Linking the storm cells position and high values of instability indices – a case study in the southeast of Western Siberia

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Abstract. Improving the identification accuracy of spatial distribution of hazardous convective phenomena has relevant meaning for territories are not covered by lightning detection systems. We perform comparison on set of instances of registered lightning discharges by a Boltek single-point lightning detector with spatial instability fields. To determine the areas of atmospheric instability over the southeast of Western Siberia, Total Totals and K-index have been used. Values for the indices were calculated from balloon sounding data and ERA5 reanalysis. The results demonstrate an acceptable spatial agreement between the fields with high instability indices according to ERA5 reanalysis data and actual positions of thunderstorm cells. A validation of ERA5 indices values with upper-air data showed that a smaller consistency error correspond to Total Totals index. Therefore, to predict the spatial position of convective clouds producing thunderstorms over the southeast of Western Siberia, it is promising to use Total Totals index, which is calculated using either aerological measurements or satellite remote sensing data.

1. Introduction
Convective hazards (thunderstorms, heavy rain-falls, hail, squalls, microbursts, tornadoes, etc.) annually cause considerable damage and losses; wherein the frequency of convection-related events is increasing in Western Siberia [1, 2]. To assess the probability of thunderstorm clouds formation and convective hazardous phenomena, a various instability indices have been developed to provide a qualitative and quantitative assessment of atmospheric stability [3–6].

The current warming in Western Siberia, especially in the summer months, leads to increased convection. With growing air temperature, moisture, as the one of key factor for convection mechanism, lifts upward from an evaporating surface of uncounted natural waterbodies in the region under study, particularly the Vasyugan Swamp. In this regard, the forecasting of thunderstorm clouds and their spatial distribution and potential lightning discharges spots is fore-most issue for Siberia.

In addition, parametrizations of lightning activity are currently being applied into climate models, combining the lightning flashes frequency with thundercloud characteristics [7–11]. The results of the paper will enable to estimate the possibility of long-term averaged values of in-stability indices for their implementation in climate models.

This paper aims to provide a qualitative assessment of the relations of centers with atmospheric instability and thunderstorm cells in different intensity. Thunderstorms were registered by a Boltek single-point lightning detector. A convective instability has been ascertained in accordance with thresholds of Total Totals and K-index, computed using ERA5 reanalysis and up-per-air sounding data.
We selected the period, when the ambient conditions was determined by specific synoptic situation most favorable to convection. Numerous thunderstorms resulted during the afternoon and night of June 28, 2008 and until next day in the southeast of Western Siberia, to which Tomsk, Novosibirsk, and Kemerovo regions assigned. Based on the purpose, a synoptic pattern and thermodynamic state of the lower and middle troposphere were taken into consideration.

2. Materials and methods
The thunderstorm presence and spatial position of storm cells have been determined based on the registration of lightning discharges with a single-point lightning detector (LD-250) by Boltek. The device is a property of the training laboratory at the Department of Meteorology and Climatology, Geology and Geography Faculty, TSU, and is the only tracking point for short and long-range thunderstorms cells in Western Siberia (hereinafter as detector "Tomsk", 56.46° N, 84.93° E). LD-250 allows detecting lightning discharges within radius of up to 480 km using NexStorm Lite software in a fully automatic mode [12–14]. The data processing carry out in the RimDataLightning author tool, the output file contains information on the polarity and time of the discharge and the coordinates of the lightning strike point. A visualization of the points on a polar coordinate system map with the center in Tomsk displays the current position of the thunderstorm centers with tracking their movement in real time.

The degree of instability and potential formation of convective hazards depend on the thickness of the unstable moist layer in atmosphere, which are evaluated by K-index (K) [15] and Total Totals index (TT) [16]:

\[
K = (T_{850} - T_{500}) + T_{850}D_{850} - (T_{700} - T_{700}D_{700})
\]

\[
TT = T_{850} + T_{850}D_{850} - 2T_{500}
\]

where T represents temperature at the indicated level (ºC) and TD represents dew point temperature (ºC).

To estimate the spatiotemporal variability of the thermodynamic atmospheric characteristics, TT and K values were calculated using ERA5 reanalysis data [17]. ERA5 is the fifth generation of the global atmospheric observations by ECMWF. Its advantages are continuous data series for the period from 1979 to the present and high spatiotemporal resolution (0.25° x 0.25° and 1 hour) [18]. According to [19], ECMWF reanalyses of previous generations had the best accuracy among all reanalyses of describing the temperature mode of Siberia that should have been passed on next-in-line projects.

Being that upper air data are usually measured by twice daily radiosonde soundings at 0000 and 1200 UTC (which corresponds to 7 and 19 hours of local time), we picked up the Boltek detector outcomes for only selected time-points on June, 28-29, 2008. All resulting files are presented in map with the spots of lightning discharges for last hour of registration. In order to compare the index values calculated on reanalysis and aero-logical information, thunderstorm events recorded at a near point in time of radiosonde launches and closest to upper-air stations were chosen for analysis. The processing and visualization of ERA5 data were performed using the MATLAB mathematical package. To validate aerological which accepted as reference and reanalysis-derived index values, the observation by WMO 29634 Novosibirsk, WMO 29231 Kolpashevo and WMO 29839 Barnaul upper-air stations were taken. Besides, we analyzed atmospheric instability characteristics based on temperature-humidity profiles obtained at abovementioned stations [20].

