PROJECTIONS OF SEVERE WEATHER AND THE IMPACTS ON TRANSMISSION LINE TOWERS IN SANTA CATARINA, BRAZIL, UNDER FUTURE SCENARIOS OF GLOBAL CLIMATE CHANGE

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ABSTRACT

Transmission line towers are highly exposed to weather hazards. In southern Brazil, several damages to transmission lines have been reported due to severe weather events. Climate change projections indicate that the frequency and magnitude of extreme events may increase, making planning and adaptation of the transmission system exposure even more critical. In this work, we propose a severe weather index (SWI) as a proxy for detecting severe storms that can potentially result in extreme weather events. The SWI combines thresholds of instability indices based on observed severe events around the transmission tower-line systems. These indices were calculated using the downscaling by the Eta model at 20 km resolution of three global climate model projections and at 5 km of one global climate model for the historical period and the near future. The results show that the SWI captures the severe storms observed in the region. All downscaling projections agree with the increase of extreme weather events in the near future and the expansion of vulnerable areas. The constructed index can be employed to assess the risks and to plan the power transmission system better.

Keywords: Energy sector; Regional climate change; Eta Model; Instability indices.

RESUMO

PROJEÇÕES DE TEMPO SEVERO E IMPACTOS EM TORRES DE LINHAS DE TRANSMISSÃO EM SANTA CATARINA, BRASIL, SOB CENÁRIOS FUTUROS DE MUDANÇAS CLIMÁTICAS GLOBAIS. As torres de linhas de transmissão estão altamente expostas aos riscos climáticos. No sul do Brasil, vários danos às linhas de transmissão foram relatados devido a eventos de tempo severo. As projeções relativas às mudanças climáticas indicam que a frequência e a magnitude dos eventos severos podem aumentar, tornando o planejamento e a adaptação do sistema de transmissão ainda mais críticos. Neste trabalho, propomos um índice de clima severo (SWI) para detectar tempestades severas que podem potencialmente resultar em eventos climáticos extremos. O SWI combina limites de índices de instabilidade baseados em eventos severos observados em torno dos sistemas de torres de transmissão. Estes índices foram calculados a partir da redução de escala (“downscalling”) do modelo Eta com resolução de 20 km a partir de três projeções do modelo climático global, e do modelo Eta com resolução de 5 km a partir de um modelo climático global, para o período histórico e futuro. Os resultados mostram que o SWI capta as fortes tempestades observadas na região. Todas as projeções concordam com o aumento de eventos climáticos extremos num futuro próximo e com a expansão de áreas vulneráveis. O índice construído pode ser utilizado para avaliar os riscos e planejar melhor o sistema de transmissão de energia.

Palavras-chave: Setor energético; Mudanças climáticas regionais; Modelo Eta; Índices de instabilidade.

1 INTRODUCTION

Severe storms are mesoscale convective systems (MCS) capable of generating large-size hail, whirlwinds with intense destructive force, or tornadoes (NASCIMENTO 2005). Insurance-based trends indicate an increase in damage to buildings, vehicles, and agriculture associated with increasing numbers of MCS-favorable weather patterns (ECCEL et al. 2012, KAPSCH et al. 2012, SANDER et al. 2013, BOTZEN & BOUWER 2016, HOEPPE 2016). Different approaches are used to characterize the occurrence of severe storms due to the limitations of observational records (ALLEN 2018). Some previous works have identified specific characteristics of this phenomenon during severe storm events (GOMES & HELD 2005) to create indices of storm severity and thus develop algorithms that can predict these events.

The mid-latitude and subtropical sectors of South America and eastern Andes Mountain have been identified as regions subject to the occurrence of severe convective storms (GUEDES & SILVA DIAS 1984). As shown by BROOKS et al. (2003), the southern region of Brazil is favorable to the occurrence of tornadoes. The authors used reanalysis data from 1997 to 1999 and considered the presence of hail over 5 cm and the presence of wind gusts greater than 12 m/s as favorable conditions for the occurrence of tornadoes. The authors also counted the number of days per year favorable to the occurrence of tornadoes. These phenomena can be associated with the frequent establishment of the low-level jet during the South American warm season (MARENGO et al. 2002), which transports moisture from the Amazon Basin to the higher latitudes of continental South America and occasionally becomes dynamically coupled with the westerly upper-level jet stream. MARTINS et al. (2017) evaluated reports of emergency assistance given to the disaster-affected population in southern Brazil. They confirmed that this region is prone to the development of MCS, with a high annual number of hail-destructive events.

The impacts attributed to MCS are of concern in several sectors, such as agriculture, industry, and the energy sector. The energy sector, in particular, has been affected by these severe storm events, which can result in the fall of transmission towers. ABOSHOSHA & DAMATTY (2015) estimated that 80% of severe storm events resulted in damages to transmission towers due to tornadoes and downbursts.

The increase in greenhouse gas emissions and, consequently, the increase in near-surface air temperature may result in more severe weather events in the future (BALLING & CERVENY 2003). Output from numerical modeling simulations suggests that the atmosphere could become more unstable in the future, thereby supporting an increase in convective activity (BALLING & CERVENY 2003). There is a need to estimate the change in frequency of MCS in the near future to take effective adaptation measures. However, modeling extreme events at the local scale is challenging. These events are, in many cases, a result of severe storms that instability indices should detect. Several studies evaluated the performance of climate models to reproduce MCS-favorable environments (NIALL & WALSH 2005, MARSH et al. 2009, DIFFENBAUGH et al. 2013, ALLEN & KAROLY 2014, SEELEY & ROMPS 2015, PÚČIK et al. 2017), as summarized by ALLEN (2018).

This work evaluates future climate conditions that may lead to more severe weather. We aim to assess future severe storms as significant hazards for the transmission line towers in Santa Catarina (SC), Brazil. We propose using the Severe Weather Index (SWI) as a proxy for estimating severe storms that potentially result in extreme events. This research expects to support the energy sector in future planning, with more accurate proxies to represent severe storms that impose risk on transmission lines in Santa Catarina, Brazil.

2 DATA AND METHODS

In this section, we present the study region and the cases of severe convective storms. We also show the datasets used, the Severe Weather Index (SWI) construction, and its classification into low, medium, and high risk.

We first identified the dates and locations where transmission lines were damaged. Then, by using reanalysis data, we calculated the SWI. Next, we estimated possible changes in the frequency of these extreme events in the future using projections from the Eta model nested with three climate models (HadGEM2-ES, MIROC5, and CanESM) in the horizontal resolution of 20 km and one climate model (HadGEM2-ES) with a horizontal resolution of 5 km.

2.1 Study region and the severe event cases

When studying MCS, we found several limitations. The spatial scale and lifetime of the phenomena make it challenging to have observational records of this phenomenon. Usually, the records of severe storms are associated with eyewitness presence near the thunderstorm, which makes the severe storm reports highly influenced by the local population (ALLEN & TIPPETT 2015, BLAIR et al. 2017). Different local trends around the world have been summarized by ALLEN (2018). There is a limited observational dataset in the world to assess the occurrence of severe storms. ALLEN (2018) states that more of these observed records are needed to evaluate trends and climate variability. Still, they can be used to calibrate models designed to estimate future severe storm occurrence.

The southern region of Brazil, especially the state of Santa Catarina, is highly exposed to severe weather (MARCELINO et al. 2006). This region is strategic for the energy sector, given the density of transmission lines and their relevance to the power distribution in the country (EPE 2015). Two transmission lines in Santa Catarina state, *West TL* and *Coast TL,* are essential in this context. The locations of these transmission lines are highlighted in figure 1.

To assess the weather hazards, we evaluate cases in which transmission lines (T.L.) were damaged and cases where severe weather occurred in the region and represented a hazard to the T.L. (as reported by CANDIDO 2012). Table 1 shows the selected cases used in our study, where * marks those with damages to the T.L. The studied cases were well distributed in the different state regions, as indicated by the location (city) of the event in table 1 and as shown in figure 2. Figure 2 also shows the spatial distribution of the cases with hazards to the T.L. in the state. These cases were used to construct the Severe Weather Index (SWI), as indicated in the next section.

2.2 Severe weather index (SWI)

Atmospheric instability indices have been used to assess storms (NASCIMENTO 2005). These indices were originally standardized for Northern Hemisphere midlatitudes, so their thresholds must be adjusted according to the environmental conditions in a specific region (TOMAZZIELO & GANDU 2009). Atmospheric instability indices consider the formation of an environment conducive to severe storms. These indices consider different aspects of the environment, such as the energy available for the storm, the vertical wind shear to sustain storm severity, and the updrafts that are mechanisms for maintaining these storms, among others.

