Differing trends in United States and European severe thunderstorm environments in a warming climate

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Abstract

Long-term trends in the historical frequency of environments supportive of atmospheric convection are unclear, and only partially follow the expectations of a warming climate. This uncertainty is driven by the lack of unequivocal changes in the ingredients for severe thunderstorms (i.e. conditional instability, sufficient low-level moisture, initiation mechanism and vertical wind shear). ERA5 hybrid-sigma data allows for superior characterization of thermodynamic parameters including convective inhibition, which is very sensitive to the number of levels in the lower troposphere. Using hourly data we demonstrate that long-term decreases in instability and stronger convective inhibition cause a decline in the frequency of thunderstorm environments over the southern United States, particularly summer. Conversely, increasingly favourable conditions for tornadoes are observed during winter across the Southeast. Over Europe, a pronounced multidecadal increase in low-level moisture has provided positive trends in thunderstorm environments over south, central and north, with decreases over the east due to strengthening convective inhibition. Modest increases in vertical wind shear and storm-relative helicity have been observed over northwestern Europe and the Great Plains. Both continents exhibit negative trends in the fraction of environments with likely convective initiation. This suggests that despite increasing instability, thunderstorms in a warming climate may be less likely to develop due to stronger convective inhibition and lower relative humidity. Decreases in convective initiation and resulting precipitation may have long-term implications for agriculture, water availability and the frequency of severe weather such as large hail and tornadoes. Our results also indicate that trends observed over the United States cannot be assumed to be representative of other continents.
Capsule summary

Stronger convective inhibition causes a decline in the frequency of thunderstorms over the United States, while a substantial increase in low-level moisture supports more thunderstorms over southern, central and northern parts of Europe.

Introduction

Increases to the frequency and intensity of severe thunderstorms are an expected outcome of anthropogenic warming over North America and Europe by 2100 (Diffenbaugh et al. 2013; Hoogewind et al. 2017; Allen 2018; Rädler et al. 2019; Trapp et al. 2019). However, detecting historical changes to the frequency of convective events has proven challenging, as direct observations are incomplete (Allen and Tippett 2015; Groenemeijer et al. 2017; Edwards et al. 2018; Chernokulsky et al. 2019; Taszarek et al. 2019). In the United States, changes in how tornadoes are reported have made it difficult to detect credible trends despite increases in the variability of these events and the intensity of outbreaks since the 1970s (Brooks et al. 2014; Elsner et al. 2015; Tippett et al. 2016). Due to these limitations, a typical practice has been to consider trends over time in environments favorable to the development of severe storms (Mohr and Kunz 2013; Mohr et al. 2015; Pistotnik et al. 2016; Rädler et al. 2018; Taszarek et al. 2019, 2020). However, studies focusing predominantly on North America have failed to identify significant trends consistent with those expected by future climate projections (Gensini and Ashley 2011; Robinson et al. 2013; Allen et al. 2015; Gensini and Brooks 2018; Allen et al. 2019).

To provide the extended record for analysis of trends, reanalysis data have typically been used to characterize convective environment, as observed upper air profiles are comparatively sparse (Brooks et al. 2003; Allen and Karoly 2014; Gensini et al. 2014; Taszarek et al. 2018; King and Kennedy 2019). These data are used to take an ingredient-based approach to identifying
the bounding distribution of environments favorable to severe convection (Johns and Doswell
1992; Doswell et al. 1996). Four relevant factors are conditional instability, sufficient low-level
moisture, an initiating mechanism, and vertical wind shear. Instability can be expressed by
convective available potential energy (CAPE), which provides an estimate of vertically integrated
buoyancy force acting on a rising air parcel. This parameter is typically used to approximate the
potential strength of an updraft (w), via the relationship \( w = \sqrt{2\text{CAPE}} \) (Emanuel 1994). The
presence of CAPE is a necessary condition for thunderstorm development. However no
thunderstorm will form if convective initiation does not take place. Convective inhibition (CIN),
quantifies the portion of the atmosphere where a rising air parcel experiences negative buoyancy
before reaching an unstable layer, and thus requires external forcing to reach a level of free
convection. An absolute CIN of around 75-100 J kg\(^{-1}\) can notably reduce chances for convective
initiation despite ample CAPE (Bunkers et al. 2010; Gensini and Ashley 2011; Hoogewind et al.
2017; Taszarek et al. 2019). However, CIN alone should not be considered as a predictor of
initiation, as other features such as dry air entrainment or availability of sufficient synoptic-scale
lift are also important factors (Trapp and Hoogewind 2016; Westermayer et al. 2017). A fourth
ingredient, vertical wind shear, governs the organization of updrafts and enables formation of
long-lived storm modes such as supercells or quasi-linear convective systems that are more
capable of producing severe weather (Smith et al. 2012; Thompson et al. 2012; Guastini and
Bosart 2016; Gatzen et al. 2019; Antonescu et al. 2020).

Our current expectations are that a wetter and more unstable troposphere in the future
climate will lead to the environment being more conducive to deep moist convection
However, whether convection initiates is a substantial limit on estimating thunderstorm
occurrence from environments. Since CIN depends on details in the thermodynamic structure, its
accurate calculation requires high resolution in the lowest part of the atmosphere. Because of the
limited boundary-layer vertical resolution of current climate models and reanalyses, it is uncertain how well those models can assess changes in CIN. In this study, we consider long-term trends in parameters associated with severe thunderstorms over Europe and the United States, and investigate the role played by changes in CIN. Based on high vertical resolution reanalysis data (including 28 levels in the lowest 2 km of the atmosphere) we show that substantial increases in CIN may offset any gains in instability and even cause a net decrease in the number of thunderstorms. Knowledge of the historical changes in convective environments can help to better understand how CIN may potentially affect the frequency of severe thunderstorms in a warmer future climate. Positive trends in instability may not necessarily result in a higher number of storms, particularly when accompanied by a considerable increase in CIN.

