Chapter 18

A Century of Progress in Severe Convective Storm Research and Forecasting

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ABSTRACTS

The history of severe thunderstorm research and forecasting over the past century has been a remarkable story involving interactions between technological development of observational and modeling capabilities, research into physical processes, and the forecasting of phenomena with the goal of reducing loss of life and property. Perhaps more so than any other field of meteorology, the relationship between researchers and forecasters has been particularly close in the severe thunderstorm domain, with both groups depending on improved observational capabilities.

The advances that have been made have depended on observing systems that did not exist 100 years ago, particularly radar and upper-air systems. They have allowed scientists to observe storm behavior and structure and the environmental setting in which storms occur. This has led to improved understanding of processes, which in turn has allowed forecasters to use those same observational systems to improve forecasts. Because of the relatively rare and small-scale nature of many severe thunderstorm events, severe thunderstorm researchers have developed mobile instrumentation capabilities that have allowed them to collect high-quality observations in the vicinity of storms.

Since much of the world is subject to severe thunderstorm hazards, research has taken place around the world, with the local emphasis dependent on what threats are perceived in that area, subject to the availability of resources to study the threat. Frequently, the topics of interest depend upon a single event, or a small number of events, of a particular kind that aroused public or economic interests in that area. International cooperation has been an important contributor to collecting and disseminating knowledge.

As the AMS turns 100, the range of research relating to severe thunderstorms is expanding. The time scale of forecasting or projecting is increasing, with work going on to study forecasts on the seasonal to subseasonal time scales, as well as addressing how climate change may influence severe thunderstorms. With its roots in studying weather that impacts the public, severe thunderstorm research now includes significant work from the social science community, some as standalone research and some in active collaborative efforts with physical scientists.

In addition, the traditional emphases of the field continue to grow. Improved radar and numerical modeling capabilities allow meteorologists to see and model details that were unobservable and not understood a half century ago. The long tradition of collecting observations in the field has led to improved quality and quantity of observations, as well as the capability to collect them in locations that were previously inaccessible. Much of that work has been driven by the gaps in understanding identified by theoretical and operational practice.

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DOI: 10.1175/AMSMONOGRAPHS-D-18-0026.1

1. Introduction

There are many variations in the definition of what constitutes a severe convective storm. From a physical perspective, a convective storm is one driven by buoyancy. Buoyancy is determined by differences in air density leading to a vertical pressure gradient that is unbalanced by gravity, leading in turn to the development of vertical acceleration (Doswell and Markowski 2004). Note that buoyancy can be either negative or positive, so the vertical acceleration due to buoyancy can be upward or downward. The ingredients for a convective storm are 1) the presence of water vapor in ascending air that releases latent heat of condensation, 2) the existence of conditional static instability, and 3) some process by which moist air is lifted to its level of free convection (LFC). These ingredients are all necessary and when moisture and instability are such that convective available potential energy (CAPE) is present, these ingredients are sufficient for the development of a convective storm. Such storms are likely to produce lightning (and thunder, of course), but do not always do so. Hence, rather than using the term "thunderstorm," some prefer to use "deep moist convection" (DMC).

Given the existence of DMC, the next challenge becomes defining what it means for such storms to be severe. In the United States, the formal definition is that to be considered severe, DMC must produce one or more of the following weather at the surface: 1) a tornado, 2) hailstones with a diameter $\geq$2.5 cm (1 in.), and/or 3) nontornadic wind gusts $\geq$25 m s^{-1} (50 kt). Many countries around the world also include heavy precipitation as a form of severe convective weather, but many different criteria for what constitutes heavy precipitation are in use. Note that with the exception of tornadoes, all these criteria are essentially arbitrary in terms of the values. Galway (1989) has chronicled how the criteria for defining severe convection evolved in the United States through the late 1970s. They continue to evolve world-wide. Hence, forecasters are faced with the dilemma of, for example, differentiating a storm that produces a 2.5-cm hailstone from one that produces a 2.4-cm hailstone. Although such accuracy is well beyond the current state of the science, the science of such storms can be employed to estimate the probability of a storm that would meet or exceed the arbitrary criteria.

From the perspective of the modern world, it can be challenging to imagine the state of the science before the year 1917 (the beginning of the century that is of concern herein). Although some considerable understanding of fluid dynamics developed by physicists and engineers existed, it was evident immediately that the equations of atmospheric dynamics were not capable of mathematical solution, owing to their nonlinearity. The notion that the physics of fluids could be applied to the challenge of weather forecasting was proposed by Bjerknes (1904) and independently by Spasskii (1847).

Efforts at forecasting the weather might be said to begin with sailors and farmers whose safety and ability to make a living depended so strongly on the weather. Any interested observer of the weather in the midlatitudes could recognize the progression of weather systems and this might lead to various forms of weather lore (e.g., "Red skies in the morning, sailor take warning"). Weather lore can be considered the first primitive methods of weather forecasting based on simple observations. The science of meteorology was essentially stagnant well into the nineteenth century, owing to the scarcity of data (especially above the surface), by the slow speed of communication of weather observations, and by the intractability of the equations governing atmospheric flow. Toward the end of the nineteenth and the beginning of the twentieth century, an isolated few began some serious studies of severe convective storms. A notable pioneer was John Park Finley (Galway 1985), whose efforts while an officer in the U.S. Army to collect tornado reports in the 1880s into what we now call a climatological database, and to attempt forecasting them were abruptly suppressed by his commander. This marked the beginning of a ban on the use of the word "tornado" in any U.S. Weather Bureau forecast that lasted until 1952. That ban evidently also had a chilling effect on any tornado research in the United States as there was to be no practical application of any science that developed. Curiously, Finley's forecasting was the source for some important developments in statistical verification of his forecasts (Murphy 1996).

By the end of the period leading up to 1917, the first efforts at a systematic understanding of what we now know as synoptic meteorology were undertaken at the so-called Bergen School, founded in 1917. That year also is marked by the publication of *Wind- und Wasserhosen in Europa* (Wegener 1917), a compilation of known European tornadoes throughout history and a summary of previous theories about tornadogenesis, setting a mark for the understanding of the problem at that time. For these and some other reasons, 1917 has been chosen as the start of the century under consideration. The century is highlighted by an intertwining of research and forecasting and increased availability and development of new observational tools, allowing both researchers and forecasters to advance their fields collaboratively, as well as separately. Historically, research on severe convective storms has been closely aligned with solving problems in forecasting. A consistent picture also emerges around the world of the importance of individual, or a small number of, weather-related disasters. Events with large numbers of fatalities or damage tend to spur research on that class of events. In the United States, the Tinker Air Force Base tornadoes of 1948 (Maddox and

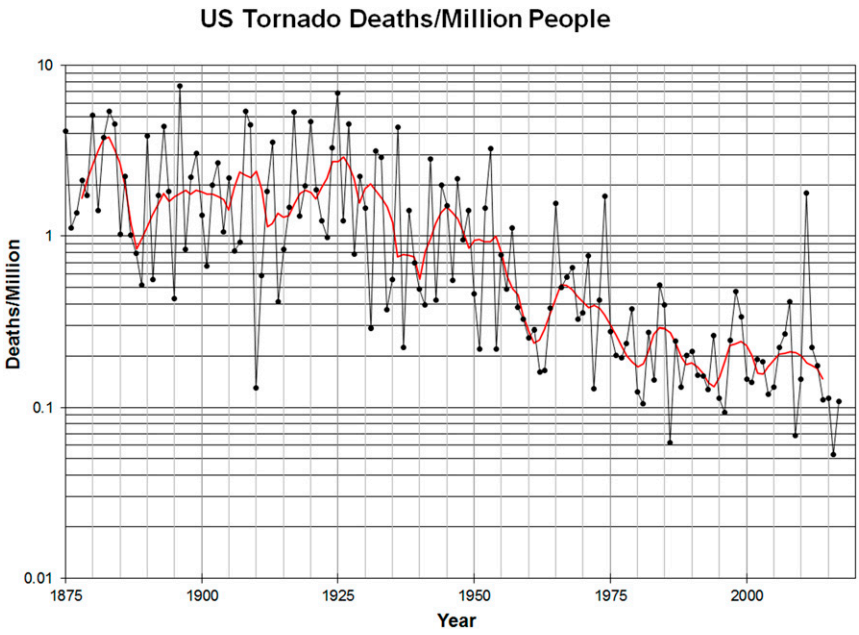

FIG. 18-1. Death rate per million population from tornadoes in United States, 1876–2017. Black dots are annual values; red is smoothed. [Updated and adapted from Brooks and Doswell (2002).]

Crisp 1999) and aircraft accidents associated with downburst winds (Fujita and Byers 1977) both led to a dramatic increase on research and forecasting of severe thunderstorms. Examples of this effect abound around the world.

The century also shows the limitations associated with the presence or absence of resources for research and forecasting and national priorities, as well as the infrastructure that can allow for research and forecasting activities in a nation. We also see the role that global conflict has played in the development of the science. No better illustration of this latter point exists than the story of Wegener, who was wounded early in World War I, leading to him having the time to compile his list of tornadoes from German archival sources, but distribution of his book in Allied countries was limited because of its publication during the war. Although war provides a particular example of the difficulty of international communication, in general researchers in one country were relatively isolated from those in other countries until after World War II, at the earliest. This was even more problematic as distances between workers grew. Any work done pre–World War II in Australia, for example, would be unlikely to be noticed by researchers in North America or Europe.

2. The importance of severe convective storm science

The impetus for funding abstract research is attributable to the immense societal impact of severe convective storms, in both the damage such storms do and the fatalities and injuries that are inflicted when humans are in the path of severe convective storms. Only part of the economic impact of severe weather is subject to mitigation by means of short-term forecasting severe storms, but certainly human lives can be spared even with relatively short notice. Figure 18-1 provides compelling evidence of operational success in limiting casualties by forecasting one particular aspect of severe convective storms: tornadoes. That such results are linked to both research and operational implementation of the fruits of that research is a major theme of this article. As discussed in Brooks and Doswell (2002), it is not possible to disentangle the effects of improvements in understanding of the atmosphere, communication of the threat, and societal changes, but the order of magnitude decrease in death rate could not have occurred in the absence of better scientific information.

There are several steps needed to establish a climatological record of severe storm occurrences. Severe storm events must be observed by someone, the events must be reported to a centralized collection agency, they must be evaluated for credibility, and finally they must be entered into a record. The United States has by far the most complete record of severe storms of any nation worldwide, but there are many issues that plague the existing historical record of severe convective storm events in the United States (see Brooks et al. 2003a; Doswell et al. 2005). The climatology of severe convective storms also provides important information in

advancing the understanding of such events. If a forecast is made, the key imperative is to know as precisely as possible what happened during the time the forecast was valid. If it cannot be learned what events did or did not happen with reasonable confidence, then it is not possible to learn much from the forecast, regardless of its apparent success or failure. Unfortunately, as discussed by Doswell (2007), even in the United States the existing climatological records of severe convective storms are not only small samples compared to the variability, but significant parts of that variability are associated with many nonmeteorological factors (e.g., population density and the diligence by which reports are sought by those individuals charged with maintaining the climatological record). Thus, we are forced to conclude that the existing climatologies around the world are not adequate for examining the data for long-term trends.

Given the limitations of climatologies, however, they represent an important step in the development of forecasting methods and set the tone for research. Simply put, if a national meteorological service does not believe an event is common enough or, if rare, intense enough for them to forecast it, they are unlikely to collect data about its occurrence. Conversely, in the absence of an understanding of the distribution of an event, agencies are unlikely to forecast it. As a result, a consistent theme, throughout the world, has been the attempt to estimate aspects of the distribution of severe convective storms. Even when the word ''tornado'' was banned from the lexicon of forecasters, the U.S. Weather Bureau still collected and made monthly reports of tornado occurrences. Stories about individual tornadoes appeared in most issues of *Monthly Weather Review* prior to the development of tornado forecasting in the 1950s. Although the picture is obviously incomplete, the information contained in those reports and case studies was important later, as more complete information was still collected for those events than for those that were less well described. Researchers using the historical record are always faced with a dilemma between large sample size and consistent reporting practices. Significant events are more likely to be reported and to have been reported for a long time, but since they are only a small subset of the total events, the sample size is necessarily much smaller. Frequently, various smoothing techniques are employed to make some sense of the data. The simplest is collecting data from an entire country over time. One cannot draw strong conclusions about the geographic distribution within the country or the annual cycle, say, but the fact that the event has occurred and, perhaps, the maximum observed intensity over the period of record can be recorded. Brooks and Doswell (2001b) collected databases from a number of countries (Argentina, Australia, Canada, France, Germany, Italy, South Africa, the United Kingdom, and the United States) and investigated the distribution of tornadoes by intensity, showing that, for strong and violent tornadoes, there were two basic distributions by intensity, perhaps representing two different physical processes.

At the same time as Brooks and Doswell (2001b), many representatives from European countries were attempting to mine archives to produce better estimates of tornado occurrence in their countries. Dotzek (2003) surveyed them to make an improved estimate of tornadoes in Europe compared to Wegener (1917). This spurred the development of the European Severe Weather Database and even better estimates within Europe, leading to a pan-European distribution (Antonescu et al. 2017). Researchers from around the world have developed climatologies for other countries as well (e.g., Newark 1984; Snitkovskii 1987; Goliger et al. 1997; Allen et al. 2011; Rauhala et al. 2012; Allen and Karoly 2014; Taszarek and Brooks 2015; Shikhov and Chernokulsky 2018.

Smoothers on subnational area and daily or hourly time scales have been applied to the severe thunderstorm and tornado data of the United States (Brooks et al. 2003a; Doswell et al. 2005; Krocak and Brooks 2018), effectively increasing the apparent sample size at any location by including information from nearby locations in space and time. The drawback is that, in areas or times of strong gradients, they will overestimate the occurrence in regions where the true occurrence is nearly zero. In keeping with one of the themes of the interaction of research and forecasting, it is important to note that the primary motivation behind such work was to provide background information for forecasters and users who might want to make long-term plans or respond to forecasts.

Although this article is associated with the 100-yr celebration of the American Meteorological Society, we have herein taken a global perspective, in an effort to provide appropriate recognition of the scientific and operational communities around the world. Atmospheric science knows no geographical borders, after all.

