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Climate Change

Climate change impact on thunderstorms: Analysis of thunderstorm indices using high-resolution regional climate simulations

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Abstract

It is generally assumed that the temperature increase associated with global climate change will lead to increased thunderstorm intensity and associated heavy precipitation events. In the present study it is investigated whether the frequency of thunderstorm occurrences will in- or decrease and how the spatial distribution will change for the A1B scenario. The region of interest is Central Europe with a special focus on the Saar-Lor-Lux region (Saarland, Lorraine, Luxembourg) and Rhineland-Palatinate.

Daily model data of the COSMO-CLM with a horizontal resolution of 4.5 km is used. The simulations were carried out for two different time slices: 1971–2000 (C20), and 2071–2100 (A1B). Thunderstorm indices are applied to detect thunderstorm-prone conditions and differences in their frequency of occurrence in the two thirty years timespans. The indices used are CAPE (Convective Available Potential Energy), SLI (Surface Lifted Index), and TSP (Thunderstorm Severity Potential).

The investigation of the present and future thunderstorm conducive conditions show a significant increase of non-thunderstorm conditions. The regional averaged thunderstorm frequencies will decrease in general, but only in the Alps a potential increase in thunderstorm occurrences and intensity is found. The comparison between time slices of 10 and 30 years length show that the number of gridpoints with significant signals increases only slightly. In order to get a robust signal for severe thunderstorm, an extension to more than 75 years would be necessary.

Keywords: CCLM, COSMO-CLM, thunderstorm, CAPE, SLI, climate change, regional climate model

1 Introduction

Severe thunderstorms are high-impact weather phenomena since they can be associated with extreme precipitation, hail, tornadoes and high wind speeds. Thunderstorms are small mesoscale events that are not resolved by most weather forecast and climate models. It is generally assumed that a temperature increase associated with global climate change will lead to increased thunderstorm intensity and associated heavy precipitation events due to the Clausius-Clapeyron relation (Berg et al., 2013; Brooks, 2013).

To determine the thunderstorm potential, thunderstorm indices are a useful tool. These indices were developed to be applied to radiosonde ascents and make use of the thermodynamic ascent of an air parcel. Since severe thunderstorms are more likely to form with high values of CAPE (Convective Available Potential Energy) and vertical wind shear, wind shear is also considered because a thunderstorm can be more intense with high wind shear and have a longer duration (Weisman and Klemp, 1982). If indices are computed from numerical model output, additional quantities like vorticity and helicity can be taken into account. A majority of studies are using CAPE (Moncrieff and Miller, 1976), the surface lifted index (SLI) (Galway, 1956) and combinations with the wind difference between the surface and the mid-troposphere.

Thunderstorm indices are often calculated in climate change studies by using climate model output or global reanalyses as large-scale environmental conditions, since thunderstorms are not resolved. Brooks (2013) studied the relation of severe weather accompanied with thunderstorms (hail, tornadoes and wind) for radiosonde data sets from the USA and Europe using maximum vertical windspeed computed from CAPE (see Section 3) and 0–6 km wind component vector difference (deep layer shear, DLS). Tornadoes and large hail are found to be more frequent for high wind shear values, while weak wind shear favors high gust wind speeds at ground level. For a specific combination of CAPE and DLS the probability of thunderstorm occurrences were higher in Europe than in the USA. However, the combination of very high CAPE and DLS was much less likely to occur in Europe than in the USA, so that the overall frequency of severe thunderstorms is expected to be higher in the USA than in Europe (see also Trapp et al., 2007). These findings are used for the interpretation of global climate models for the 21st century, which show for the USA an increase in CAPE and a decrease in wind shear (Brooks, 2013).

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In a study for the Netherlands using radiosondes for the period 1993–2000, Haklander and Van Delden (2003) found that the SLI and CAPE indices are the most suitable ones to predict deep moist convection. In a study for Italy using radiosondes for the period 1995–2001 Manzato (2003) found that SLI has a higher prediction skill than a combination of CAPE and vertical windshear (which is in contrast to Brooks, 2013).

Trapp et al. (2009) used global climate model data to compute an empirical thunderstorm parameter as the product of DLS and CAPE. For the United States over the period 1950–2099 they found a link between the increasing greenhouse gas concentrations in the A1B scenario and an increasing frequency of thunderstorm occurrences.

Diffenbaugh et al. (2013) use a CMIP5 global climate model ensemble to assess the occurrence of severe thunderstorm environments over the eastern United States in response to further global warming. They show an increase in CAPE and low-level wind shear for the USA and conclude that the future climate change is associated with an increase of severe thunderstorm occurrence.

Kaltenböck et al. (2009) use ECMWF operational analyses with 25 km horizontal resolution for the years 2006–2007 to study environmental atmospheric characteristics for severe convective storms in Europe. Instability indices and CAPE are found to have considerable skill to predict the occurrence of thunderstorms, and deep-layer shear is found to be suitable to discriminate between severe and non-severe events.

In recent years, regional climate model (RCM) simulations are increasingly used to study thunderstorm occurrences. As RCMs are generally too coarse to resolve convection, thunderstorm indices or more complex combinations of convective parameters are taken as indicators for thunderstorms. Robinson et al. (2013) created a 20 year (1990–2009) severe thunderstorm climatology for the USA using a dynamical downscaling at 4 km horizontal resolution in combination with an artificial neural network. No significant trend of thunderstorm occurrences was found. For Europe, Sander (2011) used the RCM COSMO-CLM with 18 km horizontal resolution for the recent climate and the A1B scenario for 2079–2100. An increase of frequency of thunderstorm potential environments was found by using CAPE, convective inhibition (CIN) and a new Thunderstorm Severity Potential (TSP) parameter (see also Sander et al., 2013). Mohr et al. (2015) used an ensemble of CCLM simulations with different horizontal resolutions (24 to 7 km) for Germany for recent climate (1971–2000) and for the near future for the A1B scenario (2021–2050). No significant change of CAPE and SLI is found in the ensemble mean. In contrast, the application of a statistical hail model shows a significant increase of hail events for the future in the northwest and south of Germany.

The verification of modelled thunderstorm occurrences by observational data sets is difficult. There is no global observational gridded dataset, which covers the last decades consistently. There are databases like the European Severe Weather Database (ESWD) (Dotzek et al., 2009), which consists of reported thunderstorms and other severe events, but if there is no observer of the event, there is no entry of it. Kaltenböck et al. (2009) states that there is a natural correlation between number of severe weather reports and population density, whereas Brooks (2013) found the opposite. There are also databases of proximity data such as lightnings, which can be used as indicators of thunderstorm occurrences (www.euclid.org, Virts et al., 2013; Haklander and Van Delden, 2003).

