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Trends in convective parameters in southern Brazil: a preliminary analysis

Tendências de parâmetros convectivos no sul do Brasil: uma análise preliminar

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ABSTRACT

This study is a preliminary investigation, for southern Brazil, about possible changes in the last four decades in the magnitude of two convective parameters indicative of atmospheric environments favorable to severe convective storms. The parameters selected for this research, the convective available potential energy (CAPE), and the magnitude of the vector wind difference between the surface and 6 km above ground level (DLS), are, respectively, indicative of the presence of conditional instability and vertical wind shear in a deep layer. These parameters were computed for hourly tropospheric profiles (or pseudo-soundings) extracted from the native vertical grid of the ERA5 reanalysis for the period between 1980 and 2021 for the grid points nearest to the three state capitals of southern Brazil: Curitiba, Florianópolis and Porto Alegre. The analysis, for each location, of the trend in the time series of CAPE and DLS, averaged for every single month, was carried out with the aid of the non-parametric Mann-Kendall test. The results obtained from the tropospheric profiles of the ERA5 reanalysis reveal a negative trend in the extreme values of CAPE, especially for Porto Alegre, but accompanied by an increase in the magnitude of DLS for all locations. Therefore, in this preliminary analysis, the implications from CAPE and DLS for the conditioning of environments favorable to severe storms display opposite signs for the selected locations. Additional research addressing the frequency of environments conducive to severe storms is needed for a more complete assessment of the impact of these trends.

Keywords: Convective parameters, Southern Brazil, Trends, Severe storm environments

RESUMO

Este estudo é uma investigação preliminar, para o sul do Brasil, acerca de possíveis alterações nas últimas quatro décadas na magnitude de dois parâmetros convectivos indicativos de ambientes atmosféricos favoráveis a tempestades severas. Os parâmetros selecionados para esta pesquisa, a energia potencial convectiva disponível (CAPE), e a magnitude da diferença vetorial do vento entre a superfície e 6 km de altura (DLS), são, respectivamente, indicativos da presença de instabilidade condicional e de cisalhamento vertical do vento em uma camada profunda. Para o cálculo destes parâmetros, foram utilizados perfis troposféricos (ou pseudo-sondagens) horários extraídos da grade vertical nativa da reanálise ERA5 para o período entre 1980 e 2021 para os pontos de grade mais próximos das três capitais do sul do Brasil: Curitiba, Florianópolis e Porto Alegre. A análise, para estas localidades, da tendência nas séries temporais das médias de CAPE e DLS para cada período de 1 mês foi realizada com o auxílio do teste não-paramétrico de Mann-Kendall. Os resultados obtidos a partir dos perfis troposféricos da reanálise ERA5 revelam uma tendência de redução nos valores extremos de CAPE, especialmente em Porto Alegre, mas acompanhada de um aumento na magnitude de DLS para todas as localidades. Portanto, nesta análise preliminar, as implicações advindas de CAPE e DLS para o condicionamento de ambientes favoráveis a tempestades severas apresentam sinais opostos para as localidades selecionadas. Pesquisas adicionais sobre a frequência de ambientes propícios a tempestades severas são necessárias para uma avaliação mais completa sobre o impacto dessas tendências.

Palavras-chave: Parâmetros convectivos, Sul do Brasil, Tendências, Ambientes de tempestades severas

1 INTRODUCTION

Convective storms are responsible for a considerable portion of rainfall observed in southern Brazil, but in their extreme manifestation (known as severe storms), convective storms also can produce large hail, tornadoes, and damaging winds, all of which representing threats to life, property, and ecosystems. Nevertheless, it remains mostly unclear whether changes in the frequency with which the atmospheric environments conducive to severe convective storms have been observed over southern Brazil in the past decades.

The main atmospheric ingredients characterizing severe storm environments include conditional instability (as indicated, for example, by the convective available potential energy, CAPE) and moderate to strong vertical wind shear in a deep layer (DLS) (Doswell III et al., 1996). An additional ingredient is convective initiation, when a lifting mechanism at low levels promotes the necessary ascent for the air parcels to reach their level of free convection. Hence, when only conditional instability and DLS are analyzed in the context of severe deep convection, then the environments are only identified as being potentially favorable (or conducive) to severe storms.