3. The period between the World Wars

It is not unreasonable to say that the best understanding of severe convective storms, or at least, tornadoes, at the end of World War I was found in Europe, most notably in the person of Alfred Wegener (Antonescu et al. 2019). Wegener went to the German territory in what is now Estonia and taught at the

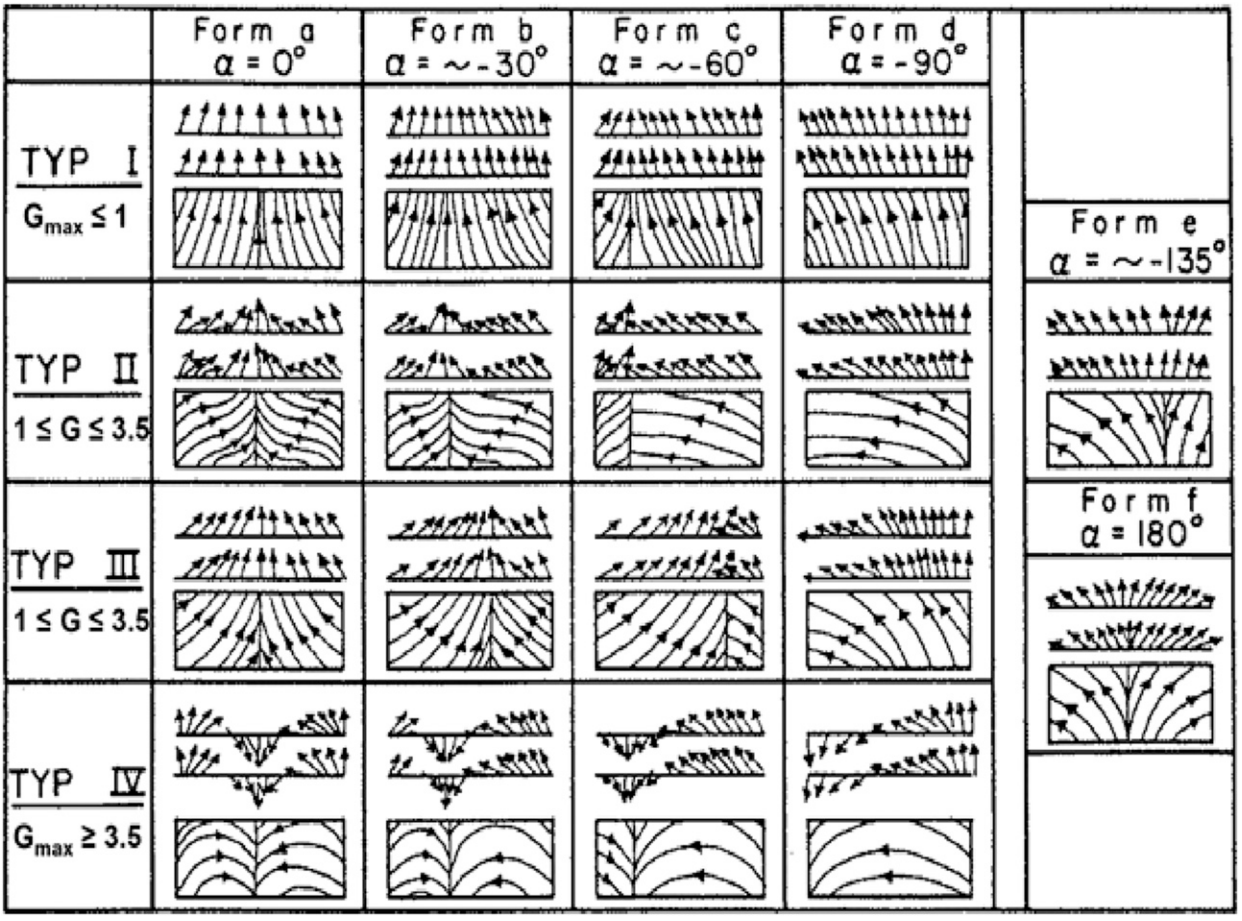

FIG. 18-2. (from bottom to top) Patterns of wind and tree fall associated with theoretical vortices [from Letzmann (1923), reprinted by Beck and Dotzek (2010)]. Gmax is the ratio between the circular component of the wind and the translation speed of the vortex and α is the angle between the velocity vector and the pressure gradient at the location of maximum velocity. The bottom panel of each pair is the velocity field and the top panel is the resultant pattern of falling trees if a vortex crossed a forest. For small Gmax (<1.0), the location of the tree that falls directly in the forward direction of the vortex moves to the left for increasing values of $|\alpha|$ and no crossing of trees occurs. The difference between swath types II and III is in the higher value of wind required to break stems. Increasing that value leads to the centerline of damage moving to the right of the center of the vortex. A wide variety of tree fall patterns can be produced with this simple model.

University of Dorpat (now Tartu), where he met his protégé, Johannes Letzmann (Peterson 1992; Dotzek et al. 2005). Letzmann would be one of the leading figures in tornado research in the period between the World Wars. His Ph.D. thesis (Letzmann 1923) described the near-surface windfield and damage in tornadoes (Fig. 18-2; Beck and Dotzek 2010). His continuing research (Letzmann 1925, 1928) led to the development of guidelines for the study of tornadoes (Koschmieder and Letzmann 1939; Letzmann 1939, 1944). Although Letzmann was in communication about the guidelines with the U.S. Weather Bureau in the late 1930s, the outbreak of World War II in September 1939 ended that relationship and Letzmann's work effectively disappeared from the scientific community until the 1970s.

One of the limitations that these early researchers faced was the lack of observations of tornadoes. The inability to forecast them meant that researchers had to rely on receiving reports relatively soon after the tornado occurred, and then they could potentially look at the damage if the event occurred close to them. Thus, many of the studies, such as those of Letzmann, focused on surface wind fields and crude, by modern standards, damage surveys. There were no upper air observations, so the notion of the environment in which storms formed was limited to the surface network.

A notable exception to the lack of upper-air observations was provided by van Everdingen (1925). van Everdingen was the director of the Royal Dutch Meteorological Institute (KNMI) and a pioneer in collection of

upper-air observations with kites. He studied the Borculo tornado in the Netherlands in 1925 and his work covered three aspects that foreshadowed future research. He carried out a detailed damage survey in Borculo. He went back through the Dutch archives of possibly tornadic events and occurrence of thunderstorms for the previous four decades to make an estimate of the climatology of the annual cycle of tornadoes and thunderstorms in the Netherlands and their relationship. Finally, he took observations from kites taken in the vicinity of the tornadic storm. The vertical wind profiles showed strong wind shear, with some curvature of the hodograph, in the lowest two kilometers, consistent with what we would now anticipate leading to rotating thunderstorms (Weisman and Klemp 1984; Davies-Jones 1984; Rasmussen and Blanchard 1998). At that time, significant work published in international journals was summarized in *Monthly Weather Review* because of the general lack of availability of the other journals. Although he discussed the upper air observations, Varney (1926) focused mostly on the damage survey aspect of van Everdingen's paper; for the next 65 years, the latter two parts of van Everdingen's work seem to have gone unnoticed. It is tempting to believe that more widespread distribution of research now would make such collective amnesia unlikely, but it is a sobering caution for modern researchers.

The most common severe convective threat in most, if not all, parts of the world where convection is reasonably common is heavy rainfall and associated flooding. Observationally, rainfall has advantages for study compared to other hazards since it is possible to create observational platforms that regularly collect data directly about the phenomenon for long periods of time. The existence of rain gauges led to their data being analyzed and the properties of rainfall being studied well before high-quality reports of any other hazard existed. Rainfall data began being investigated systematically in Russia in the nineteenth century (Berg 1914) and statistical properties of rainfall including the intensity, distribution, and area were documented by Drozdov (1936). Because of the quality of the observations and length of consistent records, the results have been used in hydrological computation for decades.

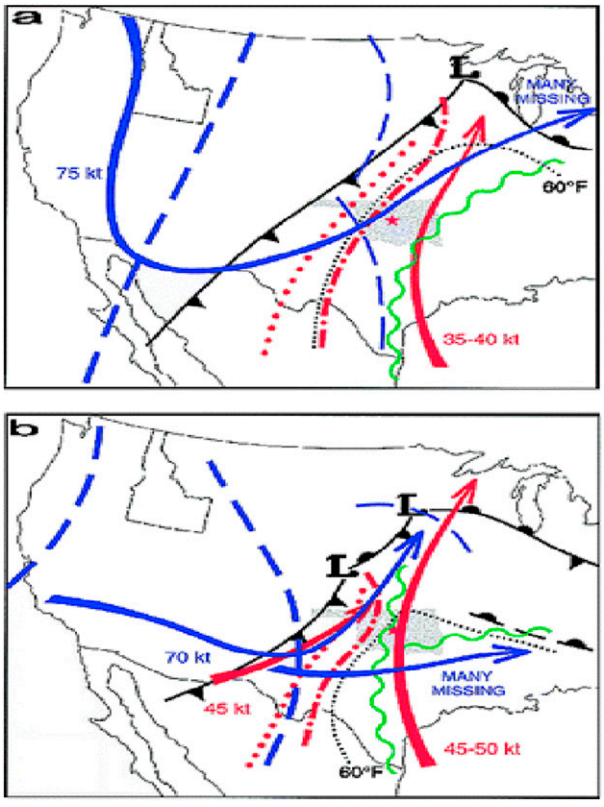

FIG. 18-3. Composite charts showing important factors for tornadoes from (a) 20 Mar and (b) 25 Mar 1948, the date that Fawbush and Miller forecast a tornado at Tinker Air Force Base [from Maddox and Crisp (1999)]. Blue indicates 500-mb features; red and green are 850-mb features. Arrows indicate jet locations, heavy (light) dashed lines are major (minor) trough axes. The surface frontal analyses and 60°F isodrosotherm are in black. The wavy green lines indicate moisture axes at 850 mb and the red dotted lines the axes of highest temperatures at 850 mb. Maximum observed wind speeds are indicated; many winds were missing at 500 mb. Oklahoma is shaded in gray and the red star indicates the location of Tinker Air Force Base.

4. The post–World War II era: Radar and the development of forecasting

The attitude against using the word "tornado" in forecasts in the United States began to change after the first modern tornado forecast issued by Fawbush and Miller on 25 March 1948 for the second Tinker Air Base tornado in a week (Fig. 18-3; Maddox and Crisp 1999). It is, perhaps, fortunate that those individuals made that forecast and that they were given permission to begin researching tornadoes and their forecasting in the aftermath of the event. They spent much of the next decade trying to understand the environmental conditions and atmospheric patterns in which tornadoes form in order to improve forecasts for the Air Force. This process represents a connection that has been repeated over the decades of forecast problems leading to research topics, which in turn led to improved forecast techniques.

The transformational importance of the Fawbush and Miller forecast cannot be overstated. It showed that forecasts of tornadoes could be made and directly led to research to systematize those warnings and expand their applicability. The implication that tornadoes and other severe thunderstorm hazards could be understood well

enough to make forecasts set the stage for decades of basic and applied research. That they had the capability to lead much of the early research was also critical in that it highlighted the interaction between operations and research.

A particularly important aspect of the study of environmental conditions was the development of so-called proximity sounding studies (Beebe 1958), in which upper-air observations taken in the vicinity of storms were used to determine the necessary conditions for particular kinds of severe thunderstorm events (e.g., tornado, hail, convective wind) to occur. The earliest studies focused primarily on tornadoes, but by the 1980s the distinction between tornadic and nontornadic thunderstorms became of greater importance. The understanding developed in proximity studies fed back into forecasting by providing the environmental conditions that forecasters should look for in the so-called ingredients-based approach to forecasting that is a feature of severe thunderstorm forecasting in the United States.

The proximity sounding work is closely tied to the development of so-called ingredients-based forecasting [described in Doswell et al. (1996)]. This powerful approach to forecasting is used around the world to look at a variety of problems. In short, physical understanding of a phenomenon of interest and observations of the conditions in which it occurs and does not occur allows the community to identify the necessary ingredients. The observational question while forecasting becomes whether those ingredients are collocated and, if not, whether there are there processes in the atmosphere that will bring them together. It also may identify those ingredients that are not well observed for the forecasting activity. Conceptually, there is not a weather phenomenon to which ingredients-based forecasting cannot be applied. Research can refine or update the ingredients list over time.

Even if it was not described that way at the time, ingredients-based forecasting was the basis for the first operational forecasts of severe thunderstorm threats in the United States. In 1953, the forerunners to the National Weather Service (NWS) Storm Prediction Center (SPC) began issuing forecast products for threats for regions of tens of thousands of square kilometers for several hours (Corfidi 1999). These products, which eventually became known as watches, described areas in which conditions were favorable for the development of the hazard. They did not specify exact location or timing, but provided background information that could be used in issuing more precise shorter-term forecasts as the day evolved. Eventually, longer-term products called convective outlooks that covered day-long periods throughout the nation would evolve with a goal of having a cascading series of forecast products that became more specific in time and space as the threat approached.

No observational technology has had greater impact on severe thunderstorm work, particularly in short-range forecasting and in providing observations for understanding basic processes, than weather radar. British radar technology was shared with Canada at the beginning of World War II. Using this technology, the Operational Research Group of the Canadian Army initiated Project Stormy Weather under the leadership of physicist Dr. J. Stewart Marshall[1] with the primary goal of better understanding weather-related radar echoes. After the war ended, Marshall moved the project work to Montreal's McGill University under the auspices of the Stormy Weather Group. Seminal studies from his group include work on drop size distribution as a function of rain rate (Marshall and Palmer 1948), development of the widely used (yet incorrectly named and often incorrectly referenced) Marshall–Palmer reflectivity–rain rate relationship (Marshall and Gunn 1952), and research on attenuation correction (Hitschfeld and Bordan 1954). It is often stated that radar meteorology got its start at McGill, leading to a rapid growth in the study of mesoscale meteorology and the use of radar internationally.

In 1953, the first hook echo associated with a tornadic thunderstorm was observed on radar north of Champaign, Illinois (Fig. 18-4; Stout and Huff 1953). Although the physical processes the hook echo represented were not fully understood at the time (Markowski 2002), the frequent association between the feature and tornadoes was adopted as an important part of the process of very short-term forecasts of tornado threat (known as warnings) in the United States.

Radar also provided the observational basis for one of the most profound advances in severe thunderstorm science, the identification of a particularly dangerous class of thunderstorm known as the supercell, which has a rotating updraft through most of its depth and can produce all of the severe thunderstorm threats. Based on our current understanding, the location where the supercell was first identified, southern England, is remarkable. On 9 July 1959, a storm developed over France, crossed the English Channel near the Isle of Wight, and produced a hail swath longer than 200 km. The town of Wokingham was hit by golf ball–sized hail for 14 min. Keith Browning, a Ph.D. student under Frank Ludlam, was helping operate a radar at East Hill, part of a research station that had been established during World War II. The so-called "Wokingham

[1] The material on Marshall is mainly drawn from Rogers (1996).

