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The occurrence of convective systems with a *bow echo* in warm season in Poland

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ABSTRACT

The characteristics of occurrence of convective systems with a *bow echo* in Poland in the warm season between 2007 and 2014 were presented. Using the identification criteria proposed by Fujita (1978), Burke and Schultz (2004), Klimowski et al. (2000, 2004), and supplemented by Gatzen (2013), 91 *bow echo* cases were identified in the analysed period. Depending on the year, the maximum number of cases usually occurred in July or August. From the multi-annual perspective, 28 and 30 cases occurred in those months. The diurnal variation of *bow echo* occurrences showed that it developed, or entered the Polish territory, usually between the hours of 13:00 UTC and 21:00 UTC, while it disappeared or receded beyond the country border in the hours between 15:00 UTC and 23:00 UTC. The areas most exposed to the occurrence of *bow echo* included the northern part of Lubuskie and Wielkopolska provinces, the southern part of West Pomerania province, Łódź province and Silesia province. In the period studied, the south-western direction of movement of convective systems with a *bow echo* was prevalent. This direction changed, however, depending on the region and the month of occurrence. The type and development mode of a *bow echo*, as well as synoptic conditions conducive to its occurrence were defined for selected cases. The results showed that BECs (*bow-echo complex*) and BEs (*classic bow echo*) were the predominant types (respectively 43 and 29 cases). *Bow echoes* developed most frequently from a squall line, or from a combination of a few, often weakly organized convective cells.

1. Introduction

Strong wind gusts are often associated with the occurrence of convective systems that take a bow shape visible on radar depictions. This radar signature is called a *bow echo*. The first researcher of destructive convective systems that evolve and take on the shape of a bow was Fujita (1978). He linked the occurrence of strong downbursts to the occurrence of a characteristic image of radar reflectivity in the shape of a bow. Fujita (1978) suggested that the transformation of convection cells is a result of the existence of a strong rear inflow jet (RIJ). This current causes that different parts of such a cell move at different speeds. The fastest moving middle part outdistances the outermost ones, and a bulge is visible on the radar image. In the rear part, however, a zone of much lower reflectivity appears, which is referred to as a *rear inflow notch* (*RIN*). Research on the conditions of RIJ development, its intensity, lifetime, and impact was conducted by among others Duke and Rogash (1992), Przybylinski (1995), Wheatley et al. (2006), and Atkins and Laurent (2009).

Publications in which causes of development of specific *bow echo* cases are analysed dominate in world literature (e.g. Punkka et al., 2006; Walczakiewicz and Ostrowski, 2010; Pucik et al., 2011; Simon et al., 2011; Hamid, 2012, Peng et al., 2013; Devajyoti et al., 2014). Studies involving the long-term characteristics of *bow echo* structure occurrences have been carried out so far mainly in the United States (Burke and Schultz, 2004; Klimowski et al., 2000, 2004; Adams-Selin and Johnson, 2010), and in Germany (Gatzen, 2013).

Long-term convective systems with a *bow echo* are often responsible for the occurrence of a *derecho*. Research on the occurrence and development of the *derecho* phenomenon is mainly focused on the area of the United States (Johns and Hirt, 1987, Bentley and Mote, 1998, Evans and Doswell, 2001, Bentley and Sparks, 2003, Ashley et al., 2007, Coniglio et al., 2011, Bentley et al., 2015). Analyses of the long-term occurrence of a *derecho* in Europe were performed by Gatzen et al. (2011), and Celiński-Mysław and Matuszko (2014). Studies of both the American and European meteorologists were mainly related to the analysis of synoptic situations conducive to the development of mesoscale convective systems with a *bow echo*, which are a direct cause of *derecho* occurrences. They also focused on determining the corridors of movement of convective systems causing this phenomenon and, thus, on the determination of areas of an increased risk of *derecho*

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occurrence (e.g. Bentley and Sparks, 2003; Coniglio and Stensrud, 2004; Celiński-Mysław and Matuszko, 2014; Celiński-Mysław, 2015).

The aim of the study was to determine the temporal variability of *bow echo* occurrence in Poland in the warm season in the years 2007–2014, and to designate the areas of their most frequent occurrence. In addition, the main routes of movement of convective systems with a *bow echo*, the frequency of occurrence of different types of *bow echo*, and modes of their development were determined. The synoptic conditions accompanying the occurrence of selected cases of severe anemological events over the area of Poland were also specified.

2. Data and methods

The identification of a *bow echo* in this study is based on slightly modified criteria, which were developed and used in their work by, among others, Fujita (1978), Klimowski et al. (2000, 2003), Burke and Schultz (2004), and Gatzen (2013). These criteria relate to the shape of the structure, mode of development, and conditions of occurrence. A *bow echo* was defined in the study as radar imaging of a convective system:

- Bow or crescent-shaped radar echoes (Fujita, 1978),
- Those whose movement was accompanied by strong wind gusts at the Earth's Surface (Fujita, 1978) (a minimum of 24 m/s was assumed), or whirlwinds (Fujita, 1978; Trapp et al., 2005),
- Additionally, a tight reflectivity gradient occurred on the convex (leading) edge at a short range (Klimowski et al., 2000, 2003),
- An area with reduced reflectivity (RIN) occurred in the rear of a convective system (Fujita, 1978),
- The development and horizontal structure were consistent with the expanding cold pool, therefore, the bowing echo had a radius increasing with time or a persistent arc (Klimowski et al., 2003; Burke and Schultz, 2004),
- The minimum time of *bow echo* existence is 30 min (Klimowski et al., 2003; Gatzen, 2013).

