RESEARCH PAPER

ASSOCIATION OF SPATIAL AND TEMPORAL WINDTHROW DISTRIBUTION WITH CONVECTIVE PARAMETERS AND LIGHTNING DENSITY IN RUSSIA

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ABSTRACT. Windthrow is one of the major causes of forest loss in most forest types, depending on the frequency and intensity of severe winds and forest vulnerability. This study focuses on analyzing of the association of the spatio-temporal distribution of windthrow with the atmospheric convective parameters and lightning activity in the Russian forest zone for the period 2001-2020. The windthrow data include 1816 events that are associated with tornadoes and non-tornadic convective windstorms and are obtained from the previously developed satellite-derived database. Convective parameters are calculated based on the ERA5 reanalysis, while the Worldwide Lightning Location Network (WWLLN) is used for lightning data. It is found that both the spatial distribution and the interannual variability of windthrow events are significantly correlated with the corresponding variability of convective parameters, especially with the significant tornado parameter (STP), both in the European Russia (ER) and in Siberia. The spatial correlation between windthrow events and lightning density is also significant, with a stronger relationship in the ER than in Siberia. For inter-annual variability, it is also found a strong relationship between the number of days with supercritical STP values and the total windthrow area per season. Our results highlight STP and lightning density as informative predictors that can be used as characteristics of windthrow in the Russian forests and for further estimation of associated risks, which is important for sustainable forest management.

KEYWORDS: windthrow, non-tornadic convective windstorms, tornadoes, ERA-5 reanalysis, convective indices, lightning density

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INTRODUCTION

Strong winds, squalls, and tornadoes cause substantial loss and damage to forests every year. Predicting and mapping wind-related risks to forests remains both a scientific challenge and an important issue for sustainable forest management, especially in the context of climate change (Panferov et al. 2009). Previously developed methods for windthrow risk prediction include an assessment of hazard (i.e., frequency and intensity of severe wind events causing damage to forests), and vulnerability (i.e., forest stand characteristics, landscape parameters such as slope, aspect, soil type, forest management, etc.) [Seidl et al. 2011; Venäläinen et al. 2020]. The previously compiled datasets of windthrow events [e.g. Shikhov et al. 2020; Forzieri et al. 2020; Senf and Seidl 2021b] are used for training and validation of the prediction models.

Numerous studies present an assessment of forest vulnerability to windthrow events at a regional scale, based on statistical or mechanistic (tree-based) models [see e.g., Peltola et al. 1999; Dobbertin et al. 2002; Gardiner et al. 2008; Panferov and Sogachev 2008; Seidl et al. 2011, Suvanto et al. 2019]. Estimates of the frequency of severe wind events for windthrow risk prediction are based on 10-year maximum wind speeds interpolated from long-term observational data [Laapas et al. 2019, 2023] or the same calculation from reanalysis data and downscaled with digital elevation models [Venäläinen et al. 2017]. However, the characteristics of severe wind events observed by weather stations or extracted from reanalysis data are not suitable for local convective windstorms and tornadoes, which induced more than 50% of the windthrow area in the forest zone of European Russia and Siberia [Shikhov et al. 2023]. The observational network (Chernokulsky et al. 2021) misses most of these events due to their local nature and the low density of weather stations. Other data sources, such as the European Severe Weather Database [Groenemeijer et al. 2017] also do not provide a reliable estimate of the spatial distribution of convective wind events due to a strong "population bias" [Taszarek et al. 2020a].

In recent decades, several proxy parameters have been widely used to estimate the climatic characteristics of the atmospheric environment that favor the occurrence of convective hazardous events, rather than the events themselves [Rasmussen and Blanchard, 1998; Brooks et al. 2018]. In total, more than 50 atmospheric parameters are now used to estimate the main so-called 'ingredients' necessary for the formation of severe convective storms that produce non-tornadic convective windstorms (squalls) and tornadoes, such as convective instability, precipitable water content, wind shear, helicity, and others [Doswell and Shultz, 2006; Taszarek et al. 2023;]. In recent studies, these parameters are mainly calculated from reanalysis data, which allows for the obtaining of a homogeneous data series and for its comparison with the spatial and temporal distribution of observed convective events [Taszarek et al. 2017, 2020b; Chernokulsky et al. 2023].

Previously published studies for Russia [Shikhov et al. 2021; Chernokulsky et al. 2023] analyzed convective parameters only for specific days when hazardous convective events occurred. It was shown that the so-called composite convective parameters are the most informative for diagnosing and predicting the environments favorable for the formation of such events. However, the climatic characteristics of these parameters have not been considered, except for long-term trends [Chernokulsky et al. 2022a], and have not been compared with the data on the spatial distribution and interannual variability of windstorms and tornadoes. This study presents such a relationship. Additionally, this study presents the relationship between the spatial and temporal distribution of lightning density and that of tornadoes and non-tornadic convective windstorms.

MATERIALS AND METHODS

Windthrow data

Data on windthrow events is obtained from the GIS database [Shikhov et al. 2020; Tornadoes…, 2024]. The sample includes 1816 windthrow events caused by non-tornadic convective windstorms and tornadoes in the period from 2001 to 2020, including 1068 cases in the ER and 748 cases in Siberia. Among them, 1052 cases (total area 57,359 ha) are tornado-induced events, and 764 cases (total area 325,942 ha) are squall-induced events. For each year, the number of windthrow events, the number of days with events, and the total windthrow area were calculated separately for the forest zone of the ER and Siberia. Note that the number of days with windthrow events is calculated taking into account only those events whose date of occurrence is known with an accuracy of at least one month.

Convective parameters

The statistical properties of the convective atmospheric parameters were evaluated based on a dataset of these parameters previously developed for Northern Eurasia [Chernokulsky et al. 2022a] using the ERA5 reanalysis [Hersbach et al. 2020]. The calculation of the indices is based on 20 vertical levels from the surface to 300 hPa, with high spatial (0.25°) and temporal (1 h) resolution. The output dataset includes 50 convective parameters characterizing thermodynamic instability, precipitable water, condensation level, wind shear, and helicity. It also includes several composite parameters. We have selected several key parameters that indicate favorable environments for the formation of convective windstorms and tornadoes.

We used such well-known and widely used parameters as convective available potential energy calculated for air parcel characteristics averaged in a mixed 0-1000 m layer above ground level (hereafter ML CAPE), and deep layer shear (DLS), which represent thermodynamic and dynamic 'ingredients', respectively [Rasmussen and Blanchard, 1998; Brooks et al. 2018]. We also used composite convective parameters, which have been found to be the most informative for diagnosing and predicting the environments favorable for the formation of severe convective windstorms and tornadoes for Europe [Taszarek et al. 2017, 2020b] and Russia [Shikhov et al. 2021; Chernokulsky et al. 2023]. In particular, we selected three composite parameters, such as ML WMAXSHEAR, significant tornado parameter (STP) and supercell composite parameter (SCP), which represent strong predictors for severe convective storms, tornadoes, and supercell storms, respectively [Taszarek et al. 2017, Thompson et al. 2003].

The ML WMAXSHEAR (Eq. 1) parameter characterizes the maximum vertical velocity (associated with CAPE) combined with wind shear in the 0-6 km layer [Taszarek et al. 2017]:

$$MLWMAXSHEAR = (2MLCAPE)^{0.5}DLS \quad (1)$$

where denotes maximum vertical velocity, and is the deep-layer shear (the magnitude of the vector difference between the winds at 10 m (near-surface wind) and 6 km). The Supercell Composite Parameter (SCP) (Eq. 2) takes into account convective instability, helicity, and wind shear and is calculated as follows:

$$SCP = \left(\frac{MUCAPE}{1000Jkg^{-1}}\right)\left(\frac{SRH_{0-3km}}{100m^2s^{-2}}\right)\left(\frac{DLS^2}{40m^2s^2}\right) \quad (2)$$

where is convective available potential energy calculated for a parcel lifted from the most unstable layer, is the storm-relative helicity in the 0-3 km layer[1].

