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DOI:
10.1175/BAMS-D-17-0316.1

Document Version
Accepted author manuscript

Citation for published version (APA):
Antonescu, B., Ricketts, H., & Schultz, D. (2019). 100 Years Later: Reflecting on Alfred Wegener's Contributions to Tornado Research in Europe. *Bulletin of the American Meteorological Society*, *100*(4), 567-578. https://doi.org/10.1175/BAMS-D-17-0316.1

Published in:
Bulletin of the American Meteorological Society

100 Years Later: Reflecting on Alfred Wegener's Contributions to Tornado Research in Europe

Bogdan Antonescu[1,2] *, Hugo M. A. M. Ricketts[1], and David M. Schultz[1]

[1]*School of Earth and Environmental Sciences,*

The University of Manchester, Manchester, United Kingdom

[2]*National Institute of Research and Development for Optoelectronics INOE2000*

Măgurele, Ilfov, Romania

Manuscript for submission as an Article to the

Bulletin of the American Meteorological Society

(deadline 12 June 2018)

4 May 2018

**Corresponding author address:* Dr. Bogdan Antonescu, currently at the National Institute of Research and Development for Optoelectronics INOE 2000, Str. Atomiştilor 409, Măgurele, Ilfov, Romania.

E-mail: bogdan.antonescu@inoe.ro

ABSTRACT

Alfred Wegener (1880–1930) was a leading geophysicist, atmospheric scientist, and an Arctic explorer who is mainly remembered today for his contributions to the theory of continental drift. Less well known are his contributions to research on tornadoes in Europe. Published 100 years ago, Wegener's 1917 book *Wind- und Wasserhosen in Europa* (*Tornadoes and Waterspouts in Europe*) is an impressive synthesis of knowledge on tornadoes and is considered the first modern pan-European tornado climatology with 258 reports from 1456–1913. Unfortunately, Wegener's book was overlooked after the 1950s amid declining interest in tornadoes by European researchers and meteorologists. The recent revival of tornado studies in Europe invites a reflection on Wegener's book. His climatology of 154 tornadoes from 1800–1899 compares favorably to that of a more recent climatology of 1303 tornadoes from the same period. Wegener's lasting scientific contributions to tornado research are presented in the context of European research on this topic. Specifically, his book showed the utility of reports from citizen scientists and inspired other researchers, namely Johannes Letzmann who continued to study European tornadoes after Wegener's death.

CAPSULE

Alfred Wegener not only proposed the theory of continental drift, but was also the founder of modern tornado research in Europe.

Alfred Wegener (1880–1930; Fig. 1) is mainly remembered today for his contributions to continental drift from which the modern theory of plate tectonics—"one of the key scientific concepts of the past century" (Greene 2015)—is derived (Romano and Cifelli 2015). Wegener not only made major contributions to geology and geophysics, but also to astronomy and geodesy (Wegener 1905, he was an astronomer by training), glaciology (Koch and Wegener 1911, he was a pioneer explorer of Greenland), paleoclimatology (Köppen and Wegener 1924), and meteoritics (Wegener 1925a). He performed research in atmospheric physics and meteorology, including cloud microphysics (e.g., Wegener–Bergeron–Findeisen process, Wegener 1910), thermodynamics (Wegener 1911c), the vertical structure of the chemical composition of the atmosphere (e.g., Wegener 1925b), and atmospheric optics (e.g., a subhelic arc is named the Wegener arc, Wegener 1925c).

Lesser known are his contributions to the study of tornadoes. In 1917, Wegener published the seminal book *Wind- und Wasserhosen in Europa* (*Tornadoes and Waterspouts in Europe*). This book not only contains the first pan-European tornado climatology, but is an exhaustive treatise on all aspects of tornadoes, from the weather associated with tornadoes, tornado rotation, and damage paths to the noise, smell, and electrical phenomena accompanying tornadoes. Wegener wrote the book between January–August 1916 "in the field" during the First World War with limited access to publications and data. But his meticulous working style led to a dataset of 258 tornadoes between 1456–1913 and a climatology that has comparable behavior to modern ones.

Wegener's book received relatively little attention at the time of its publication, despite being, as a reviewer from the United States wrote in 1920, "a monograph [that] very satisfactorily fills in a missing chapter of modern meteorological science" and which "merits [a] careful study" (Ward 1920, p. 218). One such careful student of the book was the Estonian-born meteorologist Johannes Letzmann (1885–1971), another pioneer researcher on tornadoes in Europe, whose career was inspired by Wegener's book[1]. Thus, during a period (1883–1937) in which the word "tornado" was banned by the U.S. Weather Bureau and its predecessor the U.S. Army Signal Corps (Galway 1985), Wegener and his collaborators were actively researching tornadoes across the Atlantic in Europe (e.g., Wegener 1928; Letzmann 1931; Letzmann and Koschmieder 1937). Unfortunately, due to the relative isolation of German scientists and the declining interest of both researchers and meteorologists in European tornadoes after the Second World War, Wegener's book and articles on tornadoes were almost forgotten. The purpose of this article is to tell the story of *Wind- und Wasserhosen in Europa* in the context of European research on tornadoes and thus bring greater exposure to the pioneering tornado research of Alfred Wegener. To understand the importance of Wegener's study, we need first to look at the history of tornado research in Europe.

Tornado research in Europe between 1840–1910

There is a long history of tornado observations in Europe and of natural philosophers, starting with Aristotle, who attempted to explain their formation. The systematic study of tornadoes began in the 17th century (e.g., Peterson 1982; Antonescu 2017), and the first efforts to develop a pan-European tornado climatology date back to the 19th century (Antonescu et al. 2016). In 1840, Jean Charles Athanase Peltier (1785–1845), a French physicist who is credited with the discovery

[1]The interest of the first author of this article on the climatology of tornadoes in Romania, and later on European tornadoes, originated from a sentence on p. 73 of *Wind- und Wasserhosen in Europa* describing a tornado that occurred at Bucharest, Romania, on 9 June 1886 (Hepites 1887).

of the thermoelectric effect (i.e., Peltier effect), published a book-length study on tornadoes and waterspouts (Peltier 1840).

Peltier became interested in tornadoes when a tornado produced susbtantial damage in Châtenay-en-France, France, on 18 June 1839 (most likely an EF4 tornado, KERAUNOS cited 2018). Given his expertise on electricity and meteorology, Peltier was asked by a certain Monsieur Hérelle, whose property was destroyed by the tornado, to determine "the real character of this phenomenon" as his insurance company would only cover damages associated with electrical phenomena (e.g., cloud-to-ground lightning) (Peltier 1847). On 28 October 1839, Peltier presented a summary of his findings before the French Academy of Sciences, in which he argued that "everything proves the tornado to be nothing else than a conductor formed of clouds, which serves as a passage for a continual discharge of electricity" (Peltier 1840). His conclusion that tornadoes are an electrical phenomenon supported a popular hypothesis at the end of the 18th century and the beginning of the 19th century. In his attempt to prove that the electrical hypothesis was the only one able to explain the formation of tornadoes, Peltier (1840) collected 91 reports of tornadoes and waterspouts that occurred in Europe between 1456 and 1839, and thus developed the first pan-European tornado climatology.