3. Results
The average long-term density of lightning discharges into the earth at mid-latitudes varies in the range of 1–7 disch. km⁻² yr⁻¹. Previously [21] it was found that the average values of lightning discharges density for the Western Siberian territory changes from 0.1 to 5 disch. km⁻² yr⁻¹ with maximum possible values of the lightning discharges density range up to 10 disch. km⁻² yr⁻¹. In the framework of studies presented here, we assess the variability of the instability indices values depending on the activity of the thunderstorm process for each day. In this case, the density of
lightning discharges has been estimated taking into account two factors: 1. at an hour close to aerological observations; 2. areas occupied by thunderstorms were located near upper-air stations. The activity of the thunderstorm process was divided into follow categories: “severe” – more than 50 disch./min, “moderate” – 50 disch./min and “weak” thunderstorms up to 20 disch./min occurred.

Convection-favoring environments were associated with series active cyclones arrangement. In the warm sectors of cyclones shifting to east, warm subtropical air moved toward the northerly [22], which contributed to the heating of the underlying surface and temperature contrasts favorable for convection development. According to weather observations in the Novosibirsk, Tomsk, Kemerovo regions and Altai Territory, on the afternoon of June, 28 and during the next two days moderate to heavy showers, thunderstorms, hail with a diameter of 7–11 mm, and squally gusts up to 18-24 ms\(^{-1}\) were reported [22]. Tracking of thunderstorms trajectory by Boltek maps indicated the southeast direction.

In accordance to the threshold indices in [23], the atmospheric state for June 28 and 29 was determined to be highly unstable up to a 90% probability of thunderstorms and other hazardous convective phenomena over the territory. A variations of the indices values are directly correlate to formation extent of thunderstorm center. It is reasonable to expect that the stronger the convection, the values of TT and K indices are the higher. The convection intensity expressed by an extensive storm center and a greater number of lightning discharges under the registration of detector “Tomsk”. The spatial arrangement of high instability areas according to ERA5 (figures 2–4), in general, is consistent with the actual positions of the thunderstorm centers (figure 1). The pre-convective state of the atmosphere for June 28 (0000 UTC) is characterized by a range of K index values from 27.1°C (upper-air station Novosibirsk) to 36.3°C (upper-air station Kolpashevo), TT index 47.0 up to 61.0°C. According to Boltek registration, by the time of 1200 UTC, weak thunderstorms were observed in the study area near the Novosibirsk station (TT values 49.0°C, K equal 28.7°C) and moderate storms in Kolpashevo (TT and K indices 50.5 and 33.1°C respectively). By the next day, there was a decreasing of the indices values, while the potential for the convection development has been maintained.

![Figure 1. Lightning discharges registered by detector “Tomsk” on June, 28 at 0000 UTC (a) and 1200 UTC (b), June, 29 at 0000 UTC (c).](image)

Further, the absolute values of K and TT indices calculated on the basis of upper-air data at the observation sites (table 1) are compared for spatially interpolated ERA5 fields of chosen indices. The consistency of ERA5-calculated mean values with selected as reference upper-air data was evaluated on the basis of the mean root error (MAE) regardless of its sign with an accuracy of 0.1 [24]. TT index is characterized by a qualitative agreement between analyzed values (MAE 3.8°C); for K index, MAE exceeded 11.1°C. Despite the fact that both indices characterize the degree of convection development based on a temperature lapse rate and vertical extent of high humidity layers, such a significant difference for K index can be attributed to the fact that the index also takes into account humidity
characteristics at 700 hPa, while TT index describes in less detail the thermodynamic state of the instability layer.

**Table 1.** Total Totals (TT) and K-index (K) values according to upper-air sounding and ERA5 reanalysis data.

| Date       | Time   | Upper-air station / reanalysis | TT (°С) | K (°С) |
|------------|--------|--------------------------------|---------|--------|
| 6/28/2008  | 00 UTC | Novosibirsk / ERA5             | 47 / 47 | 27 / 22|
|            |        | Kolpashevo / ERA5              | 49 / 44 | 33 / 14|
|            |        | Barnaul / ERA5                 | 61 / 47 | 36 / 29|
|            | 12 UTC | Novosibirsk / ERA5             | 49 / 42 | 29 / 7 |
|            |        | Kolpashevo / ERA5              | 51 / 44 | 33 / 16|
|            |        | Barnaul / ERA5                 | 46 / 41 | 30 / 7 |
| 6/29/2008  | 00 UTC | Novosibirsk / ERA5             | 49 / 52 | 29 / 23|
|            |        | Kolpashevo / ERA5              | 45 / 48 | 32 / 35|
|            |        | Barnaul / ERA5                 | 51 / 49 | 30 / 26|

**Figure 2.** Spatial distribution of K (a) and TT (b) values for 0000 UTC 28 June by ERA5.
4. Conclusion and discussion
A comparative analysis of the spatial distribution of instability areas derived from ERA5 data with the actual positions of the severe thunderstorm in Western Siberia has shown a good qualitative agreement. Validation of ERA5 indices values with reference values belonging to upper-air soundings demonstrated their predominant underestimation. It has been confirmed, that TT index has the best quantitative correspondence (MAE 3.8 °C) in comparison with K index. The quantitative disparity between the indices values obtained from ERA5 reanalysis and upper-air data is presumably due to the interpolation of the spatial fields of meteorological quantities used to calculate the index values at the grid nodes. As a result, there is a “smoothing” of spatial micro- and mesoscale heterogeneities and the underestimation of the maximum values.
It was found that in weak thunderstorms, TT index values did not exceed 49.0°C, K index – 28.7°C, for moderate thunderstorms TT and K indices valued 50.5 and 33.1°C respectively.

Note that earlier for the south-eastern territory of Western Siberia it was established that MOD07_L2 product spatial distribution of TT indices is more applicable for detecting of thunderstorm [25].

Inasmuch as the parameters of lightning activity are currently being implemented into climate models, joining of lightning flashes frequency with the convective cloudiness characteristics and hazardous phenomena produced by it, the presented results is highly to be interesting and relevant in this aspect.

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