In the past decades, a substantial increase in the global mean temperature has been observed, predominantly attributed to the progressive amplification of anthropogenic greenhouse gas emissions (Intergovernmental Panel on Climate Change (IPCC) 2023). As informed by the Clausius–Clapeyron equation, an increase in temperature also incresases the saturation vapor pressure leading to the potential enhancement in the concentration of atmospheric water vapor. Therefore, conditional instability in deep atmospheric layers may also experience an enhancement in the long term (Riemann-Campe et al., 2009).

In terms of severe convective storms, there has been evidence of regional changes in both their frequency and intensity over the past few decades (Laviola et al., 2022; Pilguj et al., 2022; Pinto Jr et al., 2013; Rädler et al., 2018; Taszarek et al., 2021). These changes are frequently connected to complex regional circulation characteristics, highlighting the importance to develop studies focused on local trends. Associated with the previous discussion about the temperature and moisture relationship, the understanding of how convective environments are affected by global warming suggests that higher levels of low-level moisture (leading to increased CAPE) will create a more favorable atmosphere for the development of severe storms. Nevertheless, there is considerable uncertainty in these projections, as more recent studies suggest a combination of mixed trends (Pilguj et al., 2022; Taszarek et al., 2021).

Given this uncertainty, it becomes important to examine historical changes that have taken place in terms of convective parameters that compose favorable storm environments regionally. The introduction of the global ERA5 reanalysis, which provides hourly resolution and adequate horizontal and vertical grid spacing to capture local-scale convective environments, enables the creation of a climatology and the examination of associated trends in a manner that was not feasible with previous reanalyses (Taszarek et al., 2021). Nonetheless, it is crucial cautious when interpreting results derived from reanalyses, considering that each reanalysis has inherent limitations associated with model formulation, applied parameterizations, and assimilation techniques. This is particularly true when examining thermodynamic instability, as systematic errors may be present and can impact the findings (Taszarek et al., 2021; Varga & Breuer, 2021).

Considering the two necessary ingredients to characterize severe weather environments, namely CAPE and deep-layer shear (DLS), this study aims to examine how the magnitude of CAPE and DLS has changed over the last four decades (1980-2021) in three state capitals is southern Brazil: Curitiba, Porto Alegre, and

Florianópolis, with the first two having the highest populations (IBGE, 2022). These cities account for approximately 13% of the total population of southern Brazil. If severe storm environments become more frequent in these densely populated areas, the risk for deflagration of natural disasters will be enhanced; i.e., the vulnerability of the local population would increase.