Datasets and methodology

Reanalysis data

For the purposes of this study we used the fifth generation of ECMWF (The European Centre for Medium-Range Weather Forecasts) atmospheric reanalysis (ERA5; Hersbach et al. 2020) over a period of 41 years from 1979 to 2019. The dataset has a 0.25° horizontal grid spacing with 137 terrain-following hybrid-sigma model levels, which contrasts many earlier studies that have used fewer pressure levels for parcel computations. For both Europe and the United States the domain contains 149 meridional and 244 latitudinal grid points at 1-hourly temporal resolution. As a result, a total of 25.4 billion vertical profiles were post-processed to derive descriptive convective parameters. All computations performed in this work are based on hourly resolution, which contrast prior studies that used daily or 6-hourly intervals. An aspect of diurnal cycle in convective variability (e.g. highest CAPE during the day) should be also considered when interpreting the results based on percentiles.
Lightning data
Cloud-to-ground (CG) lightning flash counts for the observational validation of trends were derived from the National Lightning Detection Network (NLDN; Cummins and Murphy 2009; Kingfield et al. 2017) for the years 1989-2018. Since detection efficiency of CG lightning has been more stable in NLDN over time compared to intra-cloud (IC) flashes (Koehler et al. 2020), the latter was not taken into account. Flashes with a peak current lower than 15 kA were removed as many of them result from IC flashes (Wacker and Orville 1999, Kingfield et al. 2017, Medici et al. 2017, Koehler et al. 2020). Detection efficiency of NLDN has improved from around 70% in 1989 (Orville 1991) to 95% since 2013 (Murphy and Nag 2015). In this study, lightning counts were summed on a 0.25° grid at the hourly step to match the ERA5 resolution.

Trend and parameter computations
The long-term climatology used herein is expressed by a fraction, frequency or percentiles of a specific variable, which is then evaluated unconditionally or conditionally on covariate parameters. Trends at each grid point are then derived by obtaining values for each individual year and applying the non-parametric Sen’s slope analysis (Wilcox 2010). We chose this metric due to its insensitivity to outliers and frequent application for evaluating robust trends in the atmospheric sciences. Significance of the trend is assessed using a two-tailed $p$-value at the 0.05 threshold, and are denoted as ‘$x$’ signs on each figure. Slope units are normalized to correspond to changes over a period of 10 years. Following Rädler et al. (2019) we use 50th percentile to investigate climatology and changes in a wind shear, and upper distributions (95th and 99.9th percentiles) for thermodynamic parameters.

For parcel parameter calculations, a surface to 500 m above ground level (AGL) mixed-layer was used while also applying a virtual temperature correction (Doswell and Rasmussen 1994). CAPE is calculated using the vertical integral of positive parcel buoyancy (relative to the
environment) from the lifted condensation level to equilibrium. CIN is calculated using the integral of negative parcel buoyancy between the mixed-layer and the level of free convection. Vertical wind shear (BS06) was calculated by interpolation of winds to the height profile, taking the magnitude of the vector difference between surface and 6 km AGL. In order to compute storm-relative helicity (SRH03) we applied the internal dynamics method to estimate storm motions (Bunkers et al. 2000), then integrated between the surface and 3 km AGL. Temperature lapse rates (LR75) were computed between 500 and 700 hPa. A list of all parameters used in the study can be found in Table 1.

Definition of environmental proxies

The choice of environmental covariates to define thunderstorm, severe thunderstorm and tornadic thunderstorm situations was based on previously evaluated thresholds. For thunderstorms, a number of studies (Craven and Brooks 2004; Van den Broeke et al. 2005; Kaltenböck et al. 2009; Westermayer et al. 2017; Taszarek et al. 2017, 2019) have compared unstable non-thunderstorm and thunderstorm environments and obtained a best discriminator in the range between 50 and 200 J kg⁻¹. For this study, a proxy of CAPE exceeding 150 J kg⁻¹ was defined as meeting the conditions favorable for a thunderstorm, the same as in Taszarek et al. (2019, 2020).

A number of studies have demonstrated that the likelihood of severe convection increases along with increasing instability and increasing vertical wind shear that governs the organization and longevity of updrafts (Weisman and Klemp 1982; Brooks et al. 2003; Trapp et al. 2007; Allen et al. 2011; Brooks 2013; Pučík et al. 2015; Taszarek et al. 2017). For this reason, we used a composite product of CAPE and BS06 (WMAXSHEAR; a theoretical estimate of the updraft’s vertical velocity multiplied by a vertical wind shear) for assessing the climatological aspects of severe thunderstorm environments. A threshold of WMAXSHEAR exceeding 500 m² s⁻² (with
the assumption that BS06 should be no lower than 10 m s⁻¹) is used here to define a severe
thunderstorm environment, based on results from prior work (Brooks et al. 2003; Allen et al.

To define a potential tornadic thunderstorm we use a significant tornado parameter (STP)
based on updated formula from Coffer et al. (2019), which consists of CAPE, lifted condensation
level, SRH, effective shear and CIN. STP values of approximately 1 have been shown to be
capable of discriminating between significant tornadic and non-tornadic supercells over the
United States (Grams et al. 2012; Gensini and Bravo de Guenni 2019). However, over Europe
this threshold is less effective in predicting significant tornadoes (Kaltenböck et al. 2009;
Rodriguez and Bech 2018), as from a climatological perspective instability and helicity are
typically lower compared to environments in the United States (Gensini and Ashley 2011;
Taszarek et al. 2018). To account for this effect, in this study we apply a lowered STP threshold
of 0.75 (for both domains) to define situations with potential tornadic thunderstorms. The formula
for the supercell composite parameter (SCP) is taken from Gropp and Davenport (2018), while
significant hail parameter (SHIP) is based on the original equation available in NOAA Storm
Prediction Center (www.spc.noaa.gov).