Several studies indicate the use of instability indices applied to MCS observations and reanalysis as a good strategy to forecast and identify characteristic conditions favorable to a given phenomenon, the ingredients-based approach (DOSWELL et al. 1996, CRAVEN et al. 2002, BROOKS et al. 2003, RASMUSSEN 2003, KAPSCH et al. 2012). The improvement of climate models and reanalysis products assessing

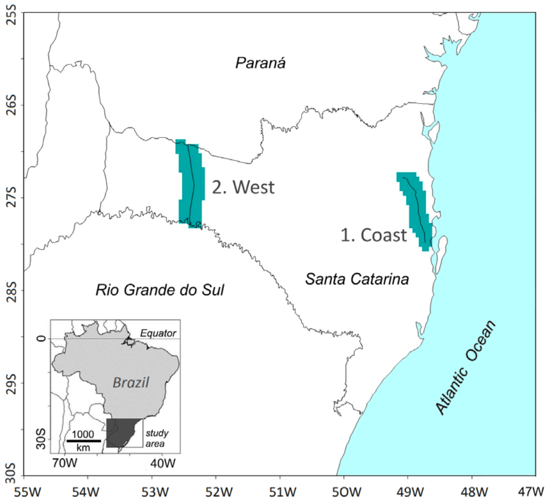

FIGURE 1 – Selected transmission lines (*West TL* and *Coast TL)* in Santa Catarina state (SC), Brazil.

TABLE 1 – Severe weather occurrence in Santa Catarina, Brazil.

Cases	*Location*	*Date*
1*	Campos Novos	18/09/1998
2*	Xavantina	14/07/2015
3*	Tubarão	16/10/2016
4*	Imbituba	17/10/2016
5*	Palmeira	22/01/2018
6	Maravilha	08/10/1984
7	São Joaquim	13/05/1987
8	Xanxerê	07/07/1987
9	Indaial	15/10/1987
10	Xanxerê	11/11/1989
11	Garuva	24/11/1989
12	Benedito Novo	09/01/1995
13	Rio dos Cedros	28/11/1995
14	Ilha de São Francisco do Sul	27/01/1996
15	Meleiro	27/02/1996
16	Ilha de São Francisco do Sul	27/07/1996
17	Itapoá	02/02/1997
18	Piçarras	07/02/1997
19	Abdon Batista	07/02/1998
20	Joinville	31/01/1999
21	Forquilhinha	24/11/1999
22	Florianópolis	23/02/2000
23	Itapoá	01/03/2000
24	Criciúma	03/01/2005
25	São Joaquim	29/12/2005
26	Florianópolis	02/01/2006
27	Criciúma	25/01/2006
28	Joinville	22/02/2006
29	Florianópolis	23/03/2006
30	Tubarão	24/03/2007
31	Campos Novos e Chapecó	13/11/2007
32	Papanduva	01/02/2008
33	Tubarão	16/02/2008
34	Florianópolis	02/03/2008
35	Abelardo Luz	24/10/2008
36	Canoinhas	26/10/2008
37	Urupema	31/12/2008
38	Sombrio	31/01/2009
39	Blumenau	22/02/2009
40	Ponta Alta e Turvo	08/03/2009
41	Guaraciaba	07/09/2009
42	Araranguá	28/09/2009
43	Florianópolis	31/03/2015
44	Xanxerê	20/04/2015

* Cases with damages in the transmission lines.

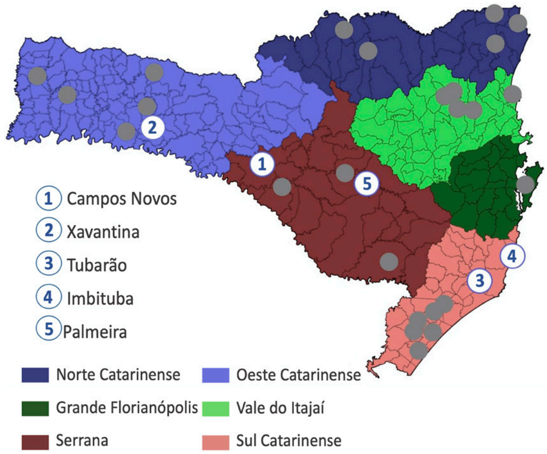

FIGURE 2 – Distribution of severe weather occurrence in Santa Catarina, Brazil. The numbers identify the studied cases presented in table 1. Different colors show the subregions within the Santa Catarina state.

long-term trends made it possible to assess severe storms and favorable environmental conditions for a potential MCS occurrence (ALLEN 2018). When evaluating severe storms, there are some challenges to overcome related to (1) the different criteria used to define the occurrence of severe storms since there are no specific thresholds to define MCS favorable environments; (2) the distinction between almost severe and severe storms, and the non-conditionality of environments. Therefore, even if an environment is favorable, there is no guarantee that a storm will form within the environment; (3) the variability of these definitions according to the study region.

From the cases in table 1, we analyzed the extreme events that caused damage to the infrastructure. Based on the historical and bibliographic survey of EPAGRI (MMA & GIZ 2018), some cases were studied using atmospheric instability indices and conditions. From ERA-Interim reanalysis data (DEE et al. 2011), atmospheric instability indices were calculated and adjusted to reflect the amount and intensity of observed severe storm events. Favorable atmospheric conditions were identified for the formation of tornadoes and MCS with the potential to cause damage to transmission lines in South Brazil.

From the atmospheric instability indices, the Severe Weather Index (SWI) was defined according to the thresholds indicated in table 2. The index was classified into three categories of

TABLE 2 – Classification and description of the Severe Weather Index (SWI).

Classification	*Description of Severe Weather Index (SWI)*			
	CAPE	*IEH*	*SUP*	*HELI*
Low-risk or absent	CAPE < 400 J/kg	IEH > -1	SUP > -0.99	-
Moderate risk	CAPE ≥ 400 J/kg	IEH ≤ -1	SUP ≤ -0.99	100 ≤ |HELI| < 250
High risk	CAPE ≥ 600 J/kg	IEH ≤ -1	SUP ≤ -0.99	|HELI| ≥ 250

occurrence of severe storm events and normalized to represent the percentage of days per year with the potential to cause damage to the transmission lines. In table 2, CAPE is the Convective Available Potential Energy (HOUZE 1993); HELI is the Relative Storm Helicity (DAVIES-JONES et al. 1990); IEH is the Energy-Helicity Index (HART & DOROTKY 1991, DAVIES 1993); and SUP is the Supercell Parameter (THOMPSON et al. 2003). A full description of the indices can be found at NASCIMENTO (2005). In summary, CAPE represents the Convective Available Potential Energy between the level of free convection and the balance level. The IEH indicates when the atmospheric conditions create a high probability of severe weather. Even though it was developed for supercells, the SUP parameter can serve as a starting point for the formulation of indices that have broader applicability in Brazil, as the occurrence of storms capable of generating high precipitation rates (NASCIMENTO 2005).

The thresholds presented in table 2 were primarily defined using the first guess based on literature (e.g., NASCIMENTO 2005). Then, we re-scaled these values to capture the phenomenon´s occurrence in the study cases. Therefore, these thresholds are specific to the region of Santa Catarina. Application to other regions requires to follow the same steps. In this work, we focused on the high-risk SWI, therefore, with a higher potential to cause damage to transmission lines due to the occurrence of MCS.

2.3 Climate data

In this research, we use two different types of data. First, we use reanalysis to calculate, classify, and calibrate the SWI index. Second, we use climate projections to evaluate the future occurrence of severe storms in Santa Catarina. This section presents more information regarding the ERA-Interim reanalysis and the Eta climate model.

a) Observational data

Reanalysis datasets can help in severe storm research, as they are spatially and temporally consistent (ALLEN 2018). Reanalysis datasets have been used to study the climatology of severe storms worldwide. However, it is essential to highlight that this data has some limitations in resolving the finer-scale initiation processes due to the coarse vertical and horizontal resolution (BROOKS et al. 2003, ALLEN & KAROLY 2014, ALLEN 2018). BROOKS et al. (2003) used NCEP/NCAR reanalysis to describe favorable conditions for developing severe storms using proxies. The use of severe storms proxies enables the study of severe storms in regions with fewer observations.

