ARTICLE IN PRESS

Remote Sensing of Environment xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

A satellite-derived climatology of unreported tornadoes in forested regions of northeast Europe

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ARTICLE INFO

Keywords:
Tornadoes
Tornado climatology
Tornado-induced forest damage
Satellite data
Landsat images
Global Forest Change data
Tornado outbreaks

ABSTRACT

This study presents a novel method of tornado track identification in forested regions in Europe based on remote sensing data. The method enables an objective estimate (i.e. independent of population density and observational networks) of tornado climatology in forested regions. The method is based on the identification of narrow and elongated areas as forest disturbances obtained using Landsat satellite images and Landsat-based Global Forest Change (GFC) data. These areas were subsequently verified with high-resolution satellite images for verification of a tornadic cause of forest damage. Landsat and MODIS satellite images, weather station observations and reanalysis data were additionally involved in order to determine tornado dates. A minimum F-scale tornado intensity was estimated by a Weibull distribution model using information on tornado path lengths and widths. The method is applied to the forested regions of northeast Europe, where 110 tornado tracks were identified between the 2000 and 2014 years, 105 of which were previously unreported and discovered for the first time. For some regions, tornado density estimates using the new method is 2–3 times higher than other previously published estimates. The largest number of tornadoes occurred in 2009, and June is the most favourable month for tornado formation (including strong tornadoes and tornado outbreaks). Most identified tornadoes have path length < 10 km with maximum and mean widths of approximately 200–300 m and 100–200 m, respectively. A few tornadoes with long and wide paths were found; four of them likely had F3 minimal intensity.

1. Introduction

Tornadoes are among the most destructive weather phenomena on the Earth, and have been observed on all continents except Antarctica (Goliger and Milford, 1998; Feuerstein et al., 2005).Tornadoes are reported more frequently in the United States (U.S.) where approximately 1000–1500 tornadoes are recorded per year (Coleman and Dixon, 2014). The maximum tornado frequency is found in the Midwestern U.S. (Coleman and Dixon, 2014; Rosencrants and Ashley, 2015), where up to 400 tornadoes per 10,000 km^2 were reported between 1950 and 2015 (Storm Prediction Center (SPC) Tornado Database; Schaefer and Edwards, 1999). Tornado frequency in Eurasia is significantly lower. According to the European severe weather database (ESWD) (Dotzek et al., 2009), 9529 tornadoes (over land and water) were recorded in Europe between 1800 and 2014 (Groenemeijer and Kuhne, 2014). During the last decade, around 300–400 tornadoes have been recorded annually. Approximately 10% of tornadoes have been classified at F2 or greater on the Fujita scale (Fujita, 1981).

In Europe, tornado reports are mostly based on eyewitness observations and damage surveys (Antonescu et al., 2016) in contrast to U.S., where an X-band Doppler radar network is used for real-time tornado detection (Chen and Chandrasekar, 2016). The population density may therefore exert an influence on the number of identified tornadoes (Anderson et al., 2007). Similarly, the highest tornado density across Europe is found in Belgium, the Netherlands, and in northern Germany (50 tornadoes per 10,000 km^2) (Groenemeijer and Kuhne, 2014), which are among the most densely populated regions (around 500 people/km^2, https://esa.un.org/unpd/wpp/). On the other hand, the minimum tornado density is found in sparsely populated regions such as Scandinavia and the northern part of Russia (i.e. north of 60° N) where fewer than 2 tornadoes/10000 km^2 have been observed (Groenemeijer and Kuhne, 2014). Thus, the existing climatology of tornadoes in areas with a low population density may be non-representative.

Estimates of tornado-induced forest damage can serve as an important additional source for evaluating tornado climatology in forested and sparsely populated regions. For instance, it is known that foresters have found elongated windthrows caused by tornadoes in Eastern

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http://dx.doi.org/10.1016/j.rse.2017.10.002
Received 30 December 2016; Received in revised form 17 September 2017; Accepted 5 October 2017

Europe and Siberia since the 19th century (Voznyachuk, 1954a, 1954b). The width of these windthrows varied mostly between 10 and 100 m, but sometimes reached 400 m (Voznyachuk, 1954a). The tornadoes with F1 intensity and higher are known to possibly cause significant forest disturbances, which are represented by large groups of fallen or uprooted trees and can be identified from satellite or airborne observations (Bech et al., 2009). Satellite-derived information on tornado-induced forest damage can be used to improve the climatology of tornadoes with F1 intensity and higher in low-populated forested areas.

Sayn-Wittgenstein and Wightman (1975) made the first attempt to utilise satellite images for assessing the aftermath of tornadoes in boreal forests (in Canada). They used Landsat Multi-spectral Scanner images, which had a combination of spectral (including visible and near infrared bands), spatial (60 m) and temporal (16 day) resolution. Dyer (1988) was the first to conduct detailed analysis of elongated forest cover anomalies in South America by comparing Landsat images with aerial photos and meteorological records, and reported that these anomalies were caused by tornadoes.