Environmental proxies are only an imperfect conditional approximation of convective
activity, as not every favorable environment produces a severe thunderstorm, or a thunderstorm at
all. For this reason we add an additional condition using the convective precipitation (CP) hourly
accumulation as a proxy for convective initiation. The underlying ERA5 convective
parameterization (Bechtold et al. 2014) applies a mass flux closure scheme with entrainment that
triggers convection based on either surface fluxes or synoptic motions, thereby providing greater
confidence of initiation. We apply a CP threshold of 0.25 mm h⁻¹, following Taszarek et al.
(2020) who used the same proxy to construct a climatology of thunderstorm environments with
ERA5. Similar approaches have also been used in many prior studies using reanalyses and
climate projections (Trapp et al. 2009; Tippett et al. 2012; Romps et al. 2014; Allen and Tippett 2015; Pučik et al. 2017; Tippett and Koshak 2018; Taszarek et al. 2019; Tippett et al. 2019). The CP proxy in this study is applied by taking into account hourly precipitation accumulation for the hour following instantaneous characterization of environmental parameters (i.e. CAPE threshold from 17 UTC is matched with CP for 17-18 UTC). A summary of applied conditional proxies is presented in Table 2. Since the majority of above described proxies have been developed for convective events occurring over land, in this study we do not evaluate modeled (severe) thunderstorm and tornadic environments over the sea and ocean surface.

As demonstrated by Tippett et al. (2019) performance of thunderstorm proxies vary by the region and time of the year. This poses challenges, particularly given how different convective environments are between the United States and Europe. Thus, such an analysis will be always burdened with some degree of inaccuracy, no matter the parameter chosen. Application of convective proxies obviously does not provide an explicit number of storm events (Hoogewind et al. 2017), but it helps to narrow situations to those that may most likely result in (severe) thunderstorms. Evaluation of long-term changes in such environments should be representative of relative changes in the frequency of actual convective events, even though magnitude of these changes may not be in a perfect agreement.

Results

Ingredients for deep moist convection

Consistent with the recent reports of the Intergovernmental Panel on Climate Change (IPCC, 2018), statistically significant upward trends are found in the upper distribution of surface temperature (T2M; Fig. 1a) over the last 4 decades for the majority of Europe (>0.75 °C per decade). In contrast, over the United States this trend is limited mainly to the high elevation mountain west. Temperature lapse rates between 700 and 500 hPa (LR75: Fig. 1b) describe the
vertical gradients in the mid-atmosphere, and values exceeding 6.5 °C km⁻¹ can be linked to 
environments promoting severe thunderstorms (Brooks et al. 2003; Banacos and Ekster 2010; 
Taszarek et al. 2017). While the spatial climatology of LR75 is distinct from T2M, increasing 
trends in surface temperatures and reductions in low-level moisture are driving greater dry static 
stability over high terrain, and thus may lead to increasingly steep vertical gradients of 
temperature. These changes result in orographically correlated increases in LR75 over the 
western United States and parts of the Great Plains (>0.1 °C per decade), particularly during 
spring and summer (seasonal changes of LR75 and T2M are available in the Supplementary 
Material). Over Europe significant increases occur mainly over eastern part of the continent, 
especially around the Black Sea (>0.05 °C per decade). This pattern may be related to small 
changes in near surface moisture (mixing ratio - MIXR; Fig. 1c), which along with increasing 
temperature leads to reduced relative humidity, and increasingly deep boundary layer mixing 
(Byrne and O’Gorman 2016). Similarly, over the mountainous west United States, negative 
trends in low-level moisture feedback to the generation of dry adiabatic lapse rates suggesting 
intensification of the process in which elevated mixed-layer (EML; Carlson and Ludlam 1968) is 
generated. MIXR has increased substantially over northern and central Europe (0.2-0.3 g kg⁻¹ per 
decade; Fig. 1c), while greater increases have occurred across the Mediterranean and Black Sea 
(>0.4 g kg⁻¹ per decade), particularly during summer and autumn (Appendix A). Over the United 
States increases are confined predominantly to the northern Great Plains (0.2 g kg⁻¹ per decade), 
but on a seasonal basis large wintertime increases have been observed over the Southeast (0.4 g 
kg⁻¹ per decade).

Combining the components from Fig. 1 we consider trends in vertically integrated 
thermodynamic instability using CAPE (Fig. 2a). Increases in CAPE are well-correlated with 
rising MIXR (Fig. 1c) and indicate significant positive trends over northern and central Europe 
(25-50 J kg⁻¹ per decade) with substantial increases over the Black Sea, northern Italy and parts of
the Mediterranean (>100 J kg$^{-1}$ per decade). While the greatest changes in instability were

detected over the northern Great Plains of the United States (> 75 J kg$^{-1}$ per decade), there are

widespread robust negative trends of more than -50 J kg$^{-1}$ per decade over the majority of the

continent. Changes in CAPE are spatially collocated with seasonal changes in MIXR and indicate

increases over the Midwest during spring, the northern Great Plains during summer and the

Southeast during winter (contrasting decreases in summer and autumn; Appendix B). Over

Europe significant decreases in CAPE are found over the Iberian Peninsula.

However, the presence of instability itself is not sufficient for the formation of

thunderstorms, as convective initiation is necessary to benefit from the availability of CAPE. This

process may be inhibited if stable layers with negative parcel buoyancy occur in the lowest

portions of the troposphere. Increases in CIN over Europe are generally modest (5-15 J kg$^{-1}$ per

decade) and spatially collocated with increasing CAPE (Fig. 2b). The largest trends, exceeding 20

J kg$^{-1}$ per decade, occur over eastern portions of Mediterranean and Black Sea seasonally tied to

summer (Appendix C). Robust increases in CIN occur over the majority of the United States,

particularly over the Great Plains (>15 J kg$^{-1}$ per decade), including areas where the underlying

trend in CAPE has also shown decreases (Fig. 2b). On a seasonal basis the highest significant

increases have occurred over southern Great Plains during spring (>30 J kg$^{-1}$ per decade).