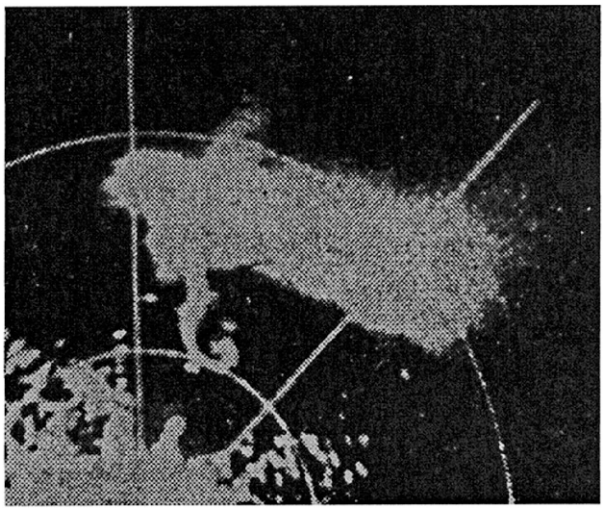

FIG. 18-4. First radar-observed hook echo associated with a tornado. [From Stout and Huff (1953).]

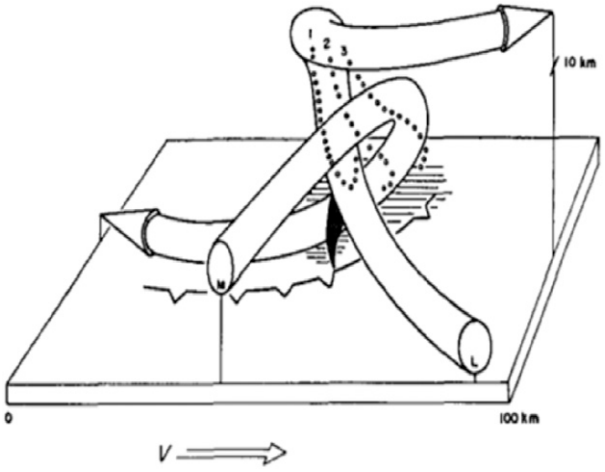

FIG. 18-5. Conceptual model of airflow in a supercell thunderstorm, relative to storm motion [from Browning (1964)]. Arrows indicate general directions of low-level and midlevel air entering the thunderstorm. The surface gust front is indicated by the frontal symbol and a funnel cloud indicates the location of a tornado, if one is present. Dotted lines are precipitation trajectories and the hatched area is precipitation at the ground.

storm'' passed over the radar site, providing excellent coverage of the evolution of the storm (Grazulis 2001; Atlas 2001). Browning analyzed the dataset and deduced the presence of a quasi-steady-state updraft, in contrast to the prevailing understanding at the time of severe storms as a succession of discrete updrafts. Browning and Ludlam (1962) and Browning (1964) identified an ''echo-free vault'' with that steady updraft that was strong enough to carry cloud droplets to a high altitude before they could grow to a size that could be detected by radar. They coined the term ''supercell'' to describe such storms. Following his Ph.D., Browning came to the United States and showed that such storms are relatively common. Even without velocity data from the storms, Browning and Landry (1963) and Browning (1964) were able to describe the basic flow structure of supercells (Fig. 18-5) and suggest that the rotation of the updraft came from the horizontal inflow in the storm, a process that would be explained theoretically by Rotunno (1981) and Davies-Jones (1984), via the tilting of environmental vorticity. The combination of the early observational and conceptual work of Browning and the theoretical work of Rotunno and Davies-Jones led to improved forecasting of supercells, based upon the environmental conditions needed and the unique structure of the storms.

In parallel, weather radars were developed in the USSR. The first radar observations in the USSR were performed in 1943 at the Central Aerological Observatory (CAO) for wind measurement. At the end of 1940s, the 3-cm ''Kobalt'' radar was constructed and observations for storm prediction were started within approximately 50 km of the radar. In 1951, a 10-cm radar was developed that could obtain cross sections of thunderstorm within 200 km. Sal'man and colleagues (e.g., Sal'man et al. 1962, 1969) estimated the vertical and horizontal structure of radar reflectivity of thunderstorms and showers. Kotov and Nikolaev (1958) found a threshold for temperature of radio echo top height of −22.4°C successfully discriminated between thunderstorms and non-thunderstorms. In the late 1950s and early 1960s, a specialized meteorological weather radar was developed and constructed (MRL-1). which operated at 0.8- and 3-cm wavelengths. Special experiments were conducted in 1962–63 comparing MRL-1 observations with airborne and special rawinsonde observations (Brylev et al. 1986). It was shown that MRL-1 could reliably detect thunderstorms within 150–200 km, showers and non-showery precipitation within 100 km, and non-showery snowfall within 50 km. A network of 120 radars was constructed to cover most of the USSR. Brylev et al. (1971) created a unified methodology for the use of radar data for storm prediction. In the late 1960s, at CAO, the Main Geophysical Observatory, and the High-Mountain Geophysical Institute, Doppler radars were independently developed (Brylev et al. 2009). The first studies on polarization characteristics of radar echoes were conducted in CAO in the 1960s. These characteristics were used to determine regions with liquid and ice particles inside a cloud, which helped more effectively recognize hail processes in clouds (Shupyatskii et al. 1975). In the mid-1970s, the new MRL-5 radar was developed (3 and 10 cm) for storm prediction and hail prevention duties. From 1976 to

1990, more than 200 MRL-5 radars were built (around 50 of them were exported from the USSR), with most of them still operated today. Beginning in the 1960s, the automation of radar observations began to be developed. In particular, "Meteoyacheika" was developed, tying radar observations with other meteorological observations. In recent years, MRL-5 radars have been replaced with a new dual-polarized Doppler radar, DMRL-C (Dyaduchenko et al. 2014).

The threat of severe convective weather in Australia was established in the period around World War II and was motivated by three devastating storms that hit Sydney. Tornadoes occurred in 1937 and 1940 and a storm with 7-cm diameter hail hit the city in 1947. Seven deaths and many tens of millions of dollars (in 2018 U.S. dollars) in damage resulted. Weather radars began to be installed in the 1950s and used results from American studies to look at severe convection. Australia also installed a network of upper air observations and relied heavy on the work of Fawbush and Miller from the U.S. Air Force for analyzing the sounding data for forecasting. Australian knowledge of storm environments was enhanced through a number of case studies. Typically, these documented the location and impact of the storms together with a description of the synoptic setting, including the surface and upper-level features, along with rawinsonde soundings (e.g., Phillips 1965; Plukss 1979; Colquhoun et al. 1982; Bureau of Meteorology 1972).

In Japan, the threat of heavy rainfall in the baiu season (June–July) led to a Severe Rainstorm Research Project from 1967 to 1971. As described above, observations of the hazard, the larger-scale setting in which it occurred, and attempts to forecast it took place. The typical nature of baiu fronts associated with heavy rainfall was described by Matsumoto et al. (1971) and the synoptic and subsynoptic setting for such fronts was defined (Ninomiya 1978). Akiyama (1974, 1978) investigated the characteristics of the rainfall within the convective clusters that produced heavy rain. Finally, there were experimental forecasts with numerical data to help with prediction (Ninomiya and Kurihara 1987).

One of the most remarkable figures in the post–World War II era of severe thunderstorm research was T. Theodore Fujita.[2] Fujita began his meteorological career in Japan in 1942. The isolation of Japan during the war and immediately thereafter prevented him from being aware of the nascent work in the United States at that time. Fujita pioneered the use of time–space conversion of observations, critical to the understanding of convective-scale systems, which may be sampled by only a few observation sites at any particular time (Fujita 1951). His work attracted the attention of Horace Byers of the University of Chicago, the director of the 1947 Thunderstorm Project intended to improve aviation safety (Braham 1996). The Thunderstorm Project studied storms in Florida and Ohio, using aircraft to penetrate them. The project was, in a sense, made possible by the war. Numbers of surplus military aircraft with trained personnel were available to carry out the missions. A range of other observational platforms (e.g., radar and radiosondes) supported the field project. From the observations, Byers and Braham (1948) constructed a schematic of the life cycle of a convective cell. What drew Fujita to Byers's attention was that Fujita had deduced most of that structure independently in Japanese storms. Byers invited Fujita to visit the University of Chicago and Fujita remained there for the rest of his career.

One of the early accomplishments of Fujita in the United States was his collaboration with U.S. Weather Bureau researchers in the area they dubbed "mesoanalysis" (Fujita 1955; Fujita et al. 1957), which performed time-to-space conversion on time series of observations, resulting in a two-dimensional field of pseudo-observations. Focusing primarily on pressure traces, they were able to identify small-scale pressure changes associated with convective storms, leading to improved understanding of storm structure and behavior.

Fujita's attention soon turned to tornadoes. Fujita was passionate about data and, as such, began to collate the U.S. Weather Bureau's monthly reports of tornadoes back to 1916. He produced various statistics and maps to provide a background for where and when tornadoes occurred in the United States. This was the beginning of efforts to create a systematic climatology of tornadoes, the first major effort since Finley in the 1880s. The beginnings of the work prepared Fujita for his analysis of the well-photographed 1957 Fargo, North Dakota, tornado (Fujita 1960). By triangulating the many photographs and movies taken of the tornado, he created a life cycle of the development of the tornado from what we would now refer to as a "wall cloud" and the various scales of motion in the low levels of the storm. Fujita's gifts of visualization and ability to consider the relationship of time and space in a moving meteorological feature were amply illustrated in this event.

Fujita was concerned about the impacts of tornadoes and began studying the damage they produce. He investigated tornado damage on the ground, beginning with a tornado in Japan in 1948, but also pioneered the use of aerial surveys. An early example of the latter was associated with the 1965 Palm Sunday outbreak (Fujita et al. 1970). There were 36 tornadoes on the day, some of them with long tracks (Fig. 18-6**)**. Through the use of aircraft, most of the tracks were able to be surveyed. Additionally, the perspective

[2] Much of the discussion of Fujita's career is drawn from his autobiography (Fujita 1992), *The Mystery of Severe Storms*.

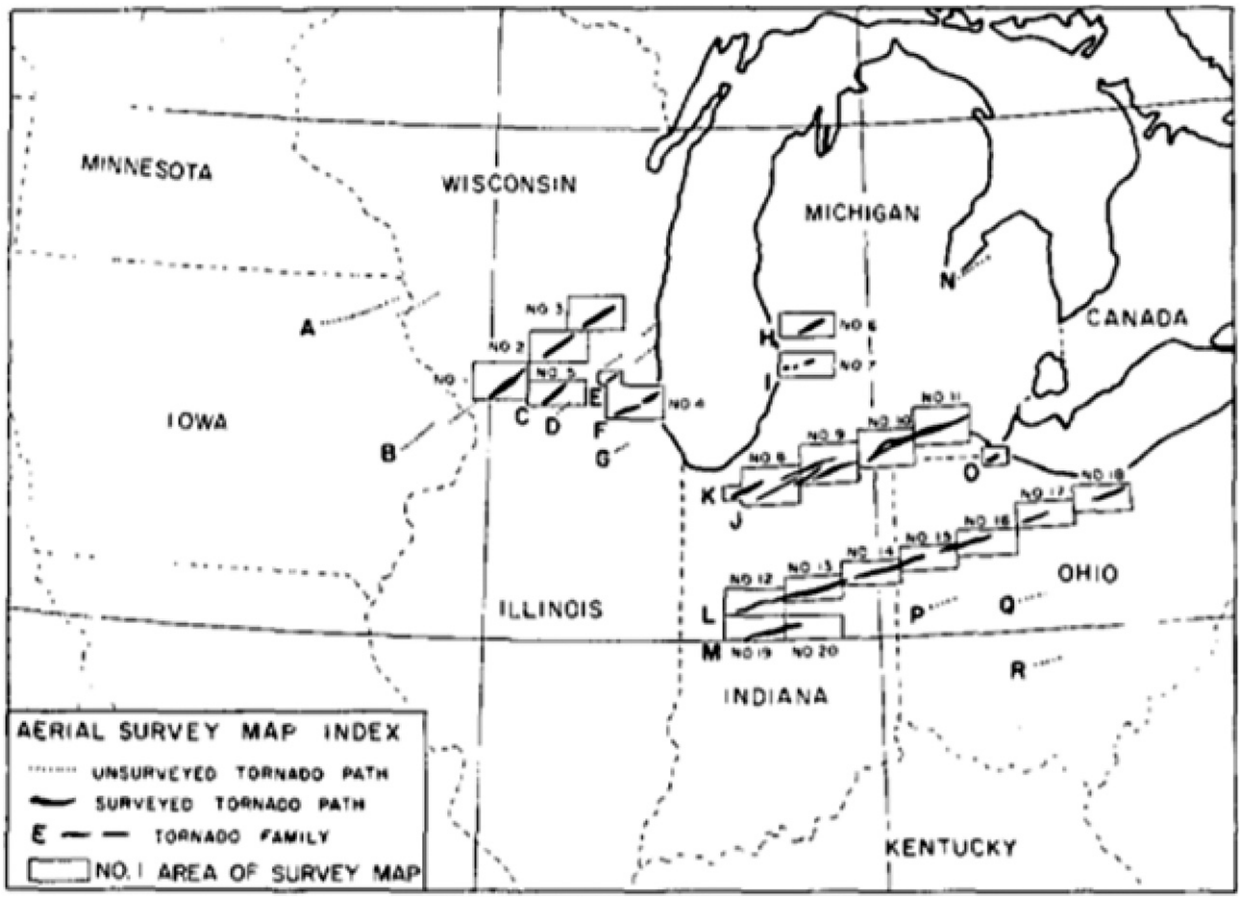

FIG. 18-6. Tracks of tornadoes from 1965 Palm Sunday outbreak, showing extent of surveys. Letters indicate the parent supercell and numbers indicate particular tornadoes [from Fujita et al. (1970)].

from the aerial views allowed Fujita to get a better overall view of what occurred within the storms.

