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# 1984 Ivanovo tornado outbreak: Determination of actual tornado tracks with satellite data

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ABSTRACT

The 1984 Ivanovo tornado outbreak is one of the most fatal tornado events in Europe with previously unspecified tornado track characteristics. In this paper, we used Landsat images to discover tornado-induced forest disturbances and restore actual characteristics of tornadoes during the outbreak. We defined boundaries of tornado-induced windthrows by visual comparison of satellite images and specified them with Normalized Difference Infrared Index. We confirmed the occurrence of eight tornadoes during the outbreak and determined their location, path width and length. Other tornadoes occurrence during the outbreak was discussed. Fujita-scale intensity of confirmed tornadoes was estimated based on the related literature corpus including previously omitted sources. In addition, information on tornado path lengths and widths was used to estimate minimal tornado intensity for those tornadoes that passed no settlements. In total, the Ivanovo outbreak includes 8–13 tornadoes with F-scale rating mean ranges from 1.8–2.5 and has adjusted Fujita length around 540 km, which makes the outbreak one the strongest in Europe and places it within the upper quartile of U.S. outbreaks. Characteristics of certain tornadoes within the Ivanovo outbreak are exceptional for Russia. The widest tornado path during the Ivanovo outbreak is 1740 m; the longest is from 81.5–85.9 km. With the example of the Ivanovo outbreak, we showed that existing databases on historical Russian tornadoes tend to overestimate tornado path length (for very long tornadoes) and underestimate maximum tornado path width.

## 1. Introduction

The 1984 Ivanovo tornado outbreak is one the most destructive tornado events in the history of Russia and among the most fatal tornadoes in Europe (Antonescu et al., 2017). The outbreak on 9 June 1984 resulted in at least 69 officially confirmed fatal victims (Vasiliev et al., 1985a, hereafter V85a); however, the exact death toll may be several times higher (Berdyshev, 2011; Finch and Bikos, 2012, hereafter FB12). Almost one thousand people were injured, and several settlements were heavily damaged or completely destroyed. One tornado during the outbreak was violent with F4 intensity on the Fujita damage scale (Fujita, 1981), which is only the second F4-tornado in the Russian history (Snitkovskiy, 1987, hereafter S87).

Despite thorough evaluation of synoptic and mesoscale aspects of the outbreak (FB12; Kapitanova, 1986; V85a), key tornado characteristics are still obscured. Particularly, a lack of systematic tornado damage survey in USSR (due to the rarity of that kind of events) resulted in relatively schematic tornado localizations and fairly approximated estimates of paths and widths of tornadoes during the outbreak. Thus, V85a suggested the presence of four tornadoes; two of them were confirmed by eyewitnesses and two were suspected based on wind-induced forest damage analysis. S87 also indicated four tornadoes; however, they do not match with those from V85a. Using satellite images for cloud evolution, FB12 constructed paths of eight thunderstorms (TS) that produced wind damage on that day. Finally, 17 tornadoes for the outbreak were included into the European Severe Weather Database (ESWD) (Groenemeijer and Kühne, 2014, hereafter GK14). Because of the importance of the outbreak, the uncertainty on tornado's number and characteristics is needed to overcome.

The main scope of this paper is to estimate tornado characteristics for the Ivanovo outbreak using satellite-derived information on forest damage. Indeed, because the outbreak developed mostly over forested regions, it caused considerable forest loss. This kind of forest disturbances can be identified from satellite observations (Shikhov and Chernokulsky, 2018). The first attempt to utilize satellite data for assessing the aftermath of tornadoes was made by Sayn-Wittgenstein and Wightman (1975) for boreal forests of Canada. Afterward, satellite images were successfully applied to specify the characteristics of well-

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known remarkable tornadoes and tornado outbreaks [see e.g. (Dyer, 1988; Molthan et al., 2014; Myint et al., 2008; Yuan et al., 2002)]. Shikhov and Chernokulsky (2018) used satellite data to find previously unreported tornadoes in European Russia. They showed that Landsat information on forest loss can be used to evaluate characteristics of tornadoes with F1 intensity and higher, if they passed through forested regions.

In this paper, using Landsat satellite images, we found the actual number of tornadoes during the 1984 Ivanovo tornado outbreak, pinpointed their position, specified their path width and length with a relatively good accuracy, and compared them with the previous estimates.

## 2. Data and methods

To determine the exact position of tornadoes, we searched elongated windthrows that appeared in 1984 close to possible tornado locations. First of all, we focused on TS paths (from FB12) and attributed elongated windthrows that found along these paths and have the same direction to tornado-induced forest damage. Together with information on TS paths, we also verified satellite images for regions close to tornado tracks from V85a, tornado events from S87 and GK14 databases, other events from previously omitted newspapers and non-scientific literature (Androshin and Bystrova, 1984; Berdyshev, 2011; Korobeinikova, 2017; Meteoclub, 2008; Sklyarenko et al., 2009; Sklyarenko et al., 2009; Solenikov, 2006; Yakshanga Wiki, 2017).