Substantial changes in CIN can be partially explained by the robust increases in LR75 over

western mountainous regions (Fig. 1b) and subsequent advection of an EML over the lower

elevations of the continent (especially southern and central Great Plains). This process may lead

to a more stable stratification between the boundary layer and the EML, and hence stronger CIN

as a result. Substantial increases in CIN suggest that convective initiation may be delayed within

the diurnal cycle, precluded in totality, or lead to explosive convective initiation with severe

weather when instability is allowed to reach its diurnal peak (Trapp and Hoogewind 2016;

Hoogewind et al. 2017).
Vertical wind shear is an important component related to storm severity (Brooks et al. 2003; Allen et al. 2011; Brooks 2013; Pučík et al. 2015; Taszarek et al. 2017) and can be vectorized by a difference of wind speed and direction between the surface and a height of 6 km (BS06; Fig. 2c) or by changes in the speed and direction of the vertical wind profile up to 3 km (SRH03; Fig. 2d). Long-term changes in the median of BS06 and SRH03 conditional on CAPE > 150 J kg⁻¹ indicate negative trends over portions of southern and southeastern Europe (-0.5 m s⁻¹ per decade). This contrasts with significant increases over northwestern Europe (0.75-1.25 m s⁻¹ per decade), seasonally tied mainly to the summer (Appendix D). These changes may be driven by shifts and/or weakening in the jet stream (Archer and Caldeira 2008; Pena-Ortiz et al. 2013) as a result of decreasing horizontal temperature gradient between the mid-latitudes and the Arctic (Coumou et al. 2015). Over the United States a modest change in BS06 (0.4 m s⁻¹ per decade) and a significant increase of SRH03 (6 m² s⁻² per decade) is found over the Great Plains, partially collocated with increasing CAPE. Seasonally, these increases take place mainly during spring and summer (Appendix E). A possible explanation for a change in SRH03 may be related to strengthening of the Great Plains low-level jet that was noted over a historical period (Barandiaran et al. 2013) and is an expected outcome of a warming climate (Cooke et al. 2008, Tang et al. 2017).

Seasonal variability of severe thunderstorm environments

Combining CAPE and BS06 into a bivariate proxy (Brooks et al. 2003) of conditions favorable to severe thunderstorms, trends in the seasonal distribution of the WMAXSHEAR product (Del Genio et al. 2007; Brooks 2013; Taszarek et al. 2017, 2018, 2019) were considered (Fig. 3). Climatology of WMAXSHEAR over Europe indicates that severe thunderstorms are most likely to occur during summer in the corridor from northeastern Spain through portions of central Europe, Italy and the Balkan Peninsula. The strongest long-term increases in that period...
are observed over northwestern, northern, central and parts of southern Europe, with localized
decreases over Iberian Peninsula, Balkan Peninsula and far eastern Europe, consistent with
changes in MIXR (Fig. 1c). Increases during autumn are more closely related to sources of
moisture, with changes proximal to the Mediterranean, Black Sea and North Sea. Little to no
trend is found during the winter, which is also a period of climatologically low WMAXSHEAR.
During spring there are positive trends for portions of northwestern, central and southern Europe,
suggesting spring is an increasingly active severe thunderstorm season. These changes are driven
mainly by significant increases to MIXR and CAPE, and hence potential updraft intensity,
despite modest changes to BS06.

Over the United States the spatial pattern in severe convection has greater variability in
response to the seasonal cycle, shifting from the southeastern United States in the winter
northwards towards the Great Plains in spring and summer (Fig. 3). Consistent with changes in
MIXR, during spring there is a significant increase of WMAXSHEAR over the Midwest. During
summer a robust increase is observed over the northern Great Plains, which is a result of positive
trends in both CAPE and BS06. This signal persists in autumn but is generally weaker, and is
counterbalanced by modest decreases over the southern Great Plains and the Southeast. Despite
climatologically low WMAXSHEAR during winter, robust trends of over 50 m² s⁻² per decade
are found over the Southeast, suggesting increasing potential for severe thunderstorms including
tornadoes. These winter patterns are mainly driven by rising MIXR, T2M and resulting CAPE,
rather than modulations in BS06. As illustrated by Molina and Allen (2020) these changes are
induced by increases in advective moisture fluxes from the Gulf of Mexico.

An evaluation of composite parameters used in the operational forecasting of severe
thunderstorms (Fig. 4) indicate increases in extreme convective environments for even broader
areas across the United States. Tail-distributions (99.9th percentile) of SCP and SHIP feature
positive trends over Great Plains, Midwest and portions of Southeast (seasonally consistent with
WMAXSHEAR), but not all of the trends in these areas are significant or spatially cohesive. Increases over the Midwest are partially consistent with Tang et al. (2019) for changes in large hail environments based on the NARR reanalysis. Extremes of STP (Fig 4c) feature slightly different spatial patterns with climatological peaks occurring over portions of southern Great Plains and Southeast. Significant increasing trends are observed over the Southeast and are explicitly tied to spring and winter (Appendix F), which is in agreement with Gensini and Brooks (2018).

Over Europe, there are positive increases to SCP, SHIP and STP over northwest, central and south, along with minor decreases over the east that are broadly consistent with changes to WMAXSHEAR (Fig. 3. and 4). However, climatologically these parameters reach much lower values over Europe compared to the United States (where SCP, SHIP and STP were originally developed), and the rate of change is also much smaller. Compared to tornado reports presented in Groenmeijer et al. (2017) and Taszarek et al. (2019), our modelled tornadic thunderstorm environments likely underestimate frequencies for the northwest, and overestimate over the southwest of Europe. However, these differences may be a result of reporting biases with more cases of weak and short-lived tornadoes reported over densely populated areas such as Benelux. The increased climatological number of tornado environments over western Russia is consistent with tornado reports evaluated by Chernokulsky et al. (2020).

Importance of convective inhibition and initiation

A factor that has not been widely considered in analyzing historical trends in severe thunderstorms is CIN. This is partly driven by the lower vertical resolution of reanalysis in earlier studies as compared to the dataset applied here, which allows for better detection of CIN. Here we consider the fraction of environments that may inhibit convection (absolute CIN > 75 J kg$^{-1}$; Bunkers et al. 2010; Gensini and Ashley 2011; Westermayer et al. 2017; Taszarek et al. 2019)

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conditional on all potential thunderstorm environments (CAPE > 150 J kg\(^{-1}\)). Long-term trends of
this parameter feature significant increases over the eastern Europe (2-3% per decade; Fig. 5a). However, climatologically, CIN has generally low values across Europe, and hence changes
reflect relatively small differences (Fig. 2b). Over the United States where CIN is typically much
higher, a robust increase in environments that inhibit convection (3-5% per decade) has taken
place over almost the entire country. Similar results regarding spatial patterns were obtained
when applying a CIN threshold of 50, 100, and 150 J kg\(^{-1}\) (Supplementary Material).