The French botanist Charles Martins (1806–1899) published the first instructions for observations of tornadoes (Martins 1849), which was translated into German a year later (Martins 1850). These instructions—together with an increase in the number of tornado reports during the 19th century (from 403 reports between 1800–1849 to 900 reports between 1850–1899; Antonescu et al. 2016)—showed that European researchers and meteorologists had an active interest in collecting tornado reports during this period. Toward the end of the 19th century and the beginning of the 20th century, research focused on postdisaster investigations (e.g., Hepites 1887; Mohorovičić 1892), theoretical aspects (Reye 1872), and laboratory experiments (Weyher 1889). Unfortunately, no other efforts were made to continue pan-European data collection on tornadoes, despite the development of national meteorological services and severe-weather databases across Europe during this period (Antonescu et al. 2016). Enter the scene, Alfred Wegener.

Wegener's research on tornadoes before 1915

In June 1906, a 26-year old Alfred Wegener embarked on the first of his four Greenland expeditions, the Danish *Danmark* Expedition (1906–1908) led by Ludvig Mylius-Erichsen (1872–1907). The goal of the expedition was to explore and map northeastern Greenland. Alfred Wegener was the physicist and meteorologist of the expedition in charge of the aerological measurements using kites and balloons. On 10 July 1907, Wegener observed a series of waterspouts that he described in his expedition diary.

> This morning we saw[2] multiple waterspouts hanging down from a stratocumulus deck. They appeared to be a lot more peaceful than the ones in Europe. I photographed them and prompted Bertelsen to draw them as well as Koch and Lundager to photograph them with their cameras. So, a big waterspout [*XXXXX*, translated literally as "skypumper"] photography competition — 'All hands to the pumps [waterspouts]!' as Friis[3] said when he saw this. Then I went out with both cameras (with newly loaded plates) and photographed some subjects. (Wegener 1907, p. 37).

It is not clear if this was the first time when Wegener witnessed a waterspout, but his diary entry suggests at least an interest in this weather phenomenon (i.e., "lot more peaceful than the ones in

[2] From Cape Bismarck, in the Northeast Greenland National Park.

[3] Aage Bertelsen (1873–1945) was a Danish painter and one of the *Danmark* Expedition's artists. Johan Peter Koch (1870–1928), a Danish captain and explorer, was the expedition's cartographer. Andreas Lundager (1869–1940) was the expedition's botanist, and Achton Friis (1871–1916), another of the expedition's artists, published a book in 1909 about the expedition (Friis 1913).

Europe"). Unfortunately, our research so far has not uncovered the actual photos or drawings of the waterspouts described by Wegener in his diary.[4]

This experience indicates that, even before the beginning of the First World War, Wegener was already interested in tornadoes and waterspouts. In December 1910, in parallel with putting the finishing touches on his book *Thermodynamik der Atmosphäre* (*Thermodynamics of the Atmosphere*) (Wegener 1911c), in which he included a short section on tornadoes, Wegener also finished a study on the origin of tornadoes (Wegener 1911d). In this study, Wegener argued that *tromben* (tornadoes) are the descending part of the gust front and are not caused by the heating of the surface layer as was hypothesized by the German mathematician Theodor Reye (1838–1919) (Reye 1872). Wegener's argument against Reye's hypothesis was a simple one—"neither cumulus clouds rotate [around a vertical axis] nor does the rising smoke of a cigar", and, if cumulus clouds are rotating, "their rotation is weak and is not enough to lead to the strong rotation of a tornado" (Wegener 1911d, p. 205). Wegener's hypothesis was that tornadoes were associated with the *wirbelfaden* (vortex filaments) that form along the gust front. The hypothesis was based on observations of a tornado that occurred at Oldenburg, Germany, on 5 July 1890. The observations were collected and analyzed by the German climatologist Wladimir Köppen (1846–1940), Wegener's mentor and father-in-law, as well as one of the major figures in meteorology at the beginning of the 20th century.

Wegener's hypothesis was also based on photographs published by Frank H. Bigelow (1851–1924) showing the evolution of a waterspout that occurred off the coast of Cottage City, Massachusetts, on 19 August 1896 (Bigelow 1906). Using the observations of the Oldenburg tornado,

[4] A note by Andreas Lundager (1869–1940), another member of the Danish *Danmark* expedition, retrieved from the archives of the Danish Arctic Institute suggests that the two photographic plates mentioned by Wegener "were impossible, it's fair to say overexposed" **[CITATION FROM HUGO]**.

Wegener also speculated that tornadoes formed on the right flank of the precipitation region. This happens, according to Wegener, because the wind turns to the right with increasing height in the Northern Hemisphere, causing the volume of precipitation to be rotated to the right with increasing height. Thus, the gust front would grow on the right flank and disappear on the left flank of the storm (Wegener 1911c, p. 209). Wegener concluded that he did not have enough observations to transform his hypothesis into a theory, but "it remains for the future to provide the definitive, strict proof" (Wegener 1911c, p. 209).

By July 1911, Wegener's interest in tornadoes evolved into a full-fledged research project, being mentioned amongst other research projects in a letter to Köppen (Wegener to Köppen, 6 July 1911). Over the next year, Wegener's research focused on the stratosphere (Wegener 1911a), continental drift (Wegener 1912a), turbulence (Wegener 1912b), meteoritics (Wegener 1915d), and lunar atmospheric tides (Wegener 1915e). Wegener would return to the study of tornadoes in 1915.

With the outbreak of the First World War, Wegener was mobilized in the German army in August 1914 (Fig. 3) and was injured in a battle at Puisieux, France, on 4 October. Wegener was sent home to recover, resulting in some productive months of convalescence. In July 1915, toward the end of his convalescence leave, Wegener received a letter from Köppen with comments emphasizing some inconclusive sections of his book on continental displacement theory. The reply from Wegener contained a self-assessment that allows us to understand his approach to research.

