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On characteristic reanalysis-based values of convective instability indices for Northern Eurasia tornadoes

A V Chernokulsky[1], M V Kurgansky[1] and I I Mokhov[1,2]

[1]A.M. Obukhov Institute of Atmospheric Physics, Russian Academy of Sciences (IAP RAS), Pyzhevsky 3, Moscow, 119017, Russia
[2]Lomonosov Moscow State University, Leninskie Gory 1, Moscow, 119991, Russia

E-mail: a.chernokulsky@ifaran.ru

Abstract. Characteristic values of nine convective instability indices (CII) including parcel and shear parameters and simplified indices are obtained for tornadoes and waterspouts over Northern Eurasia using ERA-Interim data for the 1979–2016 period. Tornado and waterspout data are extracted from a new database collected in IAP RAS. In general, strong and significant tornadoes are associated with higher values of CII, while waterspouts occur for lower values (especially of shear parameters). Magnitudes of CII for Northern Eurasia significant tornadoes are in general concordance with those for tornadoes in Europe and North America. Threshold values that discriminate between weak and significant tornadoes, and between landfalling and non-landfalling waterspouts, were found by maximizing Threat Score metrics for a particular CII index or for a pair of such indices. Shear parameters show the highest skill as it concerns separating significant and weak tornadoes. CIIs show lower skills for separation of landfalling and non-landfalling waterspouts.

1. Introduction

Tornado is a rare and hard-to-predict hydrometeorological phenomenon of deep moist convection (DMC) nature that may cause catastrophic consequences. An ingredient-based methodology is a common way for DMC prediction that assesses the presence of four major ingredients (lift, instability, moisture, wind shear) [1,2] and can be described by several convective instability indices (CII) [1-4]. Knowing characteristic values of CII for tornadoes is desirable for both improved short-term prediction and proper diagnosis of projected changes of tornado formation frequency in the coarse of the global climate change. Estimates for tornado-associated CII are performed for Northern America [5], Europe [6,7], and Australia [8]. However, similar estimates are absent for Northern Eurasia (NE) regions. At the same time, a particular interest of CII evaluation arises in these regions, where the warmest decades throughout the whole era of instrumental observations are accompanied with an increase of convective events [9-11].

In this study, we evaluated characteristic ranges of several CII for tornadoes and waterspouts over NE using ERA-Interim reanalysis data and a new tornado climatology [1,2,12]. In addition, we obtained threshold values that discriminate between weak (with F0 and F1 intensity [3,4,13]) and significant (F2, F3, and F4 intensity) tornadoes, and also between landfalling and non-landfalling waterspouts.

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2. Data and methodology

We evaluated CII for the so-called 'proximity soundings' that represent measurements of atmosphere vertical structure close to severe weather events in space and time [5,6,14]. These soundings can be estimated using reanalysis data [2,6,7,14]. We used ERA-Interim reanalysis [8,15] data for the 1979-2016 period to calculate convective indices (Table 1). Indices were calculated within 3 hours and 200 km off the tornado time of occurrence and location and the maximum value in this area/time period was assigned to the tornado event. This assumption is similar to those used for estimating CII in Northern America [5,9-11] and Europe [6]. We evaluated a parcel parameter (CAPE), kinematic (shear) parameters (DLS, MLS, LLS), a composite parameter (WMAXSHEAR) and several simplified indices (3D, TT, k-index, SWEAT) (Table 1).