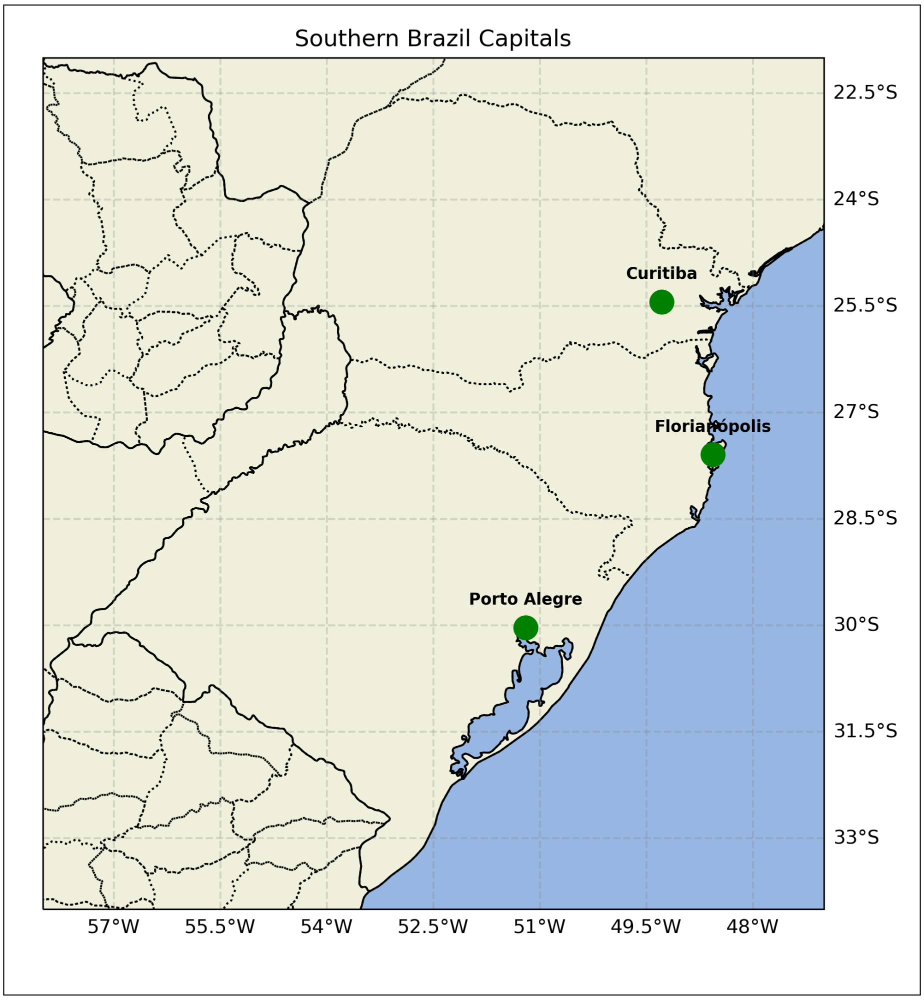
2 DATA AND METHODS

Figure 1 shows a map of the southern Brazil region with the location of the three state capitals: Curitiba, Florianópolis and Porto Alegre, with an elevation of 908m, 5m and 3m, respectively. The domain shown in Figure 1 spans over the region encompassed between 22.5°S and 33.7°S, and 57.6°W and 48.0°W.

ERA5 is the fifth-generation atmospheric reanalysis produced by the European Centre for Medium-Range Weather Forecasts, ECMWF (Hersbach et al., 2020). It has a regular spatial resolution of 0.25° and temporal resolution of 1 hour, with data available on 137 hybrid-sigma vertical levels. The higher vertical resolution at low levels allows a more accurate depiction of vertical gradients of atmospheric variables that influence the characterization of the convective environments. In fact, evaluations conducted by Taszarek et al. (2021) and Varga & Breuer (2021) indicated that ERA5 reanalysis is one of the most effective tools currently available for examining climatologies of convective parameters.

In this study, tropospheric profiles were produced from pressure, temperature, specific humidity, zonal and meridional (u and v) winds on ERA5's native hybrid-sigma vertical coordinates for the grid points closest in space to the selected cities in southern Brazil (Figure 1). The computation of parameters was implemented using the xcape python package (https://github.com/xgcm/xcape). CAPE, mean specific humidity (Qmean), and mean temperature (Tmean) were computed for 100 hPa mixed-layer (ML) whereas bulk vertical wind shear (of u and v) was calculated between 0–6 km (DLS). In order to consider only environments with a minimum amount of energy to develop convection, only parameters occurring in profiles with CAPE greater than zero were taken to account for the percentiles computation and, as a result, in the trend analysis.

Figure 1 – Map showing the location of capitals in southern Brazil



Source: the authors (2023)

To assess trends, we utilized three metrics that depict different extents of the environmental distribution: the 50th (median), 75th (P75), and 95th (P95) percentiles. These intervals were applied to CAPE, DLS, Qmean, and Tmean distribution and were chosen in order to evaluate trends not only for mean values representing convective parameters but for extremes as well. We employed nonparametric statistical methods, namely the Mann-Kendall two-tailed test and Sen's slope estimator, to determine significant trends at a significance level of α = 0.05. The trend analysis was implemented using the Python package "pyMannKendall" (Hussain & Mahmud, 2019). These metrics were selected based on their prevalent utilization in evaluating robust trends within the context of atmospheric sciences (Laviola et al., 2022; Pilguj et al., 2022; Taszarek et al., 2021).