The Significant Tornado Parameter (STP) is calculated as follows (Eq. 3):

$$STP = \left(\frac{DLS}{20}\right)\left(\frac{SRH_{0-1km}}{150}\right)\left(\frac{SBCAPE}{1500}\right)\left(\frac{2000-SBLCL}{1000}\right)\left(\frac{200+SBCIN}{150}\right) \quad (3)$$

where is the storm-relative helicity in the 0-1 km layer, is the convective available potential energy calculated for a parcel lifted from the surface, is the lifted condensation level for that parcel, and is the convective inhibition for it [Thompson et al. 2003].

The summer months (June-August) of 2001-2020 were chosen as the study period because data on windthrow for these years are available for the forest zone both in the ER and in Siberia [Shikhov et al. 2023]. On the basis of hourly data, statistical characteristics of the convective variables, such as the mean value for each summer season and the recurrence of critical values (Table 1), were calculated. The critical thresholds (median and 90th percentile) were

[1] *Grieser J. Convection parameters [online]. Available at: http://www.juergen-grieser.de/CovectionParameters/ConvectionParameters.pdf [Accessed 20 Aug. 2024].*

obtained from a sample of 281 cases of severe windstorms and tornadoes that caused forest damage in the ER and Western Siberia [Chernokulsky et al. 2023]. The median values are further considered as the critical values, which are typical for the formation of windstorms and tornadoes. The 90th percentile threshold characterizes the extremely high values of the convective parameters (the most favorable environments for the formation of severe windstorms and tornadoes). We picked these critical values, which were found specifically for the forest zone of Russia, because windstorms and tornadoes happen in different regions of the world at substantially different values of convective parameters [Taszarek et al. 2020b].

Lightning data

We used global lightning climatology data from the WWLLN for the period 2010-2020 [Kaplan et al. 2021], and calculated the annual lightning density (for summer months only, as for convective parameters) per 1000 km^2. We also used another global lightning detection system, LIS-OTD (Lightning Imaging Sensor – Optical Transient Detector), available for the period from 1995 to 2014 [Christian et al. 2003], and calculated the mean lightning density for the period 2001-2014.

Relationship assessment

Correlations between windthrow characteristics, WWLLN-based lightning density and convective parameters derived from the ERA5 reanalysis were evaluated both in time and in space. To calculate correlations in space, we aggregated all the above data into a 100×100 km grid. Such a grid size corresponds approximately to three cells of the ERA5 reanalysis and is close to the size (1.25˚×1.00˚) that was used by [Taszarek et al. 2020b] to avoid duplication of convective environments at the local scale. In addition, 100×100 km cells were used to estimate the spatial distribution of the wind-damaged area and to smooth out local anomalies associated with the rarity of these events [Shikhov et al. 2020].

Cells with < 10% forest cover according to the vegetation map of Russia [Bartalev et al. 2016] were excluded from further calculations. In total, the forest zone of the ER and Siberia is covered by 787 grid cells (266 cells in the ER and 521 cells in Siberia). In each grid cell, the ratio of the total windthrow area for the period 2001-2020 to the forest area was calculated and then considered as the dependent variable (predictand). Convective parameters and lightning density were averaged in each grid cell and considered as the predictors. Correlations between the predictors and predicted were calculated based on the averaged values for each grid cell. As the distribution in the data deviated from the normal law, both Pearson (linear) and Spearman (rank) correlation coefficients were calculated. The significance level was set as 0.05.

Relationships between windthrow characteristics and convective atmospheric variables in time were evaluated on the basis of the data averaged annually and over the study area (separately for the forest zone of the ER and Siberia). Thus, we calculated correlation coefficients between windthrow characteristics and convective parameters averaged for June-August of each year (i.e., the sample size was 20 values).

RESULTS

Spatial distribution of windthrow events, convective atmospheric parameters and lightning density in forests

On average, the area of windthrow as a percentage of the total forested area in the ER is about 4 times larger than in Siberia [Shikhov et al. 2023]. In the ER, squall- and tornado-induced windthrow events are most widespread in the central part of the forest zone, approximately along 60°N (from the Leningrad region in the west to the Komi Republic in the east) (Fig. 1a). The largest area of windthrow (up to 1% of the forest area) is observed in the Yaroslavl, Vologda, and Novgorod regions, where two catastrophic windthrow events occurred in the summer of 2010 [Chernokulsky et al. 2022b; Shikhov et al. 2023]. In the spatial distribution of windthrow events in Siberia, several local peaks are observed east of the Yenisei River (where tornado-induced damage predominates), in the west and northeast of the Irkutsk region (due to squall-induced windthrow), and in the Tomsk region, where both squall- and tornado-induced windthrow events are widespread (Fig. 1).

The spatial distribution of windthrow events in the forest zone has a statistically significant correlation with lightning density according to the WWLLN data (Fig. 1b). In the forest zone of the ER, lightning density is highest northwest of Moscow, where windthrow density is also higher than the average for the ER. In Siberia, lightning density is highest in the central part of the forest zone of Western Siberia and decreases further east, especially over Eastern Siberia (in the Irkutsk region). Such a decrease in lightning density is not consistent with the spatial distribution of windthrow. For example, the area of wind-damaged forest in the Irkutsk region is larger than in the neighboring regions (Fig. 1). It is likely that this inconsistency is related to the uneven coverage of WWLLN stations and hence, lightning data [Holzworth et al. 2021; Tarabukina and Kozlov, 2020].

According to the LIS-OTD data, the lightning density in the ER is generally similar to the WWLLN data and also agrees well with the distribution of windthrow events (not shown). The highest lightning density is observed along the Urals and over the central regions of the ER, while in Siberia several local peaks can be highlighted. According to the LIS-OTD data, the lightning density over the Irkutsk region is slightly lower than over the more western regions of Siberia (i.e., a strong decrease observed according

Table 1. Median and 90th percentile thresholds of convective variables for a sample of cases with linear convective windstorms and tornadoes [Chernokulsky et al. 2023]

Variable	Median	90th percentile
ML WMAXSHEAR	850	1126
STP	0.5	1.42
SCP	3.71	11.75
ML CAPE	887	1330
DLS	23.8	29.7