In this study we are using SLI, CAPE and TSP to determine the future change of frequencies of conditions conducive to thunderstorm formation from high-resolution RCM simulations. The model is run at 4.5 km horizontal resolution for 30 year time slices for recent climate and for the A1B scenario for the end of the 21st century. The model domain covers Central Europe and a special focus was set on the region of western Germany and Luxembourg, which is the area of Rhineland-Palatinate and the so-called Saar-Lor-Lux region (Saarland, Lorraine, Luxembourg).

2 Model configuration, data and domain

Data of the regional climate model COSMO-CLM (CCLM; Rockel et al. (2008), which is the climate version of COSMO (COnsortium for Small-scale MOdelling)) was used. CCLM is coupled with the multi-layer soil model TERRA-ML with 10 levels (Schrodin and Heise, 2001; Heise et al., 2006). The CCLM is a non-hydrostatic limited-area atmospheric prediction model developed for the applications on the meso-β and meso-γ scale using primitive thermodynamical equations (Schättler et al., 2009). CCLM was used in a multi-nesting chain approach to dynamically downscale global data. The CCLM consortium runs (18 km) used for the IPCC AR4 are used as driving data. These runs are driven by ECHAM5 (Hollweg et al., 2008).

The whole model domain consists of 256 × 256 grid boxes and is shown in Figure 1 a). The region of interest, the state of Rhineland-Palatinate (RLP) and the region Saarland, Lorraine, Luxembourg (Saar-Lor-Lux) containing of 65 × 65 grid boxes, can be seen in Figure 1 b). The horizontal resolution is 4.5 km.

The model has the following configuration: 40 vertical levels with 14 levels below two kilometer height, a Runge-Kutta numerical time-stepping scheme of order 3 (Wicker and Skamarock, 2002) coupled with a fifth order advection scheme (Doms and Baldauf, 2015). For the vertical turbulent diffusion parameterization a turbulent kinetic energy closure of level 2.0 is used (Mellor and Yamada, 1974). In addition, an advanced Kessler's scheme for microphysics with a three

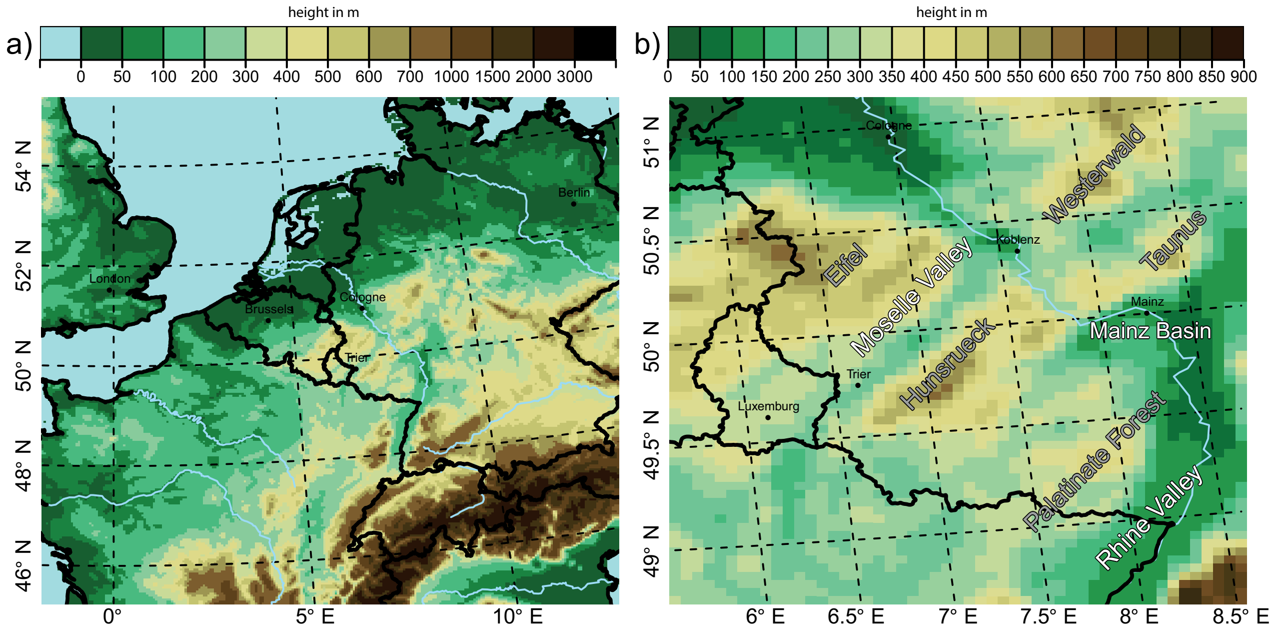

Figure 1: The domain of the COSMO-CLM model with a resolution of 4.5 km and the height of orography plotted in a) and b) shows the region of interest: Rhineland-Palatinate and Saar-Lor-Lux.

category ice scheme including graupel (Doms and Baldauf, 2015), as well as the Tiedtke scheme (Tiedtke, 1989) for moisture deep convection was used. The radiation transfer is calculated every hour with the scheme of Ritter and Geleyn (1992). No spectral nudging is applied.

The simulations were carried out for two different times slices of 30 years: 1971–2000 (C20) and 2071–2100 (A1B). Only one run is used. Within this study only the summer months June, July and August are evaluated for the assessment of thunderstorm activity.

3 Methods

3.1 Thunderstorm indices

Three thunderstorm indices were applied to detect thunderstorm-prone conditions and to derive differences in their frequency between the two 30-years periods 1971–2000 and 2071–2100. The indices used are CAPE (Moncrieff and Miller, 1976), SLI (Galway, 1956) and TSP (Sander, 2011).

The CAPE is calculated using the following formula after Moncrieff and Miller (1976):

$$CAPE = \int_{z_f}^{z_N} \frac{g}{T_{ve}}(T_v - T_{ve})dz, \qquad (3.1)$$

with z_f = level of free convection, z_N = height of the equilibrium level, g = acceleration due to gravity, T_v = virtual temperature of a parcel and T_{ve} = virtual temperature of the environment. The SB-CAPE (surface-based CAPE) is calculated in the model which uses a parcel lifted from the surface to the Level of free convection and up to the equilibrium level. CAPE is only calculated when the convection scheme is active.

The SLI is calculated by the difference between the temperature of the environment at 500 hPa and the temperature of an air parcel lifted adiabatically up to its lifted condensation level and further pseudoadiabatically up to 500 hPa.

$$SLI = T_{e500} - T_p. \qquad (3.2)$$

If the difference is positive, thunderstorms are unlikely to occur, negative values indicate a potentially unstable atmosphere and therefore thunderstorms can develop.