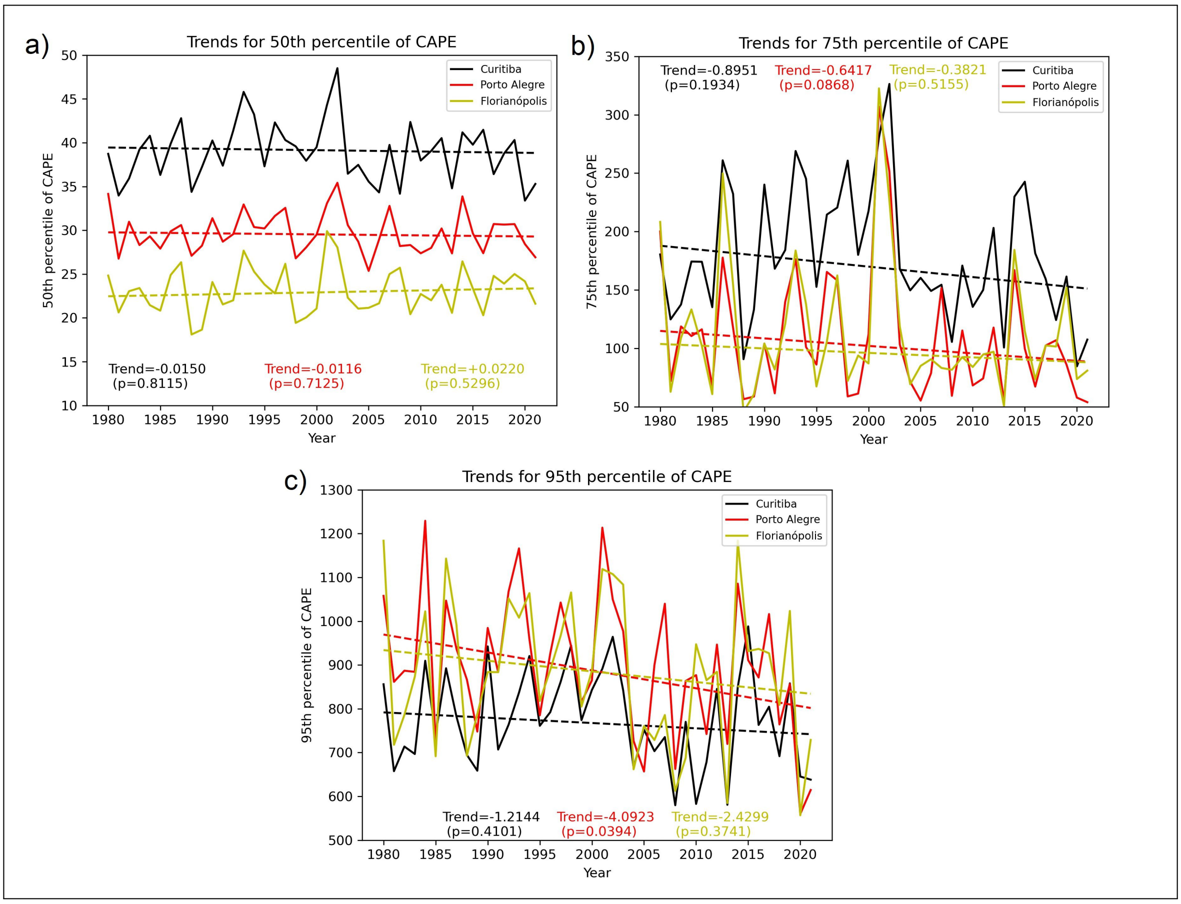
3 RESULTS

3.1 Convective Available Potential Energy

Trend analysis of P95 CAPE over the last 4 decades indicates modest decreases across Curitiba and Florianópolis, but with significant reductions and changes of as much as -4 Jkg^{-1} per year in Porto Alegre (Figure 2c). Modest and mostly insignificant changes occur in P50 and P75 CAPE for all cities, suggesting that the only robust decrease in instability is observed for extreme (P95) values and only in Porto Alegre.

These results are to some extent consistent with what was documented by Taszarek et al. (2021), who assessed severe storm environment trends globally and found that there is considerable variation in the changes of CAPE in mid-latitudes, with relatively modest declines observed over the Southern Hemisphere.