By 1970, Fujita was surveying tornado damage on the ground or from the air from many tornadoes around the United States and Canada (Fig. 18-7**)**. He desired to infer the wind speeds from the damage that had resulted. To do this, he developed the F-scale for tornado damage, ranging from 0 to 5 (Fujita 1981). In a strict sense, he failed at the goal of developing a strong relationship between damage and inferred wind speed, in large part because of the variability of construction. The quality of a structure was, and is, taken into account in deriving a value on the F-scale, but the empirical conversion to a wind speed depended upon many assumptions about how buildings would perform when exposed to wind and, in practice, the scale was based on the damage. Three decades later, an ''enhanced'' version of the F-scale was introduced in the United States that included expert elicitation on damage to various kinds of structures in an effort to make the conversion from damage to wind speed more accurate (Doswell et al. 2009). Other countries (e.g., Canada and Japan) implemented enhanced Fujita scales tailored to their typical building structures. Nevertheless, the F-scale radically transformed the way that tornado climatology was interpreted. The NWS adopted it as an official method of describing tornadoes in the mid-1970s, beginning with a small experiment and then as a national effort. Collectors of tornado data in other countries used or adapted it to local practice or used a similar concept. Despite the limitations inherent in the methodology (differences in wind speed compared to differences in construction, how much of the tornado interacted with any structure, etc.), many aspects of the statistics of tornadoes rated on the F-scale show consistency in time and space (Brooks and Doswell 2001b). Given that the majority of casualties occur with higher-rated and, presumably, stronger tornadoes, it also helped guide research and forecasting efforts by providing a way to stratify events when looking at environmental conditions (Rasmussen and Blanchard 1998; Craven and Brooks 2004).

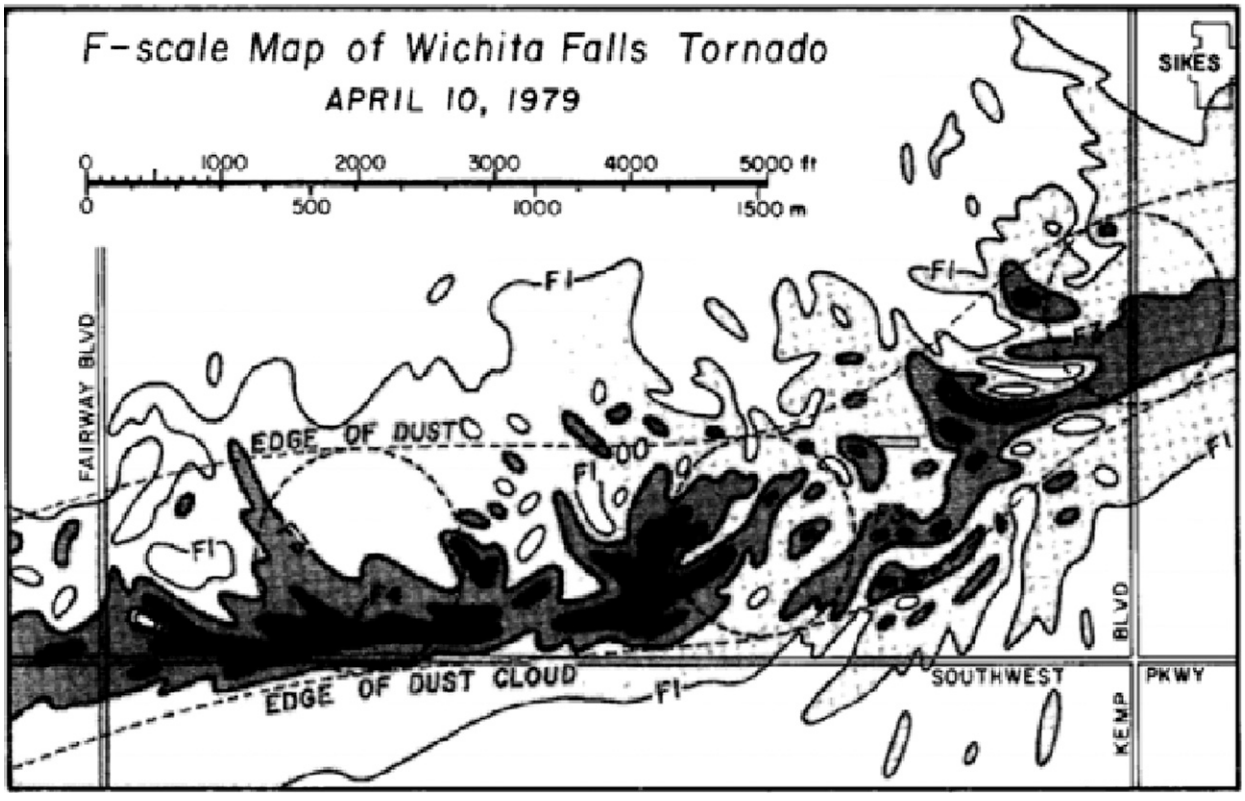

FIG. 18-7. Contours of F-scale as analyzed by Fujita (1981) for part of the Wichita Falls tornado of 10 Apr 1979. Edge of dust cloud is shown by dashed lines.

In the aftermath of commercial aviation disasters stemming from aircraft encounters with thunderstorms, Fujita turned his attention to winds produced by thunderstorms (Fujita and Byers 1977), in an echo of the original basis of the Thunderstorm Project, which had indirectly led to him coming to the United States. In surveying the damage pattern associated with winds in nontornadic thunderstorms, Fujita identified a "starburst" pattern in the damage with what he dubbed a "microburst," where strong, small-scale downdrafts encountered the ground and outflow spread out along the ground in all directions (Fig. 18-8**)**. A plane at low altitude encountering such an event would experience strong headwinds and, hence, enhanced lift, followed soon after by strong tailwinds and reduced lift. If the pilot had not avoided the area and was not prepared for those changes, the immediate reaction to reduce power when the added lift was encountered frequently led to disaster when the plane reached the tailwind. Fujita's work describing microbursts led to a number of field projects in a variety of geographic and atmospheric settings, such as NIMROD (Northern Illinois Meteorological Research on Downburst) in northern Illinois (Fujita and Wakimoto 1982), JAWS (Joint Airport Weather Studies) in Colorado (McCarthy et al. 1982), and MIST (Microburst and Severe Thunderstorm) in northern Alabama (Atkins and Wakimoto 1991). The projects led to dramatic improvements in pilot training, leading to improved aviation safety. Thunderstorm outflow was not the first time Fujita had encountered the starburst damage pattern. He had first seen it in the damage from the atomic bombs at Hiroshima and Nagasaki in 1945, which could be considered his first damage surveys.

5. Improved remote sensing and observations from the field lead to numerical modeling and forecasting improvements

In addition to the work of Fawbush and Miller in the 1950s, the National Severe Storms Project began in 1953 with the forerunners of the NWS Storm Prediction Center (SPC) and the National Severe Storms Laboratory (NSSL) forecasting and carrying out research, respectively. The research activities included the earliest dedicated storm observation activities, using aircraft and radar. Taking observers to the storm and using radar to look at the same storms would be a hallmark of activities associated with NSSL since then, which led to larger community involvement in those projects through the decades. In the

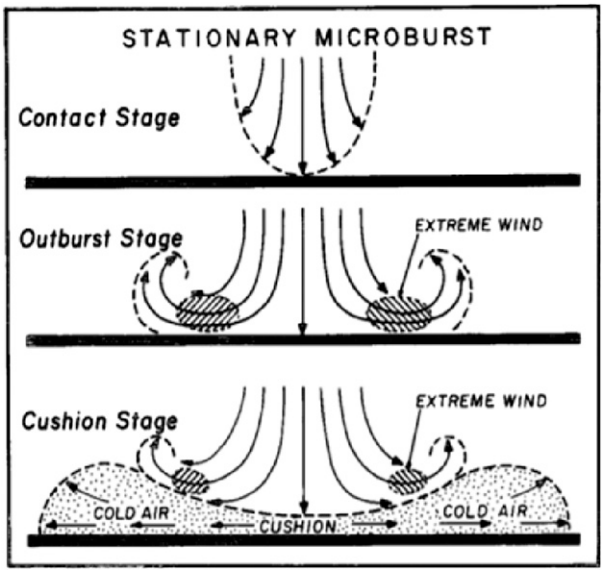

FIG. 18-8. Schematic of evolution of downburst, showing development of regions of strong horizontal winds near ground [from Fujita (1981)]. Arrows indicate direction of airflow and hatched areas indicate strongest winds. Dotted area is cold air that sometimes prevents future downdrafts from reaching the ground.

early 1970s, coordinated observations of tornadic thunderstorms from two Doppler radars with field teams collecting observations led to a clearer understanding of the relationship between the rotation within the parent thunderstorm and the development of tornadoes, with a parent circulation seen near the tip of the hook echo prior to the tornado (Brown et al. 1975). This combination of observations began a two-decade-long effort to identify radar observations that could be used to help NWS operational forecasters issue useful tornado warnings well before tornadoes formed. In particular, the field observation campaigns helped set the standards by which the WSR-88D Doppler radar network was developed and deployed across the United States in the early 1990s. In passing, it is not a coincidence that one of the leaders of the campaigns participating in data collection in the field was Robert Davies-Jones, whose theoretical contributions to understanding thunderstorm rotation have been noted.

At about the same time as the field projects began operating as part of the National Severe Storms Project in the United States, hail became the focus of study for two projects lasting nearly 30 years in Alberta, Canada. The first, the Alberta Hail Studies, ran from 1956 to 1973 and was a joint effort of a number of organizations in Canada, including Marshall's Stormy Weather Group at McGill (Strong et al. 2007). The project investigated the physics of hail and thunderstorm dynamics using a circularly polarized radar (McCormick and Hendry 1975), upper-air observations, stereo-pair time-lapse movies, hail reporting cards, and even mobile hail collection vehicles (Fig. 18-9**)**. Area farmers provided information about the hail that fell and mobile hail collection vehicles penetrated storms to collect observations of hail. The Alberta Hail Project continued this work until 1985 after the end of the Hail

FIG. 18-9. Alberta Hail Project storm vehicle circa 1969–70 (courtesy of Dejan Ristic; D. Ristic, B. Wesley, and G. Isaac are pictured from left to right).

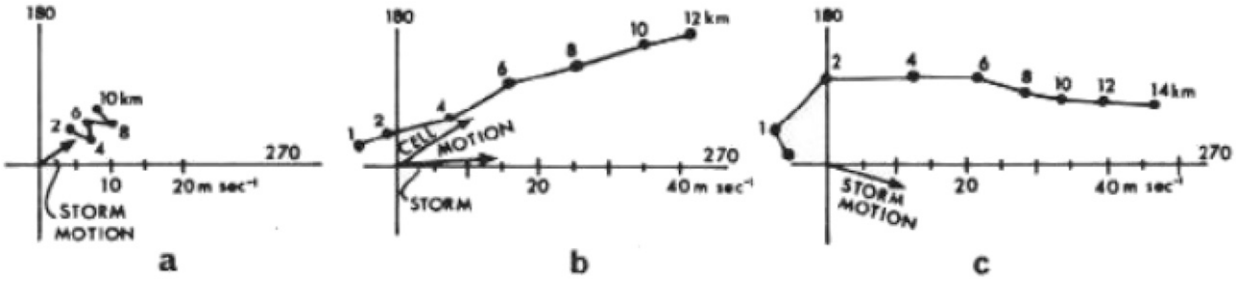

FIG. 18-10. Typical hodographs for severe thunderstorms observed during the Alberta Hail Project [from Chisholm and Renick (1972)]: (a) single cell, (b) multicell, and (c) supercell. Heights in the atmosphere above ground are indicated along the hodograph. Storm motions shown by arrows.

Studies. The large amount of data collected provided a wide array of information on the growth of hail within storms and the environments in which hailstorms formed, dovetailing with the work carried out in eastern Colorado as part of the Cooperative Convective Precipitation Experiment (Knight 1982). Chisholm and Renick (1972) identified characteristic wind profiles for idealized conceptual models of single-cell, multicell, and supercell thunderstorms (Fig. 18-10**)**. In particular, they found that, while thermodynamic instability was necessary for convective storms to form, the structure of those storms was largely determined by the wind profile in the environment. Relatively weak single-cell storms formed when there was little wind shear. These storms were typically short-lived. More persistent convection required higher values of wind shear. So-called multicell storms consisted of a series of single cells that moved in a direction relatively near the hodograph with the hodographs being straight. In contrast, supercell storm environments were characterized by strong shear, with the winds veering with height in the lowest few kilometers of the environment. On radar, supercells had the appearance of being a single, persistent cell, potentially lasting for hours.

At about the same time, efforts to understand hail in Russia were taking place. The first climatology of hail was presented by Pastukh and Sokhrina (1957). The statistical properties of the distribution of hail size were derived by Abshaev and Chepovskaya (1966). Radar observations of hailstorms were used to construct composite schematics of the supercell hail process by Abshaev (see Fig. 18-11) and Abshaev (1982) developed techniques to identify hail from radar, which allowed one to describe the characteristics of hail swaths. Satellite methods for the detection of hail were derived for a variety of satellite platforms (Bukharov 1991; Bukharov and Alekseeva 2004; Alekseeva et al. 2006). A slice-method technique to calculate instability (Bjerknes 1938) was used for hail forecasting (Shishkin 1961; Sulakvelidze et al. 1970).

The problem of hail also featured in research from South America. Zipser et al. (2006) identified northern Argentina through southern Brazil as having the strongest convective cores on the planet based on satellite data. Decades before that, severe convection in the region of the La Plata basin was the focus of Argentinian research. Some of the first studies were motivated by initiatives seeking to mitigate hail impact over crops (Saluzzi and Nuñez 1975), most notably, wineries in the Mendoza Province in the Andes foothills of far western Argentina (e.g., Grandoso and Iribarne 1963; Grandoso 1966; Grandoso and Cantilo 1968; Nicolini and Norte 1978, 1979a,b, 1980; Ghidella de Hurtis and Saluzzi 1980; Norte 1982; Saluzzi 1983). Based on the review by Grandoso and Cantilo (1968), it was already known that hailstorms in the Andes foothills of Argentina occurred more frequently in the midsummer months and that these storms could reach maturity within a rather broad time interval between the early afternoon and late night hours (Grandoso 1966). These are, essentially, the same findings described for that region in more recent climatological studies, such as by Romatschke and Houze (2010) and Rasmussen et al. (2014).