> I think, by the way, that it is a weakness of all my work that I am forever going into too many side issues. I managed to cut out many of them from this book, but I should limit myself to an even greater extent to the straightforward establishment of the

> displacement. (Wegener to Köppen, 13 July 1915, translated from German by Greene 2015, p. 343)

This tendency for Wegener to diverge from the main topic in his writings sometimes resulted in theoretical digressions and excessive speculation, a trait that had already been identified by both the Austrian meteorologist Felix Exner (1876–1930) in his review of *Thermodynamik der Atmosphäre* and Köppen in his letter about the manuscript on the displacement theory. This research approach was due to Wegener's belief that new ideas are not so much rooted from theoretical work as from "careful empirical work" (Greene 2015, p. 343). By the end of July 1915, as Wegener was determined to correct these tendencies, he was able to find a project that fit this purpose. He wanted to return to the study of tornadoes, "not necessarily [a subject] á la mode". In this project, he could work only with empirical data without any theoretical speculation (Wegener to Köppen, 13 July 1915). In a letter to Köppen dated 30 July, Wegener provided the first details of this new project for which he "already [had] collected a series of interesting observations and each day I've been collecting new material from the literature." From the start, he was planning to write a book on *tromben* that would include "all the important descriptions word for word and with the original illustrations", short reports about the less important events, and a summary of the existing hypotheses on tornado formation, which would also include his opinions (Wegener to Köppen, 13 July 1915).

Wegener thought that such a book, mainly containing descriptions of tornadoes in Europe without any theoretical speculation, could be read by both professional meteorologists and also by the general public (Wegener 1915c). This approach for studying tornadoes in Europe was used before, for example by Peltier (1840) who selected reports that supported his hypothesis that tornadoes are electrical phenomena, and by Reye (1872) who included depictions of tornadoes that were "a lot more unnatural than the originals" (Wegener to Köppen, 13 July 1915). Wegener's aim was to develop a catalog that would include original descriptions and depictions of tornadoes and waterspouts, based on which he would construct a climatology and would search for commonalities (e.g., origin, direction of movement, speed, rotation). As indicated by Greene (2015, p. 344), Wegener was familiar with this research approach. For example, Wegener had developed a catalog of historical observations of the motion of the Moon going back to the 13th century that he used in his dissertation in astronomy (Wegener 1905); he also collected and analyzed historical observations of the color change of meteorites entering the terrestrial atmosphere in a study on the chemical layering of the upper atmosphere (Wegener 1915d).

Writing *Wind- und Wasserhosen in Europa* (1916–1918)

By January 1916, Wegener was the commanding officer of Field Weather Station 12, one of the weather stations of the Field Weather Service of the German army (Greene 2015, p. 346). The station was located on the Western Front at Mülhausen (today in France, but in 1916 a part of the German Empire). As a commanding officer with the only responsibility of taking routine weather observations, Wegener devoted his free time to his meteorological research. Thus, the plan to write the book on tornadoes in Europe started to materialize.

In a letter addressed to Köppen from early February 1916, Wegener mentioned that he was continuing his empirical investigations on tornadoes where he was making new discoveries every day and that the source materials were not easy to go through (Wegener to Köppen, 2 February 1916). Gathering source material for a catalog of all past European tornadoes was not an easy job as Wegener had access only to the collections of the library at the University of Freiburg, Germany. Due to the frequent rail service—Mülhausen was an important administrative center of the German army on the Western Front—Wegener also obtained publications from Köppen from the library of the German Marine Observatory in Hamburg. Julius von Hann (1839–1921) in Vienna and Gustav Hellmann (1854–1939) in Berlin were also able to help Wegener by providing some of the more obscure references on tornadoes (Greene 2015, p. 347).

At the beginning of March, besides working on collecting descriptions of European tornadoes, Wegener started negotiations with his publisher Vieweg Verlag. The editor wanted to include Wegener's book in a popular science collection. This meant that Wegener's book, with the provisional title *Die Großtromben Europas* (*The Big Tornadoes of Europe*), would not be a thorough scientific study, but rather a book for a general audience (Wegener to Köppen, 11 March 1916). The letters to Köppen from late March showed that Wegener was struggling to organize his material, which by now contained more descriptions than he was planning to include in the manuscript (Wegener to Köppen, 30 March 1916). The variety of descriptions in different languages, and spanning multiple centuries, resulted in difficulties in organizing the material and extracting accurate descriptions.

Despite these problems, and despite his intentions to avoid speculation and theorizing, Wegener started to draw some conclusions concerning the geographical distribution of tornadoes in Europe (Wegener to Köppen, 6 April 1916). First, tornadoes often formed leeward of hills. Second, at the northern foot of the Pyrenees (mainly in the eastern half) and in Sweden, tornadoes seemed to be more frequently observed compared with other regions of Europe. Third, in the United States, "the storms in Spring are rich in tornadoes and the storms on Autumn are poor in tornadoes; [i]n Europe is the other way around" (Wegener to Köppen, 6 April 1916). Wegener was speculating that this difference in the annual distribution of tornadoes in the United States and Europe "has something to do with the fact that America had the ocean to the east and Europe has it to the west" (Wegener to Köppen, 6 April 1916).

At the end of April, Wegener was back home in Marburg for Easter. He soon learned about an event, which is known today as the Treysa meteor, that occurred on 3 April in Hesse, a state in central Germany. Knowing Wegener's prior interest in meteors (Wegener 1915d), Franz Richarz (1860–1920) and Emanuel Kayser (1845–1927), both professors at the University of Marburg, asked for his help to find the location of the meteorite. Based on eyewitness reports, Richarz and Kayser hypothesized that the area where the meteorite fell was close to Marburg. Finding the location of the meteorite not only gave Wegener the opportunity to pursue his interest in this subject, but also to understand how eyewitness reports made by citizen scientists could be used for scientific research. This was the essence of his catalog of tornadoes, a collection of observations made mainly by untrained observers that Wegener used to understand the occurrence of this phenomenon in Europe.

Plotting newspaper accounts of the meteorite on a map, Wegener was able to obtain a rough estimate of the landing site. At the beginning of May, he requested an extension of his leave to collect more information about the meteorite. Being approved, he traveled around Treysa and conducted more than 100 interviews during 9–12 May. Putting together all this information, he was able to estimate the landing site 125 km away from Treysa. According to Greene (2015, p. 350), Wegener's paper on the Treysa meteorite (Wegener 1925a) was "one of the most polished and thorough pieces of work he [Wegener] ever did." Indeed, the meteorite was later discovered on 5 March 1917, very close to his calculated location.

With these new insights on the utility of reports made by citizen scientists, Wegener returned to Mülhausen in May, making steady progress on the book throughout May and June. In July, the British army started an offensive, and Wegener and his staff were moved to a holding location closer to the front (Greene 2015, p. 354). The Battle of the Somme, fought between July and November 1916, was the largest battle on the Western Front and one of the costliest of World

War I. As the British and French offensive was stopped, Wegener returned to Mülhausen ("still situated next to the war, away from the action") and to his working routine. By the second week of July, Wegener was able to send to Köppen the third part of the manuscript. At this point, the only missing chapter from the book was the one containing the hypotheses on the formation of tornadoes (Wegener to Köppen, 12 July 1916). The book was finished "in the field" (as indicated in the Preface) in August 1916 and, due to wartime paper shortages in Germany, published one year later.