The identification of tornado-induced forest disturbances is usually based on the analysis of satellite images obtained before and after the tornado event, preferably in the growing season [see for instance (Myint et al., 2008)]. Different change detection methods are successfully used for assessing storm- and tornado-induced forest damage; these are, for instance, univariate image differencing (Vorovencii, 2014; Wang and Xu, 2010), selective principal component analysis (Wang and Xu, 2010; Yuan et al., 2002), or vegetation indices change analysis (Vorovencii, 2014; Yuan et al., 2002). Wang and Xu (2010) showed, that the use of vegetation indices including short-wave infrared (SWIR) bands of Landsat Thematic Mapper (TM) sensor may greatly increase accuracy in detecting forest disturbances by strong winds [up to 12% compare with Normalized Difference Vegetation Index (NDVI)]. Wang et al. (2010) found that Normalized Difference Infrared Index (NDII), has higher disturbance detection accuracy than other vegetation indices (like NDVI or Enhanced Vegetation Index). NDII is calculated as:

$$\mathrm{NDII} = (\mathrm{TM4} - \mathrm{TM5})/(\mathrm{TM4} + \mathrm{TM5}),$$

where TM4 and TM5 are the reflectance in bands 4 and 5 (at 0.85 and 1.65 μm wavelengths, respectively) of Landsat TM (Hardisky et al., 1983). The TM4 reflectance correlates with plant chlorophyll content, while the TM5 reflectance has an inverse relationship with plant moisture content. Therefore, the areas with substantial decline of NDII may be reliably associated with forest cover disturbances (Toomey and Vierling, 2005).

However, the overall accuracy of automated separation of forest disturbances using spectral characteristics only does not allow to accurately distinguish windthrows from other types of disturbances, such as clear-cuttings or burned areas. For instance, the overall accuracy of automated separation of forest disturbances into windthrows and man-made cuttings does not exceed 76–77% (Baumann et al., 2014). Spectral analysis should be accompanied with evaluation of geometrical features of forest damaged areas (Shikhov and Chernokulsky, 2018). This kind of identification can be performed based on a visual analysis of geometrical characteristics of forest damaged areas by visual comparison of satellite images obtained before and after the outbreak.

Moreover, all change detection methods should be applied for images that were taken in the same phase of two growing seasons (one is before and another is after of the event). However, Landsat TM images are available on a regular basis only from 1984, while the studied outbreak happened in the beginning of the 1984 growing season. Landsat Multi-spectral Scanner (MSS) images, which are available before 1984, have a lower spatial resolution (60 m instead of 30 m for Landsat TM) and different spectral bands (only visible and near infrared bands, without SWIR bands). Most of the obtained Landsat TM images of undisturbed forest (before the outbreak) were made in April 1984 that is earlier of the growing season beginning. Consequently, intra-seasonal NDII changes in forests may affect the results of the comparison.

Given limitations associated with the need of shape identification and absence of SWIR data for the previous growing season, we used the visual analysis of Landsat TM images as the primary step for identification tornado tracks during the studied outbreak. We used TM images, acquired from the United States (U.S.) Geological Survey (USGS) Data Center during the April and May 1984 (before the tornado outbreak), and over the summer seasons of 1984–1986 (after the tornado outbreak) (supplementary Table S1). If clouds covered the area of interest, more than one image was used. We compared the Landsat TM composite images of the TM3, TM4 and TM5 bands to find elongated forest damaged areas close to possible tornado locations (TM3 is the reflectance in band 3 at 0.71 μm wavelength).

In total, we have identified eight tornado tracks. Fig. 1 presents an example of two tornado tracks, which were identified by visual comparison of satellite images (see also supplementary Fig. S1). In addition, we have identified two amorphous forest damage areas, which could have also been caused by tornadoes or by downbursts, which may be observed during tornado outbreaks [see for instance (Forbes and Wakimoto, 1983; Peyraud, 2013)]. Lack of aerial images does not allow us to accurately discriminate the damaging mechanism of these two amorphous areas. In total, we analyzed 41 Landsat TM images and one Landsat MSS image to pinpoint tornado tracks (supplementary Table S1).

The second step was to specify discovered tornado track boundaries with NDII difference (ΔNDII) for each pair of images. Firstly, the classification into four classes (forests with prevailing of coniferous, forests with predominance of deciduous, non-forested areas, clouds and clouds shadows) was performed using the Iterative Self-Organizing Data Analysis Technique Algorithm (Ball and Hall, 1965). We used the TM3, TM4 and TM5 bands as input for the classification. The unsupervised classification method was applied since the absence of ancillary data on tree species composition did not allow using this information as training samples. Therefore, we distinguished between coniferous and deciduous forests using the spectral difference in the so-called "Near-infrared plateau" (0.75–1.30 μm) (Cipar et al., 2004). Then, non-forested regions and cloudy regions covered by clouds or cloud shadows were excluded. Consequently, NDII was calculated only for the forested regions for images obtained before and after the tornadoes. ΔNDII were computed (where $\Delta\mathrm{NDII} = \mathrm{NDII}_{\mathrm{before}} - \mathrm{NDII}_{\mathrm{after}}$).

Fig. 2 presents an example of ΔNDII for two tornado tracks (see also supplementary Figs. S2–S3). Because of intra-seasonal changes, ΔNDII varies for the 5-km zone around the track (that consists mostly of undisturbed forest) between −0.01 and −0.02 (see supplementary Table S2). Instead, ΔNDII is mostly positive for disturbed areas in the tornado track (especially for coniferous forest). To specify the boundaries of tornado tracks, we focused on pixels with values of ΔNDII that lie in the upper quartile of all pixels within the 5-km zone of the track (Table S2). Because of several peculiarities like swamped terrain (in the tornado track #4) or a long period between images [more than two years because of cloud effects (for the tornado track #6)], we had to check all areas with such high values of ΔNDII manually. This analysis allowed us to specify tornado track boundaries that were primary obtained by composite images visual comparison.

Boundaries of identified tornado tracks were used to determine tornado characteristics such as tornado path length $L_{\mathrm{tp}}$, mean and maximum tornado path width ($WM_{\mathrm{tp}}$ and $WX_{\mathrm{tp}}$, respectively), and