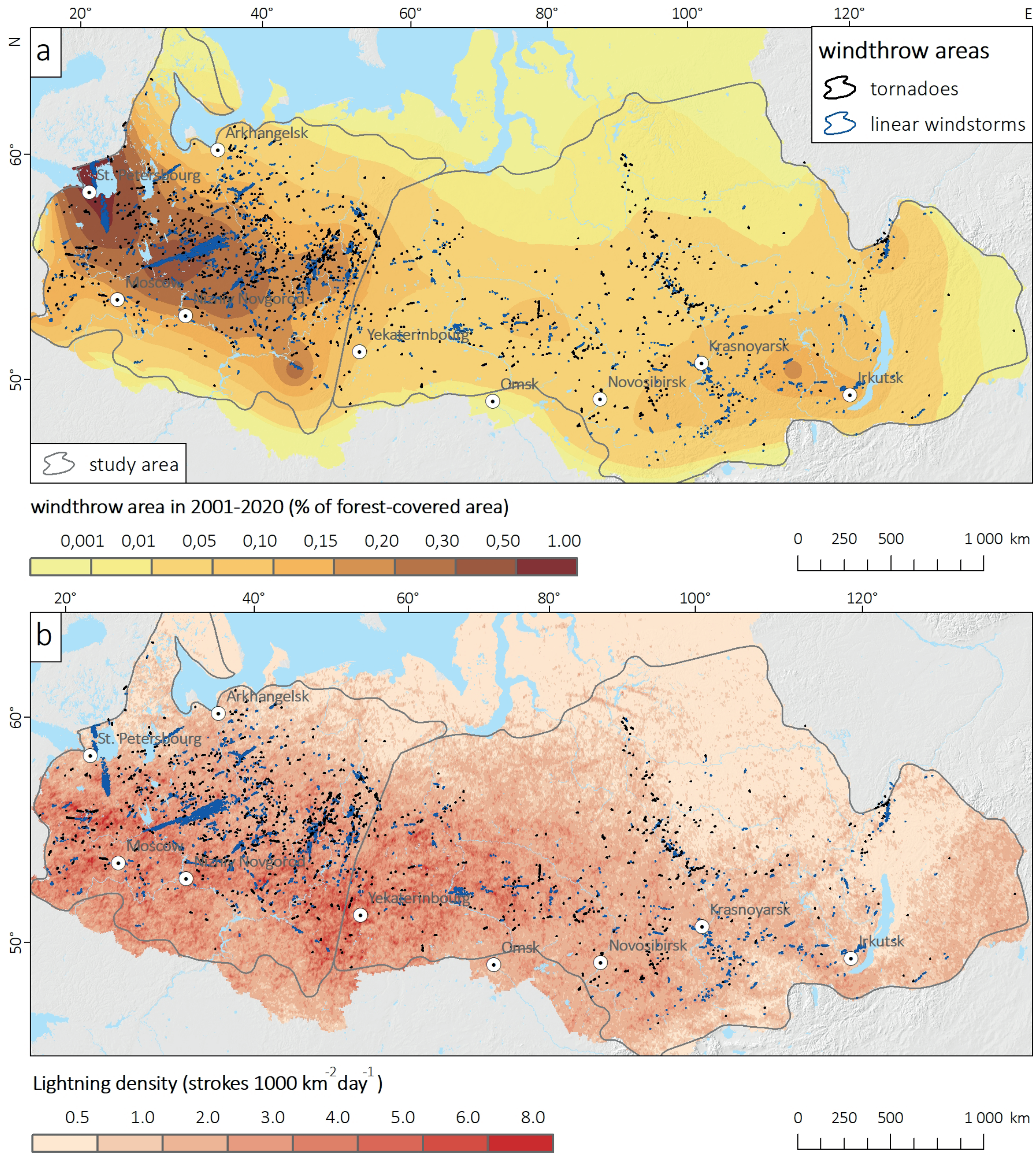

Fig. 1. Ratio of windthrow area to forest-covered area (a) and lightning density averaged over summer seasons 2010-2020 (b) in the ER and Siberia

to the WWLLN data is not confirmed). However, the LIS-OTD dataset has a much lower spatial resolution than the WWLLN. In addition, it has a large number of no data cells over Central Siberia, the northern part of the ER, and Western Siberia, which prevents us from further using this dataset in the present study.

Fig. 2-6 show the values of convective variables averaged for the summer months of 2001-2020 over the forest zone of ER and Siberia, as well as the number of days with excess convective parameters over critical values (Table 1). The frequency of extremely high values of convective parameters, corresponding to the 90th percentile for the cases with non-tornadic convective windstorms and tornadoes [Chernokulsky et al. 2023] is not shown since such high values are rarely observed and their spatial distribution mainly coincides with that of the days with supercritical values.

The spatial distribution of all convective parameters considered, except for DLS, has a significant positive correlation (Spearman rank coefficient) with the spatial distribution of windthrow events (Table 2). However, the Pearson linear correlation coefficient is statistically significant only when the ER and Siberia are considered together (probably due to a larger sample size). For the ER and Siberia separately, only certain convective parameters are significantly correlated with the wind-damaged forest area (STP in the ER, ML CAPE and ML WMAXSHEAR in Siberia). In contrast to other convective indices, which have their highest values located in the southern part of the forest zone, the highest values of DLS are often associated with the climatic location of the Arctic front, which extends along the Arctic coast in summer (Fig. 2). Thus, DLS is negatively correlated with the spatial distribution of windthrow events. In the ER, the distribution of windthrow events coincides quite well with the distribution of STP values (both mean and number of days with supercritical values). The highest STP values are observed in the western Urals and in the central part of the forest zone of the ER, where squall- and tornado-induced windthrow events are widespread (Fig. 6). Further south, the mean STP values decrease due to an increase in the lifted condensation level (LCL). The obtained estimates of the spatial distribution of STP are consistent with those previously published for Europe [Taszarek et al. 2020b].

The highest values of other composite convective parameters are observed south of the zone of the maximum density of windthrow events. Thus, the highest values of ML WMAXSHEAR (Fig. 4) and SCP (Fig. 5) are observed in the Southern Urals, Tatarstan, and the Nizhny Novgorod region, and for ML WMAXSHEAR also southwest of Moscow. It is important to note that the maximum in the Southern Urals is associated with mountainous terrain and does not coincide with the distribution of windthrow events. At the same time, the ML CAPE distribution (especially the number of days with supercritical values) has a well-defined maximum east and northeast of Moscow, while the maximum in the South Urals is absent. Thus, ML CAPE has a stronger correlation with the distribution of windthrow events than ML WMAXSHEAR and SCP (Table 2). It is also noteworthy that the lowest values of convective parameters within the forest zone of the ER are observed in the northwest (Republic of Karelia). This corresponds to the lowest windthrow area and indicates a low frequency of severe convective windstorms and tornadoes.

In Siberia, the mean values of convective parameters are substantially lower than in the ER, and their correlation with the distribution of windthrow events is weaker than in the ER (according to the Spearman rank coefficient). Note that the highest values of most of the convective parameters, especially the SCP and STP, are observed in the mountains of southern Siberia, which does not correspond to the spatial distribution of windthrow events. Only ML CAPE does not increase in the mountains compared to the plains of Western Siberia, which explains its higher correlation with the distribution of windthrow events (Table 2). It is also important to note that the southern part of the forested zone of Western Siberia, where the values of convective parameters are close to the highest in Siberia, is characterized by a relatively low percentage of forest area (20-40%) and a high proportion of deciduous forests [Bartalev et al. 2016], which leads to a decrease in the frequency and area of windthrow in comparison with the adjacent regions of the Urals and Central Siberia.

As in the ER, the spatial distribution of windthrow in Siberia corresponds better to the distribution of STP than to other convective indices (Fig. 6). The highest values of other convective parameters are observed in the southern part of the forest zone (east of Ekaterinburg, north of Omsk), and in the mountains of southern Siberia. For STP, a secondary maximum is also found east of the Yenisei River, where the density of tornado-induced windthrow has a well-defined maximum (Fig. 6). In the Irkutsk region, the values of convective parameters (except for ML CAPE) are rather low, which does not correspond to a large windthrow area.

Interannual variability of windthrow characteristics and convective atmospheric parameters

For the period 2001-2020, we found a statistically significant correlation between the annual number of windthrow events and the damaged area and the values of the composite convective parameters averaged over the summer months. A particularly strong correlation is found for the SCP and STP (Table 3), while it is absent for ML CAPE. In the forest zone of ER, the interannual variability of the number of windthrow events and convective parameters SCP, STP, and ML WMAXSHEAR are similar (Fig. 7). Consequently, the years 2004, 2006-2007, 2010, and 2020 recorded the highest mean values of these parameters and the highest number of days with supercritical values. In the same years (except for 2006), the number of windthrow events and the damaged area were also higher than average. In 2002-2003 and 2018-2019, the lowest values of convective parameters coincide with a relative decrease in the number of windthrow events. The coefficient of determination (square of the Pearson correlation coefficient) shows that 37% of the interannual variability in the number of windthrow events can be explained by the variability in STP. However, this relationship cannot be applied to the windthrow area, because specific events, such as two derechos in the summer of 2010 [Chernokulsky et al. 2022b], contribute significantly to the interannual variability of the damaged area.