Changes in inhibition can be a limiting factor to the increase in the number of
thunderstorms resulting from the more frequent unstable environments. To confirm this result, we
consider the modeled convective precipitation variable as a proxy for convective initiation (Fig.
5b), using the fraction of unstable environments that simultaneously are associated with
precipitating situations (Brooks 2009; Groenemeijer et al. 2017). There has been a significant
decrease in the fraction of thunderstorm environments resulting in precipitation that is partly
coincident with areas of increasing convective inhibition. Over western and northern Europe, the
decreasing fraction of precipitating environments does not appear to be related to significant
changes in CIN fractions, which can be explained by overall weak inhibition (CIN > 75 J kg\(^{-1}\) is
rare over these regions). However, the “efficiency” of convective environments may be also
explained by long-term changes in the frequency of cyclones (Sepp et al. 2005; Parding et al.
2019), which over northwestern Europe are an important trigger for convection. These systems
provide strong synoptic-scale lift, and drive the progress of atmospheric fronts that are often
associated with deep moist convection (van Delden 2001; Kolendowicz 2012; Wapler and James
2015; Piper et al. 2019). The relative scale of these changes to initiating environments are also
important. For example, a few percent per decade over the British Isles is a small fractional
change relative to climatology (20-40%). In contrast, over the Great Plains the climatological
mean efficiency is 5-10%, and thus a change of a 1-2% represents a more significant reduction.
Another relevant factor is changes in the mean relative humidity (RH04; Fig. 5c). A robust decrease of around 2-3% per decade in the median is observed over the majority of Europe and portions of western and central United States, partially intersecting increases in CIN (Fig. 2b). According to Westermayer et al. (2017), decreasing low and mid-level relative humidity and resulting dry air entrainment into a developing updraft may lead to reductions in thunderstorm initiation despite availability of ample CAPE. This process may be partially responsible for decreases in initiating environments that are observed over Europe, and are not related to changes in CIN. While this hypothesis has not been tested over the United States, it offers a potential direction of future exploration. Pronounced decreases in land surface relative humidity are also relevant to a warming climate, as indicated by Byrne and Gorman (2016).

Changes in the frequency of modeled thunderstorms

To empirically estimate how the frequency of thunderstorms has changed since 1979 we combine changes to convective initiation with proxies for environments favorable to thunderstorms, severe thunderstorms and tornadic thunderstorms (Table 2, Figs. 6 and 7). Consistent with rising instability, there is an increase in the number of (severe) thunderstorm environments over northwestern, central and southern Europe, which partly contrasts the decrease to the overall fraction of precipitating environments. This suggests that while a lower fraction of environments results in convective precipitation, there is a considerable increase in the number of periods with conditions favorable to (severe) thunderstorms, which is also an expected outcome of the projected future European climate (Rädler et al 2019). This change is most pronounced over Italy, contrasting smaller decreases over eastern Europe that result from an increasing fraction of inhibiting environments (Fig. 5a) and decreases in relative humidity (Fig. 5c).

Decreases over Iberian Peninsula are primarily associated with reductions in instability (Fig. 2a). Positive trends in tornadic thunderstorms, which are relatively rare over Europe, are more
Over the United States there is a robust negative trend for both thunderstorm and severe thunderstorm environments over the majority of southern and western parts of the country. Despite robust increases to favorable environments over the Great Plains and Midwest (Fig. 3 and 4, Appendix B), there is no increase in the frequency of thunderstorm environments conditional on initiation (Fig. 6a). Instead, there is only a slight increase in severe thunderstorms over portions of northern Great Plains (Fig. 6b). Regional changes indicate decreasing trends over the southern Great Plains, mountains, and Midwest with mean rates of -18.8, -12.7, and -4.7 hours with thunderstorm per decade, respectively (Fig. 7). In contrast, there are increases over northwestern and southern Europe (2.6 and 8.4 hours per decade respectively; Fig. 7). Considering instead a trend in days (with at least one favourable environment), the spatial patterns and the fractional magnitude of the difference is very similar to hourly estimates over both continents (not shown).

Cross-validating changes in thunderstorm hours over the United States with convective frequency based on CG lightning data for 1989-2018, there is a similar spatial pattern with the biggest decreases observed during the summer and smaller during spring and autumn over the southern Great Plains (Fig. 8). This result supports the ability of reanalysis-derived trends in convective environments to reproduce changes in observational data, and is suggestive that thunderstorms have become less frequent over the last few decades. However, we note that proxies applied in this study tend to overestimate thunderstorm frequency during summer, and along the coastline. Conversely, underestimation is observed during winter and over the mountains (Fig. 8). This results is consistent with Tippett et al. (2019) that performance of thunderstorm proxies typically vary by region and time of the year.

For tornadic storms, there is a shift in the spatial frequency of environments towards the Southeast that is in agreement with the results obtained by Gensini and Brooks (2018). Consistent
with patterns obtained for 99.9th percentile of STP (Fig. 4c, Appendix F), the highest increases in
the frequency of tornadic thunderstorm environments are observed during spring and winter.
However, when an areal mean is considered for Southeast (Fig. 7), trends in tornadic
thunderstorms are insignificant (p-value of 0.07). Conversely, significant positive trends in
tornadic environments are observed over southern Europe, but they are very small (0.3 hours per
decade; Fig. 7).

Finally we assess trends for southeastern Oklahoma and northeastern Italy (Fig. 9), two
locations characterized by similarly high frequencies of severe convective storms (Smith et al.
2012; Taszarek et al. 2019), but representative of the differences in historical trends between
Europe and the United States. Decreasing CAPE over southeastern Oklahoma contrasts with
substantial increases over northeastern Italy. In both cases the changes in CAPE occur mainly
during the summer (a median change of ~200 J kg⁻¹ over both locations considering the
difference between 1979-1988 and 2009-2019; Fig. 9a). However, there are significant increases
to CIN throughout the whole distribution over Oklahoma, which causes a reduction in the
frequency of initiating environments. Over Italy there is little change to CIN, resulting in a rising
frequency of thunderstorms as a result of substantial increases to instability (Fig. 8c). This further
reinforces that changes to convective environments are less representative without the context
provided by the variations in CIN, and the resulting likelihood of convective initiation. These
results imply that further increases to CIN induced by a globally warming climate, may have
more significant implications for the future frequency of severe thunderstorms than is currently
expected (Diffenbaugh et al. 2013, Trapp and Hoogewind 2016, Hoogewind et al. 2017, Rädler et
al. 2019).