The TSP after Sander (2011) combines DLS and the maximum vertical velocity:

$$TSP = DLS \times w_{\max} \qquad (3.3)$$

DLS is taken as the wind component vector difference between 6 km height and 10 m. $w_{\max}$ is calculated from CAPE

$$w_{\max} = \sqrt{2 \times CAPE} \qquad (3.4)$$

The indices are used as indicators for the possibility that a thunderstorm event may occur. For a thunderstorm to develop more pre-conditions have to be met. To overcome convective inhibition large-scale lifting or orography induced uplifting is required. Low relative humidity in the mid-troposphere may have an suppressive effect on thunderstorms (Westermayer et al., 2016). The terms thunderstorm events or occurrences are used for the thunderstorm-prone conditions of the different indices. The individual classes (see Table 1) were defined

Table 1: Classes for CAPE, TSP and SLI.

class	CAPE/TSP in J/kg	SLI in K	effect
1	0–100	> 0	none
2	100–300	0 to −3	shower
3	300–1000	−3 to −5	light thunderstorm
4	1000–2500	−3 to −5	medium thunderstorm
5	2500+	< −5	severe thunderstorm

after the German Meteorological Service (DWD, 2015). Note that Class 3 and 4 for SLI are the same and are considered as one class.

3.2 Statistical analysis

We counted all occurrences of thunderstorm-prone conditions and classified the severity based on the magnitude of the indices (see Table 1) on an hourly basis. Only the strongest event was taken for each day. For each grid box, the thunderstorm occurrences were counted separately for every year of the 30 year time slices (1971–2000 and 2071–2100), yielding the number of potential thunderstorm days in the respective periods.

The significance of a potential climate signal was tested with a two sided t-test. A power analysis (Cohen, 1988) was performed to quantify the uncertainty of the signal.

The t-test was applied at every grid box with the H_0 hypothesis that the mean of the resulting 30 values of the present climate and the mean of the future climate are not different at the 95 % significance level. Furthermore, if H_0 is rejected, i.e. the differences in mean occurrences is significant (H_1 hypothesis), we applied the power analysis. The power is defined as the probability of detecting a signal if there is a true signal or the probability of rejecting H_0 if H_0 is actually false.

The power analysis after Cohen (1988) relates the power with the significance criterion ($\alpha = 95\,\%$), the sample size ($n = 30$) and an effect size which is the ratio of the absolute climate signal D and the combined inter-annual standard deviation of the present and future thunderstorm occurrences. If the power is low (high) then either the climate signal D is weak (strong) or the inter-annual variability is large (small) compared to D. For example, a power of 0.8 means a probability of 80 % to detect a correct climate signal D if H_1 is true. Instead of showing the absolute signals, we present the actual climate change signals in the result section as relative changes.

In addition to the above procedure, we repeated the analysis with 10 year time slices (1991–2000 and 2091–2100) in order to investigate the effect of time-series length on the results, since in many high-resolution RCM simulations only 10 year time slices are used.

4 Results

4.1 CAPE

For Central Europe, CAPE decreases overall for all thunderstorm classes, meaning less thunderstorm favorable conditions in the future scenario. The change of the non-thunderstorm class indicates a domain-wide increase with a high power of 0.99 for both timeseries, as shown in Tab. 2.

The classes 2 and 3 of CAPE show a significant decrease over the whole domain with high power in the 10 year time slice and a power of 1.00 in the 30 year time slice. Class 2 shows an increase of significant gridboxes and power between the two timeseries. For the classes of severe thunderstorms the number of significant gridboxes also increases when extending the time slice from 10 and 30 years, but the power and variance remain the same, meaning no clear improvement the longer the time series.

The average number of events per year of CAPE class 4 is shown in Figure 2 a) with nearly no occurrences over the sea and an average of up to 9 events in the western and northern part of the domain. The Alps show a high number of occurrences of high CAPE in the valleys (> 20 per year for CAPE class 4), while the high mountains of the Alps have values of about 5 per year, which is less than for lower mountain regions in southern Germany.

The change of class 4, which represents medium to severe thunderstorms, is illustrated in Figure 3 a). Belgium, Netherlands and the northern part of Germany show significantly decreasing occurrences of up to −50 %. In the Alps and over some parts of the English Channel, there is a significant increase in occurrences. Over the North Sea there is a slight increase, but it is not significant.

The average number of events per year for severe thunderstorms of CAPE class 5 is shown in Figure 2 b) with no occurrences over the western and southern part of the domain. The spatial distribution is the same as in Figure 2 a), but with less events. For the change in severe thunderstorms, which is displayed in Figure 3 b), an strong increase from northwest to southeast over the continent is visible. The relative differences gradually change from a decrease in the northwestern part to an increase over the Alps. Over the Alps the increase of ca. two occurrences per year is significant and over northern Belgium and the Netherlands the slight decrease of one occurrence per year is also significant. The increase over the Alps could be seen as a result of the strong orography dependence of thunderstorms.

For the Saar-Lor-Lux and RLP region the number of possible thunderstorm occurrences related to CAPE greater than 300 J/kg is shown in Figure 4 a). Between 1971 and 2000 there are up to 40 potential thunderstorm favorable events per summer with a clear dependence on the orography. The amount of thunderstorm-favorable

Table 2: Area-mean climate change signals (D) of potential thunderstorm occurrences (in events per year) of the significant grid boxes for the CAPE classes of the 10 and 30 year time slices (Jun.–Aug.). In addition, the spatial median of the power ($\tilde{x}$) and its standard deviation (σ) of corresponding two-sided t-tests ($\alpha = 95\,\%$) are given. The ratio of significant grid boxes to the total number of grid boxes is shown in the % column. n shows the area-mean of occurrences per year in the whole domain for C20/A1B. Areas are shown in Fig. 1 a) (Central EU) and Figure 1 b) (RLP), respectively. Classes are in the first column (C).

	RLP 10 years					Central EU 10 years				
C	n	%	D	$\tilde{x}$	σ	n	%	D	$\tilde{x}$	σ
1	50.9/67.3	100	16.4	1.00	0.02	56.2/69.8	98	13.7	0.99	0.09
2	15.0/9.1	87	−6.2	0.79	0.12	13.4/8.5	73	−5.7	0.82	0.13
3	17.1/8.6	100	−8.6	0.99	0.03	15.4/8.1	97	−7.5	0.97	0.11
4	6.8/5.8	2	−2.9	0.60	0.09	5.8/4.7	8	−1.9	0.65	0.14
5	1.05/0.6	9	−1.7	0.62	0.08	1.1/0.9	3	−0.5	0.64	0.10
	RLP 30 years					Central EU 30 years				
1	48.2/65.5	100	17.3	1.00	0.00	54.4/68.0	99	13.6	1.00	0.02
2	15.5/9.8	99	−5.8	1.00	0.08	13.7/9.2	82	−5.1	1.00	0.13
3	18.6/8.7	100	−9.9	1.00	0.00	16.4/8.5	99	−7.9	1.00	0.04
4	7.4/6.3	10	−2.4	0.62	0.09	6.1/5.1	23	−1.9	0.68	0.14
5	1.1/0.85	9	−1.1	0.60	0.09	1.3/1.2	8	−0.1	0.63	0.13