Wind- und Wasserhosen in Europa (1917)

Wind- und Wasserhosen in Europa began with a chapter in which Wegener discusses the definition of tornadoes. Wegener considered tornadoes and waterspouts (i.e., *Großtromben*, big whirlwinds) as a distinct phenomenon situated between cyclones and dust devils. He then defined tornadoes as rotating columns of air stretching from a cumulonimbus cloud to the ground and visible as a cone of condensed water vapor. This chapter on definitions and terminology was followed by a chapter containing detailed descriptions from the literature of 11 tornadoes that occurred between 1535 and 1890. The next chapter was the core of the book, a catalog containing descriptions and references for 258 tornadoes and waterspouts (Wegener 1917, **pp. 58–83**). Given that Wegener had limited access to scientific literature due to the war, it is not surprising that the tornado reports were mainly over western Europe (Fig. 4). For example, a literature survey by Antonescu et al. (2016) found 1303 reports for tornadoes and waterspouts that occurred in Europe between 1800–1899 compared to 154 reports in Wegener's catalog during the same period. Antonescu et al. (2016) were able to retrieve information on tornado occurrence for a more geographically diverse area, and thus fill the gaps in Wegener (1917).

Based on his dataset, Wegener showed that the European tornadoes mainly occurred in June–August and during the afternoon (Fig. 5). He also estimated that at least 100 tornadoes and waterspouts occurred each year in Europe. Wegener compared the climatology of European tornadoes with the climatology of U.S. tornadoes developed by John Park Finley (1854–1943) (Finley 1887), an American meteorologist and Army Signal Service officer who was the first to study U.S. tornadoes intensively (Galway 1985). Specifically, whereas 35 tornadoes were reported in Europe between 1884–1887, 777 tornadoes were reported in the United States during a similar interval (1883–1886).

The remainder of the book was devoted to the analysis of different aspects of tornadoes including the weather conditions associated with tornadoes (Chapter 5; tornadoes were generally reported east-southeast of the cyclone center), their rotation (Chapter 9; of the 25 tornado reports in which the direction of rotation was reported, 18 were cyclonic and 7 anticyclonic), and their associated damages (Chapter 14; European tornadoes were less damaging compared with the U.S. tornadoes, and fatalities were reported only in 5% of all analyzed reports).

The last chapter "*Ansichten über die Entstehung der Tromben*" ("Views on the Origin of Tornadoes") contained descriptions of the main hypotheses for tornado formation. First, Wegener rejected the volcanic hypothesis, downpour hypothesis, wave hypothesis, and electrical hypothesis (Fig. 2). Another hypothesis, the thermodynamic hypothesis, was previously rejected by Wegener in his early articles on tornadoes (Wegener 1911d). The only hypothesis that Wegener said could explain the formation of tornadoes was the mechanical or the hydrodynamic hypothesis, a hypothesis that can be traced back to Lucretius and further to Aristotle (Fig. 2). As stated by Wegener, "the temperature conditions are not considered the primary cause and the rotation the effect, but the rotation, whether produced mechanically or hydrodynamically, is believed to be the cause of the thermodynamic effects, the latter manifesting themselves in the condensation of the funnel cloud" (Wegener 1917, translated from German by Ward 1920).

Wegener's research on tornadoes (1918–1930)

Toward the end of the First World War, Wegener was reassigned to the Eastern Front as a commanding officer of the Central Meteorological Station in Sofia, Bulgaria, and then in July 1918 back to the Western Front (Greene 2015, p. 371–380). In October 1918, Wegener moved to Dorpat (today Tartu) in Estonia where the German army had opened the University of Dorpat, thus allowing some of the German soldiers to continue their studies. Wegener stayed at the University of Dorpat for about a month while the German army evacuated the Baltic countries after the armistice on 11 November 1918. There is one aspect of his stay in Dorpat that had great consequences for his study of tornadoes in Europe—there, Wegener met Johannes Letzmann (1885–1971), an Estonian meteorologist who was interested in storms and who developed a climatology of tornadoes for the Baltic region (Letzmann 1920). Under Wegener's mentorship, Letzmann became even more interested in tornadoes (Peterson 1992a; Lüdecke et al. 2000). Unfortunately, after November 1918, Wegener and Letzmann stopped their collaboration for almost ten years because Wegener's research interest in tornadoes faded after returning to Marburg (e.g., Wegener published a book on the origin of Moon craters, Wegener 1921).

Letzmann remained at the University of Dorpat, studying Wegener's book and continuing his own research on tornadoes. In June 1927, he wrote to Wegener expressing his interest to move to Austria and work with him. Letzmann also mentioned that Wegener's book had inspired him to collect tornado observations for the Baltic area and also to conduct theoretical and experimental work on tornadoes. Letzmann's letter arrived at a very good time. Wegener's interest in tornadoes had just been reawakened by a tornado that occurred on 23 September 1927 near Graz, Austria.

Wegener and his wife Else investigated this tornado by walking along the tornado path and talking with the eyewitnesses. Thus, Wegener agreed to Letzmann's proposal for collaboration and, starting in 1928, they worked together at the University of Graz where Wegener was a professor.

Their research was focused on finding the mechanism responsible for tornado formation. Wegener was working on a hypothesis that tornadoes were associated with what he called a *Mutterwirbel* (mother vortex), a vortex tube tilted by the updraft of the thunderstorm. He speculated that this vortex tube would have a cyclonic tornado at one end and an anticyclonic tornado at the other end connected by a horizontal section of the vortex (Wegener 1928; Peterson 1992b). Letzmann and Wegener worked on this hypothesis, also trying to collect observations, in particular of the anticyclonic and horizontal part of the vortex tube that would confirm their hypothesis (Peterson 1992b; Greene 2015). Unfortunately, their collaboration ended due to the tragic death of Wegener in November 1930 during his fourth expedition to Greenland.

During the 1930s, Letzmann became one of the leading figures on tornado research with an interest in the theory of vortex dynamics, analyses of historical tornado events, tornado damage investigations, and laboratory simulations (Dotzek et al. 2005). In 1937, at the invitation of the World Meteorological Organization, Letzmann and German meteorologist Harald Koschmieder (1897–1966) published extensive guidelines for the investigation of tornadic phenomena. Unfortunately, these guidelines were initially dismissed by the meteorological community, only to be be revived four decades later when researchers from the United States started to actively research tornadoes as as recommended by Letzmann and Koschmieder (Peterson 1992c).