WESTERMAYER et al. (2017) and PÚČIK et al. (2017) used the ERA-Interim reanalysis to study the ingredients favorable to severe convective storms and thunderstorms over Europe. WESTERMAYER et al. (2017) concluded that the latent instability is only required up to a certain amount of approximately 200–400 J kg^{-1} CAPE and, for higher values of CAPE (~ 800–2800 J kg^{-1}), the relative frequency of lightning is relatively constant. ALLEN & KAROLY (2014) studied the influence of a warmer climate on the occurrence of severe thunderstorms over Australia based on the ingredients and the environmental conditions favorable to these events. They used ERA-Interim reanalysis and observed data against climate models to evaluate the capability of the models to represent convective environments in the current climate. They concluded that the distribution of severe thunderstorm environments depends on the model biases.

We use data from ERA-Interim reanalysis to study the occurrence of severe storms. The ERA-Interim data is available from 1979 to 2019. The horizontal resolution of the data set is approximately 80 km with 60 levels in the vertical from the surface up to 0.1 hPa. The temporal scale used was 6 hours to capture the development of the severe storms. More information about the ERA-Interim dataset can be found by DEE et al. (2011) and BERRISFORD et al. (2011). As presented in the 2.3 section (SWI construction), we adjusted the SWI to match the observed occurrence of severe storms and the hazard to the transmission lines in SC, as indicated by the reanalysis.

b) Climate regional model projections

Over the years, increases in computational capacities allowed the development of climate models, making it possible to produce more realistic predictions. Numerical representation of severe storms is challenging because of the proxies and the high temporal and spatial resolution needed to represent these phenomena. Therefore, important features of the climate models are the grid size and the ability to resolve convective processes (CUBASCH & MEEHL 2001). Global climate models with coarse spatial resolutions tend to underestimate the release of convective instability (YE et al. 1998, LEPORE et al. 2021). In this context, regional climate models with higher spatial resolution are more appropriate for numerically describing MCS (CORFIDI 2017).

PÚČIK et al. (2017) evaluated the occurrence of environmental conditions favorable for severe convective storms in a regional climate model ensemble over Europe and the Mediterranean, using two climate scenarios (RCP4.5 and RCP8.5). They concluded that the ensemble simulates a robust increase in the frequency of occurrence of unstable environments across central and south-central Europe in the RCP8.5 scenario in the late twenty-first century. Large intermodel variability is present in the ensemble. It is primarily due to the uncertainties in the climate projections, which result in uncertainties in the frequency of the occurrence of unstable environments.

The Eta regional climate model (GOMES et al. 2023, MESINGER et al. 2012) is a limited area model that requires global models to provide information on the lateral contours. This model has a complex representation of the physical and dynamic processes of the atmosphere. One feature of the model, which gives its name, is the use of the eta (η) vertical coordinate, considered more suitable for simulations in regions of complex topography, such as the Andes region and the Brazilian highlands (SELUCHI et al. 2003).

The Eta model version used to generate projections of climate change scenarios over Brazil was developed by PESQUERO et al. (2010) and CHOU et al. (2012) at 40-km resolution. CHOU et al. (2014a, 2014b) performed Eta model integrations at 20-km resolution nested in three global climate models of the Coupled Model Intercomparison Project Phase 5 (CMIP5), while LYRA et al. (2018) developed a non-hydrostatic version of the model and produced integrations at 5-km resolution over Southeast Brazil, as the second nesting. The simulations reproduce the historical climate of South America, and the integrations in higher resolution favor a better representation of the extremes of rain and temperature in Southeast Brazil. These climate simulations and future projections were also used in the Brazilian Third National Communication to the United Nations Framework Convention on Climate Change (MCTI 2016) and have been used to support various impact studies (TAVARES et al. 2017, FERREIRA et al. 2019, FERREIRA & HONORIO 2020, FERREIRA & MIRANDA 2021).

We use the Eta model nested with three different models: MIROC5 (WATANABE et al. 2010), CanESM (CHYLEK et al. 2011), and HadGEM2-ES (COLLINS et al. 2011), in the horizontal resolution of 20 km. The experiments were named EtaMIROC5-20km, EtaCanESM-20km, and EtaHadGEM2-20km, respectively. This work added a 5-km resolution Eta model setup over South Brazil, centered in Santa Catarina. The run is nested into the HadGEM2-ES (run named EtaHadGEM-5km). A more detailed topography representation is achieved at a 5-km resolution, which is impossible at a lower spatial resolution. High resolution is important in severe storms to indicate flow patterns and provide sources of convective initiation (PÚČIK et al. 2017). Therefore, the downscaling data from the Eta model can better capture these events′ intensity and detailed description. Figure 3 shows the topography maps for Eta simulations at 20-km and 5-km resolutions.

Future climate integrations performed with this model are based on the representative greenhouse gas (GHG) concentration paths, the so-called Representative Concentration Pathway (RCP) (MOSS et al. 2010). The intermediate concentration (RCP4.5) and high concentration (RCP8.5) scenarios were considered in this research. The Severe Weather Index (SWI) was calculated based on the parameters described in table 2.

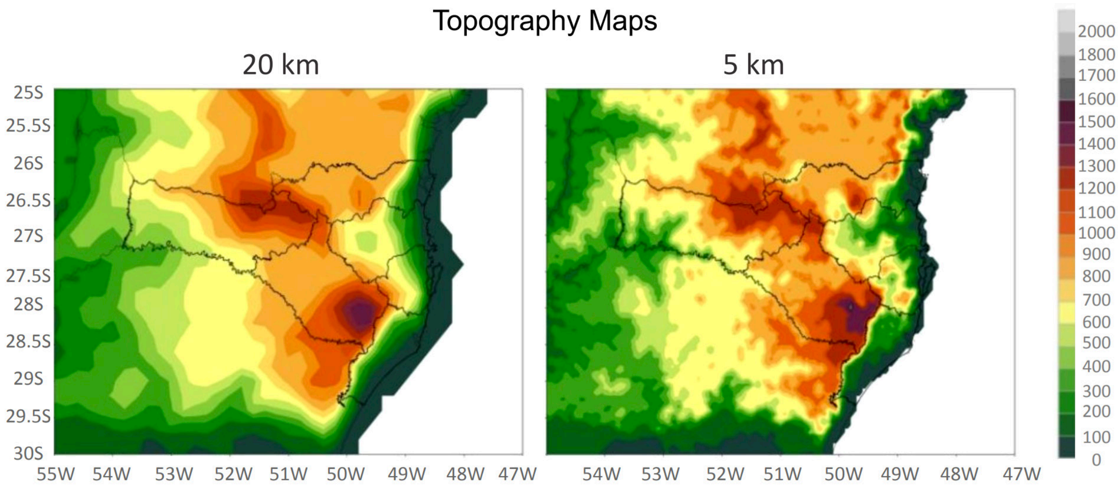

FIGURE 3 – Eta model topography (m) at 20-km and 5-km resolutions.

3 RESULTS

The results below present the Severe Weather Index (SWI) evaluation based on cases with damages to the selected transmission lines. The index is also presented considering future climate scenarios.

3.1 Validation using past events

The SWI was constructed based on the cases in table 1 and adjusted according to the atmospheric instability indices in table 2. This adjustment aimed to refine the thresholds of the indices used in the SWI calculation. We analyzed the 5 cases with direct consequences on the transmission lines to validate these values. To demonstrate the index detection capability, figure 4 indicates the SWI calculated for the day before the damage occurred (d1), the day that the damage occurred (d2), and the day after the damage (d3). Those three days were evaluated since the reports did not specify the exact time that the event occurred. At this stage, the SWI was calculated using ERA-Interim data.

Figure 4 illustrates that the SWI can capture the high-risk character of the events that caused damage to the transmission lines. However, due to the coarse spatial resolution of the data, in some cases, the event is positioned near the location where the damage occurred. It is also noteworthy that in case 5, the SWI was classified as moderate rather than high risk. The results indicated in this research agree with the results presented by PÚČIK et al. (2017), which suggest that ERA-Interim reanalysis can capture severe storm conditions when the severe weather conditions are well described.

3.2 Future changes in severe storms

To assess the future changes in severe storms, SWI was calculated using the EtaHadGEM-5km model (forced by the EtaHadGEM-20km model) and the EtaHadGEM-20km, EtaMIROC5-20km, and EtaCanESM-20km models. Before projecting future changes in the risk of severe storm occurrences, we also calculate the risk for the baseline period. The baseline period is from 1981 to 2010, and the near-future period is from 2011 to 2040. The simulations generated by these models, and the simulation errors were previously discussed in CHOU et al. (2014 a, b). Figure 5 shows the 30-year average of SWI, classified as high-risk (Table 2). We also present the SWI calculated from Era-Interim reanalysis to evaluate model errors in the baseline period.

