Atmospheric Research 191 (2017) 101–114

Contents lists available at ScienceDirect

Atmospheric Research

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

Atmospheric circulation and sounding-derived parameters associated with thunderstorm occurrence in Central Europe

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ARTICLE INFO

Article history:
Received 15 July 2016
Received in revised form 8 March 2017
Accepted 9 March 2017
Available online 14 March 2017

Keywords:
Thunderstorm
Convection
Atmospheric circulation
CAPE
DLS
Central Europe

ABSTRACT

The main objective of this study is to examine the influence of atmospheric circulation patterns and sounding-derived parameters on thunderstorm occurrence in Central Europe. Thunderstorm activity tends to increase as one moves from the north to the south of the research area. Maximal thunderstorm occurrence is observed in the summer months, while between October and March such activity is much lower. Thunderstorms are also more frequent in spring than in autumn. In the warm season, the occurrence of thunderstorm is associated with the presence of a trough associated with a low located over the North Sea and Scandinavia. In the cold season, the synoptic pattern indicates a strong zonal flow from the west with significantly higher horizontal pressure gradient compared to the warm season. Thunderstorms are more likely to form when the boundary layer's mixing ratios are higher than 8 g kg^{-1}. Deep convection is also more likely to occur when the vertical temperature lapse rates (between 800 and 500 hPa pressure layers) exceed 6 °C km^{-1}. During the cold season, considerably higher lapse rates are needed to produce thunderstorms. The values obtained for the convective available potential energy indicate that at least 50 J kg^{-1} is needed to produce a thunderstorm during wintertime and 125 J kg^{-1} during summertime. Cold season thunderstorms are formed with a lower instability but with a more dynamic wind field having an average value of deep layer shear that exceeds 20 ms^{-1}. The best parameter to distinguish thunderstorm from non-thunderstorm days for both winter and summer months is a combination of the square root of the convective available potential energy multiplied by the deep layer shear.

1. Introduction

Thunderstorms belong to meteorological phenomena that pose risks to humans as well as being able to inflict serious harm on the economy. Damage caused by thunderstorms is primarily due to tornadoes and severe wind gusts (Markowski et al., 2002; Weisman and Rotunno, 2003; Atkins et al., 2005; Grzych et al., 2006), large hail (Tuovinen et al., 2009; Mohr and Kunz, 2013; Punge and Kunz, 2016; Puskeiler et al., 2016), and excessive precipitation that sometimes leads to flash flooding (Doswell et al., 1996; Smith et al., 2001; Dotzek et al., 2009; Lang et al., 2004; Market et al., 2003). Apart from the dangerous phenomena they often produce, thunderstorms also play an important role in the global electric circuit (Rycroft et al., 2012).

It is commonly known that deep moist convection and thunderstorm formation need three basic ingredients to form: static instability (resulting from boundary layer solar heating and cold air at mid-levels), sufficient moisture content at low levels, and a lifting mechanism to release the convective available potential energy (CAPE) (Doswell et al., 1996). Important for understanding thunderstorm formation is research concerning the use of environmental parameters because it helps to determine whether convection is likely to form or not given certain conditions. Thermodynamic and kinematic parameters derived from the atmospheric soundings, can be a useful tool for predicting thunderstorms and their accompanying severe weather phenomena. Sánchez et al. (2009), Vujović et al. (2015), and Gascón et al. (2015) all indicated that indexes such as Lifted Index, Showalter Index, and 850 hPa dew point temperature are indeed variables that best characterize preconvective conditions. However, the vast majority of studies associated with investigating thunderstorm environments do take into account CAPE (Kunz, 2007; Trapp et al., 2007; Riemann-Campe et al., 2009; Allen et al., 2011; Brooks, 2013) since it is the most reliable and simplest way to measure thermodynamic instability. CAPE consists of two main ingredients that influence its magnitude: vertical temperature lapse rates, and the boundary layer's moisture content. The higher they become, the greater the CAPE values that can be obtained. It is likely that in low CAPE environments, the probability for thunderstorms decreases, mainly due to the insufficient strength of the updraft. However, the one

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http://dx.doi.org/10.1016/j.atmosres.2017.03.009
0169-8095/

factor that can support the development of thunderstorms in low CAPE environments is a dynamic wind field with a strong vertical wind shear and a synoptic-scale lift. These conditions, known as low CAPE/high shear environments (Clark, 2009; Evans, 2010), are often responsible for thunderstorms during autumn and winter; and if they are present, they usually result in severe thunderstorms (Brooks et al., 2003; Brooks et al., 2007; Gatzen et al., 2011; Taszarek and Kolendowicz, 2013).

Researchers also point to a strong relationship between thunderstorm frequency and cyclonic activity in mid-latitudes (USA: Changnon and Changnon, 2001; Czech Republic: Brazdil, 1998; Poland: Kolendowicz, 2012; Germany: Wapler and James, 2015; Romania: Paraschivescu et al., 2012; Spain: Ramos et al., 2011). When observed on a synoptic scale, circulation determines the transport of both humidity and heat, as well as influences the intensity and duration of the thunderstorms (Doswell, 2001; Van Delden, 2001).