In Siberia, the correlation between the values of the composite convective parameters and the windthrow characteristics is somewhat weaker than in the ER, but it is also statistically significant for ML WMAXSHEAR, STP, and SCP (Table 3 and Fig. 8). The peaks of 2007, 2015, and 2020 are well pronounced in terms of the number of windthrow events. In addition, 2004 and 2020 are characterized by the largest windthrow area. At the same time, 2002, 2007 and 2015 have the highest values of convective parameters. In both the ER and Siberia, there is no increase in the values of convective parameters for the period 2001-2020, and in Siberia there is even a downward trend, which is somewhat in contrast to previously published trend estimates [Chernokulsky et al. 2022a]. However, these results are not directly comparable because [Chernokulsky et al. 2022] considered a longer time interval (1979-2020), excluding the spring and autumn months.

Seasonal mean ML CAPE values have no correlation with the number of windthrow events and their area, but such a correlation is statistically significant for DLS (Table 3). The interannual variability of windthrow events shows a

Table 2. Spearman (numerator) and Pearson (denominator) correlation coefficients between windthrow characteristics and convective parameters. Statistically significant coefficients are shown in bold

Windthrow area (% of forest-covered area)	Lightning density	ML WMAXSHEAR			SCP			STP			ML CAPE			DLS		
		Mean*	N_{crit}*	N_{90p}*	Mean	N_{crit}	N_{90p}	Mean	N_{crit}	N_{90p}	Mean	N_{crit}	N_{90p}	Mean	N_{crit}	N_{90p}
ER and Siberia	0..48/ 0..16	0..40/ 0..12	0..39/ 0..07	0.33/ 0.02	0.36/ 0.09	0.31/ 0.10	0.40/ 0.05	0.43/ 0.10	0.44/ 0.09	0.34/ 0.03	0.40/ 0.13	0.52/ 0.18	0.54/ 0.23	-0.06/ -0.02	-0.17/ -0.11	-0.26/ -0.14
ER only	0.41/ 0.10	0.35/ 0.10	0.36/ 0.07	0.32/ 0.10	0.37/ 0.11	0.46/ 0.10	0.42/ 0.09	0.57/ 0.13	0.55/ 0.10	0.31/ 0.00	0.31/ 0.09	0.41/ 0.10	0.46/ 0.13	-0.07/ -0.08	-0.01/ -0.09	0.02/ -0.10
Siberia only	0.37/ 0.10	0.36/ 0.15	0.34/ 0.06	0.26/ 0.01	0.30/ 0.09	0.23/ 0.00	0.20/ -0.02	0.31/ 0.04	0.32/ 0.05	0.26/ 0.01	0.39/ 0.19	0.44/ 0.15	0.43/ 0.17	-0.18/ -0.14	-0.26/ -0.18	-0.29/ -0.17

**Mean – mean value for June-August, N_{crit} – number of days with supercritical values (values above the critical level), N_{90p} – number of days with values above the 90th percentile of the sample from [Chernokulsky et al. 2023]*

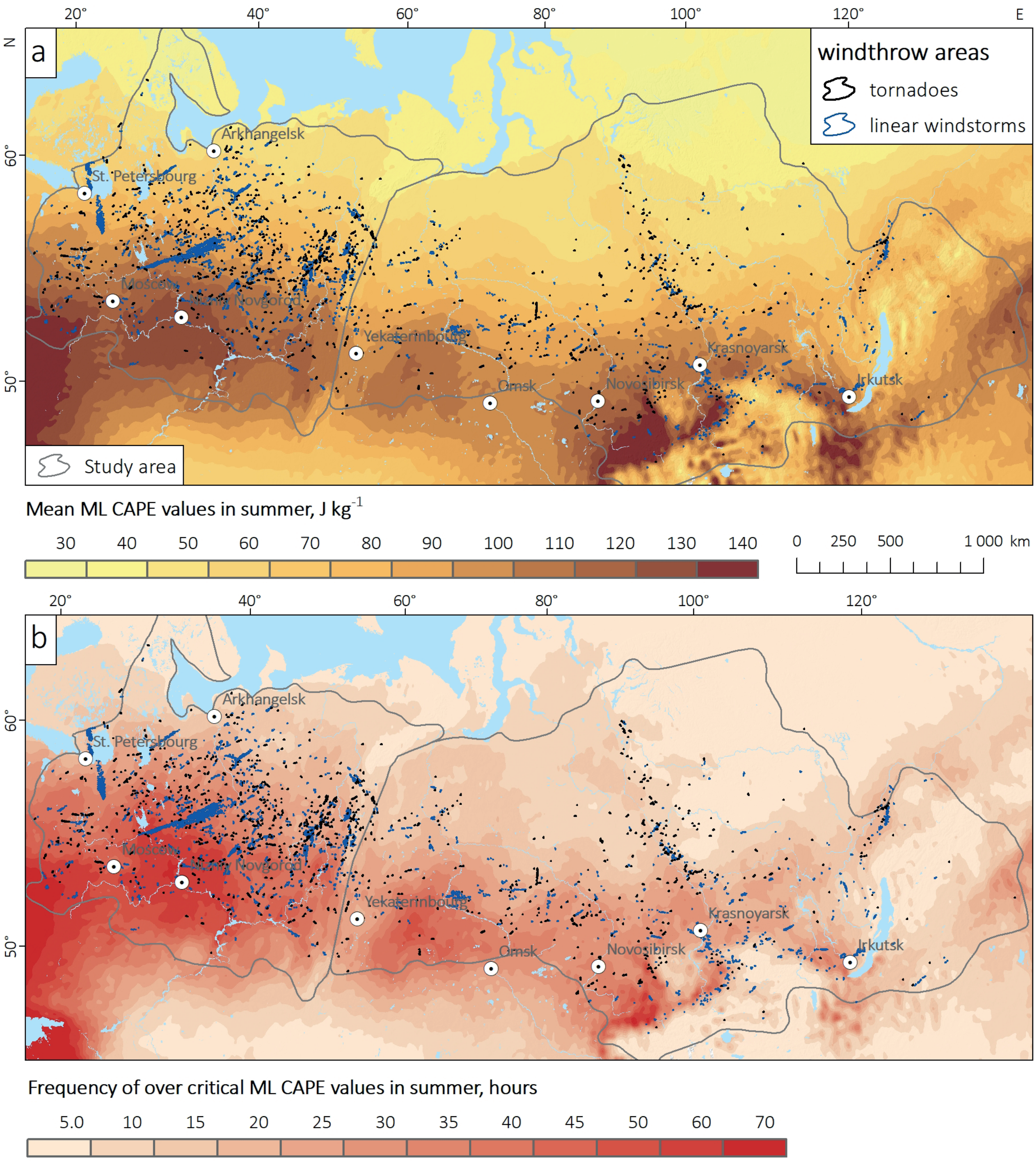

Fig. 2. Spatial distribution of ML CAPE and windthrow events in the forest zone of the ER and Siberia: a) mean values for the summer seasons in 2001-2020; b) number of days with supercritical values