Figure 2 – A 42-year (1980–2021) annual distribution of the (a) 50th percentile and (b) 75th percentile and (c) 95th percentile of CAPE. Trends are indicated as a dashed line. Numbers within linear plots indicate the trend per year and p-value < 0.05 indicates the trend is statistically significant at a confidence level of 95%



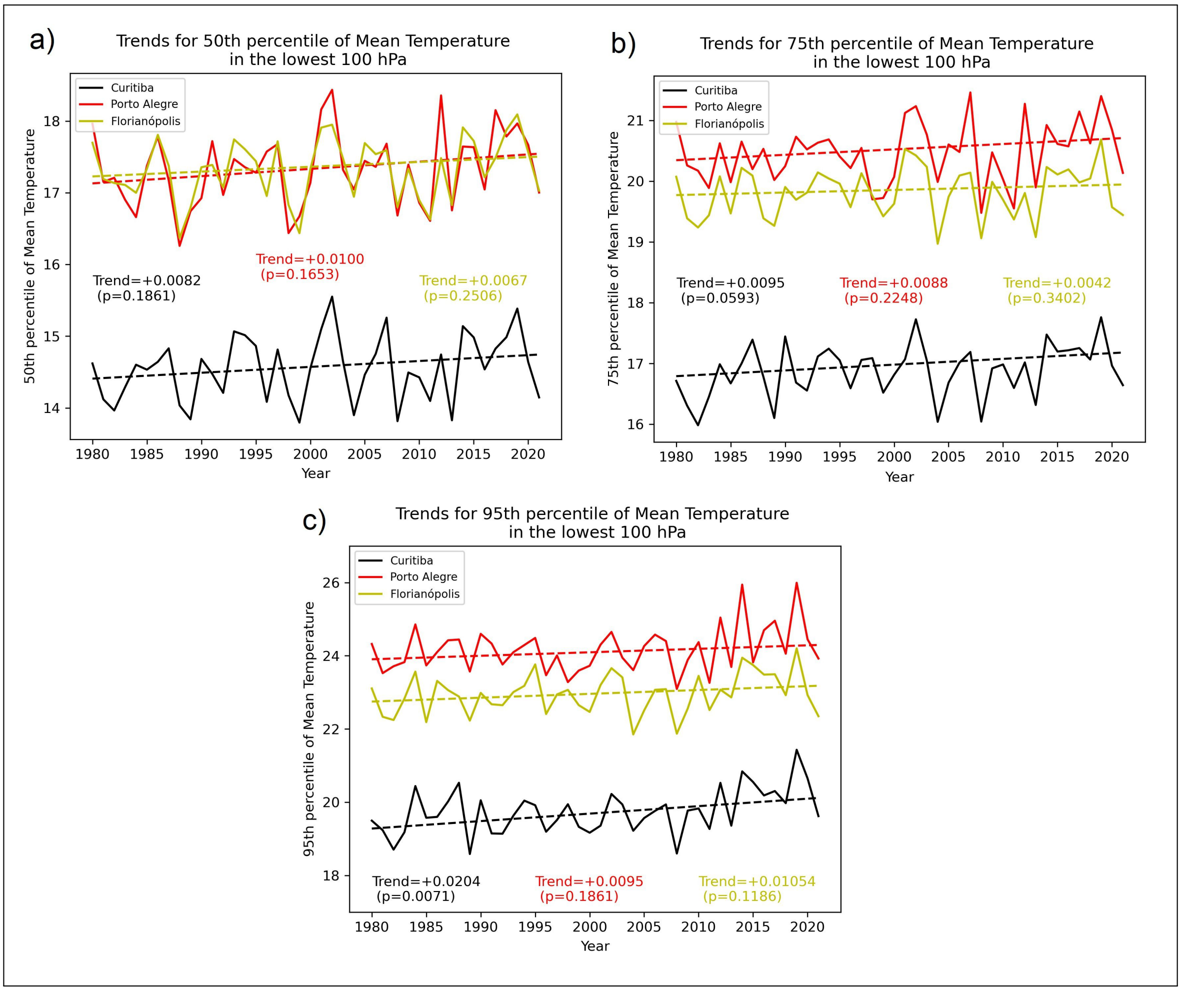
Source: the authors (2023)

3.1.1 Mean Temperature in the lower troposphere

Due to its dependence on temperature and moisture, the observed changes in CAPE can be attributed, in part, to the changes in near-surface temperature and moisture levels, which serve as potential drivers of such variations. In light of this, we additionally examined the trends for Tmean and Qmean.