After the end of the Second World War, Letzmann lost his position at the University of Graz and over the next decades faced a difficult personal situation (Dotzek et al. 2005). By the time of his death in 1971, his research on tornadoes had been forgotten both in Europe and the United States.

After the 1950s, the lack of researchers or meteorologists working on this topic led to a decline in European tornado research. After 2000, however, interest was revived, mainly due to the efforts of Nikolai Dotzek (1966–2010) who founded the European Severe Storms Laboratory, in part for the purpose of collecting and verifying tornado reports from a pan-European perspective (Feuerstein and Groenemeijer 2011; Groenemeijer et al. 2017).

Almost one hundred years since the publication of Wegener (1917), Antonescu et al. (2016) have revised and updated Wegener's study on tornadoes in Europe. Having access to a larger number of publications and datasets on tornadoes across Europe, Antonescu et al. (2016) showed that 2096 tornadoes were reported in 27 countries between 1054–1919 compared with 258 reports from 14 countries between 1456–1913 in the dataset developed by Wegener. Wegener estimated that "at least 100 tornadoes per year in Europe" compared to the 242 tornadoes per year between 2000–2014 (Antonescu et al. 2016). Antonescu et al. (2016) showed that maximum in the number of tornado reports for most of Europe is in June–August. Wegener (1917) identified the same interval as in Antonescu et al. (2016) for the maximum in the monthly distribution, but he mentioned that his results are mainly applying to *Mitteleuropa* (central Europe). According to Wegener (1917), tornadoes were reported more frequently between 1200–1500 UTC compared with other times of the day. The peak in the diurnal distribution was found by Antonescu et al. (2016) 1100 and 1700 UTC.

Conclusion

Today, Alfred Wegener is largely recognized for being the first to propose a complete theory for continental drift. During his lifetime, however, Wegener was mainly known as a polar explorer and as an atmospheric scientist. We argue that Wegener should also be remembered for his contributions to the study of tornadoes. As recognized by Greene (2015), Wegener's book is the only one of his publication that is still cited in the 21st century more as a piece of research and less as a piece of history. The isolation of German scientists after the First World War and the decline of the German language as an international language of science (e.g., Gordin 2015) had a great impact on the scientific legacy of Wegener. For example, there are no translations of Wegener (1917), as far as we know.

The story of *Wind- und Wasserhosen in Europa* is not a surprising one and does not have, to a certain extent, elements of an inspiring story, but "it is Wegener's way from one end to the other" (M. Greene 2017, personal communication). Wegener thought that his research on tornadoes would be useful for three main reasons (M. Green 2017, personal communication). First, Wegener had the tendency in his scientific work to go into details about side issues and also to include speculations based on empirical observations. He wanted to correct this, and thus by working on the book on tornadoes in Europe he wanted to focus on a single subject (i.e., tornadoes) without any theoretical speculations. Second, from his investigations into the Treysa meteor, Wegener realized the utility of observations made by citizen scientists. In fact, most of the tornado and waterspout reports in his catalog were made by citizen scientists. Third, as a commander of one of the German army field weather stations and thus being away from the front, Wegener had free time and access to publication from German libraries and thus he was able to work on research.

Wegener's research on tornadoes in Europe was continued by Johannes Letzmann, but his research became nearly unknown to the scientific community after the 1960s. Both Wegener and Letzmann's research remained in the background of tornado research in Europe to be rediscovered after the 1990s when the interest in European tornadoes increased (e.g. Antonescu et al. 2016). With this article, we hope to bring forward a part of Wegener's lesser-known scientific legacy to the meteorological community, especially outside Europe. There was a long history of tornado research in Europe before the beginning of the 20th century when Wegener started to study tornadoes. Wegener (1917) synthesized all the known research that occurred in Europe, as well as a catalog of all known tornadoes and waterspouts in Europe before 1915. Then, he meticulously constructed the first pan-European climatology for Europe. One hundred years later, the pan-European tornado climatology was updated following a methodology similar to the one used by Wegener (Antonescu et al. 2016) and shows remarkable confirmation of Wegener's results (e.g., monthly distribution, diurnal distribution).

Acknowledgments. We are indebted to Mott T. Greene, John B. Magee Professor of Science and Values Emeritus at the University of Puget Sound, and Affiliate Professor of Earth and Space Sciences at the University of Washington who wrote the definitive biography on Alfred Wegener. That book provided essential details about Wegener's life and research that made this article possible. We also have benefited considerably from discussions with and comments from Prof. Greene. Antonescu and Ricketts have received funding for this research from the University of Manchester School of Earth and Environmental Sciences Research Fund. Funding for Antonescu and Schultz was provided by the Risk Prediction Initiative of the Bermuda Institute of Ocean Sciences through Grant RPI2.0-2016-SCHULTZ. Partial funding for Antonescu was provided by the AXA Research Fund to the University of Manchester for the "Assessing the Threat of Severe Convective Storms across Europe" project. Partial funding for Schultz was provided by the Natural Environment Research Council to the University of Manchester through Grants NE/H008225/1, NE/I005234/1, and NE/N003918/1. We thank the Archiv Deutsches Museum for providing access to Alfred Wegener's correspondence with Wladimir Köppen.

Sidebar: A Short History of Tornado Research in Europe

Clouds, winds and thunderstorms have long been an object of fascination for mankind. The potentially destructive and frightening weather phenomena (e.g., lightning and thunder, hail, tornadoes) were regarded in the Ancient world as linked with gods and not explained as natural phenomena. The ancient Greeks were the first to make regular meteorological observations and also the first to propose hypotheses about different weather phenomena (Hellmann 1908). The majority of the speculations introduced by the ancient Greek philosophers about the weather phenomena formed the basis of *Meteorologica*, "the earliest known effort at a systematic discussion of meteorology" (Zinszer 1944) written by Aristotle (384–322 BC) and dated approximately between 356–330 BC. In *Meteorologica* Aristotle was one of the first to propose an explanation for the formation of tornadoes and waterspouts. Thus, in Book 3 of *Meteorologica* Aristotle discusses the formation of πρηστῆρος αυλός (*presteros aulos*[5]). The term has been usually translated as *whirlwind* (e.g., Webster 1984; Wilson 2013), but Hall (1969) argued that *presteros* is the funnel-shaped body of a tornado or waterspout and thus an accurate translation would be *tornado* or *waterspout*. It is clear from the recent tornado and waterspout climatologies (e.g., Matsangouras et al. 2014) that the ancient Greeks would have been familiar with these weather phenomena.