Discussion and concluding remarks

Historical changes to the frequency and incidence of convection have long proven elusive
to identify. Here we show that changes in favourable convective environments derived from reanalysis data are only partially consistent with the expectations for both continents under a warming climate (e.g. different outcomes regarding changes in BS06 as compared to Hoogewind et al. 2017 and Rädler et al. 2019 or decreases in CAPE over the southeastern United States during summer). The factor that drives the increase in convective environments is predominantly thermodynamic instability tied to more readily available low-level moisture, in agreement with future projections over the northern Great Plains (Diffenbaugh et al. 2013, Hoogewind et al. 2017) and the majority of Europe (Pučík et al. 2017, Rädler et al. 2019). However, this does not necessarily translate to an increase in the frequency of thunderstorms.

Whether convection initiates is a substantial contribution to the resulting changes in thunderstorms. The expected increases from growing thermodynamic favorability are limited by decreasing fraction of initiating environments. While increases in convective environments are present over parts of the Great Plains and Midwest, these are partially offset by the reductions in the frequency of convective initiation events. The increases to CIN in the United States over the past four decades are substantial, and occur throughout the whole parameter distribution. In Europe, thermodynamic parameters become more favorable over southern, central and northern parts of the continent during spring, summer and fall, but increases in CIN and reductions in relative humidity partially offset these gains. Changes to conditional BS06 and SRH03 play a reduced role in contributing to convective environments, with most of trends being insignificant. Modest significant increases have been observed over northwestern Europe and the Great Plains. This indicates that trends in the severe thunderstorm environments over the last decades have been mostly driven by changes in instability, and factors leading to convective initiation, rather than modulations in the wind profile.

As both observational and radar-based approaches to estimate convective frequency are limited in their spatio-temporal coverage and consistency, whether trends presented in this study
are manifesting in observations can be challenging to quantify (Brooks et al. 2014, Allen and
is because trends driven by the physical processes are difficult to separate from temporal and
spatial biases arising from increased severe weather reporting that has taken place over the recent
years (Mahoney 2020). This problem strongly influences European severe weather observational
data, as noted by Groenemeijer et al. (2017) and Taszarek et al. (2019). Nonetheless, our results
are consistent with prior European studies considering historical trends in convective
environments using numerical weather prediction data that offers a more consistent record both

Implications for the change to convective environments stretch beyond those for severe
thunderstorms as well. Convective precipitation plays a substantive role in the hydroclimate of
both Europe and the United States, particularly in the spring and summer (Punkka and Bister
2005; Chemokulsky et al. 2019; Haberlie and Ashley 2019; Knist et al. 2020). Decreasing rates
of convective initiation and resulting precipitation may have long-term implications for
agriculture and water availability. While a degree of caution must be stressed when using
reanalysis data, our result reinforces the hypothesis that lower fraction of convective
environments yield fewer thunderstorms in the present climate due to the significant increases in
convective inhibition, and reductions in relative humidity.

These findings suggest that changes to severe thunderstorms are not straightforward, and
increases inferred purely on the basis of unstable environments may be offset by the resistance to
convection initiating. Therefore, a stronger emphasis should be placed on the convective
initiation problem in future analyses of trends and projections, similar to the approach of Trapp
and Hoogewind (2016) and Hoogewind et al (2017). Since CIN depends on details in the
thermodynamic structure in the lowest part of the atmosphere, its accurate calculation requires
high resolution near the ground. In this context it is advisable to use native model levels for CIN
computations, instead of basing it on less well-resolved pressure level data, which has been a
typical practice in the past. Finally, the results here also highlight that regional factors play a
significant role in convective trends, meaning that trends obtained over one region cannot
necessarily be extrapolated to different parts of the world.

Acknowledgements
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Bekker Programme (project number: PPN/BEK/2018/1/00199). The reanalysis and sounding
computations were performed in the Poznań Supercomputing and Networking Center (project
number: 331). J.T. Allen acknowledges support from the National Science Foundation under
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the United States determined through convection-permitting dynamical downscaling. *J.


### List of tables

**Table 1.** List of parameters used in the study

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full name</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIXR</td>
<td>0-500 m above ground level mixed-layer mixing ratio</td>
<td>g kg⁻¹</td>
</tr>
<tr>
<td>CAPE</td>
<td>0-500 m above ground level mixed-layer convective available potential energy</td>
<td>J kg⁻¹</td>
</tr>
<tr>
<td>CIN</td>
<td>0-500 m above ground level mixed-layer convective inhibition</td>
<td>J kg⁻¹</td>
</tr>
<tr>
<td>LR75</td>
<td>700-500 hPa temperature lapse rate</td>
<td>°C km⁻¹</td>
</tr>
<tr>
<td>T2M</td>
<td>2 m above ground level temperature</td>
<td>°C</td>
</tr>
<tr>
<td>BS06</td>
<td>0-6 km above ground level bulk wind difference (shear)</td>
<td>m s⁻¹</td>
</tr>
<tr>
<td>SRH03</td>
<td>0-3 km above ground level storm-relative helicity</td>
<td>m² s⁻²</td>
</tr>
<tr>
<td>RH04</td>
<td>0-4 km above ground level mean relative humidity</td>
<td>%</td>
</tr>
<tr>
<td>WMAXSHEAR</td>
<td>A square root of two times CAPE multiplied by BS06 (Taszarek et al. 2017)</td>
<td>m² s⁻²</td>
</tr>
<tr>
<td>STP</td>
<td>Significant Tornado Parameter (Coffer et al. 2019)</td>
<td>N/A</td>
</tr>
<tr>
<td>SCP</td>
<td>Supercell Composite Parameter (Gropp and Davenport 2018)</td>
<td>N/A</td>
</tr>
<tr>
<td>SHIP</td>
<td>Significant Hail Parameter (NOAA Storm Prediction Center)</td>
<td>N/A</td>
</tr>
<tr>
<td>CP</td>
<td>ERA5 1-hour accumulated convective precipitation</td>
<td>mm h⁻¹</td>
</tr>
<tr>
<td>Category</td>
<td>Proxies</td>
<td></td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------------------------------------------------------------------</td>
<td></td>
</tr>
<tr>
<td>Thunderstorm</td>
<td>CAPE $&gt;$ 150 J kg$^{-1}$, CP $&gt;$ 0.25 mm h$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>Severe thunderstorm</td>
<td>CAPE $&gt;$ 150 J kg$^{-1}$, CP $&gt;$ 0.25 mm h$^{-1}$, BS06 $&gt;$ 10 m s$^{-1}$, WMAXSHEAR $&gt;$ 500 m$^2$ s$^{-2}$</td>
<td></td>
</tr>
<tr>
<td>Tornadic thunderstorm</td>
<td>CAPE $&gt;$ 150 J kg$^{-1}$, CP $&gt;$ 0.25 mm h$^{-1}$, STP $&gt;$ 0.75</td>
<td></td>
</tr>
</tbody>
</table>
List of figure captions