Table 1. Used convective indices

Indices (acronym)	Indices (full name)	Formula	Reference	Comments on the computation
CAPE, J Kg^{-1}	Convective available potential energy	$\mathrm{CAPE} = \int_{LFC}^{EL} g\left(\frac{T_{v,parcel} - T_{v,env}}{T_{v,env}}\right)dz$	[3]	Taken from ERA-Interim directly (as a forecasted parameter)
3D, ºC	Dewpoint, depression of dewpoint index	$3\mathrm{D} = D_{surf} - DD_{surf}$	[16,17]	
TT, ºC	Total totals	$\mathrm{TT} = T_{850} - T_{500} + D_{850} - T_{500}$	[3]	
k-index, ºC	k-index	$\mathrm{K} = T_{850} - T_{500} + D_{850} - DD_{700}$	[3]	
SWEAT	Severe Weather Threat Index	$\mathrm{SWEAT} = 20(\mathrm{TT} - 49) + 12D_{850} + 2V_{850} + V_{500} + 125(\sin(\Delta V_{500\text{–}850}) + 0.2)$	[3]	
DLS, m s^{-1}	Deep layer shear	$\mathrm{DLS} = \Delta V_{500\text{–}surf}$	[7]	500 hPa level was taken instead of 6 km
MLS, m s^{-1}	Midlevel shear	$\mathrm{MLS} = \Delta V_{700\text{–}surf}$	[7]	700 hPa level was taken instead of 3 km
LLS, m s^{-1}	Low-level shear	$\mathrm{LLS} = \Delta V_{900\text{–}surf}$	[7]	900 hPa level was taken instead of 1 km
WMAXSHEAR, m^2 s^{-2}	WMAXSHEAR	$\mathrm{WMAXSHEAR} = \mathrm{DLS}\ (2\mathrm{CAPE})^{1/2}$	[7]	

The following notations are used: LFC – height of level of free convection, EL – height of equilibrium level, $T_{v,parcel}$ – virtual temperature of the individual parcel, $T_{v,env}$ – virtual temperature of the environment, D – dew point temperature, DD – depression of dew point temperature, T – air temperature, V – wind speed. Subscripts denote vertical levels (surf – near surface; 900, 850, 700, and 500 – corresponding isobaric levels).

Tornado event data were extracted from a database of NE tornadoes collected recently in the Obukhov Institute of Atmospheric Physics (IAP) [12]. The database contains information on 2878 tornado cases over land and water in NE regions (specifically, for the fUSSR countries) for the period from 979 to 2016 years. The database was compiled using a variety of sources including primary (for instance, photos or textual reports of tornado witnesses in social networks) and secondary sources (descriptions of historical events, news reports, existed climatologies, case studies and others). Satellite data on tornado-induced forest disturbances were used as well for uncovering previously unreported tornadoes [18] or for specifying characteristics of well-known cases [19]. The database includes information on various tornado characteristics including time and location (with accuracy estimates), Fujita-scale intensity, degree of certainty (very low, low, medium, and high), underlying surface features etc.

Here, we utilized cases with the medium or high degrees of certainty and the time accuracy less than 3 hour for the 1979–2016 period (1184 cases in total). It includes 840 tornadoes over land (among them 158 significant (with the F2 (137), F3 (20), or F4 (1) intensity), 582 weak (with the F0 (249) or

F1 (333) intensity), and other (100) with undefined intensity), 289 non-landfalling waterspouts, and 55 landfalling waterspouts.

Thresholds for each CII were determined to discriminate between weak and strong tornadoes, and also between landfalling and non-landfalling waterspouts. The Threat Score (TS) was used to find the exact threshold values [20]. This index is useful for unbalanced samples – specifically, when the event (in this case, strong tornadoes or landfalling waterspouts) occurs substantially less frequently than the alternative event does (weak tornadoes or non-landfalling waterspouts) [20]. TS was computed as:

$$TS = TP\,(TP + FP + FN)^{-1},$$

where TP is true positive, FP is false positive, and FN is false negative outcome, correspondingly (with a particular CII value acting as a forecast). CII with the maximum TS was assigned as a threshold value.

3. Results

Distributions of CIIs for tornadoes are shown in figure 1. Tornadoes over NE are characterized with relatively high CII values (note that we chose proximity sounding with maximum CII in the 200-km radius; therefore, actual CII values may be lower) that vary in a broad range. Distributions of CIIs tend to be skewed toward higher values for kinematic and parcel parameters (CAPE, LLS, MLS, DLS, WMAXSHEAR) and toward lower values for simplified indices (3D, k-index, TT). Significant tornadoes are characterized with higher CII values than weak tornadoes and waterspouts (especially for shear, which is particularly low for waterspouts). Characteristic values of CII for strong tornadoes (≥F3) are even higher (except for 3D and DLS). In general, non-landfalling waterspouts are characterized with the lowest CII values. Note, that CII distributions for significant tornadoes tend to be skewed toward higher indices values; while for non-landfalling waterspouts, CII distribution is skewed toward lower indices values (primarily for shear).