In a joint project between academic researchers, operational forecasters, and agricultural interests, Grandoso and Cantilo (1968) studied the behavior of typical summer convective storms in the Mendoza region monitored by radar, a surface mesonetwork composed of 14 stations, and one rawinsonde station. Several aspects of the storms were documented, including the prevailing synoptic forcing (classified as weak or strong); environmental hodographs and convective instability; storm initiation, motion, organization, and new cell development; characterization of storm mergers; and the formation and evolution of surface cold pools. Based on radar and visual observations, Grandoso and Cantilo (1968) acknowledged the topography as an important mechanism for storm initiation, and, with surface and upper air observations, described that the combined presence of a lee cyclone along the eastern foothills of the Andes and northwesterly flow "aloft" (referring, in fact, to lower-tropospheric winds) was a typical pattern observed during the storm season.

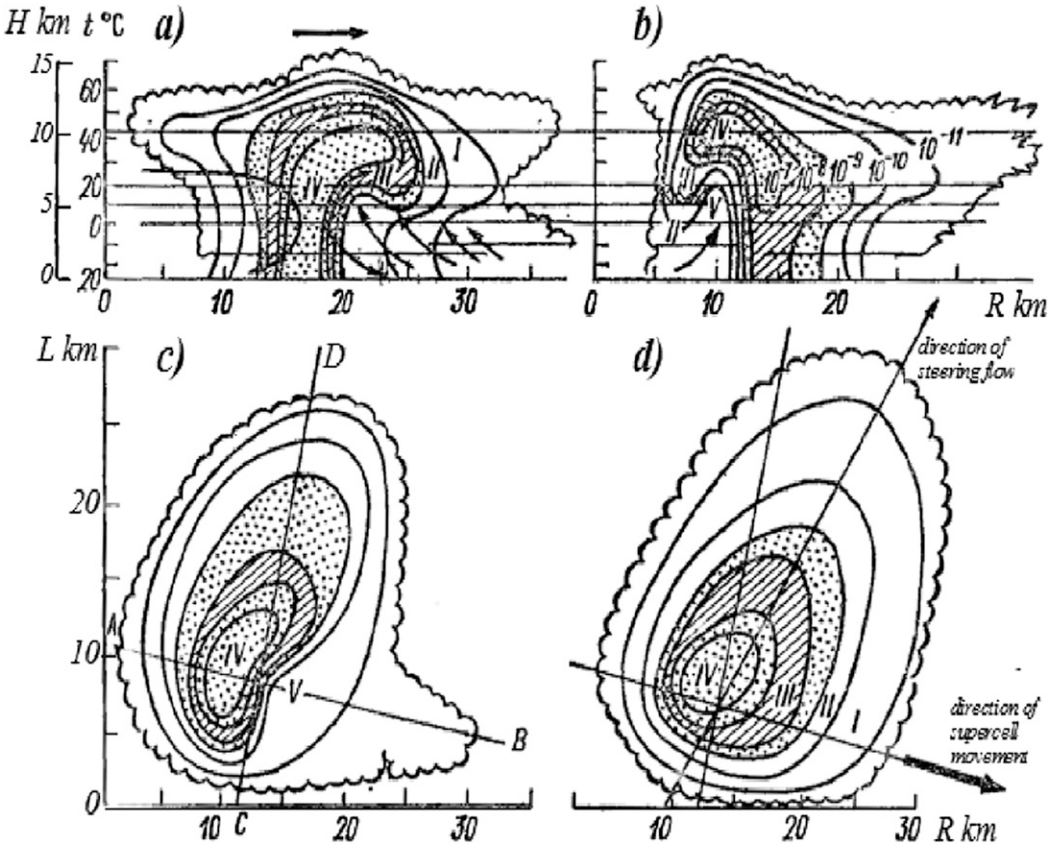

FIG. 18-11. Russian schematic of a supercell hailstorm based on radar observations. (a) Vertical profile AB (in the direction of storm movement), (b) vertical profile along CD (perpendicular to storm movement), (c) horizontal profile at 5-km height ($T = -6$°C), and (d) horizontal profile at 6-km height ($T = -12$°C); I–area of hail formation, II–area of hail initiation, III–area of hail growth, IV–area of maximum hail, and V–area of strong updraft. [Adapted from Abshaev et al. (1980).]

From the mid-1970s to the early 1980s, a series of annual field projects led to studies published by Matilde Nicolini and Federico Norte, combining observations from a radar located in northern Mendoza Province, a local network of rain gauges, hailpads, rawinsondes (launches performed at 0000, 1200, and 1800 UTC), the surface synoptic network from the Argentinean Meteorological Service, and hail reports. They investigated the preconvective environments and storm behavior in the Mendoza Province, and transferred this knowledge into operational procedures to predict severe hailstorms (Nicolini and Norte 1978, 1979a,b, 1980; Norte 1980, 1982). Their contribution included a storm classification that followed previous studies (e.g., Marwitz 1972) but was modified to combine information about convective mode and environmental hodographs. The classifications were ordinary cells (or unorganized multicells; OR), associated with short ''chaotic'' hodographs; organized multicells under straight long hodographs (MO); organized multicells with curved hodographs displaying clockwise turning of the shear at low levels (MO^{+}); supercells with low-level inflow coming from the right of the storm (SC^{D}); and supercells with low-level inflow coming from the left of the storm (SC; which they also called ''orthodox supercells'' for being the most expected behavior for supercells in the Southern Hemisphere).

From the compilation of their findings, Nicolini and Norte (1979b, 1980) described a step-by-step operational procedure for severe hailstorm forecasting that was strongly based on a quantitative analysis of hodographs and thermodynamic profiles, with the goal of predicting the most probable convective mode, and thus, the likelihood of hail occurrence. They attempted to utilize a one-dimensional cloud model to aid the prediction of liquid water content and vertical velocities in the convective storms, which used an observed thermodynamic profile as input (Ghidella de Hurtis and Saluzzi 1979, 1980). Output from this model was employed in the work by Nicolini and Norte to help assess storm severity.

The earliest known tornado report in Argentina is from 16 September 1816, in the Province of Buenos Aires (Schwarzkopf 1984), while the 20 September 1926 Encarnación tornado in extreme southern Paraguay (which is believed to have reached F5 intensity; Schwarzkopf and Rosso 1993) was the first occurrence of a catastrophic tornado in the La Plata basin for which videos of the damage are available.[3] The scientific documentation of La Plata basin tornadoes began in the early 1970s with the work led by Schwarzkopf (1984) in Argentina, and in the late 1980s in southern and southeastern Brazil. However, as pointed out by Silva Dias (2011), there is at least one much earlier description in the scientific literature of a severe weather event that occurred in southern Brazil (in October 1927) that could had been associated with a tornado, by de Sampaio Ferraz (1927): ''A destructive whirlwind swept over Ponta Grossa, in Parana, with tornado effects, which fact is of very rare occurrence in Brazil.'' It would take several decades for the inaccurate notion that tornadoes represent a ''very rare occurrence in Brazil'' to be corrected.

In the La Plata basin, the first known photograph of a tornado dates from 1912 in Argentina and was reproduced in the 1984 issue of the annual (sometimes biannual) bulletin named *Tormentas Severas y Tornados* (Spanish for ''Severe Thunderstorms and Tornadoes'' and hereafter referred to as TSyT) edited under Schwarzkopf's supervision. The TSyT bulletins were published regularly from 1982 to 1994 in the scope of a scientific project entitled *Estudio de los Tornados en la Republica Argentina* (''Study of Tornadoes in the Argentinean Republic'', in a free translation) that had Schwarzkopf, then at the University of Buenos Aires, as the principal investigator. Each TSyT issue contained information regarding all (known) episodes of tornadoes and other convectively induced damaging winds that occurred in Argentina, following a format somewhat similar to that of ''Storm Data'' from the U.S. National Climatic Data Center. Damage assessment of all events was conducted in person by Schwarzkopf and her damage survey team, who adopted the Fujita scale in 1971 (Schwarzkopf and Rosso 1993).

The first publication addressing the atmospheric conditions accompanying a tornado (or, more accurately, the occurrence of a tornado-like vortex) in Brazil was conducted by José Soares Lima, then chief meteorologist of the Brazilian Air Force. His study (Lima 1982) was motivated by the photographic documentation of a funnel cloud near Santa Maria Air Force Base in southern Brazil several years earlier. In that sense, it is impossible not to notice a somewhat similar unfolding of circumstances to that involving Fawbush and Miller several decades earlier in the United States. In fact, building on forecasting procedures followed by the Meteorological Service of the U.S. Air Force pioneered by Fawbush and Miller, Lima based his analysis mainly on atmospheric profiles obtained from nearby upper air soundings. He proposed a procedure, adapted to southern Brazil, for identifying sectors favorable for severe convective weather that followed the general concept of ingredients-based forecasting. However, because tornadoes were considered exceptionally rare events then, his study remained mostly unnoticed from the operational meteorology community of Brazil.

China, in large part as a result of nearly continuous conflict and upheaval into the mid-1970s, was relatively slow to begin meteorological research into convective hazards. However, China provides excellent examples of how a few significant events can lead to a research emphasis on hazards. Lei et al. (1978) described the hail threat in China and Tao et al. (1979) and Tao (1980) documented heavy rainfall events. In the early 1980s, remarkable advances in observational capabilities were made. An experimental array of 21 radars in eastern China tested the ability to produce short-term warnings (0–6 h) in 1980–82. The test proved successful and the network went operational in 1983. Soon after, other regional networks were installed, many of them focused on specific regional threats, such as those to ships from thunderstorm winds in the Pearl River basin. By 1985, the surface observation network had a spacing of approximately 50 km and grew to over 2500 sites. The observational platforms led to a series of field projects and improved the monitoring of severe convective weather. China did not launch a weather satellite until 1997, but it was immediately part of the mix of observations.

As geostationary satellites began to employ relatively high-resolution sensors, the use of time-lapse movies made from geostationary images became commonplace in the diagnosis and forecasting of convective storms. Among the early results of using infrared remote sensing was the ability to follow the life cycle of large groups of thunderstorms. Maddox (1980) used these observations to identify and understand the processes associated with mesoscale convective systems (MCSs), beginning with the class of MCSs referred to as mesoscale convective complexes (MCCs). MCCs were defined originally by Maddox in terms of the geostationary satellite observations to be MCSs which satisfied several criteria in terms of the size, duration, and circularity of the storm anvils. Maddox described a simple conceptual model of MCCs, including the conditions in which MCCs formed, matured, and dissipated, although many aspects of those conditions

[3] Photographs and original footage of the damage are at www.youtube.com/watch?v=K_ioM4fuiD8.

awaited further research to understand. Typically occurring in the late spring or summer, a group of individual thunderstorms would form in a region with conditions favorable for storms and, in the course of their individual life cycles, would produce outflow associated with evaporating rain. The outflows would help initiate new storms and, on some occasions, the collective outflow from the system could form a mesohigh associated that would initiate new convection over a broad area, leading to rapid upscale growth of the convection to larger sizes. The convective system would then become self-sustaining until it moved into an area lacking in the warm, moist, boundary layer air needed for new storms. Following the recognition that MCSs can produce significant severe weather (winds, hail, and tornadoes), they became the topic of extensive research, some of which had the goal of improving the forecasts of such systems (e.g., Maddox 1983; Chappell 1986; Fritsch et al. 1986; Laing and Fritsch 1997, 2000; Fritsch and Forbes 2001).

As with the microburst field projects, over the years, field projects were designed and carried out to address aspects of MCSs [e.g., Oklahoma–Kansas Preliminary Regional Experiment for STORM-Central (PRESTORM; Cunning 1986), International H_2O Project (IHOP_2002; Weckwerth et al. 2004), Bow Echo and MCV Experiment (BAMEX; Davis et al. 2004), the Mesoscale Predictability Experiment (MPEX; Weisman et al. 2015), and the Plains Elevated Convection at Night field project (PECAN; Geerts et al. 2017)]. Because of the size and movement of the MCSs, these were necessarily extremely large in geographic extent.

Most MCSs, included the subclass of MCCs, were associated with severe weather in one or more forms, including the production of heavy rainfall with the potential to create flash flooding. Although heavy rainfall associated with a thunderstorm does not officially make the storm severe in the United States, many nations around the world classify it as severe and have defined threshold criteria for what is a dangerous rainfall.

With their work on MCSs well underway, the group at NOAA's Applied Physics and Chemistry Laboratory (APCL) in Boulder, Colorado, was stimulated to study the meteorology of heavy rainfall when the flash flood in Big Thompson Canyon, Colorado, occurred near their office on 31 July 1976, with 143 deaths. This event was preceded by another tragic flood disaster in Rapid City, South Dakota, that left 238 dead. Both of these floods occurred with relatively small areas of extremely heavy rain occurring in a small basin in mountainous terrain, and neither was well forecast (Maddox et al. 1978).

This research program led not only to many publications (e.g., Caracena and Fritsch 1983; Maddox et al. 1980) in scientific journals, but APCL was asked by NOAA's

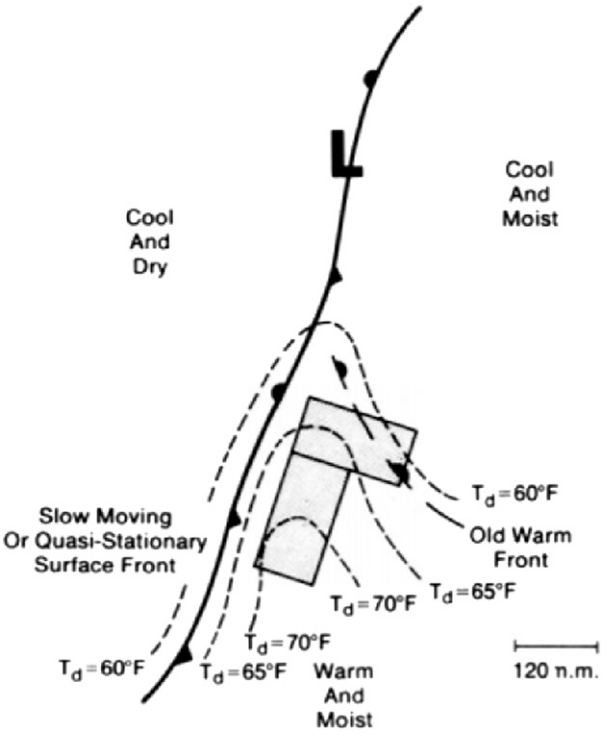

FIG. 18-12. Composite chart showing favorable pattern for development of heavy rain for a synoptically driven event. Heavy rain potential is in shaded boxes. [From Maddox et al. (1979).]