The SWI simulated by the Eta model captures a pattern similar to the reanalysis, with higher percentages in the western part of Santa Catarina (SC). The percentage of days with the potential conditions to cause damage to transmission lines (T.L.) due to MCS and tornadoes varies around 2 and 4% (except for the EtaCanESM-20km model). These values also match the results found by BROOKS et al. (2003) for the region, around 12 days per year, with favorable conditions for tornado development.

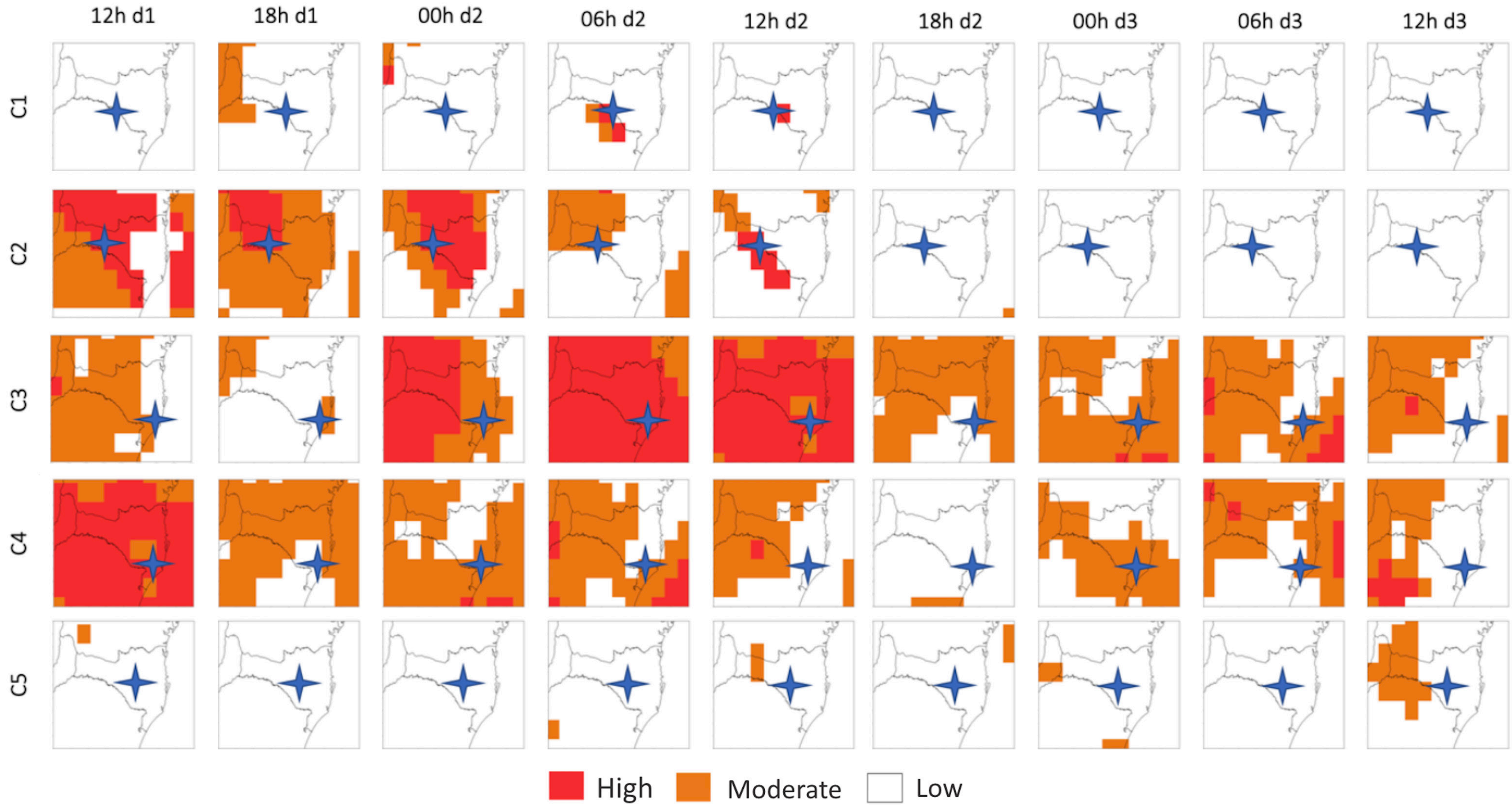

FIGURE 4 – Severe Weather Index (SWI) potentially damaging transmission lines. The rows show the different cases. The columns show the hour (Local Time) of the day before the hazard (d1), the day of the hazard (d2), and the following day of the hazard (d3). The stars locate the regions where these cases occurred.

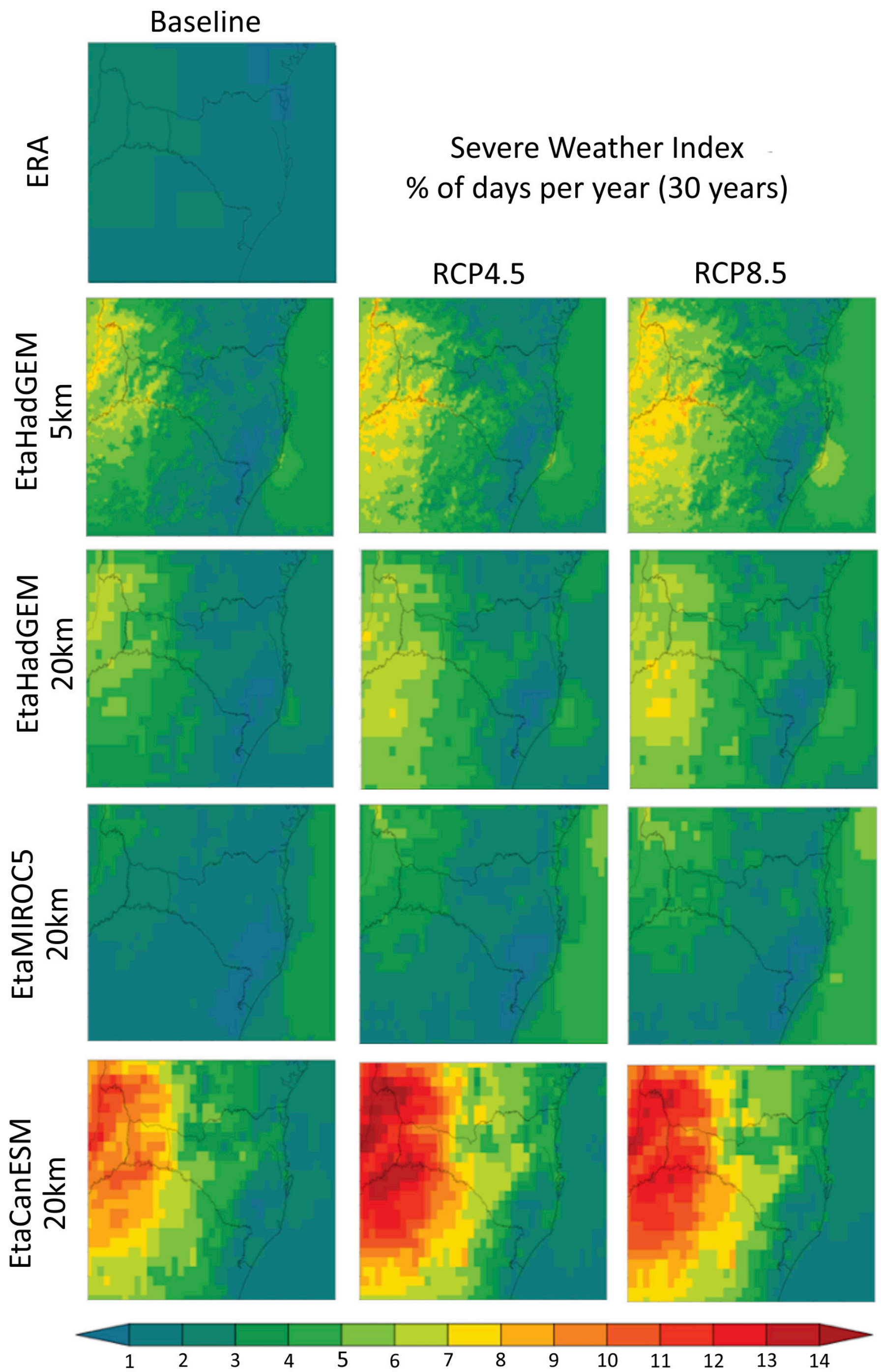

FIGURE 5 – A severe Weather Index (SWI) is classified as a high risk of causing damage to transmission lines. The index was calculated using data from ERA-Interim, EtaHadGEM-5km, EtaHadGEM2ES-20km, EtaMIROC5-20km, and EtaCanESM-20km. SWI indicates the 30-year mean values considering the baseline period (from 1981 to 2011) and future scenarios (RCP4.5 and RCP8.5, from 2011 to 2040).