**Fig. 1** A 41-year climatology (first and third column) of the 95th percentile of surface temperature (T2M - a), mid-level temperature lapse rate (LR75 - b) and low-level moisture (MIXR - c) for Europe and the United States. Long-term trends (second and fourth column) are derived from annual values in hourly resolution and corresponding Sen’s slope (values denote change per decade).

**Fig. 2** As in Fig. 1 but for the 95th percentile of convective available potential energy (CAPE - a), absolute value of convective inhibition (CIN - b), and 50th percentile of vertical wind shear (BS06 - c) and storm-relative helicity (SRH03 - d). For BS06 and SRH03 only situations with CAPE > 150 J kg⁻¹ are considered.

**Fig. 3** As in Fig. 1 but for the convective available potential energy and vertical wind shear composite (WMAXSHEAR) by season (spring - a, summer - b, autumn - c, winter - d) and whole year (e).

**Fig. 4** As in Fig. 1 but for the 99.9th percentile of Supercell Composite Parameter (SCP - a), Significant Hail Parameter (SHIP - b) and Significant Tornado Parameter (STP - c).

**Fig. 5** As in Fig. 1 but for the fraction of inhibiting (a) and initiating (b) environments (relative to all CAPE > 150 J kg⁻¹ situations), and 50th percentile of mean 0-4 km relative humidity (RH04 - c) only for situations with CAPE > 150 J kg⁻¹.

**Fig. 6** As in Fig. 1 but for the frequency (hours) of thunderstorm (a), severe thunderstorm (b) and tornadic thunderstorm (c) environments (with convective initiation included). Please note that color bar ranges differ between Europe and the United States. Modification of this figure where convective precipitation proxy is excluded is available in the Supplementary Material.

**Fig. 7** Long-term trends in the frequency (hours) of thunderstorm (TSM - orange), severe thunderstorm (SEV - red) and tornadic thunderstorm environments (TOR - magenta) derived as areal mean from selected regions. Values at the top of each chart indicate Sen’s slope (values denote change per decade) and p-value. Please note that values on the x axis are presented in a square root scale.

**Fig. 8** A 30-year (1989-2018) climatology (first and third column) of the number of hours with potential thunderstorm environments and cloud-to-ground lightning from National Lightning Detection Network (NLDN) for the United States by season (spring - a, summer - b, autumn - c,  

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winter - d). Long-term trends (second and fourth column) are derived by seasonal values in hourly resolution and corresponding Sen’s slope (values denote change per decade). Please note that color bar ranges differ between two methods.

**Fig. 9** Box-and-whisker plots (the median is denoted as a horizontal line inside the box, the edges of the box represent the 25th and 75th percentiles, and whiskers represent the 10th and 90th percentiles) representing diurnal and seasonal cycle of convective available potential energy (CAPE J kg\(^{-1}\) - a) and convective inhibition (CIN J kg\(^{-1}\) - b) over southeastern Oklahoma and northeastern Italy (limited to CAPE > 0 J kg\(^{-1}\) situations). Fraction of inhibiting environments (as in Fig. 4a) and the frequency of unstable and initiating environments (as in Fig. 5a) over particular years are presented in c. Trend lines are derived from Sen’s slope.

**Appendix A** Climatology and long-term trends in MIXR as in Fig. 1c but for seasons.

**Appendix B** Climatology and long-term trends in CAPE as in Fig. 2a but for seasons.

**Appendix C** Climatology and long-term trends in CIN as in Fig. 2b but for seasons.

**Appendix D** Climatology and long-term trends in BS06 as in Fig. 2c but for seasons.

**Appendix E** Climatology and long-term trends in SRH03 as in Fig. 2d but for seasons.

**Appendix F** Climatology and long-term trends in STP as in Fig. 4c but for seasons.
Fig. 1 A 41-year climatology (first and third column) of the 95th percentile of surface temperature (T2M - a), mid-level temperature lapse rate (LR75 - b) and low-level moisture (MIXR - c) for Europe and the United States. Long-term trends (second and fourth column) are derived from annual values in hourly resolution and corresponding Sen’s slope (values denote change per decade).
Fig. 2 As in Fig. 1 but for the 95th percentile of convective available potential energy (CAPE - a), absolute value of convective inhibition (CIN - b), and 50th percentile of vertical wind shear (BS06 - c) and storm-relative helicity (SRH03 - d). For BS06 and SRH03 only situations with CAPE > 150 J kg⁻¹ are considered.
Fig. 3 As in Fig. 1 but for the convective available potential energy and vertical wind shear composite (WMAXSHEAR) by season (spring - a, summer - b, autumn - c, winter - d) and whole year (e).
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Climatology and long-term trends of thunderstorm, severe thunderstorm and
tornadic thunderstorm environments (with convective precipitation included)