National Weather Service to help create a training program to make forecasters more aware of the ingredients leading to flash flood potential. APCL [later the Weather Research Project (WRP)] scientists were given two days out of a 2-week Flash Flood Forecasting Course (FFFC) for NWS forecasters. This effort was led by APCL's Robert Maddox, with several others also teaching the FFFC occasionally (Drs. C.F. Chappell, C.A. Doswell III, and H.E Brooks). The original APCL team working on the topic of flash floods included Drs. R. A. Maddox, C. F. Chappell, J. M. Fritsch, F. Caracena, and L. R. Hoxit. During the course, it was evident that the forecasters had many gaps in their general understanding of deep moist convection (Doswell and Maddox 1996), so a considerable effort was made to fill those gaps as effectively as possible.

To help forecasters better anticipate potential flash floods, conceptual models of flash flood producing storms were developed to aid in recognition of dangerous weather patterns (Fig. 18-12) (Maddox et al. 1979). Later, it was recognized that some events do not fit within the set of conceptual models, and a new approach to flash flood forecasting was proposed by Doswell et al. (1996), based on monitoring the evolution and potential concatenation of the ingredients necessary for heavy rainfall: low-level moisture, midlevel potential

instability, and lift. It is perhaps one measure of the overall success of the training program that in the years since the Big Thompson tragedy, nontropical storms have not resulted in any events producing 100 fatalities or more (excluding tropical cyclone–produced events such as Katrina in August 2005). A component of the research leading to this improved forecasting was the recognition that forecasters must anticipate such events, but weather patterns resulting in flash flood events can at times be only subtly different from similar ones on previous days when little or no flooding occurred. When convective storms develop unexpectedly and with considerable power, it is typical for forecasters to spend time trying to understand the events they failed to anticipate. Given convective time scales on the order of 20 min or so, events can develop rapidly while forecasters are struggling to diagnose the weather situation. People can be in danger before the forecaster has figured out what is going on. Anticipation is critical if the event is to be handled well. It was also found during the course of the research that in the age of workstations and computer displays, many forecasters have lost familiarity with the observations (Doswell and Maddox 1996). A forecaster should be able to recognize when, for example, a 75°F dewpoint temperature ahead of an advancing short-wave trough in the convective season is unusual.

Many flash flood events are associated with ''training'' storms—a process by which storms form repeatedly in a particular location and then pass in succession over the same locations, resulting in locations being in the core of heavy precipitation multiple times and for long durations. Flash floods can occur in other situations, including persistent upslope flow of moist, unstably stratified air. The danger posed by such events is that steep terrain can magnify the intensity of the runoff from precipitation.

The development of Doppler radar, with its ability to observe velocity toward and away from the radar, changed the way that researchers and, eventually, forecasters could look at severe thunderstorms. The first Doppler radar used regularly in forecast operations was located at King City, Ontario (Crozier et al. 1991). The radar was the basis for the development of many techniques, including operational automated volume scanning and processing, and the transmission of radar images to a remote forecast office, so that forecasters did not have to be collocated with the radar. It served as the prototype for the Canadian radar network that was installed by 2003.

The observational work that was being done at NSSL on Doppler radar with field teams led to the Joint Doppler Operational Project (JDOP), beginning in 1976 (Burgess et al. 1979), which tested the potential for the use of Doppler radar in severe thunderstorm and tornado warning situations. This successful test led the way for the WSR-88D (Weather Surveillance Radar-1988 Doppler) operational radar network that would be installed around the United States in the 1990s. During the 1980s, other projects tested additional aspects of the design of the radars and network. This pattern of testing new radar technologies leading to operational deployment was repeated in the early 2000s with the Joint Polarization Experiment (JPOLE) that investigated the use of dual-polarization radar, particularly with respect to precipitation amount and type (Ryzhkov et al. 2005; Scharfenberg et al. 2005).

In the mid-1970s, as Doppler radar began to show features of severe storms in ways that conventional radar could not, computing power had advanced to a point where three-dimensional numerical models that resolved some of the important features of severe thunderstorms could be developed (Klemp and Wilhelmson 1978). Early simulations showed that relatively complex behavior in observed storms (storm splitting, movement that differed from the mean wind flow) could be produced with a single environmental vertical profile of temperature, humidity, and horizontal winds and storm initialized crudely with a warm bubble of air (Wilhelmson and Klemp 1978). The verisimilitude with observed storms, such as the 3 April 1964 event (Wilhelmson and Klemp 1981; see Fig. 18-13), encouraged the development of parameter-space studies with idealized initial conditions that could be controlled and varied to study the impact of changes in the environment. Weisman and Klemp (1982, 1984) showed the importance of strong vertical wind shear in the development of rotating thunderstorms. These computational proximity sounding studies could be compared to observed proximity sounding studies and led to better understanding for forecasting. The ability of numerical models to calculate full three-dimensional fields of all variables and, hence, calculate budgets for physical processes was invaluable in improving our understanding of how storms work. A particularly important example of this latter approach was an explanation for why storms move in a direction off of the environmental wind profile. Rotunno and Klemp (1982) evaluated terms that contributed to the buoyancy and pressure fields in simulated storms in both straight and curved hodographs. Even in the straight hodograph case, storms split and moved off of the hodograph because of perturbation pressure forces that created vertical motion on the side of the parent storm, and subsequent propagation in that direction, a nonlinear process. Storms in environments veered with height had the storm that moved to the right of the hodograph enhanced by linear effects. This provided a physical explanation for the empirical work of Maddox (1976), which had used proximity soundings to show the tendency of tornadic storms to move to the right of the mean wind profile, providing a basis for predicting severe storm motion. Decades later, Bunkers et al. (2000) would improve upon that technique by utilizing the

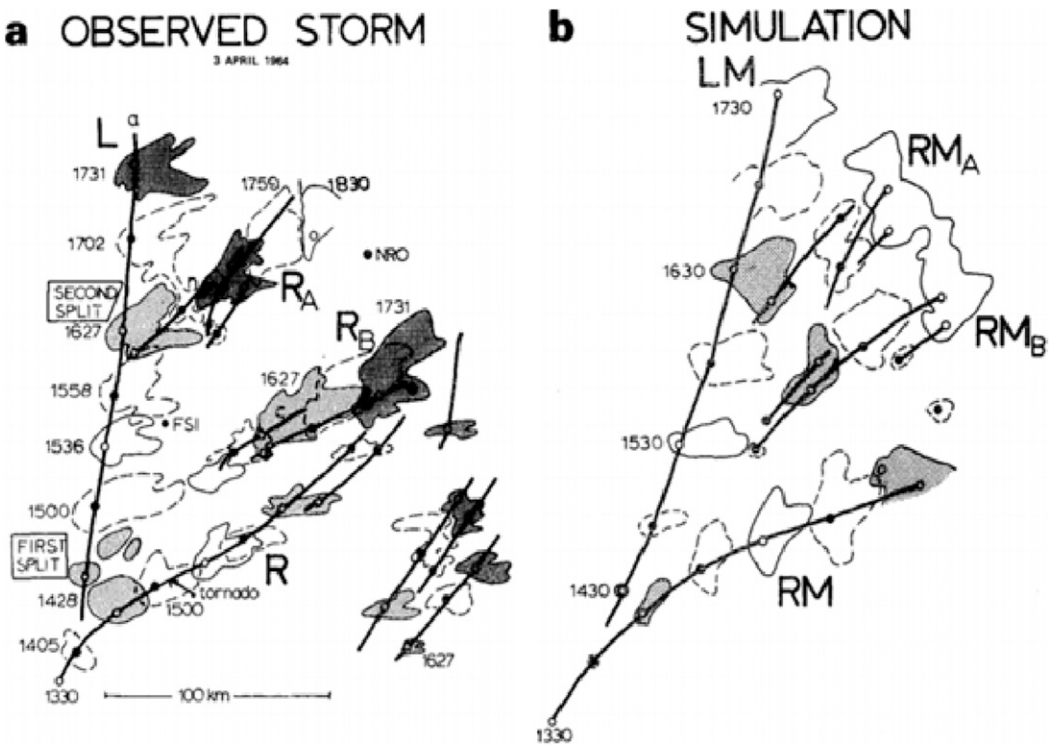

FIG. 18-13. Comparison of observed (3 Apr 1964) and simulated evolution of thunderstorms with multiple splits, shapes indicate radar echoes at various times; L or LM indicates left-moving storm from a split, R or RM are right-moving storms. Lines indicate various storm motions. [From Wilhelmson and Klemp (1981).]

theoretical understanding to guide a larger proximity sounding study for storm motion.

Perhaps one of the seminal works that highlights the combination of field and radar observations, constrained by theoretical considerations and understanding of flow fields within storms for the purpose of improving forecasts, is the schematic of a supercell thunderstorm including a tornado developed by Lemon and Doswell (1979; Fig. 18-14). It synthesized a wide variety of data about storms and was a useful guide for both researchers and forecasters to interpret observations and to point to the need for further observations that could answer remaining important questions about tornadic storms. The schematic identified the significant flow features within the supercell in the context of the precipitation region, with a strong persistent updraft and two downdraft areas, one in the forward flank of the storm ahead of the updraft, as viewed from the moving storm, and one in the rear flank. It also used an analogy with larger-scale midlatitude cyclonic systems to suggest that baroclinic processes were likely to be responsible for the development of the parent rotation from which tornadoes eventually develop, although the thermodynamic observations were insufficient to quantify those processes at the time, and whose collection required future field projects. The paper can be viewed as a significant piece of stand-alone research, but it is significant that it was carried out by people working in a unit that directly did research in support of improved forecasts. The work was not done purely for research purposes, but rather was directed toward improved service via forecasting.

The advances in radar observation tools, particularly the ability to retrieve flow fields from multiple Doppler radar observations, and numerical models led to significant advances from theoreticians in the early to mid-1980s. Most significantly, the motion and origins of the rotation in updrafts in supercell thunderstorms and their relationship to the wind profile in the environment was a subject of great interest. The outcomes of these efforts improved the understanding of the dynamics of supercells and, as a result, led to advancements in forecasting of them. Once again, the theoretical work laid the groundwork for improved forecasting and warning of thunderstorm hazards. In addition, the greater understanding of updraft rotation led to a new emphasis on the origin of rotation at low levels within storms. A primary application of this work was to improve understanding of the "tornado/no-tornado" question for severe thunderstorms. Cloud models had become sufficiently sophisticated and the computational resources reached the point that relatively large parameter-space studies could be carried out with detailed kinematic and

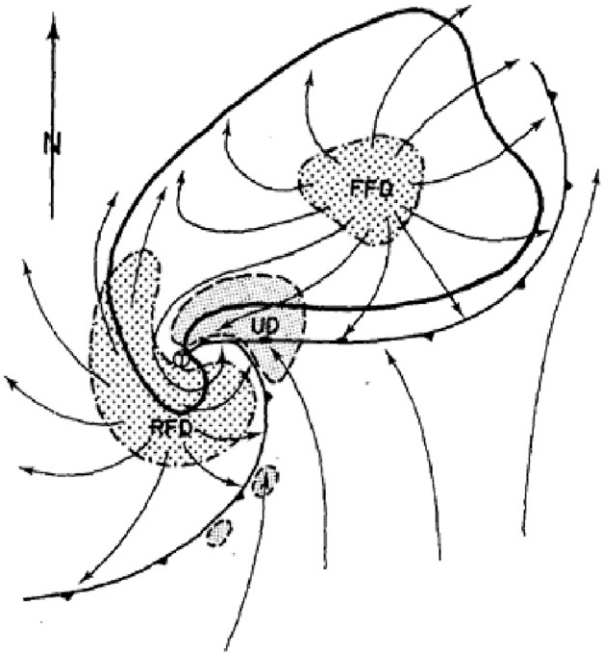

FIG. 18-14. Schematic of a supercell thunderstorm, showing rain region (heavy black line), areas of forward (F) and rear (R) flank downdrafts (FD), updraft (UD), horizontal wind flow (light arrows), and pseudo cold fronts associated with outflow. [From Lemon and Doswell (1979).]

dynamic analyses. The ability to carry out these analyses allowed theoreticians to perform more sophisticated examinations of the evolving fluid flow, including the evolution of the initial rotation to create low-level mesocyclones by tilting of vorticity in downdrafts near the ground in tornadic thunderstorms (Davies-Jones and Brooks 1993).

Another topic of great interest was the threat to aviation from microburst winds. Fujita and Byers (1977) had identified microbursts in association with aircraft accidents. Droegemeier and Wilhelmson (1985) and Proctor (1988) modeled downdrafts from thunderstorms and the associated outflow. The conceptual models developed in conjunction with observations led to improved forecasts and training for pilots, dramatically lowering the number of commercial aircraft accidents in thunderstorms.

By the early 1990s, high-resolution models had become sophisticated enough for the first experimental forecasts, rather than just simulations of previous events, to be performed. The Center for the Analysis and Prediction of Storms (CAPS) was founded with the ambitious goal of explicitly forecasting thunderstorms (Lilly 1990). It took years of model development and work on initialization to make the concept begin to work and, even then, uncertainty made the notion of explicit forecasting questionable, but their efforts over nearly three decades have been invaluable in the field. The first crude real-time forecast experiment using high-resolution models was STORMTIPE (Storm Type Operational Research Model Test Including Predictability Evaluation) in 1991 (Brooks et al. 1993). In conjunction with an ongoing field project, experiment forecasters were asked to produce an estimate of the most favorable conditions that could reasonably be expected that day and the corresponding sounding data were used to initialize a model with horizontally homogeneous initial conditions and a warm bubble. The results were mixed, but the use of human-created soundings to initialize a model foreshadowed the use of large-scale numerical model-generated soundings in the future.

The combination of all the advances of the 1970s and 1980s led researchers from a variety of subdisciplines to recognize shortcomings in our understanding of tornadoes and, perhaps as importantly, to ask detailed questions and propose the observations necessary to answer those questions. There was a realization that, because of the relative rarity of severe thunderstorms at any particular location and the challenges of obtaining observations near the ground, fixed-base observations of tornadoes were limited by extremely small sample sizes and, thus, it was necessary to take observation systems to the storms. This led to what was, at the time, the largest and most sophisticated field project to study tornadoes, the Verification of the Origin of Tornadoes Experiment (VORTEX), held in 1994 and 1995 in the U.S. plains region (Rasmussen et al. 1994). What set VORTEX apart from previous field projects was the creation of dramatically more sophisticated field observation instruments and the ability to coordinate large numbers of vehicles in a mobile mesonet (Straka et al. 1996) in the field to collect high-quality measurements in the vicinity of a single thunderstorm. As a result, fields of thermodynamic and dynamic variables could be determined around the storm. Although the number of storms observed in detail during VORTEX was still relatively small, the data collected led to major breakthroughs in many areas, particularly so-called failure modes describing why rotating thunderstorms failed to produce tornadoes. Within a short period of time, some of these failure modes and how to identify them had been incorporated into warning decision training for forecasters, improving the quality of tornado warnings issued operationally.