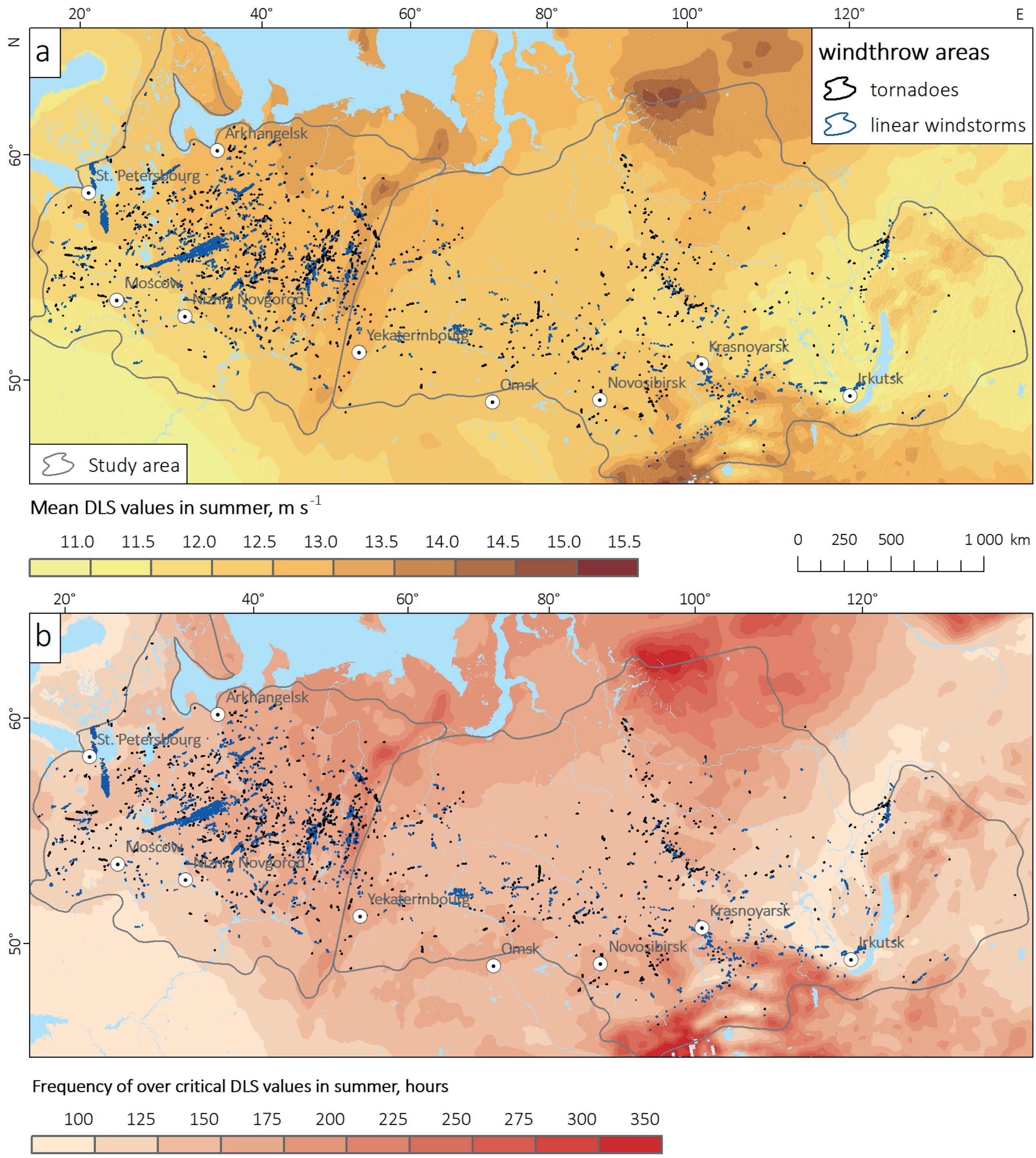

Fig. 3. Spatial distribution of DLS and windthrow events in the forest zone of the ER and Siberia: a) mean values for the summer seasons in 2001-2020; b) number of days with super-critical values

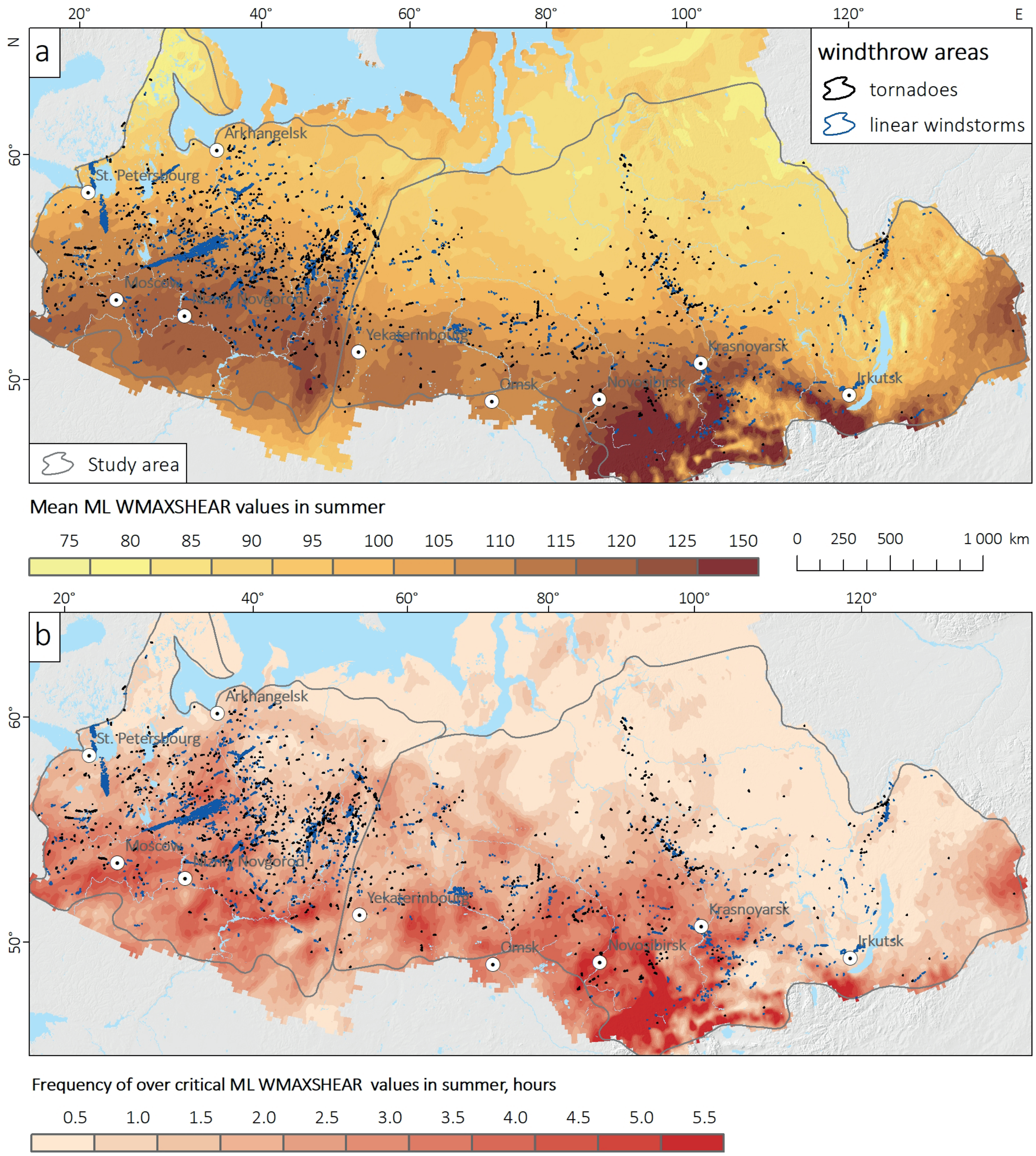

Fig. 4. Spatial distribution of ML WMAXSHEAR and windthrow events in the forest zone of the ER and Siberia: a) mean values for the summer seasons in 2001-2020; b) number of days with supercritical values