Further investigations showed an overall effectiveness of using satellite data for tornado damage survey and track detection (Yuan et al., 2002; Jedlovec et al., 2006; Myint et al., 2008; Molthan et al., 2014; Taszarek et al., 2016). In particular, Yuan et al. (2002) applied 23.5-m resolution images captured by the IRS-LISS-3 sensor to estimate damage characteristics from the 3 May 1999 tornado outbreak in Oklahoma (USA). They found that analysis of the change in normalised difference vegetation index (NDVI) is an effective method for detecting tornado damage (even for F1-intensity tornadoes), especially in rural areas. Myint et al. (2008) compared the accuracy of Landsat image processing techniques to detect tornado damage tracks and found that an object-based approach exhibits the highest degree of tornado damage detection accuracy. Jedlovec et al. (2006) and Molthan et al. (2014) showed that the use of near-real-time MODIS and high resolution ASTER imagery from the NASA Earth Observing System satellites can provide additional information on tornado damage tracks reported by the weather service. Damage tracks from tornadoes with F1 intensity or greater may be more clearly evident in forested areas compared with in grassland or low-forested areas. Taszarek et al. (2016) estimated an ability of mesoscale modeling to predict the formation of the 14 July 2012 tornado outbreak in Poland. Along with the radar data, aerial photography, local damage survey and damage reports in media, these authors also successfully used data from the Landsat-based Global Forest Change (GFC) project (Hansen et al., 2013) to pinpoint the exact position of the four tornado damage tracks. In general, all current studies of tornado-induced disturbances in forests have focused on the analysis of a-priori known tornadoes.

The main purpose of our study is to find previously unreported tornadoes, which imprinted their tracks in forests. We present a method that can help to supplement climatologies of F1 and stronger tornadoes in a boreal forest zone of northeast Europe (NE). Our method is based on accounting of tornado tracks in forests derived from GFC data, Landsat and high-resolution satellite images and additional supplementary data (weather stations observations, damage reports in media and reanalysis data).

We applied the method to forested regions of the NE located within 52°–67° N and 27°–60° E. The percentage of forestation varies here from 10% to 98% with the maximum located in the eastern part between 59°–64° N and 45°–60° E (Arino et al., 2008). This territory was chosen due to its substantial forestation, low population density (fewer than 10 people/km^2 for most of areas (National Atlas, 2009)), and lack of systematic information on tornado occurrences.

2. Tornado track identification in the forested area

2.1. Selection of tornado-induced forest damage

The proposed approach is based on the association of particular elongated windthrows with tornado tracks. A detailed analysis of geometrical features of forest disturbances allows accurate discrimination of their sources, including tornadoes. We identified tornado-induced forest disturbances with two steps: searching for candidates and then conducting a detailed inspection of the identified candidates.

Candidates for tornado-induced disturbances are determined based on the GFC data (Hansen et al., 2013). GFC data include information on global tree cover extent, forest loss and forest gain at a 30 m spatial resolution between 2001 and 2014 period (http://earthenginepartners.appspot.com/science-2013-global-forest). This information was obtained based on decision trees implemented on the Landsat satellite images: forest loss was defined as a stand-replacement disturbance or the complete removal of tree cover canopy at a particular Landsat pixel; the year of forest loss is determined using information about the maximum annual decline in the per cent tree cover and the maximum annual decline in the minimum growing season NDVI (Hansen et al., 2013). Year-to-year variations of forest cover had been validated with MODIS and high-resolution imageries from Google Earth (Hansen et al., 2013: Potapov et al., 2011, 2012, 2015).

In this study, we used information on forest loss from the GFC data to find elongated forest disturbances, which can be imprints of tornado tracks. The original Forest Loss Year (FLY) product of GFC data lacks information on the causes of forest losses; however, FLY provides geometrical characteristics of every disturbance. In general, all causes can be divided into four broad categories. These are man-made causes (e.g. logging), biological activity (e.g. outbreaks of insects), forest fires, and severe weather (e.g. windstorms, ice storms and tornadoes) (Baumann et al., 2014). Man-made clear-cuttings usually have a geometrically straight imprint in forests (e.g. squares, rectangles, lines), while impacts of pathogens and forest fires are referred to areas with no specific shape. Windstorms and ice storms usually cause amorphous spatial structure of forest disturbances and irregular distribution of the degree of forest damage. In turn, a tornado passing through a forest is usually characterised by an elongated geometry of the damaged area with almost complete removal of forest stands (Bech et al., 2009).

Because a tornado's path length usually exceeds a tornado path width by > 10 times (SPC data) (Schaefer and Edwards, 1999), we selected narrow and elongate areas of forest disturbances as candidates for tornado tracks, with a typical length from a few km to > 50 km and a width from 50 to 2000 m. We separated such forest disturbances from all other geometrical types based on visual interpretation. Their delineation was then performed automatically using a raster-vector transformation of their boundaries from FLY raster dataset. Fig. 1 shows an example of the GFC data implementation to identify the tornado track that occurred on 7 June 2009 in NE (Perm region, Russia). The Landsat images, obtained before and after the tornado, show the tornado-induced forest cover disturbances.

In the second step, we verified selected candidates for tornado tracks using high-resolution satellite images that are available from public map services (Google Maps, Bing Maps, Here, ESRI and Yandex.Maps). These images are derived from three main sources: DigitalGlobe (WorldView-2 satellite) imagery with spatial resolution reduced to 0.6 m; GeoEye (Ikonos satellite) imagery with spatial resolution reduced to 1 m, and SPOT-5 data with 2.5 m resolution (more details on satellite images that used in public map services can be found at: https://www.arcgis.com/home/item.html?id=10df2279f9684e4a9f6a7f08febac2a9, or: https://yandex.ru/company/technologies/satellite/). The main purpose of this verification was to obtain information about the direction of fallen trees. Indeed, windstorm-induced forest disturbances are characterised by a vector of fallen trees, which corresponds to the main wind direction of a storm (Fig. 2a). In turn, a counterclockwise rotation (infrequently clockwise) of fallen trees is the main feature of tornado-induced forest damage (Fig. 2b). Consequently, narrow and elongated forest disturbances with total canopy removal and counterclockwise-lying fallen trees were classified as tornado tracks. Additional examples of large tornado tracks in the boreal forests of European Russia are presented in Fig. 3.