The P95 of Tmean in Curitiba is significantly increasing over the years, which may be affecting the lower slope of decrease observed in P95 CAPE compared to the other cities (Figure 2c), but it is not sufficient to turn the slope in a positive trend.

Figure 3 – A 42-year (1980–2021) annual distribution of the (a) 50th percentile and (b) 75th percentile and (c) 95th percentile of Tmean. Trends are indicated as a dashed line. Numbers within linear plots indicate the trend per year and p-value < 0.05 indicates the trend is statistically significant at a confidence level of 95%

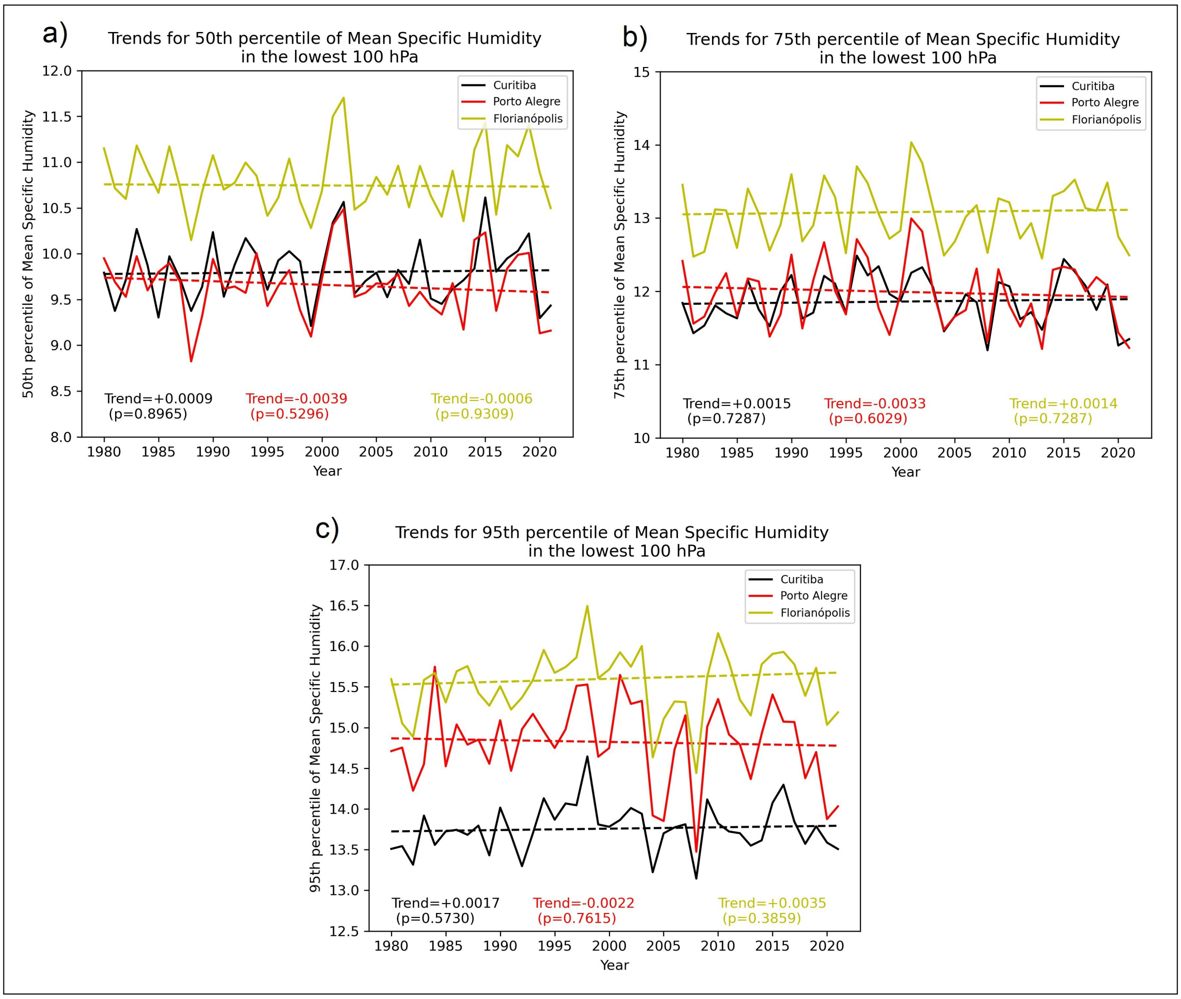


Source: the authors (2023)