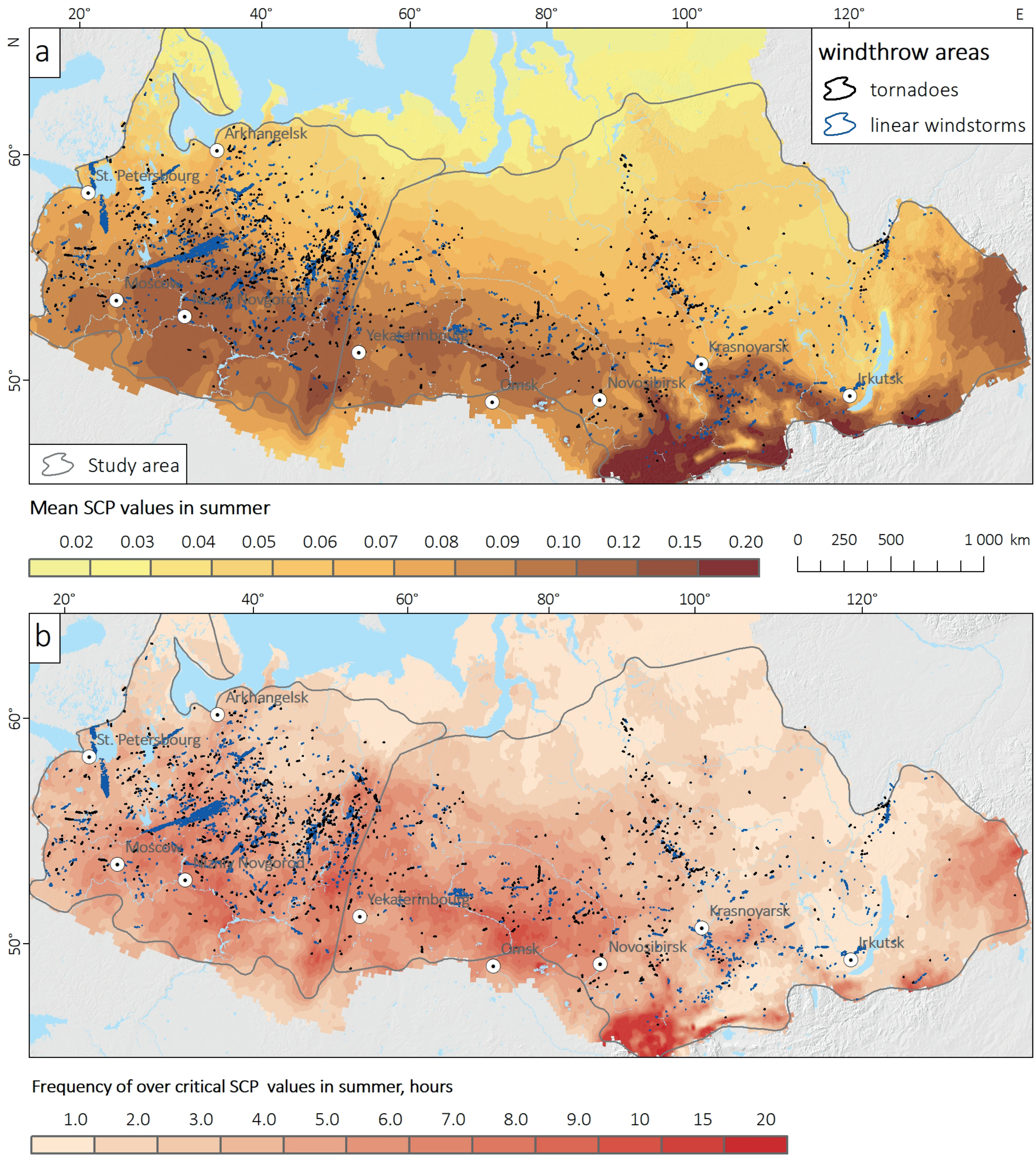

Fig. 5. Spatial distribution of SCP and windthrow events in the forest zone of the ER and Siberia: a) mean values for the summer seasons in 2001-2020; b) number of days with supercritical values

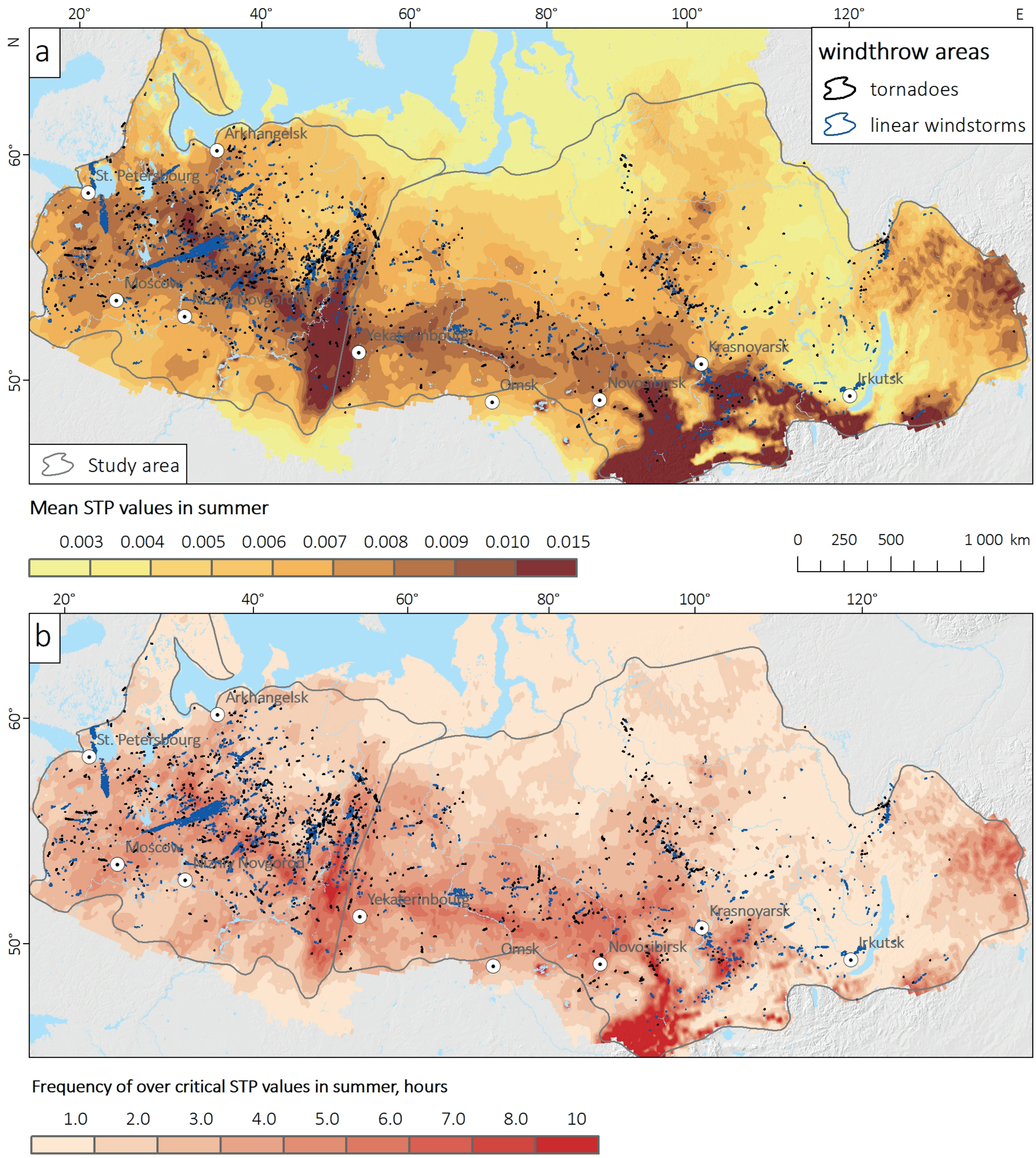

Fig. 6. Spatial distribution of STP and windthrow events in the forest zone of the ER and Siberia: a) mean values for the summer seasons in 2001-2020; b) number of days with supercritical values

weak relationship with the variability of DLS with several coincident maxima and minima, and the corresponding correlation is much weaker than for SCP and STP.