Table 2 presents CII threshold values for discriminating between significant and weak tornadoes, and also between landfalling and non-landfalling waterspouts (accompanied with the TS metrics values). In general, shear parameters have greater skill to separate significant tornadoes from weak tornadoes than other CIIs (with MLS as the best discriminator, which TS is 0.305). Prediction skill of indices for separating landfalling waterspouts from non-landfalling is generally lower (with CAPE as the best discriminator, which TS equals to 0.218).

Using two CIIs for separating between significant and weak tornadoes, and also between landfalling and non-landfalling waterspouts may increase TS metrics by 10–15% (Table 3). For tornadoes, the highest TS values are obtained when shear parameters are used along with lifting indices (such as CAPE, 3D, TT, WMAXSHEAR). Note, that using the pair consisting of simple 3D index and shear parameter (MLS or LLS) is somewhat comparable with using a more sophisticated CAPE index. This indicates on a perspective for using 3D-index as a simple diagnostic parameter for environments with high convective instability (which was mentioned previously in [11]). For waterspouts, the key index is WMAXSHEAR (particularly, the highest TS values are noted for the pairs LLS/ WMAXSHEAR and SWEAT/WMAXSHEAR).

Figures 2 and 3 present scatter plots of tornadoes with known intensity for CII pairs with relatively large TS values (for separating weak and significant tornadoes). Usage of different pairs results in different ratio among TP, FP and TN. For instance in the pairs MLS/WMAXSHEAR LLS/WMAXSHEAR, the first pair yields more misses (higher values of TN), while the second one results in increasing the false results (higher values of FP) (figure 2). In general, significant tornadoes may form with relatively low CII values (for instance with CAPE < 80 J kg^{-1}, LLS < 5 m s^{-1}, and SWEAT < 130). On the contrary, weak tornadoes are observed in conditions with large magnitudes of CII (CAPE > 4000 J kg^{-1}, LLS > 19 m s^{-1}, SWEAT up to 500). At the same time, strong tornadoes occur only for conditions with high CII values. Thus, most of strong tornadoes are discriminated well

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using the thresholds obtained for significant tornadoes. However, obtaining thresholds for strong tornadoes solely is challenging due to lack of sufficient statistics (only 22 cases for the 1979–2016 period).