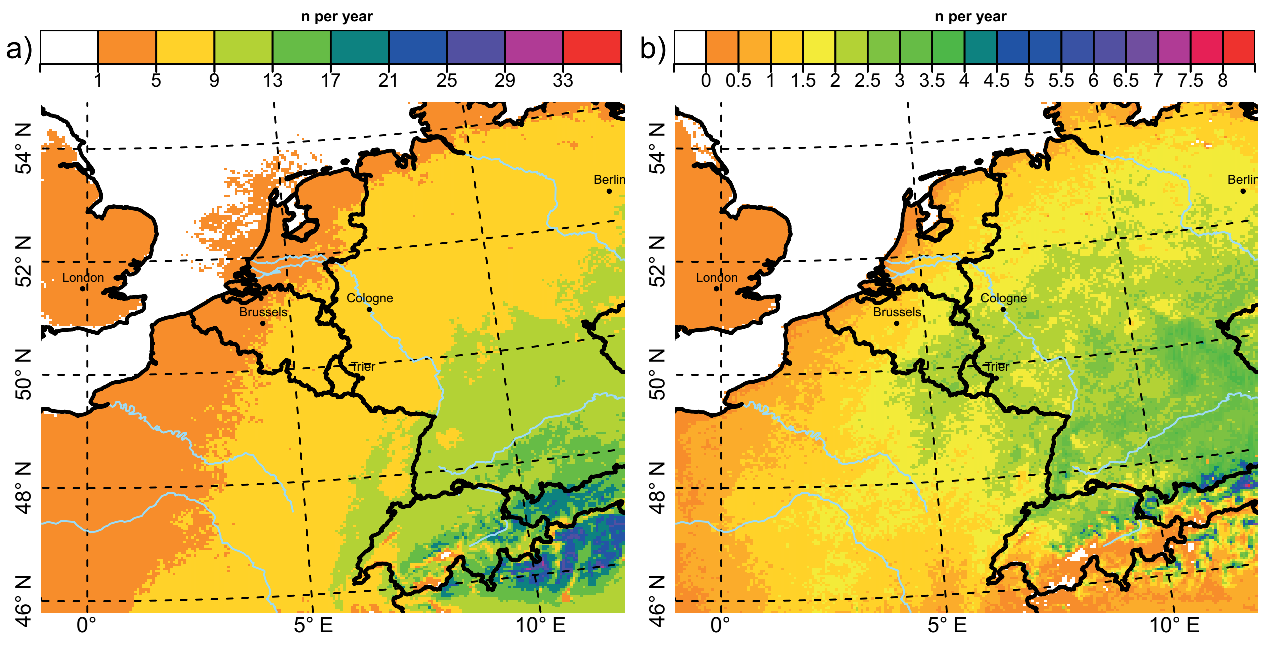

Figure 2: Mean number (n) of a) CAPE Class 4 1000–2500 J/kg per year and b) CAPE Class 5 greater than 2500 J/kg for the period 1971–2000 on daily basis for the whole domain.

CAPE situations is higher in the upper Rhine valley (south of Mainz) and lower in mountainous regions like the Eifel with 22 events per year.

The number of potential thunderstorms induced by CAPE is significantly declining about 30 to 50 % in the A1B scenario.

The distribution for light thunderstorms (class 3) is shown in Figure 4 b). The number of occurrences (Figure 4 b)) reaches values of 23 in the basin regions of Cologne and Rhine valley and only 15 in the mountainous regions like Eifel and Hunsrueck. Again a strong dependence on the orography is visible. An almost homogeneous significant decline by 50 and 60 % occurs in the future scenario.

As expected, the extreme thunderstorm class shows a low number of occurrences per year in the C20 period as seen in Figure 4 c) with up to 4 events per year in the upper Rhine valley part and an average of 2 possible events over the remaining domain of Saar-Lor-Lux. These extreme thunderstorms are declining significantly by 50 % in Belgium and surrounding areas. The remaining part of the domain is decreasing non-significantly by 10 to 40 % except the Rhine Valley which is increasing by more than 20 % (also not significant, not shown).

The percentage of significant gridboxes is dropping from 100 % from the lower CAPE classes to 9 % in the higher CAPE classes and there is no difference between the 10 and 30 years timeseries (Tab. 2).

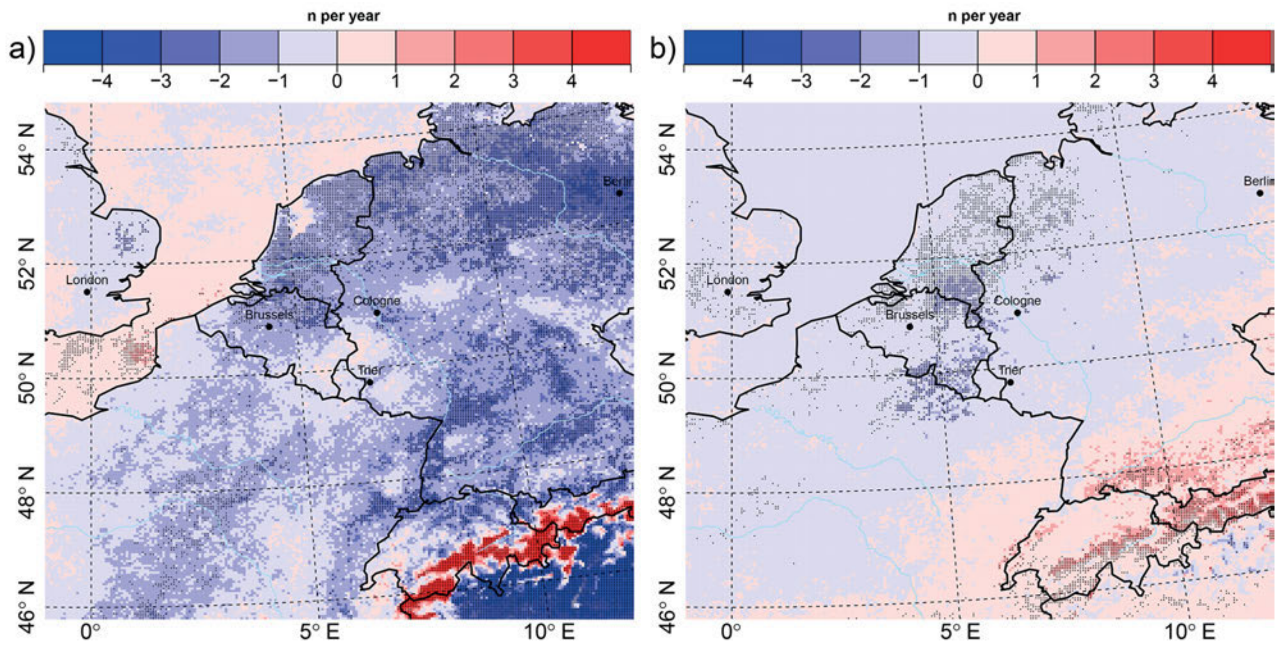

Figure 3: Difference of occurrences per year of a) CAPE Class 4 1000–2500 J/kg and b) CAPE Class 5 greater than 2500 J/kg between 1971–2000 and 2071–2100 on daily basis for the whole domain. Significant changes are marked with a dot.