Additionally, convective parameters did not correlate with windthrow days in the ER or Siberia. The strong dependence of the number of days with windthrow events on the accuracy of windthrow date determination explains this. This accuracy increases continuously from 2001 to 2020 due to the opening of additional data sources such as Sentinel-2 satellite images, storm reports in social networks, etc. This issue is discussed in more detail in [Shikhov et al., 2020]. Therefore, the number of days with windthrow events is not very meaningful in the context of the present study.

DISCUSSION AND CONCLUSION

This study presents the results of the coupled analysis of three datasets characterizing windthrow events caused by convective windstorms and tornadoes in the forest zone of the ER and Siberia (1), the values of convective atmospheric parameters as predictors of the occurrence of such hazardous wind events, calculated from the ERA5 reanalysis data (2), and the lightning density from the WWLLN dataset (3). Empirical relationships between these datasets in space and in time (correlation of inter-annual variability) are considered.

It is found that the spatial distribution of windthrow has a statistically significant correlation with the spatial distribution of convective parameters ML CAPE, ML WMAXSHEAR, STP, and SCP both in the ER and in Siberia.

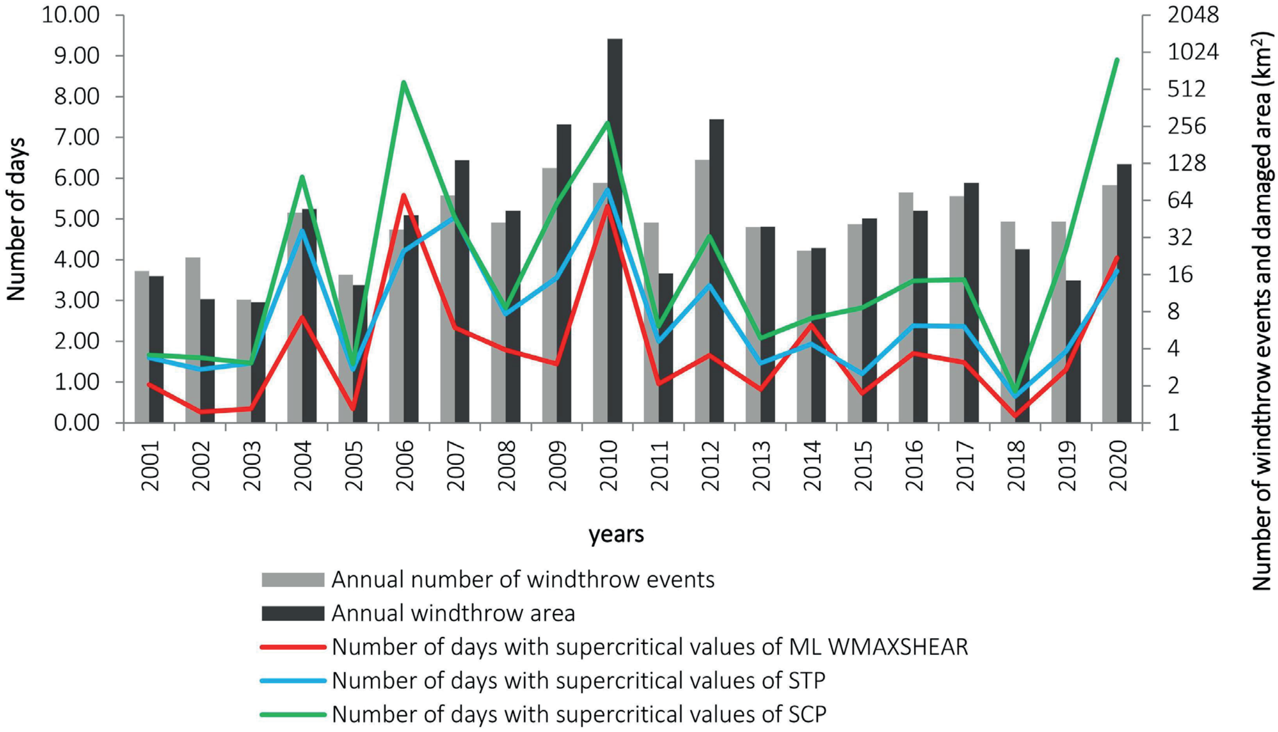

Fig. 7. Interannual variability of windthrow characteristics and the number of days with supercritical values of convective variables in the forest zone of the ER in 2001-2020

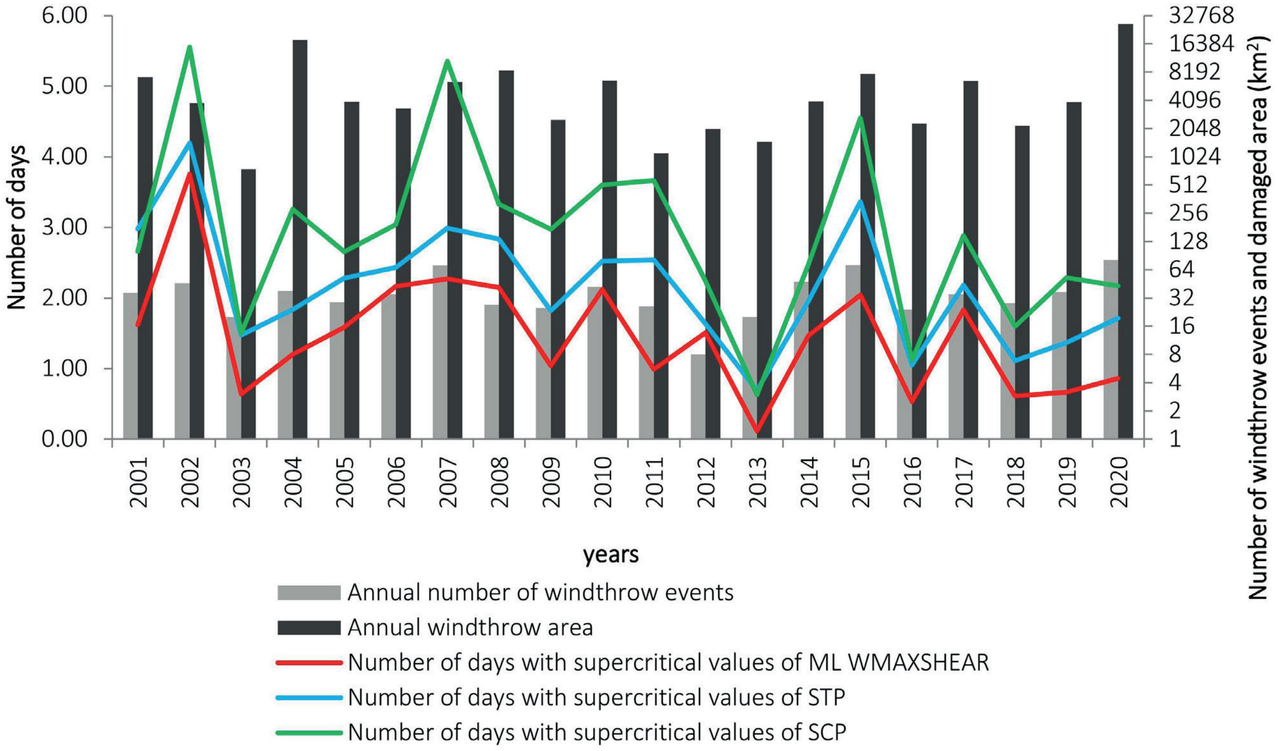

Fig. 8. Interannual variability of windthrow characteristics and the number of days with supercritical values of convective variables in the forest zone of Siberia in 2001-2020