According to Aristotle, tornadoes occur as the result of the deflection of the wind within the surrounding cloud. This is analogous, Aristotle says, with the situation in which the wind hits a narrow space in alleys and portals, or encounters wind from the opposite direction. In such situations, the wind is "deflected because of the resistance due either to the narrowness or to a contrary current" until a circle is formed. The same mechanism occurs in clouds for the formation of tornadoes but combined with a downward motion. Unfortunately, the text is not particularly clear on what produces the descent (Wilson 2013). Wegener will later call this the "mechanische Theorie" (the mechanical theory) (Wegener 1917, p. 294) (Fig. 2). Despite the fact that almost all the explanations for the meteorological phenomena described in the *Meteorologica* do not "even comes close to the modern truth", Aristotle "was wrong in profoundly interesting and significant

[5]This can be literally translated as *the nozzle of a bellows*.

ways"(Wilson 2013). Aristotle's meteorological hypotheses were adopted by other authors from the Mediterranean region and *Meteorologica* became the unquestioned authority of weather theory for the next 2000 years (Frisinger 1977). Aristotle's successor in the Peripatetic School (founded around 335 BC), Theophrastus of Ereus (c. 372–c. 287 BC) is associated with several short works on meteorological subjects (Daiber 1992). In the *Meteorology*, Theophrastus provided one of the first definitions of a tornado as "[a]n airy pillar which is stretched out from the heaven to the sea and draws the ships upwards. When it goes down to earth, it is called *hurricane*" (13.43–46, Daiber 1992, p. 297).

Approximately 250 years after the publication of *Meteorologica*, the Latin poet Titus Lucretius Carus (c. 99–c. 55 BC) included in his philosophical poem *De Rerum Natura* (On the Nature of Things)—an account of the natural philosophy of Epicurus—speculations about the formation of meteorological phenomena commonly attributed to gods. On lines 422–451 of the poem, Lucretius describes two mechanisms for the formation of tornadoes and waterspouts Lucretius, p. 229–230. In the first one, which is similar to the mechanism described by Aristotle, the wind cannot break the cloud, and it is forced down in the shape of a pillar to the sea where it bursts and causes a furious boiling and surging. In the second mechanism, the tornado forms outside the cloud by gathering "the seed of clouds" (or atoms of cloud) and wrapping them around and is sometimes observed over land, but often on the sea.

For the most part of the Middle Ages (5th–15th Century), the majority of the speculation about meteorological phenomena proposed during the Classical Antiquity was lost and the interest in meteorology was scattered and fragmentary (Frisinger 1973). During this period authors, such as Venerable Bede (6733–735) in the *De Natura Rerum*, included a chapter devoted to meteorological phenomena based on classical sources without citing Aristotle who's works were forgotten in Europe. In the 12th Century *Meteorologica* was translated, based on an Arabic compendium produced around 800 CE, into Latin by Gerard of Cremona (c. 1114–1187). For the next centuries *Meteorologica* was considered as the standard textbook on meteorology. First printed in 1474 at Padua, *Meteorologica* had more than 135 editions, some of them including commentaries, by 1600 (Khrgian 1970). Authors during this period generally repeated the hypotheses proposed by Aristotle without any criticism and thus no real scientific progress was made. Even if the Middle Ages, as argued by Khrgian (1970), have not contributed significantly to the development of meteorology the chronicles written during this period contain valuable material on the occurrence of meteorological phenomena (e.g., Britton 1937). Besides descriptions of historical events, these chronicles contain descriptions of severe weather events such as the whirlwind that hit Nizhniy Novgorod (Russia) in 1406, "a mighty storm and whirlwind ravage[d] the village" (Anonymous 1851).

The transition between the Renaissance and the Early Modern period (the second half of the 17th century) marks the beginning of the systematic study of tornadoes in Europe (Peterson 1982; Antonescu et al. 2016). In 1689, the French theologian Franćcois Lamy (1636–1711) published a book describing two tornadoes that occurred in France at Sillery (southeast of Reims) on 10 August 1680, and at Bannost-Villegagnon (southeast of Paris) on 15 August 1687, respectively. The Sillery tornado, which was eyewitnessed by Lamy himself, is described in great detail in Lamy (1689). During the same period in Italy, the astronomer and mathematician Geminiano Montanari (1633–1687) studied a tornado that occurred in the Veneto region (northeastern Italy) on 29 July 1686. Published posthumously in 1694, Montanari's study *Le Forze d'Eolo* (The Forces of Aeolus) is one of the earliest studies on tornadoes in Europe. Montanari's "physical-mathematical dialogue" is mainly a theoretical discussion on the formation of tornadoes and waterspouts. According to the damage survey conducted by Andrea Poletti (Montanari, disabled by a light stroke, was unable to conduct the survey) the tornado was first observed at Legnaro (southwest of Venice) and moved northeastward for a distance of 65–80 km to the east of Padua (Peterson 1998).

In 1749, Roger Joseph Boscovich (1711–1787), a Jesuit priest and "one of the last polymaths" (James 2004) published one of the earliest studies on tornadoes in Europe. In his book, Boscovich investigated a tornado that occurred on the night of 11–12 June 1749 (Boscovich 1749). The tornado started as a waterspout over the Tyrrhenian Sea and then moved inland, parallel with the river Tiber from Ostia to Rome (Peterson 2000). Boscovich, at the request of Cardinal Silvio Valenti Gonzaga (1690–1756), conducted a tornado damage survey over a three-week period and published the results together with accounts of other tornadoes that occurred in Italy and discussions on tornado formation. An English summary of the Boscovich's book appeared in 1750 in *Monthly Review* published in London (Anonymous 1750). Boscovich speculated that tornadoes are associated with the collision of opposing winds and that

> Wind blows from all directions toward the whirlwind. [Their] motion is circular an their action attractive. [...] A common effect [of whirlwinds] is to carry up into the air, tiles, stones, and animal, which happen to be in their path, and all kinds of objects unexceptionally, throwing them to a considerable distance. with great violence (Boscovich 1749).

Boscovich (1749) exerted a great influence on the conceptual model of the waterspout proposed by Benjamin Franklin (1706–1790) by providing evidence on the rotation and progressive advance of the June 1749 tornado throughout its long track (Ludlum 1970). Franklin presented his speculations about waterspouts and tornadoes (he believed that waterspouts and tornadoes had the same origin) in a letter dated 4 February 1753 to Massachusetts physician John Perkins (1698–1781).

A shorter version of the letter appeared as an essay (probably written in 1750 or 1751 as indicated by Ludlum 1970) read at the Royal Society after 1756 and published in 1765 (Franklin 1765).