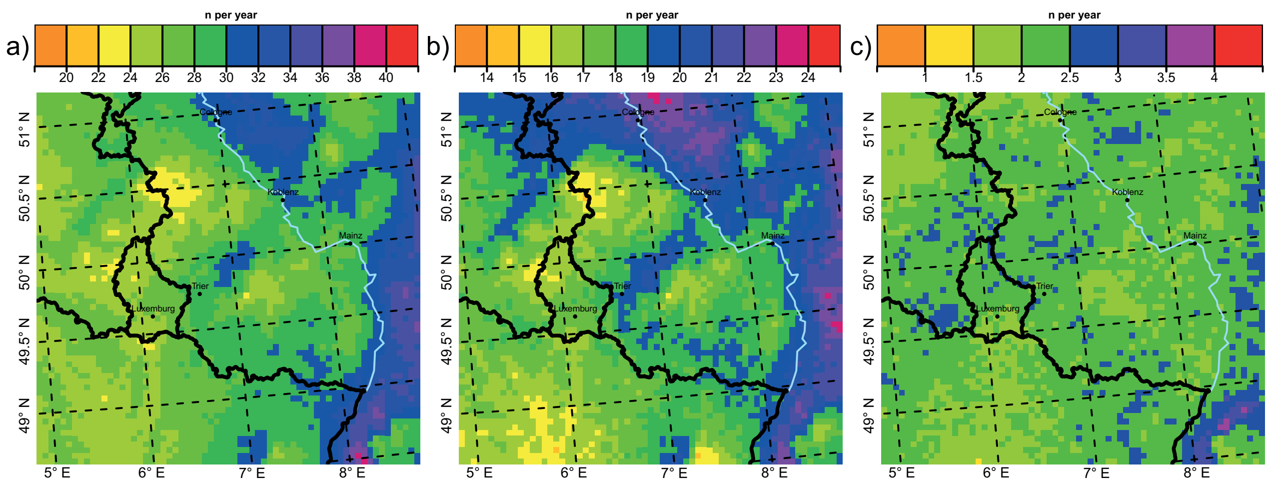

Figure 4: Mean number (n) of CAPE values per year a) greater than 300 J/kg, for b) CAPE Class 3 300–1000 J/kg and for c) CAPE greater than 2500 J/kg for the period 1971–2000 on a daily basis for Saar-Lor-Lux and Rhineland-Palatinate.

Overall, it can be concluded that the CAPE for medium to severe thunderstorms is decreasing (but not significantly) whereas the non-thunderstorm CAPE class increases significantly.

4.2 SLI

The number of the occurrences for the non-thunderstorm class (SLI > 0 K) increases significantly in the northeastern part of Central Europe by up to 20 % and in northern Italy by up to 60 % (Figure 5 a)). In western Germany, the northern parts of France, the northern Alps and the English Channel show no significant changes.

For the severe thunderstorm class of SLI, an overall decrease is found over most land areas (Figure 5 b)), meaning less unstable atmospheric conditions. But significant changes can only be seen for some areas of France, Northern Italy and mid-Germany. The English Channel shows a very high increase, which is also not significant because of initial values close to zero. All the white areas in Figure 5 b) are due to the absence of occurrences in this class of the SLI.

Comparing the statistics in Table 3 for Central Europe we see for the 30 year period an increase for the non-thunderstorm class with a high power, as well as a slight increase in the medium thunderstorm class but with a low power. The light and severe thunder-

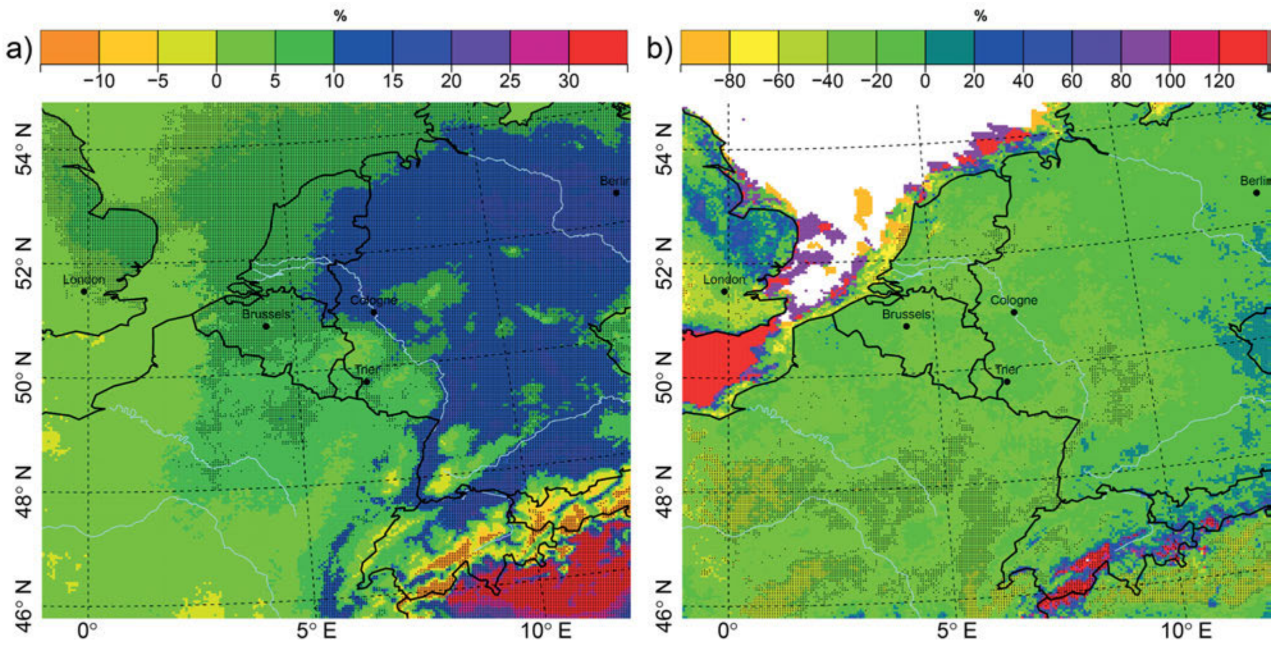

Figure 5: Like Figure 3 but for a) SLI greater than 0 K and b) SLI smaller than −5 K. White areas are NA-values due to no occurrences in the class in either C20 or A1B. Significant changes are marked with a dot.

