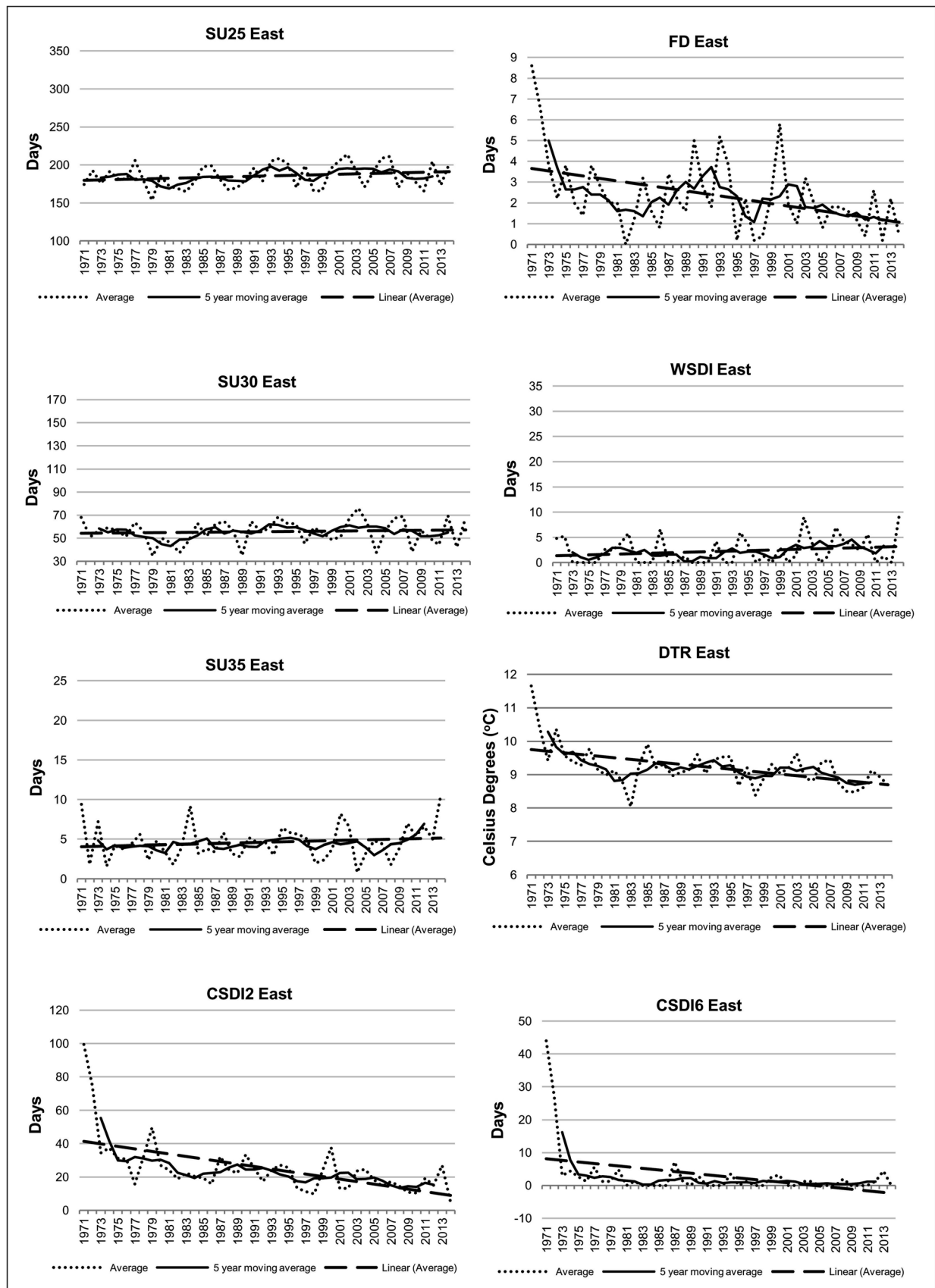


Fig. 6 Regional indices calculated based on the average values from the eastern stations

Table 5 Regional trends for the regional indices (RI)

RI	FD	CSDI2	CSDI6	DTR	SU25	SU30	SU35	WSDI
North	-0.104	-0.273	-0.058	0.059	0.275	0.404	0.324	0.173
East	-0.289	-0.462	-0.321	-0.372	0.116	0.066	0.121	0.144

The level of significance $\alpha = 0.05$.

temporal variability of frost days in south-central Brazil. Their results show a wide range of freeze events over the entire study area which could be affected by mid-fall (April) and mid-spring (October) frosts. Outside of these periods, the area is free of frost. In our study, the frost days index indicates a reduction for all stations, but with a more pronounced trend for the Morretes, Curitiba, and Paranaguá.