<table>
<thead>
<tr>
<th>Frequency (annual mean)</th>
<th>Trend (per decade)*</th>
<th>Frequency (annual mean)</th>
<th>Trend (per decade)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* - Trend computed with Sen’s slope, x marks denote statistically significant trend (p-value < 0.05)
** - Thunderstorm is considered when CAPE > 150 J kg⁻¹, CP > 0.25 mm h⁻¹
*** - Severe thunderstorm is considered when CAPE > 150 J kg⁻¹, BS06 > 10 m s⁻¹, WMAXSHEAR > 500 m² s⁻², CP > 0.25 mm h⁻¹
**** - Tornadic thunderstorm is considered when CAPE > 150 J kg⁻¹, STF > 0.75, CP > 0.25 mm h⁻¹

Fig. 6 As in Fig. 1 but for the frequency (hours) of thunderstorm (a), severe thunderstorm (b) and
tornadic thunderstorm (c) environments (with convective initiation included). Please note that
color bar ranges differ between Europe and the United States. Modification of this figure where
convective precipitation proxy is excluded is available in the Supplementary Material.
Fig. 7 Long-term trends in the frequency (hours) of thunderstorm (TSM - orange), severe thunderstorm (SEV - red) and tornadic thunderstorm environments (TOR - magenta) derived as areal mean from selected regions. Values at the top of each chart indicate Sen’s slope (values denote change per decade) and p-value. Please note that values on the x axis are presented in a square root scale.
**Fig. 8** A 30-year (1989-2018) climatology (first and third column) of the number of hours with potential thunderstorm environments and cloud-to-ground lightning from National Lightning Detection Network (NLDN) for the United States by season (spring - a, summer - b, autumn - c, winter - d). Long-term trends (second and fourth column) are derived by seasonal values in hourly resolution and corresponding Sen’s slope (values denote change per decade). Please note that color bar ranges differ between two methods.
An example of differing trends in convective environments between Europe and the United States over locations with high frequency of severe thunderstorms

Southeastern Oklahoma ($\phi 34.25$, $\lambda 95.75$)  
Northeastern Italy ($\phi 45.75$, $\lambda 13.00$)

**Fig. 9** Box-and-whisker plots (the median is denoted as a horizontal line inside the box, the edges of the box represent the 25th and 75th percentiles, and whiskers represent the 10th and 90th percentiles) representing diurnal and seasonal cycle of convective available potential energy (CAPE J kg$^{-1}$ - a) and convective inhibition (CIN J kg$^{-1}$ - b) over southeastern Oklahoma and northeastern Italy (limited to CAPE > 0 J kg$^{-1}$ situations). Fraction of inhibiting environments (as in Fig. 4a) and the frequency of unstable and initiating environments (as in Fig. 5a) over particular years are presented in c. Trend lines are derived from Sen’s slope.
**Appendix A**

Climatology and long-term trends in MIXR as in Fig. 1c but for seasons.

Seasonal climatology and long-term trends of 0-500m AGL mixing ratio [g kg\(^{-1}\)]

<table>
<thead>
<tr>
<th></th>
<th>95(^{th}) percentile</th>
<th>Trend (per decade)*</th>
<th>95(^{th}) percentile</th>
<th>Trend (per decade)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Spring (MAM)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>b</td>
<td>Summer (JA)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>c</td>
<td>Autumn (SON)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>d</td>
<td>Winter (DJF)</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

* - Trend computed with Sen's slope, x marks denote statistically significant trend (p-value < 0.05)
Appendix B

Climatology and long-term trends in CAPE as in Fig. 2a but for seasons.

Seasonal climatology and long-term trends of convective available potential energy [J kg⁻¹]

<table>
<thead>
<tr>
<th>Season</th>
<th>95th percentile</th>
<th>Trend (per decade)</th>
<th>95th percentile</th>
<th>Trend (per decade)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring (MAM)</td>
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</tr>
<tr>
<td>Summer (JA)</td>
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<tr>
<td>Autumn (SON)</td>
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<tr>
<td>Winter (DJF)</td>
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</tbody>
</table>

* - Trend computed with Sen's slope, x marks denote statistically significant trend (p-value < 0.05)
Appendix C

Climatology and long-term trends in CIN as in Fig. 2b but for seasons.

Seasonal climatology and long-term trends of convective inhibition [J kg\(^{-1}\)]

<table>
<thead>
<tr>
<th>Season</th>
<th>95th Percentile</th>
<th>Trend (per decade)*</th>
<th>95th Percentile</th>
<th>Trend (per decade)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spring (MAM)</td>
<td><img src="#" alt="Maps" /></td>
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<td><img src="#" alt="Maps" /></td>
<td><img src="#" alt="Maps" /></td>
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<tr>
<td>Summer (JJA)</td>
<td><img src="#" alt="Maps" /></td>
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<td><img src="#" alt="Maps" /></td>
<td><img src="#" alt="Maps" /></td>
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<tr>
<td>Autumn (SON)</td>
<td><img src="#" alt="Maps" /></td>
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<td><img src="#" alt="Maps" /></td>
<td><img src="#" alt="Maps" /></td>
</tr>
<tr>
<td>Winter (DJF)</td>
<td><img src="#" alt="Maps" /></td>
<td><img src="#" alt="Maps" /></td>
<td><img src="#" alt="Maps" /></td>
<td><img src="#" alt="Maps" /></td>
</tr>
</tbody>
</table>

* - Trend computed with Sen's slope, x marks denote statistically significant trend (p-value < 0.05)
Appendix D

Climatology and long-term trends in BS06 as in Fig. 2c but for seasons.
Appendix E

Climatology and long-term trends in SRH03 as in Fig. 2d but for seasons.

Seasonal climatology and long-term trends of 0-3km storm-relative helicity [m² s⁻²]

- **Spring (MAM)**
- **Summer (JJA)**
- **Autumn (SON)**
- **Winter (DJF)**

* - Trend computed with Sen’s slope, x marks denote statistically significant trend (p-value < 0.05)
Appendix F

Climatology and long-term trends in STP as in Fig. 4c but for seasons.

Seasonal climatology and long-term trends of Significant Tornado Parameter

- Trend computed with Sen's slope, x marks denote statistically significant trend (p-value < 0.05)