In the future scenarios, RCP4.5 and RCP8.5, projections indicate an increase in the SWI. The magnitude of this increase depends on the climate model evaluated. The EtaCanESM-20km model, which has already overestimated the potential to cause damages to transmission lines (T.L.s), presents the highest increase in the SWI in future scenarios.

Figure 6 shows the difference in the severe weather index (SWI, high risk) between future projections (2011–2040) and the baseline period (1981–2010). The SWI differences were calculated considering the 30-year average values of each scenario.

Differences between future climate and baseline climate indicate an increase in the frequency of SWI. This increase is always greater in the RCP8.5 scenario, which is the scenario that indicates higher atmospheric instability. Different models project different future changes and

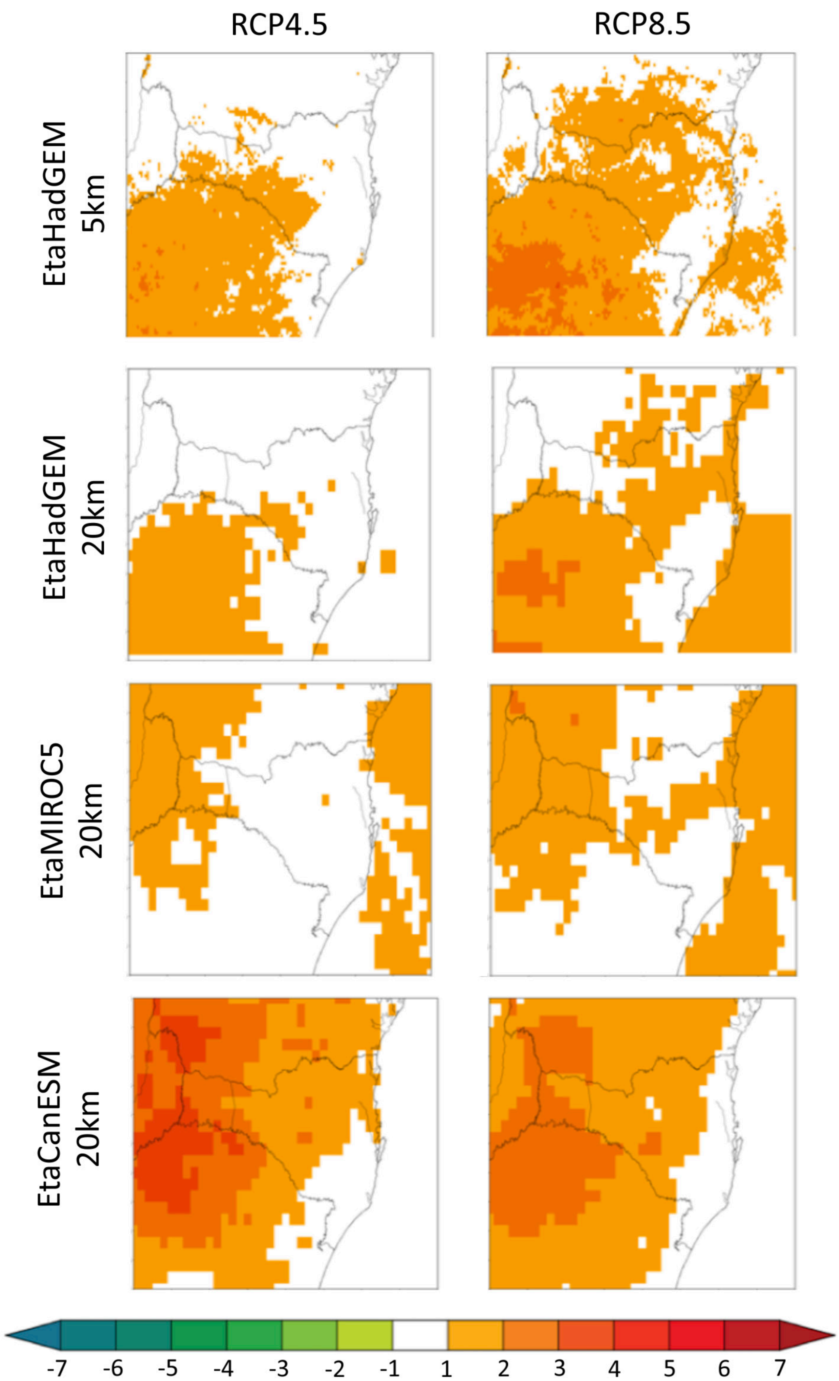

FIGURE 6 – The high-risk Severe Weather Index differences between the future projections (2011–2040, RCP4.5 and RCP8.5) and the baseline simulations (1981–2010).

indicate different results for the SWI. In general, SWI differences can reach values of up to 4%. The high-risk expansion occurs mainly in the western and southern regions of Santa Catarina in both RCP4.5 and RCP8.5 scenarios. Both emission scenarios indicate an increase in *West TL* region events.

The RCP8.5 scenario also indicates an increase in severe storms in the *Coast TL* region. Neither scenario indicated increased high-risk SWI in the state´s southeast region (disregarding the coastal area). The southeast region may be a good choice for future investments (e.g., implementation of new transmission lines, which may be less vulnerable to severe weather) due to the lower probability of future occurrence of severe weather events with the potential to cause damage to transmission lines.

The areas around the transmission lines were analyzed in detail. Figure 7 shows the average percentage of days per year for the high-risk SWI over the *Coast* and *West TL* regions, considering the baseline period (1981 to 2010) and future projections in RCP4.5 scenarios and RCP8.5 from 2011 to 2040.

In both transmission lines, the models that indicated higher and lower SWI values were EtaCanESM-20km and EtaMIROC5-20km, respectively. *West TL* (Figure 7a) shows the highest SWI, regardless of the model or scenario. In the *West TL*, the baseline period (1981 to 2010) indicates an average SWI of 4.5% among the models, with a maximum value in EtaCanESM-20km (7.3%) and a minimum in EtaMIROC5-20km (2.3%). In the RCP4.5 scenario, the highest SWI is 9.4%, the lowest is 3.2%, and the average value is 5.6%. In the RCP8.5 scenario, the SWI maximum is 9.1%, the minimum is 3.6%, and the average is 5.8%. Therefore, in the future, the RCP4.5 and RCP8.5 scenarios indicate similar average values, showing an increase in SWI compared to the historical period (an increase of 1.1% and 1.3%, respectively).

On the *Coast TL*, which has a lower SWI, the models indicated an average of 2.2% of days with potential damages to T.L. in the historical period. Again, the model that indicated the highest SWI is EtaCanESM-20km (2.9%), and the one with the lowest SWI is EtaMIROC5-20km (1.7%). In the RCP4.5 scenario, the average SWI is 2.9%. The maximum values can reach more than 4%, and the minimum is 2.3%. In the RCP8.5 scenario, the average SWI is 3.2%, the minimum is 2.7%, and the maximum is 3.5%. Therefore, as expected, RCP8.5 shows the most significant increase compared to historical. Again, regardless of the climate model, both future scenarios indicate increased risk (on average 0.7% at RCP4.5 and 1% at RCP8.5).

The results agree with the values found by BROOKS et al. (2003) for the SC region (about 12 days per year with favorable conditions for tornado development, which amounts to around 3 to 4% per year). In summary, the highest values were found in RCP8.5, and all models evaluated converged to an increase in the SWI, thus representing an increased exposure of these lines to the occurrence of tornadoes and MCS. The significance test was applied and indicated that the differences between

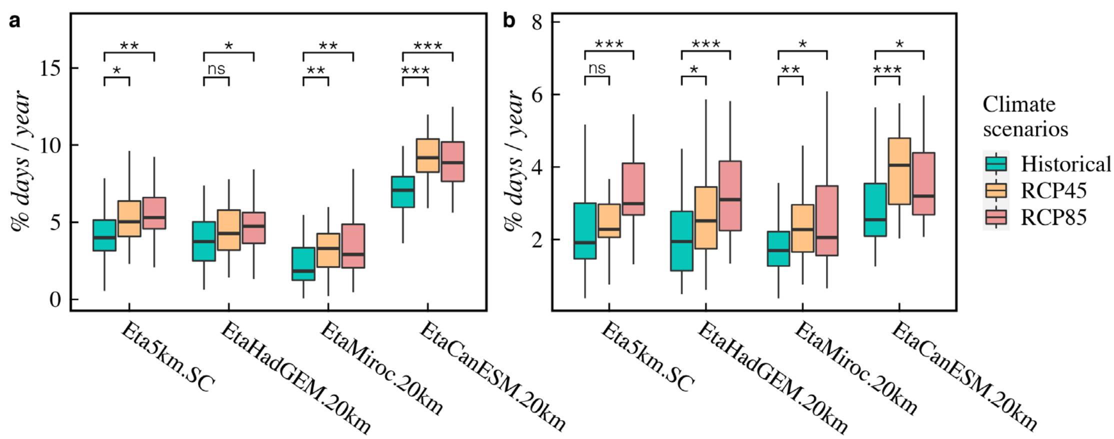

FIGURE 7 – Percentage of days per year (30-year average) with severe weather (according to SWI) over the areas of the *West* (a) and *Coast TL (b)*. The future projections RCP4.5 and RCP8.5, 2011 to 2040. Wilcoxon sum rank test *p < .05, **p < .01, ***p < .001, and 'ns' not significant.

climate projections and baseline simulation are statistically significant in most simulations. The highest values of the SWI were found on the *West TL*, located in the western state of Santa Catarina.