The number of published accounts of tornadoes in Europe increased during the second half of the eighteenth century and the beginning of the nineteenth century (e.g., Antonescu 2017). For example, in the Netherlands, Drijfhout (1757) provided a detailed analysis showing the evolution of a a tornado that occurred near the Hague in July 1751. In France, Michaud (1801) described two waterspouts that occurred at Nice on 6 January 1789 and 19 March 1789, receptively. As shown by Janković (2000), the second half of the eighteenth century is also a period when electrical experiments increased in popularity due to the invention of the Leyden jar[6] and stimulated by the publication of the experiments conducted by Albrecht von Haller (1708–1777) (von Haller 1745). Thus, electricity "became a central explanatory concept in meteorology" replacing the speculations based on Aristotle's ideas (Janković 2000, p. 147). After the 1750s, the natural philosophers agreed that at least two meteorological phenomena, Aurora Borealis and lightning, could be explained by the "accumulation and discharge of the electrical fluid" (Janković 2000). In his treatise on electricity published in 1753, Giovanni Battista Beccaria (1716–1781) speculated that "electricity is the cause of whirlwinds as shown by an experiment in which an electrical conductor is used to suspend a water droplet above a jar filled with water [...] when the conductor is charged the suspended water droplet is elongated and the surface of the water in the jar rises forming a 'conical button"' (Beccaria 1753). Other authors, for example, Bernard Germain de Lacépède (1756–1825) in France (Lacépède 1781), Thomas Young (1773–1829) in England (Young 1807), Alexander von Humboldt (1769–1859) in Germany (von Humboldt 1828) followed Beccaria in his explanation

[6]The Leyden jar, a device for storing static electricity which made possible the use of large electrical charges in experiments, was discovered accidentally in 1746 by the Dutch mathematician and physicist Pieter van Musschenbroek (1662–1761) from the University of Leyden and independently by Ewald Georg von Kleist (c. 1700–1748) in 1745 (Encyclopedia Britannica cited 2017).

on the formation of tornadoes. This lead to the development of the electrical hypothesis in which tornadoes are a result of cloud electrification which can produce intense wind by accelerating charged cloud particles (Fig. 2).

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List of Figures

Figure 1. Alfred Wegener (1880–1930) photo taken probably in Marburg around 1910. [Photo courtesy of Bildarchiv Foto Marburg Aufnahme-Nr. 426.293 via Wikipedia Commons (accessed on 8 April 2018).]

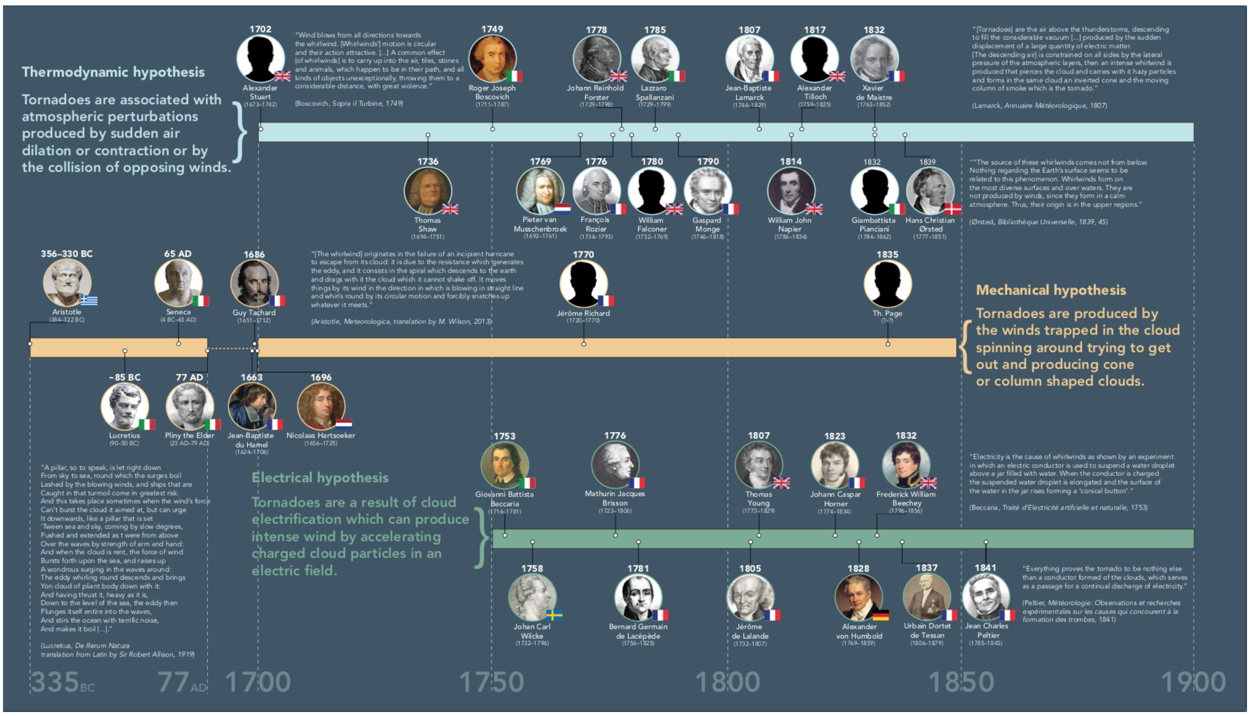

Figure 2. Hypothesis on tornado and waterspout formation. For each hypothesis, the major figures that proposed the hypothesis or they have used in their publications are shown along the timelines. We only focused on the most popular hypotheses (i.e., thermodynamic, mechanic, and electrical) based on the number of publications. [The images are courtesy of via Wikipedia Commons.]

Figure 3. Alfred Wegener photograph taken in November 1914 in Berlin by Bruno Brügner. Wegener is wearing the Iron Cross awarded for his bravery and wounding during the assault of Namur, Belgium (M. Greene 2017, personal communication). Today, the medal is at the Alfred Wegener Institute in Bremerhaven, Germany. [Courtesy of Deutsches Museum, Munich, Archive, PT_03918_01_b-01.]