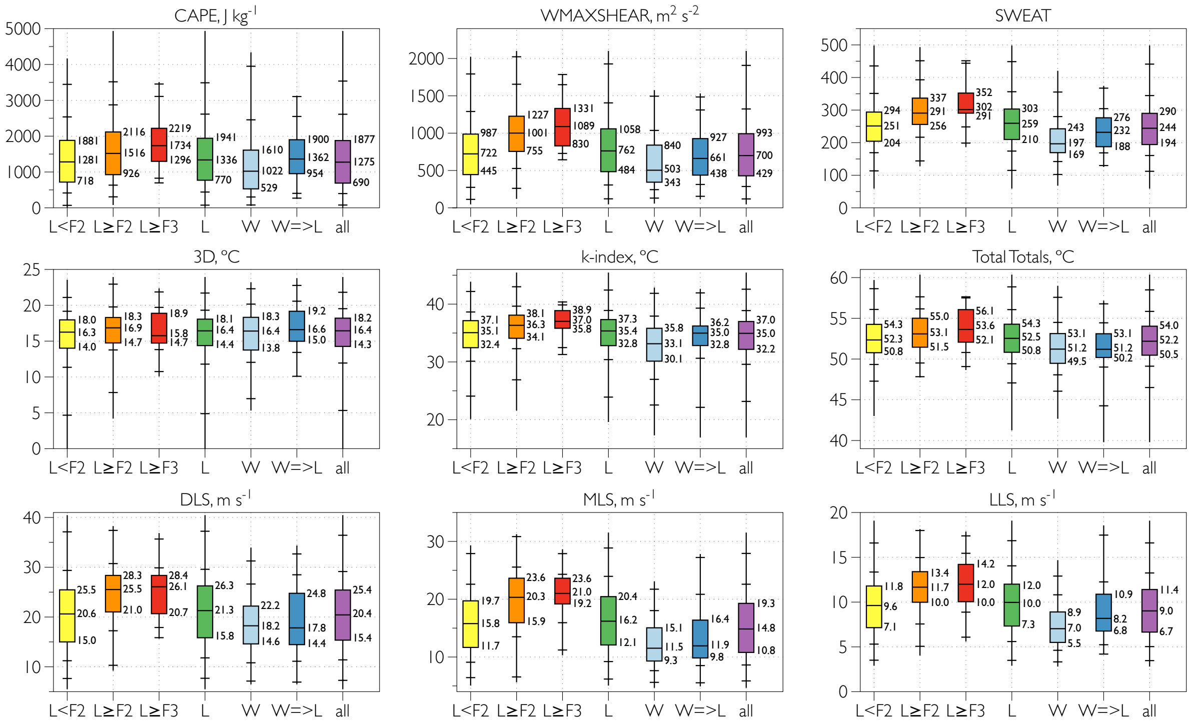

Figure 1. Box-whisker plots for nine CII (CAPE, SWEAT, WMAXSHEAR in the upper panels (from left to right); 3D, k-index, TT in the middle panels; DLS, MLS, and LLS in the lower panel) for seven samples of tornadoes: weak tornadoes over land (with the intensity <F2) (yellow boxes), significant tornadoes over land (intensity ≥F2) (orange boxes), strong tornadoes (intensity ≥F3) (red boxes), all tornadoes over land (green boxes), non-landfalling waterspouts (blue boxes), landfalling waterspouts (dark blue boxes), and all tornadoes and waterspouts (magenta boxes). Boxes depict interquartile range (with median line), horizontal lines display 1, 10, 90, and 99 percentiles.

Table 2. CII threshold values for discriminating significant tornadoes (with the F2, F3, and F4 intensity) from weak tornadoes (with the F0, F1 intensity), and landfalling waterspouts from non-landfalling waterspouts

	Threshold for discriminating significant tornadoes	*TS*	Threshold for discriminating landfalling waterspouts	*TS*
CAPE, J Kg^{-1}	623	0.233	1183	0.218
3D, °C	13.9	0.236	14.3	0.181
TT, °C	51.4	0.222	50.1	0.174
k-index, °C	33.9	0.240	33.7	0.208
SWEAT	242	0.280	246	0.215
DLS, m s^{-1}	23.4	0.284	16.0	0.162
MLS, m s^{-1}	19.2	0.305	9.0	0.171
LLS, m s^{-1}	10.0	0.278	9.3	0.204
WMAXSHEAR, m^2 s^{-2}	941	0.293	594	0.211

Table 3. Threat scores when two CIIs are used for discriminating significant tornadoes from weak ones (upper-right part of the table), and landfalling waterspouts from non-landfalling ones (lower-left part of the table).

	CAPE, J Kg^{-1}	3D, °C	TT, °C	k-index, °C	SWEAT	DLS, m s^{-1}	MLS, m s^{-1}	LLS, m s^{-1}	WMAXSHEAR, m^2 s^{-2}
CAPE, J Kg^{-1}		0.243	0.238	0.246	0.284	0.301	0.320	0.303	0.299
3D, °C	0.222		0.241	0.251	0.290	0.302	0.321	0.299	0.301
TT, °C	0.219	0.210		0.242	0.280	0.287	0.309	0.279	0.294
k-index, °C	0.232	0.211	0.214		0.284	0.297	0.313	0.292	0.297
SWEAT	0.233	0.222	0.212	0.214		0.309	0.320	0.305	0.304
DLS, m s^{-1}	0.220	0.189	0.193	0.219	0.224		0.307	0.308	0.302
MLS, m s^{-1}	0.224	0.194	0.199	0.216	0.225	0.173		0.319	0.324
LLS, m s^{-1}	0.236	0.218	0.219	0.222	0.229	0.219	0.221		0.320
WMAXSHEAR, m^2 s^{-2}	0.218	0.211	0.239	0.217	0.242	0.217	0.214	0.264	