It is important to highlight that although the models and scenarios point to an increase in the potential hazard to transmission lines, uncertainties must be considered. Among the uncertainties are (1) the use of quantitative indices to determine chaotic phenomena, such as MCS; (2) the use of reanalysis data, with a coarse spatial horizontal resolution, for method validation; and (3) the uncertainties associated with climate model biases.

According to ALLEN (2018), there is a growing consensus that the frequency of favorable environments to severe convective storms is increasing. Insured losses are frequently increasing due to the exposure to favorable thermodynamic conditions to MCS (SANDER et al. 2013, HOEPPE 2016). Severe storms are a global phenomenon; however, ALLEN (2018) highlights that most of the research in this context is made in areas with higher observational data availability, such as North America, Europe, and Australia. Therefore, there is a need to focus on regional research, looking into local aspects in different areas to evaluate the impacts of climate change on various sectors and infrastructures.

Several studies consider the climate dependence of hydropower plants (SCHAEFFER et al. 2013, DE QUEIROZ et al. 2016) to evaluate the impacts of climate change on the energy sector in Brazil. However, as Brazil is a large country and the electricity needs to be transported to different parts, the energy system is connected by transmission lines. Thus, the effects of climate change on these infrastructures need to be explored further. Therefore, this paper is the first attempt to study the potential damages over transmission line infrastructures in Brazil (SC) due to climate conditions.

4 CONCLUSIONS

The severe weather index (SWI) was developed to characterize the MCS and tornadoes and to evaluate the probability of severe weather occurrence in future climate scenarios.

We conclude that:

• The SWI detected the number of severe weather events compared to the literature but indicated overestimation compared to the ERA-Interim reanalysis. For this reason, this index should be used with caution;

• The models evaluated converge to an increase of severe weather events in future scenarios;

• Both climate projection scenarios, RCP4.5 and RCP8.5, indicate an increase in the frequency of occurrence of SCM and tornado events over the evaluated transmission lines;

• *West TL* has the highest percentage of days per year with favorable conditions for the occurrence of SCMs and tornadoes, indicating a greater risk to this line in the future;

• Climate projections indicate an upward trend in the frequency of severe events in the western region of SC (RCP4.5 and RCP8.5) and on *Coast TL* (RCP8.5);

• Climate projections suggest an expansion of areas exposed to extreme weather events.

The lack of radiosonde data limits the validation of the proposed index. For this reason, only reanalysis data were used to validate the index. Notably, the described Severe Weather Index has a regional application; therefore, the application in other regions requires re-calibrating the thresholds.

5 ACKNOWLEDGMENTS

We want to acknowledge the *Deutsche Gesellschaft für Internationale Zusammenarbeit* (GIZ) GmbH for supporting the assessment that motivated this article. Nevertheless, the GIZ is not responsible for the content of this publication. The authors also thank the *Empresa de Pesquisa Agropecuária e Extensão Rural de Santa Catarina* (EPAGRI), *Empresa Transmissora de Energia Elétrica* (Eletrosul), and the *Ministério do Meio Ambiente* (MMA) for their support. S.C. Chou thanks CNPq for the grant 312742/2021-5. We also thank the Derbyana ad-hoc reviewers for their helpful comments on the manuscript.

6 REFERENCES

ABOSHOSHA, H.; EL DAMATTY, A. 2015. Engineering method for estimating the reactions of transmission line conductors under downburst winds. *Engineering Structures*, 99: 272–284. https://doi.org/10.1016/j.engstruct.2015.04.010

ALLEN, J.T. 2018. Climate change and severe thunderstorms. In: *Oxford research* *encyclopedia of climate science*. https://doi.org/10.1093/acrefore/9780190228620.013.62

ALLEN, J.; KAROLY, D. 2014. A climatology of Australian severe thunderstorm environments 1979–2011: Inter-annual variability and the ENSO influence. *International Journal of Climatology*, 34: 81–97. https://doi.org/10.1002/joc.3667

ALLEN, J.T.; TIPPETT, M.K. 2015. The characteristics of United States hail reports: 1955-2014. *E-Journal of Severe Storms Meteorology*, 10(3): 1–31. https://doi.org/10.55599/ejssm.v10i3.60

BALLING JR., R.C.; CERVENY, R.S. 2003. Compilation and discussion of trends in severe storms in the United States: Popular perception v. climate reality. *Natural Hazards*, 29: 103–112. https://doi.org/10.1023/A:1023674722282

BERRISFORD, P.; KÅLLBERG, P.; KOBAYASHI, D.D.; UPPALA, S.; SIMMONS, A.J.; SATO, H. 2011. Atmospheric conservation properties in ERA-Interim. *Quarterly Journal of the Royal Meteorological Society*, 137: 1381–1399. https://doi.org/10.1002/qj.864

BLAIR, S.F.; LAFLIN, J.M.; CAVANAUGH, D.E.; SANDERS, K.J.; CURRENS, S.R.; PULLIN, J.I.; COOPER, D.T.; DEROCHE, D.R.; LEIGHTON, J.W.; FRITCHIE, R.V.; MEZEULL II, M.J.; GOUDEAU, B.T.; KRELLER, S.J.; BOSCO, J.J.; KELLY, C.M.; MALLINSON, H.M. 2017. High-resolution hail observations: Implications for NWS warning operations. *Weather and Forecasting*, 32(3): 1101–1119. https://doi.org/10.1175/WAF-D-16-0203.1

BOTZEN, W J.W.; BOUWER, L.M. 2016. Weather indicators for insured hailstorm damage to motor vehicles and potential climate change impacts. *The Geneva Papers on Risk and Insurance-Issues and Practice*, 41(3): 512–527. https://doi.org/10.1057/gpp.2015.16

BROOKS, H.E.; LEE, J.W.; CRAVEN, J.P. 2003. The spatial distribution of severe thunderstorm and tornado environments from global reanalysis data. *Atmospheric Research*, 67-68: 73–94. https://doi.org/10.1016/S0169-8095(03)00045-0

CANDIDO, D. 2012. *Tornados e trombas d'água no Brasil: modelo e proposta de escala de avaliação de danos*. Instituto de Geociências, Universidade Estadual de Campinas, Campinas, Dissertação de Mestrado, 230 p. https://doi.org/10.47749/T/UNICAMP.2012.901142

CHOU, S.C.; MARENGO, J.A.; LYRA, A.A.; SUEIRO, G.; PESQUERO, J.F.; ALVES, L.M.; KAY G.; BETTS, R.; CHAGAS, D.J.; GOMES, J.L.; BUSTAMANTE, J.F.; TAVARES, P.S. 2012. Downscaling of South America present climate driven by 4-member HadCM3 runs. *Climate Dynamics*, 38(3-4): 635–653. https://doi.org/10.1007/s00382-011-1002-8

CHOU, S.C.; LYRA, A.A.; MOURÃO, C.; DERECZYNSKI, C.; PILOTTO, I.; GOMES, J.; BUSTAMANTE, J.; TAVARES, P.; SILVA, A.; RODRIGUES, D.; CAMPOS, D.; CHAGAS, D.; SUEIRO, G.; SIQUEIRA, G.; MARENGO, J. 2014a. Assessment of climate change over South America under RCP 4.5 and 8.5 downscaling scenarios. *American Journal of Climate Change*, 3: 512–527. https://doi.org/10.4236/ajcc.2014.35043

CHOU, S.C.; LYRA, A.; MOURÃO, C.; DERECZYNSKI, C.; PILOTTO, I.; GOMES, J.; BUSTAMANTE, J.F.; TAVARES, P.; SILVA, A.; RODRIGUES, D.; CAMPOS, D.; CHAGAS, D.; SUEIRO, G.; SIQUEIRA, G.; NOBRE, P.; MARENGO, J. 2014b. Evaluation of the Eta simulations nested in three global climate models. *American Journal of Climate Change*, 3(5): 438–454. https://doi.org/10.4236/ajcc.2014.35039

CHYLEK, P.; LI, J.; DUBEY, M.K.; WANG, M.; LESINS, G. 2011. Observed and model simulated 20th century Arctic temperature variability: Canadian earth system model CanESM2. *Atmospheric Chemistry and Physics Discussions*, 11(8): 22893–22907. https://doi.org/10.5194/acpd-11-22893-2011

COLLINS, W.J.; BELLOUIN, N.; DOUTRIAUX-BOUCHER, M.; GEDNEY, N.; HALLORAN, P.; HINTON, T.; HUGHES, J.; JONES, C.D.; JOSHI, M.; LIDDICOAT, S.; MARTIN, G.; O'CONNOR, F.; RAE, J.; SENIOR, C.; SITCH, S.; TOTTERDELL, I.; WILTSHIRE, A.; WOODWARD, S. 2011.