3.1.2 Mean Specific Humidity in the lower troposphere

The analysis of trends in the Qmean reveals small positive trends for the three percentiles in Curitiba, contrasting with negative trends observed in Porto Alegre. In the case of Florianópolis, the trends exhibit a mixed pattern, but with minimal magnitude as well. Considering this perspective, it is noteworthy that no trend has achieved statistical significance.

Figure 4 – A 42-year (1980–2021) annual distribution of the (a) 50th percentile and (b) 75th percentile and (c) 95th percentile of Qmean. Trends are indicated as a dashed line. Numbers within linear plots indicate the trend per year and p-value < 0.05 indicates the trend is statistically significant at a confidence level of 95%

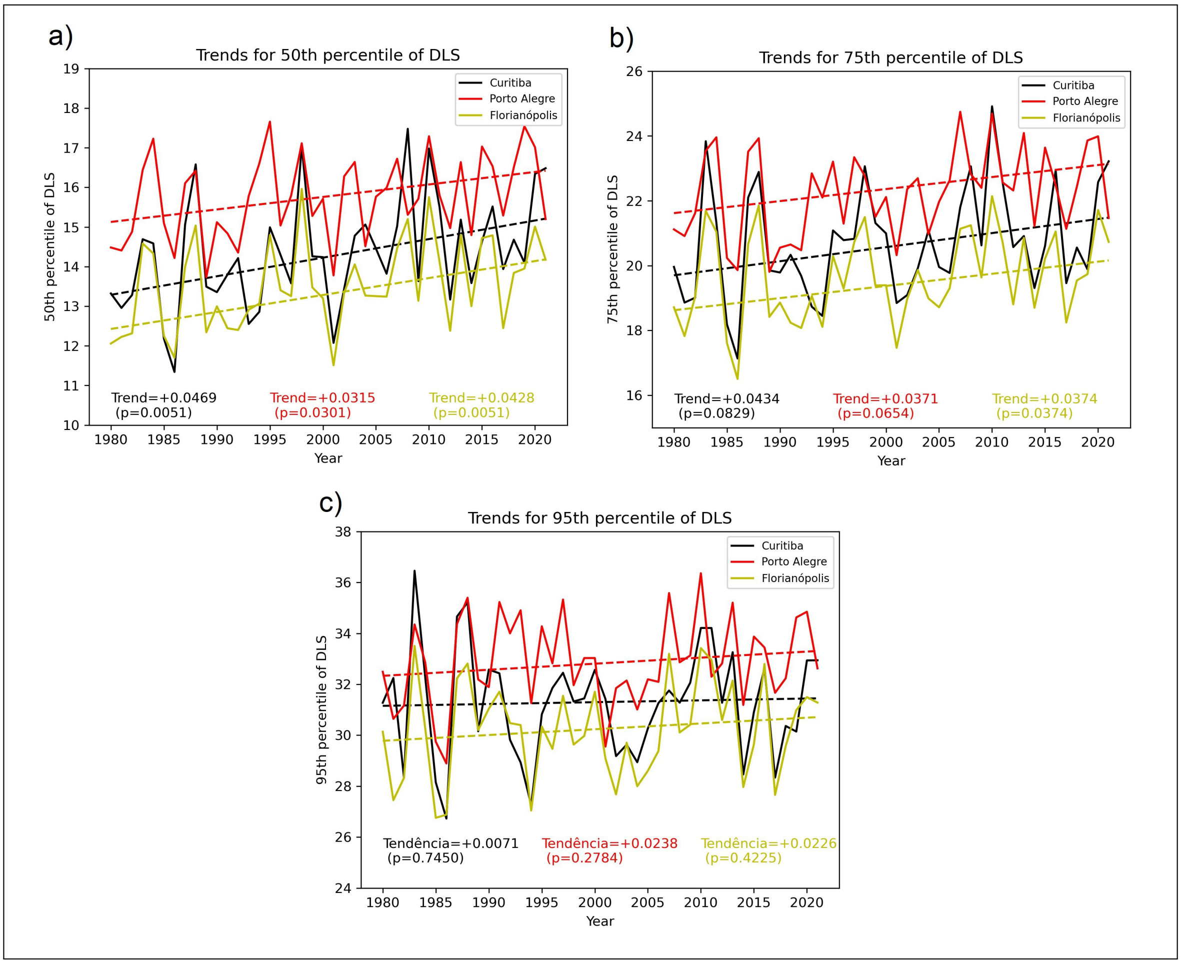


Source: the authors (2023)

The decrease of Qmean in Porto Alegre over the years, especially in P95 Qmean, may be a contributing factor, at least in part, to the significant reduction in CAPE, which depends on the moisture content in the lower troposphere. This suggests that the highest values of moisture in the lower troposphere are decreasing over the years in Porto Alegre and it can be accounting for the decrease in the highest values of CAPE as well.

3.2 Deep-layer Shear

Figure 5 – A 42-year (1980–2021) annual distribution of the (a) 50th percentile and (b) 75th percentile and (c) 95th percentile of DLS. Trends are indicated as a dashed line. Numbers within linear plots indicate the trend per year and p-value < 0.05 indicates the trend is statistically significant at a confidence level of 95%



Source: the authors (2023)

In general, the climatological distribution of DLS is correlated with baroclinic processes driven by thermal wind and, consequently, the position of the jet streams. In light of this, one should expect that the southernmost location would have the greatest value for DLS, whereas the northernmost the lower. This is true for the highest values of DLS observed in Porto Alegre (the southernmost location), but not for the following (Curitiba and then Florianópolis). Despite the latitudinal factor being important for the jet stream position, another aspect that drives the temperature gradient may be likewise playing an important role (e.g., Florianópolis is located on an island, thus the horizontal temperature gradient is influenced by the moderating effect of the surrounding water, which tends to result in a smaller temperature range on the island compared to the larger fluctuations experienced inland).