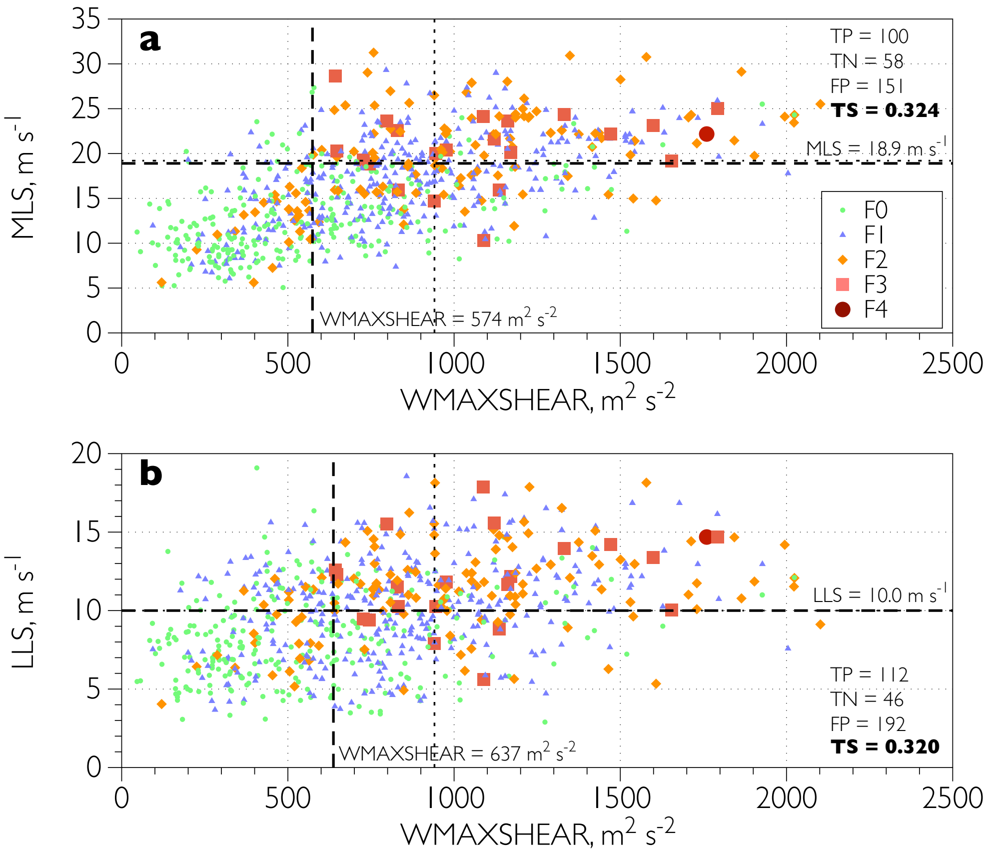

Figure 2. Scatter-plot of tornadoes with known intensity for two pairs of CII (MLS/WMAXSHEAR (a) and LLS/WMAXSHEAR (b)). Dashed lines denote threshold values when pairs of CII are used for separation (values are subscripted); dotted lines denote threshold values of individual CII (according to the Table 2).

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Note that threshold values are somewhat different from those in Table 2 (when one CII is used as a discriminating parameter instead of two parameters). For instance, CAPE thresholds vary from 548 to 668 J kg^{-1} depending on the second parameter. Threshold ranges of 3D, k-index, TT and SWEAT are 12.9–13.6 ºC, 44.1–51.4 ºC, 30.1–34.8 ºC, and 221–242, respectively. DLS threshold equals to 23.4 m s^{-1} for almost all second parameters (except for other shear parameters (MLS and LLS) and SWEAT, for them it equals to 16.2, 19.2 and 19 m s^{-1}). MLS and LLS thresholds vary in much narrower range (between 18.4 and 19.2 m s^{-1}, and between 9.5 and 10 m s^{-1} respectively). WMAXSHEAR threshold is strongly dependent on the second discriminating parameter; particularly, it equals to 574–637 m^2 s^{-2} when the second parameter is shear index (DLS, LLS or MLS) and to 938–941 m^2 s^{-2} for all other indices.