Table 3: As Table 2 but for SLI.

	RLP 10 years					Central EU 10 years				
C	n	%	D	$\tilde{x}$	σ	n	%	D	$\tilde{x}$	σ
1	59.0/60.9	4	6.4	0.61	0.06	62.9/66.1	16	−7.3	0.72	0.14
2	21.4/19.3	15	−5.1	0.73	0.13	20.1/16.9	30	6.1	0.83	0.15
3	6.0/7.2	4	3.3	0.63	0.11	5.2/5.6	5	−0.7	0.68	0.13
5	2.7/2.2	1	−2.5	0.61	0.07	3.6/3.2	4	2.7	0.65	0.12
	RLP 30 years					Central EU 30 years				
1	56.4/61.2	53	5.8	0.76	0.14	61.4/65.6	56	5.9	0.86	0.15
2	23.6/18.81	96	−4.9	0.94	0.11	21.3/17.3	69	−5.2	0.97	0.14
3	6.2/7.5	17	1.9	0.60	0.09	5.3/5.7	10	0.1	0.70	0.17
5	2.8/2.27	6	−2.1	0.56	0.07	3.9/3.2	12	−1.8	0.63	0.13

storm classes have a decreasing signal. The improvement by extending the time period from 10 to 30 years for the number of significant gridboxes is obvious, as both low and severe classes show a large improvement. The power of the lower classes increases with longer time series, but in contrast to CAPE the variance does not get smaller. Also the climate change signal is changing its sign between both periods. This is because the 20 years before the 10 year period have a larger positive signal and with averaging the signal becomes positive. This is vice versa for the light thunderstorm class.

For RLP and Saar-Lor-Lux the statistics in Table 3 show an increase in the non-thunderstorm class as well as in the light to medium thunderstorm class and a decrease in both other classes. The power values are too low to conclude a significant climate change signal, only for class 2 with a 30 year long time series the power is high enough. Comparing the percentage of significant grid boxes of the classes between 10 and 30 years a remarkable increase in coverage can also be seen for the Central Europe domain.

The SLI-Index in RLP for thunderstorm classes 2–5 (Figure 6 a)) shows the highest frequencies in the upper Rhine valley in the southeast. In the northwestern part there are about 30 occurrences in the 1971–2000 period, while there are about 50 occurrences in the southeast. Again a slight dependence on the orography is seen as for CAPE.

For A1B the amount is decreasing by 30 % in the Cologne basin and about 10 % in the rest of the domain (see Figure 7 a)) for all thunderstorm favorable situations. The changes are not significant. For the non-thunderstorm class, a significant increase occurs in more than 50 % of the domain, whereas a significant decrease in more than 90 % of the domain is found for the low thunderstorm class 2 (Tab. 3).

Figure 6 b) shows the occurrences in the period 1971–2000 for class 5 of SLI for heavy thunderstorms.

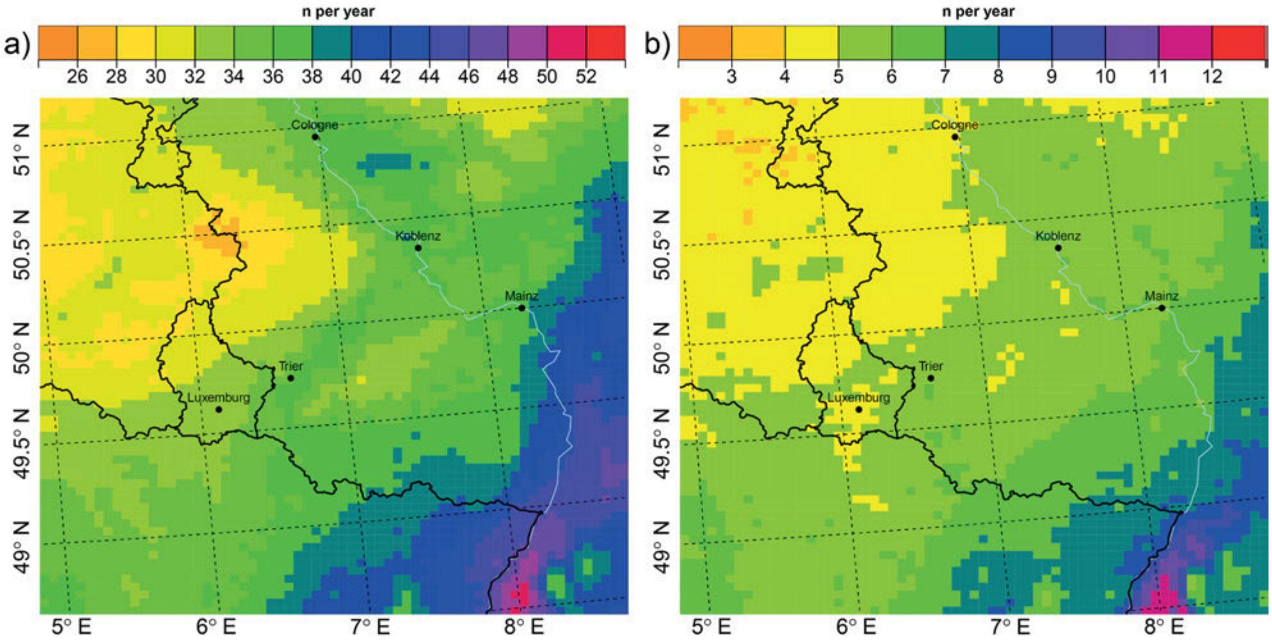

Figure 6: Like Figure 4 but for a) SLI smaller than 0 K and b) SLI smaller than −5 K.