VORTEX also marked the debut of mobile Doppler radars that could go out to storms and interrogate the lowest levels. The ability to take radars into the field for observations was a relatively new technological capability at the time. Bluestein et al. (1993) detailed the use of portable radars that were taken into the field and set up to collect information on supercells. By the second year of VORTEX, more powerful and versatile scanning radars mounted on the backs of trucks were taken into the field and provided close-range observations of

tornadoes (Wurman and Gill 2000). Bluestein and Wakimoto (2003) provide a review of the early development and use of a variety of radars taken into the field.

VORTEX also continued a tradition associated with field projects over the decades of coincident forecast experiments, testing new ideas and ways to communicate forecast information. It took place when the results of the first crude efforts to use thunderstorm-resolving models as real-time forecast tools had been published. It also brought research scientists and operational weather forecasters together to make and use the forecasts. Hallmarks of such forecast experiments were the exposure of forecasters to current research and the exposure of researchers to challenges that forecasters faced, frequently leading to new research avenues.

Although there were a number of links between the research and operational forecasting communities, the physical separation of the national forecasting operations [now the Storm Prediction Center (SPC)] from the national research facility (NSSL) was a limitation to the relationship. In particular, VORTEX, which involved a number of the forecasters, highlighted the potential and efforts began to collocate the two agencies, resulting in the SPC moving from Kansas City to Norman in 1997, along with the creation of a research group within NSSL dedicated to working with the SPC. From the earliest days of the collocation, forecast experiments involving the SPC, NSSL, and outside visitors have led to improvements in operational practice and research discoveries. For much of that time, the focus has been on the use and interpretation of high-resolution numerical models that might be used in operations in the near future. By exposing the two cultures of forecasting and research to each other, forecasters were better equipped to take advantage of new ideas and techniques and operationally interested researchers received feedback from forecasters.

Over the years, proximity sounding studies begun in the 1950s grew to have larger numbers of soundings and to use more parameters to make finer distinctions between classes of storms and their threats. Rasmussen and Blanchard (1998) and Craven and Brooks (2004) used large samples to consider which parameters did the best discriminated between deep moist convective threats. Convective available potential energy (CAPE) was good at discriminating between the existence of convection or not and between severe and nonsevere thunderstorms, but measures of wind shear (colloquially, shallow shear referred to the magnitude of the difference in the winds in the environment between the surface and 1 or 3 km, and deep shear raised the upper limit to 6 km) were better at discriminating between tornadic and nontornadic storms. There are likely to be better descriptors of the environment, but these simple bulk parameters work fairly well. Brooks et al. (2003b) and Brooks et al. (2007) extended the concept of proximity soundings to use soundings derived from reanalysis data to give more consistent and complete coverage in time and space, foreshadowing the use of climate model soundings.

Surface observations collected by mobile vehicles during VORTEX and subsequent smaller projects allowed Markowski et al. (2002) to examine the thermodynamic conditions near low-level mesocyclones, some of which produced tornadoes and some of which did not. This work tested hypotheses that had been developed by numerical modeling of conditions needed for strong low-level rotation and found that the observations showed much less cooling than models. It illustrated examples of so-called failure modes in which tornadoes did not occur in supercells despite having low-level mesocyclones (Trapp 1999), allowing for both improved understanding to help forecasters and leading to improved treatment of processes within models, particularly the microphysical parameterizations. It also coupled back with theoretical predictions of baroclinic generation of low-level vorticity in downdrafts (e.g., Davies-Jones and Brooks 1993) to give a more complete picture of tornadogenesis (Markowski and Richardson 2014, 2017). Markowski et al. (2008) used airborne dual-Doppler analyses from VORTEX to compute vortex lines in the low-level downdrafts and infer thermodynamics in the near-ground environment. Their results supported the notion of baroclinic generation of vorticity in downdrafts, but also highlighted the importance of developing systems to collect observations in the near-surface region in supercells, a topic that we will return to later.

The growth of technology and theoretical understanding developed after VORTEX led to an even larger field project in 2009 and 2010, VORTEX2. While VORTEX had had a single mobile radar in the field in the last few weeks of operations, VORTEX2 had an array of mobile radars. Small-scale portable surface observation networks were deployed in advance of storms to collect data in areas that might potentially be dangerous for field teams to operate also were used that complemented the mobile mesonets and radars (Weiss et al. 2015). The increase in ability to communicate and share information led to a much larger operational domain than the original VORTEX and it became a fully mobile field campaign with no fixed base (Wurman et al. 2012).

The constant interplay between observations, theory, and forecasting can be seen again in the work that led to the insertion of radar data into high-resolution numerical models to produce short-range (<3 h) forecasts of severe weather, as illustrated in Dawson et al. (2012; Fig. 18-15). This showed that there was potential to take observations and models to produce short-term forecasts of the potential for tornadoes on spatial scales of a

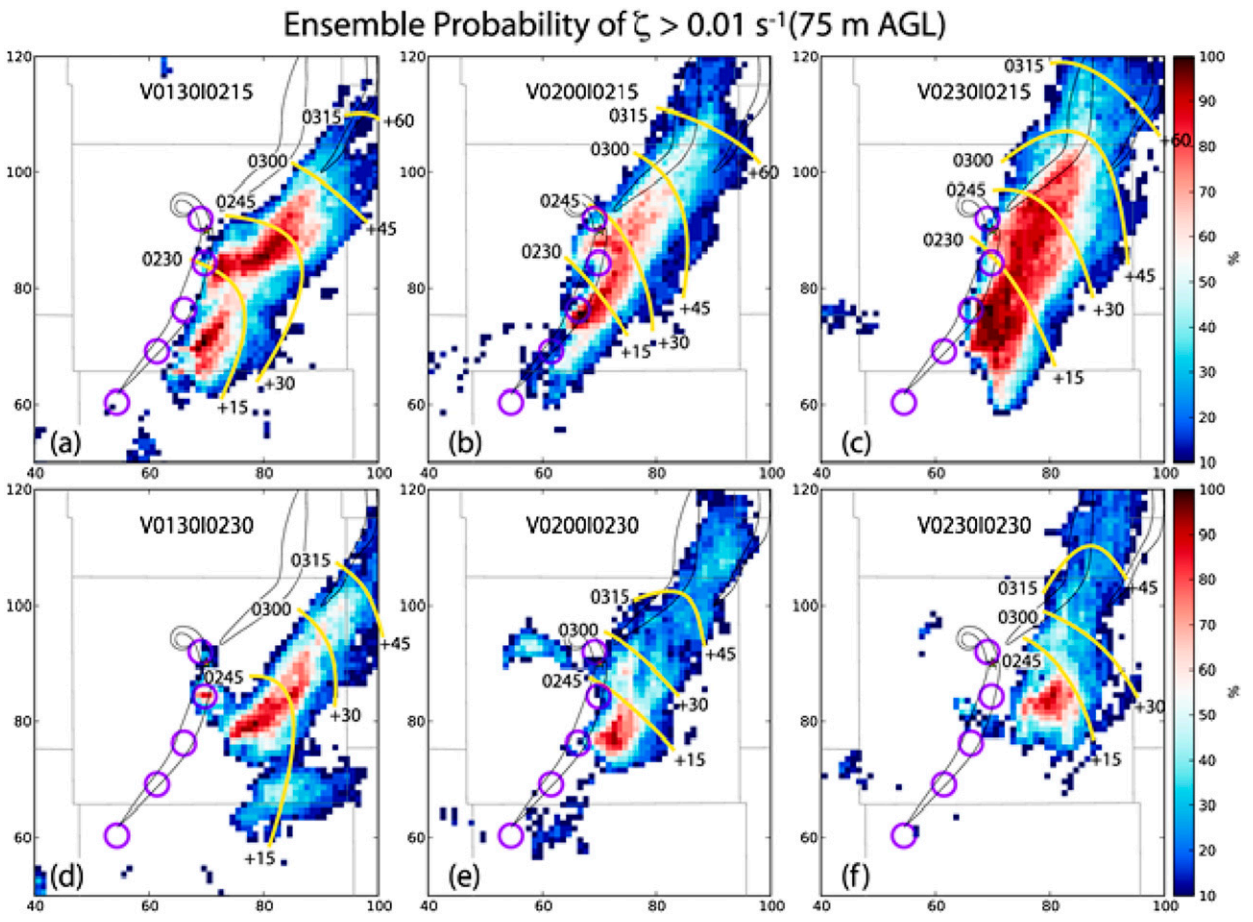

FIG. 18-15. Ensemble probability swaths (color fill) of large values of near-ground vertical vorticity ($\zeta > 0.01\ s^{-1}$) from a set of ensemble simulations of the 4 May 2007 Greensburg, Kansas, tornadic storm. Observed low-level mesocyclone locations are shown with purple circles starting at 0200 UTC in the lower left corner and then every 15 min through 0300 UTC. Tornado tracks are in light black contours. Yellow lines are isochrones of average time that the vorticity threshold was exceeded. The naming convention is that the four digits after the V represents the time of the wind profile used in the model and the four digits after the I represents the initialization time of the model in UTC. [From Dawson et al. (2012).]

few tens of kilometers. In many senses, this work represents the logical progression from the Lemon and Doswell schematic. It built upon years of radar development and numerical modeling and how to use the data most efficiently. It also highlights the focus of much of the research community to operational forecasting applications with a look toward the near to distant future. It requires an increasing understanding of the conditions leading to severe thunderstorms and their behavior, built on the field and radar observations and theoretical research.

6. Working across international boundaries

As was true in many science disciplines, severe thunderstorm researchers tended to work in relative isolation from those in other countries and, frequently, even those in other parts of their own country. Although at times, such as in the cases of Wegener and Fujita, that isolation might be forced by external politics, often it was simply owing to costs and technological barriers to interactions. There are occasions in the first half of the century on which we are focusing when individuals traveled to work in some location or technology was shared, as in the case of the British radars going to Canada, but that was not that common. Only in recent decades has it has become relatively common for international collaborations to take place and information to be shared across borders.

One of the reasons this is important concerns our fundamental understanding of the atmosphere. Consider that we have confidence in ingredients-based forecasting. If the right combination of ingredients comes together, a weather event of interest can occur.

However, there is no reason to believe that there is only one mix of the ingredients or processes that is required for an event. A simple illustration of this is seen in the climatological estimates of tornado occurrence from Krocak and Brooks (2018). The annual and diurnal cycles of tornadoes in the plains of the United States peak within a relatively narrow range of time of day (late afternoon to early evening) and time of year (spring to early summer as one moves northward) when tornadoes are most common. In the southeastern part of the United States, both the annual and diurnal cycles are much flatter with tornadoes more likely in the cool season and overnight compared to the plains. This does not mean that the exact same atmospheric conditions will make a tornado in one region and not in another, but it may mean that combinations of ingredients that can create a tornado come together more or less often in the different regions. If our understanding as a community of what the ingredients necessary are for making a weather event is limited to cases we observe from a small region or short period of time, we may never observe a set of conditions that can also lead to that same weather event. Thus, we always are forced to deal with the question of how much we know about weather is a result of fundamental understanding of the physical processes and how much depends upon the relatively small sample of events we have observed. Expanding our understanding of how the atmosphere works to include other areas expands our basic knowledge. As an example, Brooks et al. (2007) showed that the distribution of convectively important parameters in the cool season in the southeastern United States (typically weak midtropospheric lapse rates that provide more limited instability) resembled the European distribution much more so than the U.S. plains springtime distribution. As a result, they suggested that Europe might be a good model for the cool season tornadoes in the Southeast. This does not mean that the physics of storms in the Southeast and plains regions in the United States are different, but it is likely that the combination of instability with other ingredients come together much more rarely in the plains than in the Southeast cool season or Europe.

Another example of the importance of looking in other parts of the world for comparable events comes from Australia. The incidence of significant tornado impacts on the southwest coast of Australia during the cooler months of the year led to a concerted effort by the Severe Weather Section staff in the Bureau's Perth Office to understand the environmental conditions under which they form. A 10-yr (1987–96) climatology of Australian tornadoes showed that almost half of the reported tornadoes occurred in the cool season, typically along the southwest coast of Western Australia (WA) and southeast coast of South Australia (SA). Since the preferred areas of occurrence of these storms coincide with the most densely populated areas of WA and SA, and include the capital cities of these two states, Perth and Adelaide, there is a significant community need for accurate warnings of these events.

The meteorological conditions for the Australian events were compared with the cool season tornadic events in California (Hanstrum et al. 2002). The characteristics of the environments in each location were found to be similar. In both locations, cool season tornadoes were found to occur in environments with weak to moderate instability but with high values of low-level (0–1 km) shear, typically associated with the passage of strong fronts in the westerlies.

Mexico provides an interesting case study in how, often, relatively resource-limited nations have partnered with relatively resource-rich nations to address needs related to severe convective hazards. As background, in Mexico, the primary severe weather threat comes from flooding and flash flooding as a consequence of heavy rainfall (Mosiño and García 1974; Giddings et al. 2005; Fuchs and Wolff 2011). Indeed, from 2000–15, of the 6174 official disaster declarations, 1404 (22.7%) were associated with flooding, while only 199 (3.2%) were associated with strong thunderstorm winds, hail, or tornadoes (National Risk Atlas 2016). The historical evolution of the Mexican National Weather Service (SMN in Spanish) reflects that risk: the Service was founded in 1901 and, by 1946, it was absorbed into the Secretary of Hydrologic Resources. The forecast and warning systems operated by the SMN have highlighted flood risks since that merger (Celay 1963), particularly so for the agricultural sector; in 1972, responsibility of weather forecasts and warnings moved with the SMN to the Secretariat of Agriculture (SMN 2017). In 1989, a National Water Commission (CONAGUA in Spanish) was established to coordinate all forecasting and warning for weather and related hydrological hazards, and the SMN and its water-focused products remain with CONAGUA through the current day.