Discriminating between non-landfalling and landfalling waterspouts (Fig.4) is worse than for weak/significant tornadoes. On the one hand, this comes from relatively small sample size of landfalling waterspouts. On the other hand, the difference between these two types may not be determined in space of convective indices. For instance, these differences may depend on local characteristics, like a distance from a place of waterspout formation to a coastal line, or geometry of a coastal line, or a wind direction. More sophisticated analysis is needed to establish causes of falling of waterspouts to land.

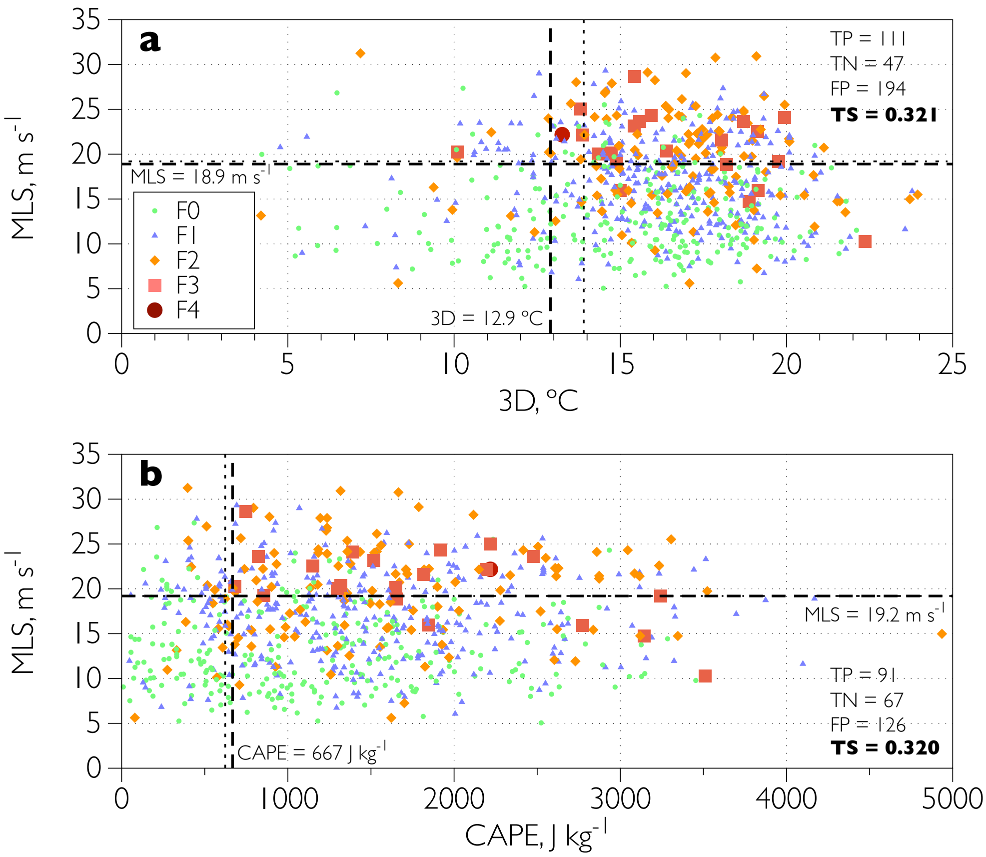

Figure 3. The same as Figure 2 but for MLS/3D (a) and MLS/CAPE (b).