Table 3. Spearman (numerator) and Pearson (denominator) correlation coefficients of the annual number of windthrow events and the damaged area with the convective parameters' values averaged over the summer months of each year. Underlined text indicates statistically significant coefficients

Region	Windthrow characteristics	ML WMAXSHEAR			SCP			STP			ML CAPE			DLS		
		Mean	N_{crit}	N_{90p}	Mean	N_{crit}	N_{90p}	Mean	N_{crit}	N_{90p}	Mean	N_{crit}	N_{90p}	Mean	N_{crit}	N_{90p}
ER	Number of events	0.41/ 0.42	0.49/ 0.34	0.47/ 0.13	0.61/ 0.59	0.69/ 0.55	0.49/ 0.41	0.65/ 0.61	0.64/ 0.58	0.47/ 0.13	-0.13/ -0.06	0.02/ 0.03	-0.18/ 0.13	0.57/ 0.49	0.48/ 0.31	0.45/ 0.23
	Number of days	0.09/ 0.72	0.27/ 0.56	0.33/ 0.27	0.33/ 0.70	0.49/ 0.46	0.39/ 0.25	0.30/ 0.56	0.33/ 0.62	0.33/ 0.27	-0.30/ 0.50	-0.15/ 0.69	-0.33/ 0.84	0.57/ 0.44	0.63/ 0.33	0.65/ 0.40
	Area	0.57/ 0.32	0.69/ 0.43	0.63/ 0.28	0.79/ 0.47	0.79/ 0.52	0.59/ 0.42	0.80/ 0.38	0.78/ 0.46	0.63/ 0.28	0.13/ -0.10	0.30/ 0.04	0.11/ 0.24	0.47/ 0.55	0.35/ 0.54	0.32/ 0.58
Siberia	Number of events	0.40/ 0.24	0.48 0.34/	0.38/ 0.25	0.62/ 0.51	0.51/ 0.52	0.60/ 0.43	0.33/ 0.42	0.32/ 0.44	0.76/ 0.25	-0.15/ –0.03	0.20/ –0.10	0.07/ 0.27	0.43/ 0.32	0.56/ 0.45	0.46/ 0.43
	Number of days	-0.16/ 0.06	-0.01/ 0.04	-0.11/ -0.05	0.11/ 0.23	0.07/ 0.12	0.24/ -0.03	-0.22/ 0.18	-0.26/ 0.09	0.30/ -0.05	-0.28/ -0.15	-0.26/ -0.10	0.13/ -0.09	0.13/ 0.18	0.20/ 0.21	0.20/ 0.19
	Area	0.44/ -0.21	0.47/ -0.19	0.31/ -0.27	0.60/ 0.09	0.40/ 0.05	0.34/ -0.08	0.56/ -0.04	0.46/ -0.1	0.31/ -0.27	-0.08/ -0.36	0.16/ -0.35	0.04/ -0.27	0.38/ 0.01	0.42/ 0.07	0.35/ 0.10

**Mean – mean value for June-August, N_{crit} – number of days with values above the critical level, N_{90p} – number of days with values above the 90th percentile from the sample [Chernokulsky et al. 2023]*

This correlation is strongest for STP, whose highest values are observed in the central part of the forest zone both in the ER and in Siberia, close to the areas with the highest windthrow density. However, in Siberia these correlations are generally weaker than in the ER, since the values of the convective parameters, in contrast to the windthrow area, increase significantly in the mountains of southern Siberia. A similar effect, but to a lesser extent, occurs over the Ural Mountains.

There is also a strong correlation between the spatial distribution of windthrow and that of lightning density. The highest lightning density in the ER is observed in the central part of the forest zone, where windthrow events also occur regularly. Thus, STP and lightning density are the most informative variables for identifying the areas with the highest probability of convective storms and tornadoes capable of causing damage to forests. The highest values of other composite parameters, ML WMAXSHEAR and SCP, are observed in the southern part of the forest zone, which is less consistent with the distribution of windthrow events.

The interannual variability of the values of the convective parameters and the windthrow characteristics is found to co-occur, especially in the ER. The strongest correlation is found between the number of days with supercritical values of the STP and the number of windthrow events per season, which shows that the climatic characteristics of the STP can be considered as strong predictors of linear convective windstorms and tornadoes. About 37% of the interannual variability in the number of windthrow events can be explained by the variability in the SCP. It is also interesting to note that the interannual variability of ML CAPE has no correlation with windthrow characteristics, while such correlation is statistically significant for DLS. Thus, the number of windthrow events and the damaged area increased in those years when DLS values were higher than the average.

The identified empirical relationships have a number of limitations or substantial limitations. Firstly, only climatic factors of windthrow occurrence were considered in this study (and only those associated with convective storms), while the level of vulnerability is assumed to be the same for different forest species. Further analysis of the association between windthrow and forest stand characteristics such as species composition, age, and tree height may be useful since these characteristics are also important for windthrow risk [Suvanto et al. 2019]. Second, the relatively short time series of windthrow data results in an insufficient sample size of large windthrow events. The distribution of windthrow area is known to be left-skewed, similar to other forest disturbances [Baumann et al. 2014; Senf and Seidl 2021a]. Thus, among 1816 windthrow events considered, the largest 1% of them is responsible for about 50% of the total damaged area. These large events have a key influence on the spatial distribution of windthrow damage in the entire forest zone of Russia. Thus, the patterns of their spatial distribution and their relationship with convective parameters may change significantly with the increasing length of the observation series. Thirdly, the spatial distribution of the climatic characteristics of convective parameters is strongly influenced by the terrain. If mountainous areas were excluded from the analysis, the results would change significantly, especially in Siberia, but the sample of windthrow events would also be greatly reduced. Finally, the windthrow dataset used has several limitations, which are discussed in [Shikhov et al. 2020]. In particular, the windthrow area may be underestimated in deciduous forests, which are widespread in the southern part of the ER forest zone and in Western Siberia

Despite these limitations, the results may be of interest both for the climatology of severe convective storms and for forestry and sustainable forest management. For example, the first coupled analysis of the windthrow dataset with climatic characteristics of convective variables for a 20-year period showed different degrees of agreement for different variables. STP and lightning density were found to be the most informative predictors of the spatial distribution of severe convective wind events causing forest damage. Together with other predictors of forest vulnerability to wind, they can be used to estimate windthrow risk in the Russian forest zone. However, such estimates are best interpreted in the long term (several decades) in order to reduce the impact of individual major storm events.

A similar approach can be used to predict windthrow risk in future climates, as convective variables can be calculated from CMIP6 model outputs [Lepore et al. 2021]. As climate warming leads to an increase in severe thunderstorm environments [Diffenbaugh et al. 2013; Chernokulsky et al. 2022], the wind-related forest damage may also increase. An increased risk of windthrow should be taken into account for sustainable forest management and long-term forest development planning.

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