The cold spell duration indicator for 2 days (CSDI2) registers a significant reduction for most stations except for Campo Mourão and Lapa. The other cold spell indicator, which considers 6 consecutive days (CSDI6) when the minimum temperature reached the 10th percentile, also shows a significant decrease for most stations except for Londrina and Lapa (Table 4). In addition, Campo Mourão station is the only one that shows a positive trend for the CSDI6 in opposition to all the others. Finally, the minimum daily temperature recorded in a month (TNn) increased in the stations analyzed except for Lapa, where a very weak reduction occurs and this is not significant statistically.

Finally, the diurnal temperature range (DTR), which represents the difference between TX and TN, tends to increase in the analyzed stations, but only Umuarama, Campo Mourão, Bela Vista do Paraíso e Londrina, and Curitiba stations showed significant increases according to the Mann-Kendall test (Table 4). The results of the linear trend calculated by ClimPACT, however, show different tendencies between the stations located east (Fig. 3) and north (Fig. 4) of Paraná. In the east, the stations show a decrease in the DTR index while in the north, (Umuarama and Londrina) an increase of about 0.7 °C was occurred after the years 2000.

In accordance with Fortin et al. (2016), a regional index (RI) was generated for the northern (Fig. 5) and eastern (Fig. 6) part of the state by calculating the average value of each index for both regions. The RI for the northern region shows that for cold indicators (FD, CSDI6), a great inter-annual variability without any clear trend over the entire study period. In addition, the CSDI2 seems rather to indicate a slight decrease of the cold spell on 2 consecutive days.

In the eastern region, there is a more significant decrease for the DTR, FD, CSDI2, and CSDI6 indices when it compared to the northern region of Paraná. In addition, the indices related to the TX (SU25, SU30,

SU35, and WSDI) rather show a more significant increase for the northern region. Our results seems to indicate that WSDI increase of about 1.26% per decade while the CSDI2 and CSDI6 decrease respectively of 3.35% per decade and 0.32% per decade.

Thereafter, the regional trend of the indices for the north and east regions was also calculated using the Mann-Kendall statistic (Table 5), which confirms the results, i.e., a more pronounced reduction in the cold indices in the east, mainly the reduction of the amplitude between the TX and the TN (DTR), and more marked increase of the warm indices in the north of the state.

4 Conclusions

Our study provides an overview of the trends observed for the periods 1971 to 2014 for ten stations which are grouped mainly in two regions in the state of Paraná, inserted on the context of the climatic transition zone in southern Brazil. Our results suggest a more pronounced increase for indices including maximum temperatures (TX) especially in the northern part of the state, while indices based on minimum temperatures (TN) show a more modest and partial increase that varies according to the location of the stations.

A reduction in the number of cold days is observed in most the analyzed stations, a fact that corroborates the results of Monteiro and Carvalho (2013) and shows evidence of a warmer climate in the state of Paraná since the 1970s. Another element pointing toward this direction is the increase of the monthly difference between the diurnal temperatures range (DTR) in all the stations, which means an increase of the thermal amplitudes that is reflected by an intensification of the thermal extremes, similar to those detected by Marengo and Camargo (2008) for all of southern Brazil and that can severely impacted different economic sectors but especially agriculture. This trend may, however, seem surprising at first glance since it contradicts the global trend (Alexander et al. 2006), which seems to indicate a decrease in temperature differences between TX and TN (DTR). On the other hand, climate variability at the regional and local scales is subject to different climatic factors (frontal situation, topography, and so on) that can result in climatic responses more or less different from what is observed at the global scale.

In spatial terms, the Lapa station, located in the eastern region at an elevation of 910 m, shows a stronger reduction of the indices of thermal extremes, especially TNn and TXx. The Curitiba station, at an altitude of 923 m, shows a decrease in the cold indices, except TNn, DTR, and SU25, an effect that is perhaps related to urbanization and its reduction in the amplitude of extreme temperature variations.

In general, when analyzing thermal extreme trends in transient climate zones, the northern region is characterized by a predominant tropical climate with a more significant increase in maximum temperature indices. While in the east, a reduction predominates. Our results indicate that WSDI increase of about 1.26% per decade while the CSDI2 and CSDI6 decrease respectively of 3.35% per decade and 0.32% per decade. Our results are in agreement with other research elsewhere around the world that found similar trends at a regional scale, for example, in China (Wang et al. 2017), South America (Vincent et al. 2005), Canada (Fortin et al. 2016), or Brazil (Marengo and Camargo 2008). With global warming, increases in maximum temperatures are generally smaller than increases in minimum temperatures, at least at a regional scale. Our study confirms this observation for the state of Paraná.

The next step will be to analyze the rainfall indices which should allow us to understand the extent of recent changes in this region and to determine whether trends for precipitation can be detected or not. However, it is well known that most of the precipitation indices are usually much less coherent than temperatures (Alexander et al. 2006). Nevertheless, a recent study made by Zandonadi et al. (2016) has found a significant increase in the total precipitation, in which extreme precipitation was found as an important index for most of the stations located in the Paraná River Basin.

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