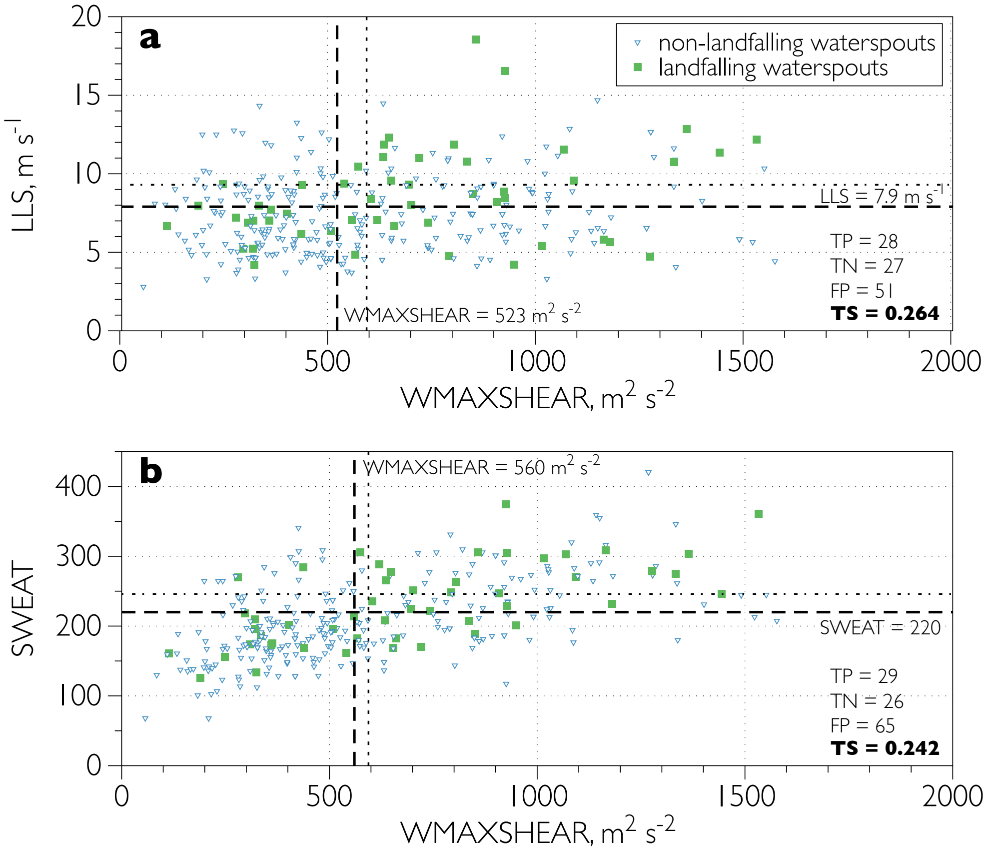

Figure 4. The same as Figure 2 but for land-falling and non-landfalling waterspouts and for CII pairs LLS/WMAXSHEAR (a) and SWEAT/WMAXSHEAR (b).

4. Discussion and Conclusions

Proximity soundings for tornadoes in Northern Eurasia are characterized with relatively high values of convective instability indices. In general, significant tornadoes are associated with higher values of indices than the weak tornadoes (strong tornadoes are associated with even higher values, while waterspouts are characterized with sufficiently lower values). This is consistent with findings of previous studies for both North America and Europe [5-7,21] (Table 4). However, our analysis generally shows higher values of convective parameters than previous studies, primarily for weak tornadoes and waterspouts. This is mostly due to the difference in the source data. In fact, radiosonde data were used in [5-7], while reanalysis data were utilized in this study. Since the aim of this study was to find the maximum value of CII in a particular area around a particular tornado, there is a great chance that the location of this maximum does not correspond to the location of the radiosonde station nearest to the event. For instance, for the F3 tornado near Yanaul in 2014 [17], the maximum of CAPE was noted to the south of tornado formation region and equaled to 1516 J kg^{-1}, while in the reanalysis data CAPE was only 948 J kg^{-1} for the cell nearest to the radiosonde station. The difference of CAPE values is particularly large for waterspouts. Note, that the 75th and 90th percentiles of parameters for strong tornadoes are similar with other regions (CAPE is even lower than in Northern America) .