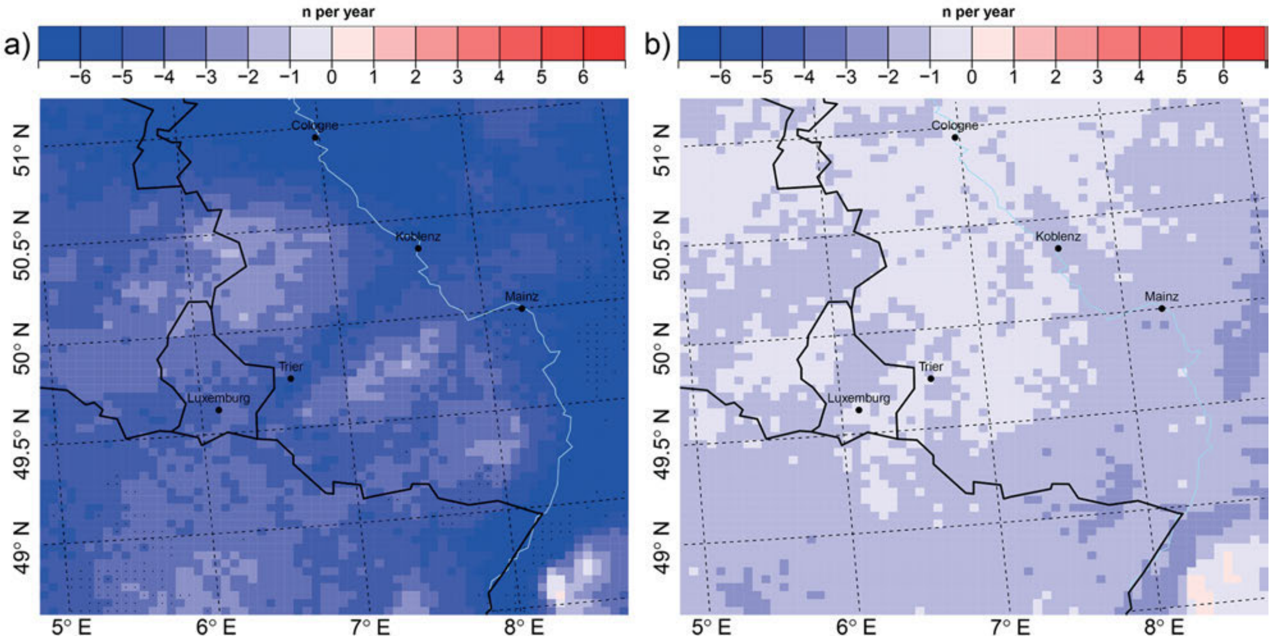

Figure 7: Difference of occurrences per year of a) smaller than 0 K and b) SLI smaller than −5 K between 2071–2100 and 1971–2000 on a daily basis for Saar-Lor-Lux and Rhineland-Palatinate.

There is again a northwest southeast gradient with 5 occurrences in the northwest and up to 12 occurrences per year in the southeast region at the Black Forest. The change of this class is plotted in Figure 7 b) and reveals an overall decrease with only some regions like Lorraine and Palatinate Forest showing a significant decrease.

Overall, it can be concluded that, similar as for CAPE, an overall significant increase in the non-thunderstorm classes and a non-significant decrease in the severe thunderstorm is found.

4.3 TSP

The Thunderstorm Severity Potential (TSP) index shows a similar spatial distribution as CAPE, but with lower values of occurrences (see also Tab. 4). Few occurrences of medium to high TSP values are found in the north, west and over the sea, but high frequencies of medium to high TSP are found for the mountainous regions of the Alps with up to 20 potential thunderstorm occurrences per year in the C20 simulation for the medium

Table 4: As Table 2 but for TSP.

	RLP 10 years					Central EU 10 years				
C	n	%	D	$\tilde{x}$	σ	n	%	D	$\tilde{x}$	σ
1	32.5/52.5	94	20.2	0.99	0.02	37.1/51.7	88	15.9	0.97	0.10
2	29.9/21.7	76	−9.1	0.77	0.13	30.1/24.0	54	−8.2	0.75	0.13
3	26.3/15.2	94	−11.3	0.99	0.07	22.2/13.9	90	−8.9	0.97	0.11
4	3.21/2.6	5	−2.6	0.96	0.18	2.5/2.3	5	−0.7	0.66	0.13
5	0.0/0.0	0	–	–	–	0.0/0.0	0	0.4	0.64	0.03
	RLP 30 years					Central EU 30 years				
1	31.5/49.7	94	18.4	1.00	0.00	35.7/49.3	94	14.3	1.00	0.08
2	29.0/23.2	82	−6.2	0.88	0.13	30.2/25.2	68	−6.5	0.98	0.14
3	27.6/16.0	94	−11.8	1.00	0.00	23.2/15.0	98	−8.3	1.00	0.06
4	3.8/2.9	18	−1.8	0.69	0.16	2.9/2.5	19	−0.9	0.68	0.14
5	0.0/0.0	0	–	–	–	0.0/0.0	0	0.1	0.55	0.05

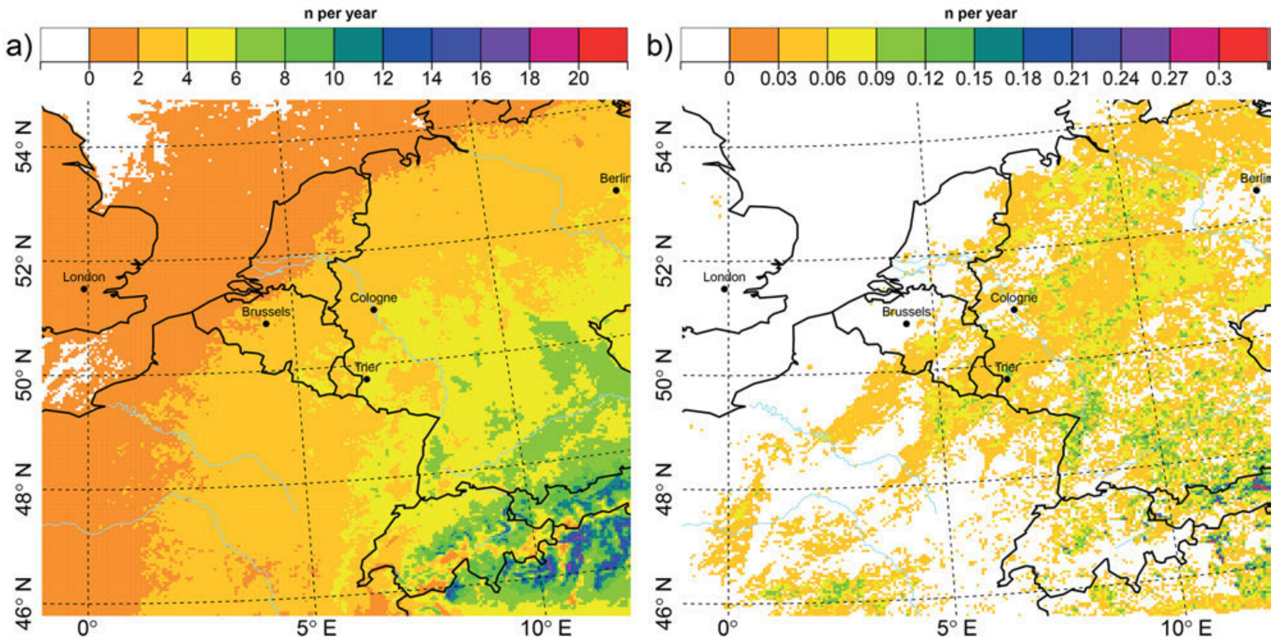

Figure 8: Like Figure 2 but a) for TSP between 1000–2500 J/kg and b) TSP greater than 2500 J/kg.

thunderstorm class (see Figure 8 a)). The severe thunderstorm class has far less occurrences with generally less than 4 events in 30 years (see Figure 8 b)). The non-thunderstorm class of the TSP reveals a significant increase as shown in Table 4 for the region of interest as well as for the whole domain. The medium to high class 4 of TSP has an overall decrease with significant changes in the low altitude regions like the Rhine valley, southern France, Belgium and Netherlands as seen in Figure 9 a). The general change pattern, also with an increase in the Alps, is similar to CAPE class 4 (Figure 3 a)). The most severe class (see Figure 9 b)) shows a slight increase in some areas, which is neither significant nor meaningful because the number of significant points is (rounded down) 0 % and the number of occurrences for C20 is very low (between 2 and 4 as seen in Figure 8 b)). The t-test even fails for our region of interest, as seen in Table 4.