Development and evaluation of an Earth-System model – HadGEM2. *Geoscientific Model Development*, 4: 1051–1075. https://doi.org/10.5194/gmd-4-1051-2011

CORFIDI, S. 2017. Forecasting severe convective storms. In: *Oxford research encyclopedia of climate science*. https://doi.org/10.1093/acrefore/9780190228620.013.59

CRAVEN, J.P.; JEWELL, R.E.; BROOKS, H.E. 2002. Comparison between observed convective cloud-base heights and lifting condensation level for two different lifted parcels. *Weather and Forecasting*, 17(4): 885–890. https://doi.org/10.1175/1520-0434(2002)017<0885:CBOCCB>2.0.CO;2

CUBASCH, U.; MEEHL, G.A. 2001. Projections of future climate change. *In:* J.T. Houghton, Y. Ding, D.J.Griggs, M. Noguer, P.J. van der Linden, X.Dai, K. Maskell, C.A. Johnson (Eds.) *Climate change 2001: The scientific basis*. New York, NY, Cambridge University Press, p. 525–582.

DAVIES, J.M. 1993. Hourly helicity, instability, and EHI in forecasting supercell tornadoes. In: American Meteorological Society, CONFERENCE ON SEVERE LOCAL STORMS, 17, St. Louis, Missouri, EUA, *Preprints*, p. 107–111.

DAVIES-JONES, R.; BURGESS, D.; FOSTER, M.D. 1990. Test of helicity as a tornado forecast parameter. In: American Meteorological Society, CONFERENCE ON SEVERE LOCAL STORMS, 16, Kananaskis Park, Canada, *Preprints*, p. 588–592.

DE QUEIROZ, A.R.; LIMA, L.M.M.; LIMA, J.W.M.; SILVA, B.C.; SCIANNI, L.A. 2016. Climate change impacts in the energy supply of the Brazilian hydro-dominant power system. *Renewable energy*, 99: 379–389. https://doi.org/10.1016/j.renene.2016.07.022

DEE, D.P.; UPPALA, S.M.; SIMMONS, A.J.; BERRISFORD, P.; KOBAYASHI, S.; ANDRAE, U.; BALMASEDA, M.A.; BALSAMO, G.; BAUER, P.; BECHTOLD, P.; BELJAARS, A.C.M.; BIDLOT, J.; BORMANN, N.; DELSOL, C.; DRAGANI, R.; FUENTES, M.; GEER, A.J.; HAIMBERGER, L.; HEALY, S.B.; HERSBACH, H.; HÓLM, E.V.; ISAKSEN, L.; KALLBERG, P.; KOHLER, M.; MATRICARDI, M.; MCNALLY, A.P.; MONGE-SANZ, B.M.; MORCRETTE, J.J.; PARK, B.K.; PEUBEY, C.; ROSNAY, P.; TAVOLATO, C.; THEPAUT, J.N.; VITART, F. 2011. The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656): 553–597. https://doi.org/10.1002/qj.828

DIFFENBAUGH, N.S.; SCHERER, M.; TRAPP, R.J. 2013. Robust increases in severe thunderstorm environments in response to greenhouse forcing. *Proceedings of the National Academy of Sciences USA*, 110(41): 16.361–16.366. https://doi.org/10.1073/pnas.1307758110

DOSWELL, C.A.; BROOKS, H.E.; MADDOX, R.A. 1996. Flash flood forecasting: An ingredients-based methodology. *Weather and Forecasting*, 11(4): 560–581. https://doi.org/10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2

ECCEL, E.; CAU, P.; RIEMANN-CAMPE, K.; BIASIOLI, F. 2012. Quantitative hail monitoring in an alpine area: 35-year climatology and links with atmospheric variables. *International Journal of Climatology*, 32(4): 503–517. https://doi.org/10.1002/joc.2291

EPE – EMPRESA DE PESQUISA ENERGÉTICA, 2015. *Plano Decenal de Expansão de Energia 2024*. EPE/MME, Brasília, 2 v. 467 p.

FERREIRA, N.C.R.; HONORIO, M.J. 2020. Potential occurrence of Puccinia sorghi in corn crops in Paraná, under scenarios of climate change. *International Journal of Biometeorology*. 64(7): 1051–1062. https://doi.org/10.1007/s00484-020-01880-6

FERREIRA, N.C.R.; MIRANDA, J.H. 2021. Projected changes in corn crop productivity and profitability in Parana, Brazil. *Environment, Development and Sustainability*, 23(3): 3236–3250. https://doi.org/10.1007/s10668-020-00715-z

FERREIRA, N.C.R.; MIRANDA, J.H.; COOKE, R.; CHU, M.L.; CHOU, S.C. 2019. Impacts of regional climate change on the runoff and root water uptake in corn crops in Parana, Brazil. *Agricultural Water Management*, 221: 556–565. https://doi.org/10.1016/j.agwat.2019.05.018

GOMES, A.M.; HELD, G. 2005. Characterization of storm properties during the TroCCiBras Experiment. In: AMS, CONFERENCE ON MESOSCALE PROCESSES, 11, and the CONFERENCE ON RADAR METEOROLOGY, 32, Albuquerque, New Mexico, *Anais*, p. 1853–1857.

GOMES, J.L.; CHOU, S.C.; MESINGER, F.; LYRA, A.A.; RODRIGUES, D.C.; RODRIGUEZ, D.A.; CAMPOS, D.A.; CHAGAS, D.J.; MEDEIROS, G.S.; PILOTTO, I.; TAVARES, P.S.; LUCCI, L.T.; VELJOVIC, K.; LAUREANTI, N.C.; MANTOVANI JÚNIOR, J.A.; LAMOSA, D.; DOURADO, M.S.C. 2023. *Manual Modelo Eta - versão 1.4.2*. INPE, São José dos Campos, 138 p. http://urlib.net/8JMKD3MGP3W34T/48G6PU5

GUEDES, R.L.; DIAS, M.A.F.S. 1984. Case study of severe storms associated with the subtropical jet in South America. In: Brazilian Meteorological Society, BRAZILIAN METEOROLOGICAL CONGRESS, 3, Belo Horizonte, *Proccedings*, p. 289-296.

HART, J.A.; DOROTKY, W. 1991. *The SHARP workstation v1.50 users guide*. National Weather Service, NOAA, U.S. Department of Commerce, 30 p.

HOEPPE, P. 2016. Trends in weather-related disasters–Consequences for insurers and society. *Weather and Climate Extremes*, 11: 70–79. https://doi.org/10.1016/j.wace.2015.10.002

HOUZE Jr., R.A. 1993. *Cloud Dynamics*. International Geophysics Series, v. 104, Academic Press, 573 p.