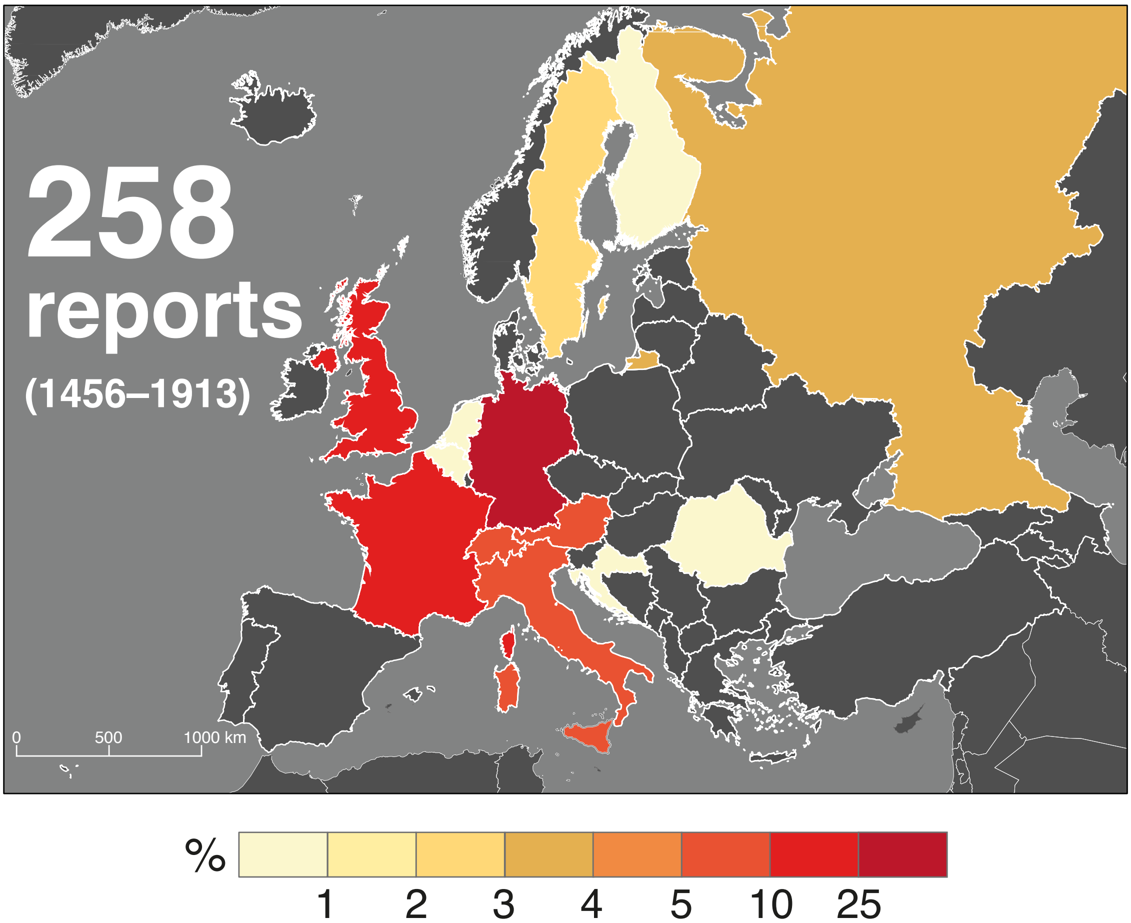

Figure 4. The spatial distribution of tornado reports in Europe based on the data collected by Wegener (1917) between 1456 and 1913. The percentage of tornado reports for each country (shaded according to the scale) is shown as the percentage from the total number of report (i.e., 258 reports) [Adapted from Fig. 3 in Antonescu et al. 2016.]

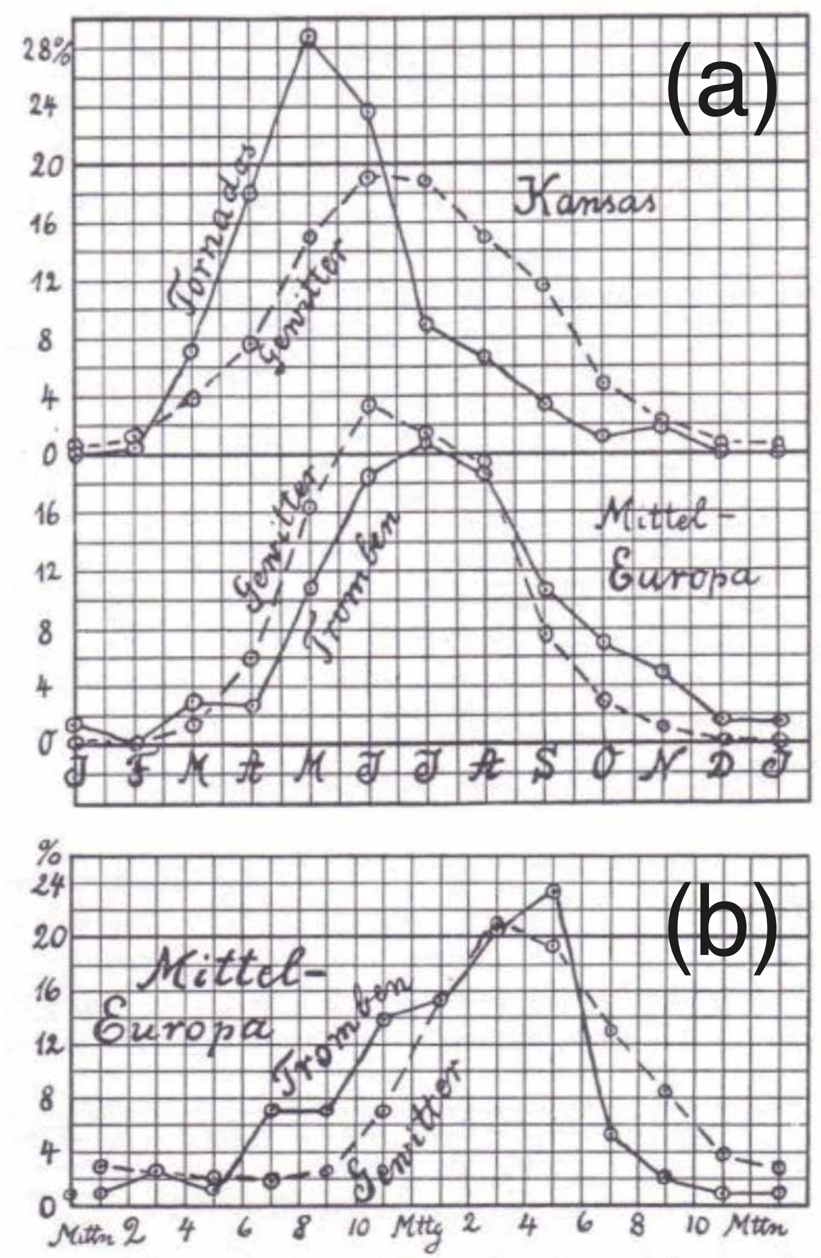

Figure 5. (a) The monthly occurrence of tornadoes (black line) and thunderstorms (dashed blacked line) in Kansas (United States) based on Finley (1882) and Central Europe based on 240 reports collected by Wegener (1917). (b) The diurnal distribution of tornadoes (black line) and thunderstorm (dashed black line) in Central Europe based on 169 reports collected by Wegener (1917). The monthly and diurnal distributions of thunderstorms in Central Europe were obtained from (von Hann 1915). [Figure adapted from Figs. 15 and 16 from Wegener 1917.]