The expansion to 30 years yields a slight improvement compared to 10 years. The power for both periods is very high for the lower classes. The low number of occurrences for the high classes of TSP could be explained with the combination of shear and vertical velocity. To be high, both vertical velocity and shear need to be high which is rare in our simulations.

5 Conclusion and Summary

In this study we investigate the potential change of thunderstorm occurrences in the A1B scenario for 2071–2100 relative to 1971–2000. We use the thunderstorm indices CAPE, SLI and TSP. A t-Test and a power analysis is applied to evaluate a calculated climate change signal for Central Europe with a special focus on Rhineland-Palatinate (RLP). Overall, it can be

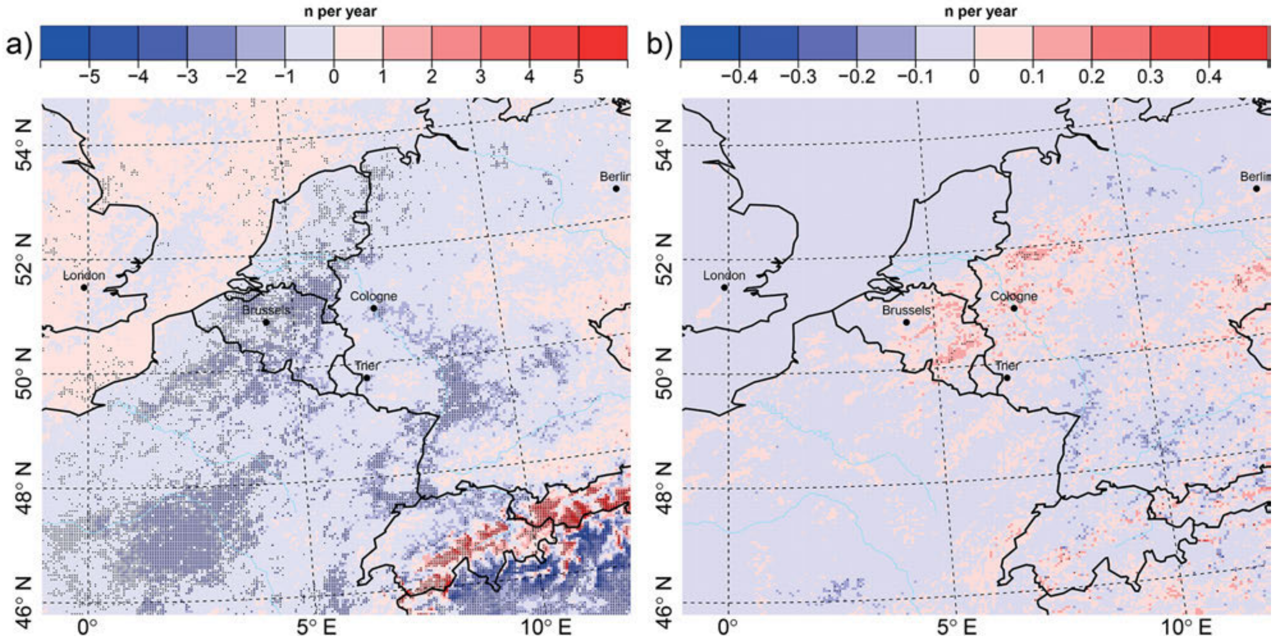

Figure 9: Like Figure 3 but a) for TSP between 1000–2500 J/kg and b) TSP greater than 2500 J/kg.

concluded that the potential for thunderstorms in mid-Germany and RLP decreases. The frequency of higher classes of CAPE and SLI shows consistent significant increases only in the Alps. For Belgium, Netherlands and Northern Germany a significant decrease of high CAPE frequency is found, which is also seen in SLI (but not significant at the 95 % level). The TSP index yields similar results as the CAPE analysis, but with less occurrences. TSP values corresponding to severe thunderstorms occur only 2–4 times in 30 years. The analyses for the area average of Central Europe and RLP yield a robust signal of an increase of non-thunderstorm conditions. The decreases of light thunderstorm conditions are significant for CAPE and TSP. The results for the higher classes are associated with high uncertainties, which is reflected in the low power values.

With regard to the comparison of the statistics between 10 years and 30 years, it can be concluded that the extension to 30 years improves the results for the SLI index, while for CAPE and TSP the improvement is small. The uncertainty of the climate change signal for no to light thunderstorms is reduced as the power values increase, but for severe thunderstorms the uncertainty remains unchanged. For the extreme thunderstorm events an even longer time series > 75 years would be needed to make the statistics more robust.

The chosen thunderstorm indices describe thunderstorm-prone conditions, which will not necessarily lead to thunderstorms, since effects like convective inhibition or large scale lifting mechanisms are not reflected by these indices. However, a study of the vertical wind at 700 hPa simulated by the CCLM model for different CAPE classes for 1971–2000 shows that for CAPE classes 4 and 5 uplift with more than 5 cm/s is present for more than 90 % of the cases. In 13–15 % of the cases, the upward velocity exceeds 50 cm/s, indicating that the thunderstorm is resolved by the model. This remains almost unchanged for the A1B scenario. Thus, at least for CAPE related indices, there is a high probability that thunderstorms are present. This is consistent with the fact that CAPE is only calculated when the convection scheme is active in the model.

In our study only one model run and thus also only one GCM as driving data is used due to computational and storage capacities. An ensemble of model runs with various driving GCMs would yield a more representative statistical results as the shortcomings of individual climate models can be reduced. The high computational demand of ensemble runs at a resolution of 5 km or less for Central Europe for present and future climate is a challenge for cooperative efforts such as EURO-CORDEX (Jacob et al., 2014). In conclusion, our findings show that during climate change the environmental conditions get less favorable for thunderstorm development in most regions of Central Europe, which is in contradiction to the generally assumed increase of severe weather based solely on the argument of the Clausius-Clapeyron equation.

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