The climatological research on thunderstorm activity in Central Europe have been conducted from various standpoints. Bielec-Bąkowska (2003) and Kolendowicz (2006, 2012) used long data series based on human observations to investigate synoptic patterns associated with thunderstorm occurrence and found a strong correlation with cyclonic activity. They also shown that the annual number of days with thunderstorms increases southeasterly from the coast of the Baltic Sea to the Carpathian Mountains. Taszarek et al. (2015), based on cloud-to-ground lightning data found that peak intensity of thunderstorms in Poland fall in July and eastern, south-central parts of the country. They also noted that the average percentage of nocturnal lightning has increased in the last 12 years and that nocturnal thunderstorms occur the most often in the western parts of Poland. Czernecki et al. (2016) examined the differences between human observations of thunderstorms and the lightning detection network and concluded that human perceive thunderstorms with an average detection range of 17.5 km. Enno et al. (2013) presented an overview of thunderstorm activity in the Baltic countries and highlighted their peak activity between June and August. They also concluded that thunderstorm climate of the Baltic countries generally resembles other mid-latitude study sites. Wapler (2013), using data on cloud-to-ground lightning, examined the frequency of thunderstorms in Germany and found that the highest number of lightning strokes occurs in the pre-alpine region of southern Germany while further local maxima exists in low mountain ranges. The lowest number of lightning strokes was found in areas of the North Sea and Baltic Sea. Novak and Kyznarova (2011) used the lightning data from the seven-year period (2002 to 2008) to estimate the spatial and temporal distributions of thunderstorms in the Czech Republic. In their study lightning was the most frequent in the western part of the country while the minimum fall on the south-southeast.

Sounding-derived parameters, associated with severe and non-severe thunderstorms in Central Europe, have recently been studied by Púčik et al. (2015) and Taszarek et al. (2017), both of which pointed out that the occurrence of thunderstorms is almost entirely a function of an available CAPE consisting of boundary layer moisture and vertical temperature lapse rates. Taszarek et al. (2017) also suggested that lightning is more likely when the temperature of the equilibrium level drops below −10 °C.

Although many studies have addressed the topic of thunderstorm occurrence in Central Europe, this study is motivated by the desire to explore the spatial and temporal climatology combined with synoptic patterns and radiosonde data. For this reason, the main objective of the present study is to investigate how the atmospheric circulation patterns and sounding-derived parameters influence thunderstorm occurrence in Central Europe during warm and cold months. In aiming to underline regional differences concerning thunderstorm occurrence, it was decided to divide the research area into smaller sub regions with the use of hierarchical grouping according to differences in the annual course of days with thunderstorm occurrence. As such, it was possible to define differences in synoptic setups that are correlated with thunderstorm formation in particular regions and then compare the results with previous studies carried out for different parts of Central Europe (Brazdil, 1998; Bielec-Bąkowska, 2003; Kolendowicz, 2006; Wapler and James, 2015).

2. Dataset and methodology

2.1. Research area

The research area comprises Central Europe, and includes 48 meteorological and 15 sounding stations in Germany, Poland, the Czech Republic, and Slovakia (Fig. 1). Two of them (Łeba and Schleswig) are both meteorological and sounding stations. The area of research is located in a temperate zone that lacks meridional mountain ranges, which thus promote latitudinal marine air flow from the Atlantic and continental air flow from Asia (Czernecki et al., 2016). Thanks to this, the research area is characterised by a transition between the marine climate of Western Europe and the continental climate of Eastern Europe. Thus, two different mechanisms for thunderstorm formation are in play here. The first is associated mainly with the westerly flow of marine moist air masses from the Atlantic, often in the form of a shortwave trough with an active cold front. Within this type, thunderstorms occur all year round, even during wintertime.

The second mechanism concerns internal air mass thunderstorm formation that often occurs in a highly unstable warm and moist air of tropical origin, usually on the western flank of the high covering Eastern Europe. This type occurs mainly during afternoon hours of days in summer and represents thermal convection (for further discussion on the circulation contributions to thunderstorm occurrence in Central Europe, the authors direct readers to Bielec-Bąkowska, 2003; Kolendowicz, 2006, 2012; and Wapler and James, 2015).

2.2. General methodology

The main focus of this study is to analyze thunderstorm spatio-temporal distribution and its accompanying atmospheric conditions in the period 1974 to 2014. The analysis is divided into three main stages. Firstly, with the use of Ward's clustering methodology (1963), we perform a territorial division for regions that share similar annual distribution of thunderstorm days. Each grouped meteorological station was characterised by the distribution of the thunderstorms on a given calendar day. At this stage, we provide detailed statistics on thunderstorm seasonal variability in the defined regions and discuss the characteristic features of the regions. The inter-annual variability and long-term trends for the number of thunderstorm days are investigated by means of linear regression. The statistical significance of the trends is verified using the Snedecor test with a significance level of $1 - \alpha = 0.95$ (Von Storch and Zwiers, 2001). Additionally, the spatial and temporal distribution of thunderstorm days in meteorological seasons and mean year is also presented. For detecting differences between particular regions in the annual cycle, we create a histogram of the mean number of thunderstorm days on each calendar day, similar to that of Allen and Tippett (2015). To improve general readability, we also add smoothed one-month running means, together with textual information indicating the average number of days with thunderstorm in a month.

We also use NCEP/NCAR reanalysis I data (Kalnay et al., 1996) to compute the climatological distributions of basic synoptic setups during thunderstorm days. We divide results according to the defined regions as well as warm and cold seasons. In the last stage, we use radiosonde data from the period 1995–2014. For 15 sounding stations, almost 90,000 soundings are being computed to obtain the climatological distribution of the chosen thermodynamic and kinematic parameters and their values during thunderstorm days, which were divided into warm and cold seasons.