For comprehensive analysis, less-severe convective events (weak tornadoes and waterspouts) and non-severe thunderstorms (no tornadoes) should be also discriminated. However, this task is challenging even for US [5] where tornadoes occur ten times more frequently than over Northern Eurasia. While, estimates for discriminating between strong convection events and less-severe events are more robust. We found shear indices being the best discriminators between weak and significant tornadoes in Northern Eurasia. In particular, LLS = 10.0 m s^{-1}, MLS = 19.2 m s^{-1}, DLS = 23.4 m s^{-1}, WMAXSHEAR = 941 m^2 s^{-2} and can be treated as threshold values for significant tornadoes. Other indices show less skill for differentiating between the different intensities of tornadoes. Land falling of waterspouts has relatively weak dependence on convective parameters and is presumably caused by other factors (e.g. a distance from a place of waterspout formation to a coastal line).

Table 4. Comparison of CII empirical distribution percentiles (25th, 50th, 75th and 90th respectively) for tornadoes in Northern Eurasia (this study) with those for tornadoes in North America [5] and Central Europe [6,7].

	Northern Eurasia (1979–2016) (this study)	U.S. (1992) [5]	Central Europe (2008–2013) [6]	Central Europe (2009–2015) [7]
	Weak tornadoes			
CAPE, J Kg^{-1}	(718, 1281, 1881, 2537)	(283, 1152, 1821, 2453)	(192, 534, 986, 1578)	(34, 140, 412, 798)
DLS, m s^{-1}	(15.0, 20.6, 25.5, 29.4)	(12.1, 19.1, 22.1, 25.8)	(9.4, 14.3, 21.0, 27.5)	(8.4, 13.7, 18.6, 24.4)
MLS, m s^{-1}	(11.7, 15.8, 19.7, 22.6)	-	-	(4.9, 8.1, 12.8, 17.0)
LLS, m s^{-1}	(7.1, 9.6, 11.8, 13.4)	-	(3.6, 6.3, 9.0, 13.3)	(2.7, 5.2, 7.8, 10.6)
WMAXSHEAR, m^2 s^{-2}	(445, 722, 987, 1290)	-	-	(89, 212, 356, 556)
	Significant tornadoes			
CAPE, J Kg^{-1}	(926, 1516, 2116, 2873)	(519, 1314, 1877, 3028)	(163, 518, 1450, 2358)	(105, 251, 663, 992)
DLS, m s^{-1}	(21.0, 25.5, 28.3, 30.7)	(13.6, 18.4, 21.8, 29.0)	(17.2, 21.7, 25.6, 31.4)	(15.6, 20.8, 26.8, 28.6)
MLS, m s^{-1}	(15.9, 20.3, 23.6, 25.5)	-	-	(12.5, 14.6, 18.4, 20.3)
LLS, m s^{-1}	(10.0, 11.7, 13.4, 15.0)	-	(6.3, 9.2, 12.0, 16.2)	(5.7, 9.2, 12.9, 14.7)
WMAXSHEAR, m^2 s^{-2}	(755, 1001, 1227, 1655)	-	-	(254, 504, 883, 1106)
	Waterspouts			
CAPE, J Kg^{-1}	(529, 1022, 1610, 2456)	-	-	(40, 82, 183, 327)
DLS, m s^{-1}	(14.6, 18.2, 22.2, 26.6)	-	-	(5.8, 10.6, 14.7, 18.5)
MLS, m s^{-1}	(9.3, 11.5, 15.1, 18.0)	-	-	(2.6, 4.8, 7.7, 10.4)
LLS, m s^{-1}	(5.5, 7.0, 8.9, 10.8)	-	-	(1.7, 3.6, 6.1, 8.0)
WMAXSHEAR, m^2 s^{-2}	(343, 503, 840, 1026)	-	-	(52, 108, 206, 553)

Exact tornado-associated values of convective instability indices may also depend on the initial data. For instance, over Europe, the radiosonde data are in better agreement with the ERA-Interim reanalysis for shear parameters than for parcel ones [2]. For future work, it is worthwhile to determine characteristic values of convective parameters in Northern Eurasia using both reanalysis and radiosonde datasets. Additionally, convective indices have a prominent annual cycle [2] and vary from one region to another [2,11,14]. Therefore, it is beneficial to supplement future analysis with regional and intra-annual refinements of tornado-associated convective parameter characteristic values and thresholds. This is particularly important in the light of an ongoing climate change and associated increase in CII values over Northern Eurasia, as emphasized in [22].

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