Burke and Schultz's (2004) research showed that no reports of strong winds were recorded for only 6 of 150 hypothetical *bow echo* cases. Therefore, it was decided that the first step in the methodology of research on *bow echo* occurrences in Poland in the warm season will consist in selecting the periods in which strong wind gusts, or tornadoes, were recorded (at least 24 m/s). For this purpose, SYNOP and METAR reports (archived on the http://www.ogimet.com website) and reports on dangerous meteorological phenomena from the *European Severe Weather Database* (http://www.eswd.eu/) were used. Using both data sources, more than 330 cases of severe anemological events that occurred in Poland, or in the immediate vicinity of the Polish border, in the warm season (i.e. from early April till late September) in the years 2007–2014, were selected. In this place, cases which had been clearly identified as being a result of a large pressure gradient, and not the activity of convective systems, were eliminated. For this purpose, known dates of reports on severe anemological events, archival MSL pressure maps (http://www.knmi.nl, http://pogodynka.pl, http://www.wetter3.de), and satellite data (VIS, IR 10.8, enhanced IR 10.8 (http://www.sat24.com, http://eumetrain.org/)), archives of lightning detection systems (Institute of Meteorology and Water Management – National Research Institute), and information about the current and past weather from SYNOP reports were used.

For such selected cases of severe anemological events, radar data were analysed for possible *bow echo* occurrences. These data included 10-minute collective radar maps for the area of Poland depicting the distribution of radar echoes on the basis of CMAX (maximum value of reflectivity) and CAPPI (the value of reflectivity at 700 m) products (Centre for Ground Based Remote Sensing - Institute of Meteorology and Water Management – National Research Institute, http://www.lightningmaps.org, http://www.meteox.com). Radar data were analysed manually, taking into account the criteria of *bow echo* identification. Radar depictions from the area of Poland for 13 cases of anemological events were not available from the above-mentioned products (which constitutes about 4% of the cases, mostly from the beginning of the study period).

It should be mentioned that spatially small and short-lived *bow echo* structures were particularly difficult to identify. However, due to the good resolution of radar data (1 km × 1 km) and their 10-minute temporal resolution, it should be assumed that the percentage of unidentified *bow echo* signatures is small. Due to the small horizontal dimensions of a *cell bow echo* (CBE), it should be assumed that an unidentified *bow echo* would be assigned to this type.

Radar data allowed us to determine the time of *bow echo* development (or entering the area of Poland), and its disappearance (or receding beyond the Polish border). A *bow echo's* beginning was defined as the time of the first appearance of a 35-dBZ within a bow-shaped structure on the basis of the CAPPI product (i.e. from the lower layers of the troposphere). The moment the bow's disappearance (its strong dispersion, straightening, or significant reduction of radar reflectivity) was considered as the *bow echo*'s end.

In order to determine the mode of *bow echo* development it was necessary to analyse radar data before the moment of formation of the *bow echo* structure. To determine the approximate time of beginning, and the place of development of convective structures responsible for the subsequent occurrence of a *bow echo*, archived radar data, satellite data, and data from the Lightning Detection Systems were used.

In this study, selected *bow echo* cases were assigned a specific type (*classic bow echo - BE*, *bow-echo complex - BEC*, *cell bow echo - CBE*, *squall line bow echo - SLBE*, and *double bow echo - DBE*) as well as a mode of development (*cell* (*and supercell*), *pair*, *group of cells*, *squall line*, *embedded* and *squall line-cell* (*supercell*) *merger*).

A *classic bow echo* (BE) referred to the cases of a size larger than single storm cells, which were not linked to other convective systems, nor to any linear complex (Fujita, 1978). A *bow-echo complex* (BEC) defined the situations of development of the characteristic bow shape inside a mesoscale convective system, in which the *bow echo* was the primary, but not the only, organized convective structure (supercells or other linear complexes could additionally occur) (Przybylinski and DeCaire, 1985), as well as situations of mesoscale convective systems with several *bow echoes* occurring at the leading edge (Gatzen, 2013). A *cell bow echo* (CBE) described cases of the smallest sizes (10–25 km), which were not linked to other convective systems (Lee et al., 1992). A *squall line bow echo* (SLBE) concerned the *bow echo* cases which were part of an elongated mesoscale convective system (with the length to width ratio of at least 5:1) (Bluestein and Jain, 1985; Lee et al., 1992). In addition, the *double bow echo* (DBE) type was introduced, which described cases of occurrence of massive bows inside two mesoscale convective systems developed in similar environmental conditions that were connected to each other for a period of time (Fig. 1).

The mode of *bow echo* development defined as *cell* (*and supercell*) concerned the cases occurring as a result of the transformation of a single storm cell (including a supercell) (Moller et al., 1990), the *pair* mode when a *bow echo* developed as a result of two isolated convective cells that merged (Bluestein and Parker, 1993), and the *group of cells* mode was characterized by cases arising from the combination of many, often unorganized storm cells (Przybylinski and DeCaire, 1985). The *squall line* mode was recognized when an arched structure developed from a squall line (Nolen, 1959; Klimowski et al., 2000), the *embedded* mode when a squall line developed in larger areas of weaker precipitation (Bluestein and Parker, 1993), while the *squall line-cell* (*supercell*) *merger* when a *bow echo* developed following the merger of an extensive squall line with a single convective cell (also a supercell), or a group of convective cells, outdistancing it (Burke and Schultz, 2004; French and Parker, 2012; French and Parker, 2014).

Each case was also analysed in terms of the synoptic situation occurring on any given day, which made it possible to determine the