The long-term trends in the P50 of DLS are of greater significance when compared to those observed for instability, with significant increases in all cities, coinciding with areas with a modest decrease of CAPE. The mean values of DLS (represented by the median in this study) are changing significantly more than the greater percentiles (P75 and P95), suggesting that, although the extreme values of DLS are increasing, the trend is more important for the mean conditions of this parameter.

4 CONCLUSIONS

This preliminary study investigated, for southern Brazil, changes over the past four decades in convective parameters that are often utilized to characterize environments favorable for severe storms. The analysis focused on convective available potential energy (CAPE) and deep-layer shear (DLS), which are crucial for organized deep moist convection. The findings shed some light on the trends in these convective parameters.

Regarding CAPE, the results showed modest decreases in the 95th percentile (P95) across Curitiba and Florianópolis, while the respective P95 for Porto Alegre experienced a significant reduction. These findings align with previous global studies, suggesting relatively modest declines in CAPE over southern Brazil.

The analysis of mean temperature in the lower troposphere revealed a significant increase in P95 in Curitiba over the years, which may be influencing the weaker reduction observed in P95 for CAPE compared with the other two cities. Additionally, the examination of mean specific humidity in the lower troposphere showed small positive trends in Curitiba and mixed patterns in Florianópolis, while Porto Alegre exhibited decreasing trends. The decrease in specific humidity, particularly in extreme values, could contribute to the significant reduction in CAPE in Porto Alegre.

Regarding deep-layer shear (DLS), significant increases were observed in all cities for the 50th percentile, indicating a more pronounced trend for mean DLS values compared to extreme values.

It is important to note that the analysis was based on the ERA5 reanalysis, which has inherent limitations associated with the model formulation and assimilation techniques. However, it offers a continuous dataset in both time and space, featuring a resolution that enables the creation of climatologies in a manner previously unviable with earlier global reanalyses.

Therefore, future studies should continue to explore and refine our understanding of the frequency and characteristics of environments conducive to severe storms in order to comprehensively assess these trends and their implications.

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