KAPSCH, M.L.; KUNZ, M.; VITOLO, R.; ECONOMOU, T. 2012. Long-term trends of hail-related weather types in an ensemble of regional climate models using a Bayesian approach. *Journal of Geophysical Research: Atmospheres*, 117(D15): 1–16. https://doi.org/10.1029/2011JD017185

LEPORE, C.; ABERNATHEY, R.; HENDERSON, N.; ALLEN, J.T.; TIPPETT, M.K. 2021. Future global convective environments in CMIP6 models. *Earth's Future*, 9(12): e2021EF002277. https://doi.org/10.1029/2021EF002277

LYRA, A.A.; TAVARES, P.; CHOU, S.C.; SUEIRO, G.; DERECZYNSKI, C.; SONDERMAN, M.; SILVA, A.; MARENGO, J.; GIAROLLA, A. 2018 Climate change projections over three metropolitan regions in Southeast Brazil using the non-hydrostatic Eta regional climate model at 5-km resolution. *Theoretical and Applied Climatology*, 132: 663–682. https://doi.org/10.1007/s00704-017-2067-z

MARCELINO, E.V.; NUNES, L.H.; KOBIYAMA, M. 2006. Mapeamento de risco de desastres naturais do estado de Santa Catarina. *Caminhos de Geografia*, 7(17): 72–84. https://doi.org/10.14393/RCG71715273

MARENGO, J.A.; DOUGLAS, M.W.; DIAS, P.L.S. 2002. The South American low-level jet east of the Andes during the 1999 LBA-TRMM and LBA-WET AMC campaign. *Journal of Geophysical Research: Atmospheres*, 107(D20): LBA 47-1-LBA 47-11. https://doi.org/10.1029/2001JD001188

MARSH, P.T.; BROOKS, H.E.; KAROLY, D.J. 2009. Preliminary investigation into the severe thunderstorm environment of Europe simulated by the Community Climate System Model 3. *Atmospheric Research*, 93(1-3): 607–618. https://doi.org/10.1016/j.atmosres.2008.09.014

MARTINS, J.A.; BRAND, V.S.; CAPUCIM, M.N.; FELIX, R.R.; MARTINS, L.D.; FREITAS, E.D.; GONÇALVES, F.L.T.; HALLAK, R.; SILVA DIAS, M.A.F.; CECIL, D.J. 2017. Climatology of destructive hailstorms in Brazil. *Atmospheric Research*, 184, 126–138. https://doi.org/10.1016/j.atmosres.2016.10.012

MCTI – MINISTÉRIO DA CIÊNCIA, TECNOLOGIA E INOVAÇÃO 2016. *Terceira Comunicação Nacional do Brasil para a Convenção Quadro das Nações Unidas sobre as mudanças climáticas – Volume II*. Brasília, Brazil. Available at https://repositorio.mcti.gov.br/handle/mctic/4312

MESINGER, F.; CHOU, S.C.; GOMES, J.L.; JOVIC, D.; BASTOS, P.; BUSTAMANTE, J.F.; LAZIC L.; LYRA, A.A.; MORELLI S.; RISTIC I.; VELJOVIC, K. 2012. An upgraded version of the Eta model. *Meteorology and Atmospheric Physics*. 116(3): 63–79. https://doi.org/10.1007/s00703-012-0182-z

MMA & GIZ. 2018. *Relatório produto 2: revisão bibliográfica, com foco na Região Sul, referente aos eventos meteorológicos causadores de danos e prejuízos* às *linhas de transmissão da Eletrosul (LT's) e ao Porto de Itajaí. Ampliação dos Serviços Climáticos para Investimentos em Infraestrutura (CSI)*. Ministério do Meio Ambiente (MMA) e Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ). Brasília, DF.

MOSS, R.H.; EDMONDS, J.A.; HIBBARD, K.A.; MANNING, M.R.; ROSE, S.K.; VUUREN, D.P.; CARTER, T.R.; EMORI, S.; KAINUMA, M.; KRAM, T.; MEEHL, G.A.; MITCHELL, J.F.B.; NAKICENOVIC, N.; RIAHI, K.; SMITH, S.J.; STOUFFER, R.J.; THOMSON, A.M; WEYANT, J.P.; WILBANKS, T.J. 2010. The next generation of scenarios for climate change research and assessment. *Nature*, 463: 747–756. https://doi.org/10.1038/nature08823

NASCIMENTO, E.L. 2005. Previsão de tempestades severas utilizando-se parâmetros convectivos e modelos de mesoescala: uma estratégia operacional adotável no Brasil. *Revista Brasileira de Meteorologia*, 20(1): 121–140.

NIALL, S.; WALSH, K. 2005. The impact of climate change on hail storms in southeast Australia. *International Journal of Climatology*, 25(14): 1933–1952. https://doi.org/10.1002/joc.1233

PESQUERO, J.F.; CHOU, S.C.; NOBRE, C.A.; MARENGO, J.A. 2010. Climate downscaling over South America for 1961–1970 using the Eta Model. *Theoretical and applied climatology*, 99(1-2): 75–93. https://doi.org/10.1007/s00704-009-0123-z

PÚČIK, T.; GROENEMEIJER, P.; RÄDLER, A.T.; TIJSSEN, L.; NIKULIN, G.; PREIN, A.F.; MEIJGAARD, E.; FEALY, R.; JACOB, D.; TEICHMANN, C. 2017. Future changes in European severe convection environments in a regional climate model ensemble. *Journal of Climate*, 30(17): 6771-6794. https://doi.org/10.1175/JCLI-D-16-0777.1

RASMUSSEN, E.N. 2003. Refined supercell and tornado forecast parameters. *Weather and Forecasting*, 18(3): 530–535. https://doi.org/10.1175/1520-0434(2003)18<530:rsatfp>2.0.co;2

SANDER, J.; EICHNER, J.F.; FAUST, E.; STEUER, M. 2013. Rising variability in thunderstorm-related U.S. losses as a reflection of changes in large-scale thunderstorm forcing. *Weather, Climate, and Society*, 5(4): 317–331. https://doi.org/10.1175/WCAS-D-12-00023.1

SCHAEFFER, R.; SZKLO, A.; LUCENA, A.F.P.; SORIA, R.; CHAVEZ-RODRIGUEZ, M. 2013. The vulnerable Amazon: the impact of climate change on the untapped potential of hydropower systems. *IEEE Power and Energy Magazine*, 11(3): 22–31. https://doi.org/10.1109/MPE.2013.2245584

SEELEY, J.T.; ROMPS, D.M. 2015. The effect of global warming on severe thunderstorms in the United States. *Journal of Climate*, 28(6): 2443–2458. https://doi.org/10.1175/JCLI-D-14-00382.1

SELUCHI, M.E.; NORTE, F.A.; SATYAMURTY, P.; CHOU, S.C. 2003. Analysis of three situations of the foehn effect over the Andes (Zonda wind) using the Eta–CPTEC regional model. *Weather and Forecasting*, 18(3): 481–501. https://doi.org/10.1175/1520-0434(2003)18<481:AOTSOT>2.0.CO;2

TAVARES, P.S.; GIAROLLA, A.; CHOU, S.C.; SILVA, A.J.P.; LYRA, A.A. 2017. Climate change impact on the potential yield of Arabica coffee in southeast Brazil. *Regional Environmental Change*, 18(3): 873–883. https://doi.org/10.1007/s10113-017-1236-z

THOMPSON, R.L.; EDWARDS, R.; HART, J.A.; ELMORE, K.L.; MARKOWSKI, P. 2003. Close proximity soundings within supercell environments obtained from the Rapid Update Cycle. *Weather and Forecasting*, 18(6): 1243–1261. https://doi.org/10.1175/1520-0434(2003)018<1243:CPSWSE>2.0.CO;2

TOMAZZIELLO, A.C.N.; GANDU, A.W. 2009. Severe weather indices: adptation of thresholds to metropolitan region of Sao Paulo, Brazill. *In*: WMO SYMPOSIUM ON NOWCASTING AND VERY SHORT TERM FORECASTING, Whistler-British Columbia, *Proceedings*. https://doi.org/10.13140/2.1.2854.4806

WATANABE, M.; SUZUKI, T.; O'ISHI, R.; KOMURO, Y.; WATANABE, S.; EMORI, S.; TAKEMURA, T.; CHIKIRA, M.; OGURA, T.; SEKIGUCHI, M.; TAKATA, K.; YAMAZAKI, D.; YOKOHATA, T.; NOZAWA, T.; HASUMI, H.; TATEBE, H.; KIMOTO, M. 2010. Improved climate simulation by MIROC5: mean states, variability, and climate sensitivity. *Journal of Climate*, 23(23): 6312–6335. https://doi.org/10.1175/2010JCLI3679.1

WESTERMAYER, A.; GROENEMEIJER, P.; PISTOTNIK, G.; SAUSEN, R.; FAUST, E. 2017. Identification of favorable environments for thunderstorms in reanalysis data. *Meteorologische Zeitschrift*, 26(1): 59–70. https://doi.org/10.1127/metz/2016/0754

YE., B.; GENIO, A.D.; LO, K.K-W. 1998. CAPE variations in the current climate and a climate change. *Journal of Climate*, 11(8): 1997–2015. https://doi.org/10.1175/1520-0442(1998)011<1997:CVITHCC>2.0.CO;2

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Manuscript submitted on 10 October 2023, accepted on 6 December 2023.