One of the major contributions to convective storm research from Mexico has come from improved understanding of the dynamics and thermodynamics of tropical and subtropical mesoscale convective complexes (MCCs; Velasco and Fritsch 1987; Howard and Maddox 1988; Smith and Gall 1989), including squall lines (Raymond and Jiang 1990). Many MCCs in Mexico form as a result of topographic influences (Farfán and Zehnder 1994), particularly during the North American monsoon (Adams and Comrie 1997; Higgins et al. 2003;

Ropelewski et al. 2005; Perdigón-Morales et al. 2018). To better understand those convective systems, Mexican researchers linked with scientists from the United States and beyond to stage two major international field programs: the Southwest Area Monsoon Project (SWAMP; Meitín et al. 1991), during the summer of 1990, and the North American Monsoon Project (NAME; Higgins and Gochis 2007), during the summer of 2004. Those projects discovered and confirmed critical contributions to the evolution of mesoscale convection from surface convergence forced by topography, inverted troughs and synoptic transients, and northward moisture surges from the tropics. Those results improved both Mexican and U.S. forecasts of monsoon-driven flooding (Douglas et al. 1993; Higgins et al. 1997; Magaña et al. 1999; Magaña et al. 2003; Gutzler et al. 2005; Gochis et al. 2006). Furthermore, because of those field programs in Mexico, we now know that one of the dominant mechanisms for precipitation there is long-lived stratiform structures. The NAME project inspired subsequent research on the initiation, diurnal cycle, and moisture sources of convection, particularly modeling efforts to better represent land–atmosphere coupling (Feng and Houser 2015) that have impacts well beyond Mexico.

While the relative frequency of flood-related disasters is greater than tornado, hail, or wind disasters, one region of Mexico stands out as an area that regularly sees supercellular convection and tornadoes. Edwards (2006) and Weiss and Zeitler (2008) documented several dozen cases of supercellular convection in this area, located in and to the east of the Serranías del Burro Mountains in northern Mexico. In perhaps the only numerical modeling study of a tornadic supercell in Mexico, and as one of only a few numerical modeling studies of a predawn supercell (e.g., Nowotarski et al. 2011), Barrett et al. (2017) examined an event that occurred in the early morning (0600 LT) hours of 25 May 2015 and was the deadliest tornado (14 fatalities) in Mexico since at least 1 January 2000 (National Risk Atlas 2016). In that event, Barrett et al. (2017) found extremely large values of instability and only modest shear produced an environment that favored the development of the deadly tornado that passed through Ciudad Acuña; such conditions appear to be typical of the convective storm environment in April–May in the region. Apart from the Serranías del Burro region in northern Mexico, there do not appear to be other locations in Mexico with environments that regularly favor tornadoes or severe convection (National Risk Atlas 2016). Those studies of tornadoes and supercell thunderstorms in northern Mexico have raised the level of awareness in both the Mexican National Weather Service (SMN) and in the Civil Defense of the hazards posed by tornadoes.

As a result of the high frequency of strong convective cores in South America, the global community has paid significant attention to that region to study dynamic and physical processes associated with convective activity. That attention is illustrated by a number of international field campaigns[4] that have been conducted in continental South America addressing not only the dynamics and microyphysics associated with deep moist convection (VIMHEX, Betts and Stevens 1974; CHUVA, Machado et al. 2014) but also regional atmospheric circulations (SALLJEX, Vera et al. 2006), surface–atmosphere interaction processes (ABLE, Garstang et al. 1990; LBA, Silva Dias et al. 2002), and chemical processes (HIBISCUS/TroCCiNOx/TroCCiBras, Pommereau et al. 2011 and Held et al. 2007; GOAmazon, Martin et al. 2017) that influence and/or are influenced by DMC. Several important findings arose from these field campaigns regarding mechanisms that affect the strength of deep convective updrafts in moist tropical environments that typically lack the strong midlevel lapse rates and vertical wind shear found in the midlatitude severe storm regimes. For instance, for the southwestern Amazon region, stronger updrafts were generally found with unstable air masses richer in biomass burning aerosols, which are more often observed either during the transition from the dry to wet seasons or during northeasterly wind regimes in the region.

In addition, with the advent of the Tropical Rainfall Measuring Mission (TRMM) satellite era in the late 1990s, a significant increase in our general knowledge of the climatology, behavior, and severity of severe convection in South America took place (e.g., Rasmussen and Houze 2011; Nunes et al. 2016). Findings from these studies led to another international field campaign in northwest-central Argentina in 2018 (RELAMPAGO, standing for Remote Sensing of Electrification, Lightning, and Mesoscale/Microscale Processes with Adaptive Ground Observations; https://publish.illinois.edu/relampago/; Nesbitt et al. 2016), which examined several aspects of some of the most extreme forms of convection in the world. Data collected from this field campaign are currently being analyzed.

[4] Campaigns' acronyms: The Venezuelan International Meteorological and Hydrological Experiment (VIMHEX); the Cloud Processes of the Main Precipitation Systems in Brazil: A Contribution to Cloud Resolving Modeling and to the GPM (CHUVA); the South American Low-Level Jet Experiment (SALLJEX); the Tropical Convection, Cirrus and Nitrogen Oxides Experiment (TroCCiNOx), and TroCCiNOx in Brazil (TroCCiBras); the Amazon Boundary Layer Experiment (ABLE); the Large-Scale Biosphere–Atmosphere Experiment (LBA); The Green Ocean Amazon Experiment (GOAmazon).

A series of international field campaigns have taken place in Europe as well. The Convective Storm Initiation Project (CSIP) had the aim of understanding the location, timing, and formation of convective clouds that produce intense precipitation in the maritime environment of southern England (Browning et al. 2007). Ground-based instruments and two instrumented aircraft from the United Kingdom and Germany were deployed in southern England during the summers of 2004 and 2005. The project was highly successful and provided observations of the processes responsible for the initiation of convection in the region (Browning et al. 2007). The data collected during CSIP were also used to quantify the role of the upper-level potential vorticity anomalies in suppressing or promoting convective storms (e.g., Russell et al. 2008).

The Hydrometeorological Data Resources and Technology for Effective Flash Flood Forecasting project (HYDRATE, http://www.hydrate.tesaf.unipd.it/) had, as its primary aims, 1) to improve our understanding of flash flood forecasting by extending the understanding of past flash flood events, 2) to advance and harmonize a European-wide innovative flash flood observation strategy, and 3) to develop technologies and tools for effective early warning systems (Borga et al. 2011). The project involved participants from 13 countries.

The Convective and Orographically induced Precipitation Study (COPS) had, as its goal, the advancement of the quality of forecasts of orographically induced convective precipitation by four-dimensional observations and modeling of its life cycle (Wulfmeyer et al. 2011). Institutions and researchers from eight countries operated in summer 2007 in southwestern Germany and eastern France covering the Vosges Mountains, the Rhine Valley, and the Black Forest Mountains.

Even before these field projects, enough interest in severe convection had regrown in Europe that a conference was organized and hosted by Jean Dessens in Toulouse to bring together 125 researchers, mostly European and some American, to focus on European storm hazards, particularly tornadoes. A significant number of the participants had been involved in bilateral projects with individuals in other countries, but had little broad interactions. Bringing the researchers together was critical and highlighted the need for cooperation and the opportunity to learn from others. It began a string of conferences that are now held every other year (in the years the American Meteorological Society's Severe Local Storms conferences are not held). It also introduced into the broader community a young German scientist with a vision for pan-European research, Nikolai Dotzek.

Given his interest in severe convective storms, Dotzek quickly became a leading figure in severe storms research in Europe. Furthermore, he was very interested in increasing awareness on severe convective storms throughout Europe (Feuerstein and Groenemeijer 2011). To achieve this goal, Dotzek started to collect and archive severe weather reports for Europe. Realizing that other researchers in Europe shared a similar goal, in 1997 he founded TorDACH, a network of scientists and amateur meteorologists with the aim of collecting information on severe convective storms in Germany (D), Austria (A), and Switzerland (CH) (Dotzek 2001). TorDACH continued the work started by Wegener and Letzmann in the first half of the twentieth century (Feuerstein and Groenemeijer 2011). Over the next years, Dotzek's research focus was on European tornadoes, and he published papers on tornadoes in Germany (Dotzek 2001), the weather conditions associated with the occurrence of tornadoes in Germany (Bissolli et al. 2007), and the global tornado intensity distribution (Dotzek et al. 2003).

In 2001, Dotzek participated in a workshop on tornadoes and hail sponsored by a network of reinsurance companies. Also in attendance were Chuck Doswell and Harold Brooks from NSSL, who had also been at the 2000 conference. These encounters in 2000 and 2001 between Dotzek, Doswell, and Brooks resulted in a collaboration that led to a fellowship that Dotzek received from Institute of Atmospheric Physics of the German Aerospace Center (DLR, Deutsches Zentrum fur Luft- und Raumfahrt e.V.) to visit the NSSL in 2002. During his visit, he worked on a proposal for a European Severe Storms Laboratory (ESSL). Based on discussions, it became clear to him that a ''Centre of Excellence'' would be the best solution to coordinate the collection of severe weather reports and to increase awareness on severe storms in Europe (Groenemeijer and Kuhne 2014; Groenemeijer et al. 2017). This led to the development and implementation of the European Severe Weather Database (Dotzek et al. 2009). Dotzek led the foundation of ESSL in 2006 as a spin-off of DLR (Groenemeijer et al. 2017). The vision for ESSL from its Articles of Incorporation was to ''research questions concerning convective storms and other extreme weather phenomena which, in the light of a changing global climate, can be treated or answered exclusively, preferably or more efficiently on a pan-European scale.'' It was not the intent to create an organization similar to NSSL, but an organization that could address research questions that could not be addressed by national organizations or meteorological services, such as a pan-European severe weather database (Feuerstein and Groenemeijer 2011). Today, the main activities of ESSL

are 1) development and management of the ESWD, 2) running a test bed to evaluate forecast products and provide forecaster training, and 3) coordination of European scientific and forecasting communities, through training activities and the European Conferences on Severe Storms (Feuerstein and Groenemeijer 2011).

As mentioned, one of the challenges in Europe is the small areas of forecast responsibility of many countries and, consequently, events that may be relatively common on a continental scale are infrequent on a national scale, thus receiving little attention in a particular country. The European National Meteorological Services Network (EUMETNET) is a network of 31 European National Meteorological that provides a framework to organize cooperative programs between the members in fields of meteorology, data processing, and forecasting. The Operational Program for Exchange of Weather Radar Information (OPERA; www.eumetnet.eu/opera) is a weather radar network within EUMETNET established in 1999 with the aim of providing a radar integrated map over Europe (Huuskonen et al. (2014).

7. Current state of forecasting

Severe thunderstorms are specifically forecast by some, but not all, national meteorological services. Here, we provide an overview of selected operational or quasi-operational forecasting systems. It is not inclusive, but intended to be illustrative.

a. United States

The United States has the most extensive severe thunderstorm forecasting enterprise. Forecasting has evolved since the early 1950s and, currently, can be thought of as being done in three stages, two of which are on a national scale and the third on a local scale.

The SPC produces convective outlooks that cover periods up to 24 h long out to 8 days in advance. These forecasts cover the contiguous 48 states. The convective outlooks end at 1200 UTC, corresponding roughly to the minimum severe thunderstorm probability in the diurnal cycle, and, except for forecasts that are issued on the day they are valid, they begin at 1200 UTC. Convective outlooks were first issued in 1973 and, for their first quarter century, were categorical in nature, indicating levels of risk of severe thunderstorm occurrence. Initially, they were only issued for so-called Day 1, the day of issuance, and would be updated at scheduled intervals during the day, covering the rest of that daily period. Those forecasts did not explicitly discriminate between individual convective hazards, although the text discussion issued with the forecasts might contain some information about tornadic versus nontornadic threat. Since the late 1990s, the underlying forecasts have been probabilistic, with limited values of probabilities being used to describe the expected areal coverage, and a categorical name being associated with probabilities of the various threats. In addition, for Day 1, tornado, hail, and convective wind probabilities are produced. Forecasts for additional days began to be added about this time, to the point that, by 2018, forecasts are issued through Day 8. Hitchens and Brooks (2012, 2014, 2017) and Hitchens et al. (2013) have carried out extensive evaluation of these forecasts, showing improvements in quality from the 1970s forward and as lead time for the forecasts get shorter for forecasts valid at the same time.

The second stage of the forecasting process is also done by the SPC. Areas of expected severe thunderstorms were forecast from the early days of the NSSP. In 1965, they began to be called ''watches'' and tornado and severe thunderstorm conditions were differentiated. Watches are typically on the size of 100 000 km^2 and valid for 6 h, beginning half an hour to an hour after issuance. Unlike the convective outlooks, watches are issued on an as-needed basis to indicate regions of the country in which conditions are favorable for severe thunderstorms and tornadoes. In the overall forecast/response system, they play an important role in providing advanced notice for emergency management and broadcast interests of impending threats, so that preparations can be made.

The final stage is the so-called warning stage, in which the threat from individual thunderstorms is highlighted. These warnings are issued by over 100 local forecast offices that have responsibility for relatively small areas of the country. Until 2007, warnings were issued for counties, but are now issued as needed, relative to a specific thunderstorm. Most warnings are in effect for 30–50 min, covering an area of 600 km^2. They go into effect immediately upon issuance and are intended as calls for protective action by emergency management and the general public. Brooks and Correia (2018) discuss long-term changes in performance of these warnings, showing improvements in quality from 1986 to approximately 2006, with changes in the implied threshold of evidence required for a warning to be issued having large effects on individual metrics (e.g., probability of detection, false alarm ratio), particularly after 2011.

b. Canada

Public alerts related to severe convective storms were issued on an ad hoc basis beginning in 1950. On 14 July of that year, the Meteorological Service of Canada's

(MSC) forecast office in Regina issued a tornado warning based on a report from a pilot. It is considered to be the world's first successful public warning of a tornado. Beginning with MSC's forecast office in Winnipeg in 1978, severe convective weather watches and warning programs were implemented across the country by the mid-1980s. National standards and coordination were fully established by 1988 (MANPUB 1988).

Another important milestone was the implementation of a volunteer storm spotting network. The first such "Weather Watchers" network in Canada was established in Manitoba in 1978. Later, in 1987, an amateur radio network for reporting severe weather called CANWARN was established, beginning in Ontario and expanding across the country. Though CANWARN and volunteer spotters still provide important data to weather offices, social media are increasingly used as a primary source of public reports of severe weather, even though extracting useful information in real time remains difficult for forecasters.

Improvements to warning dissemination and response have also progressed, aided by media partners such as dedicated cable channel The Weather Network, established in the late 1980s, and the MSC's Warning Preparedness Meteorologist program. This program, inspired by the U.S. National Weather Service's Warning Coordination Meteorologist program, involves meteorologists working closely with media and emergency managers to proactively prepare the Canadian public for the occurrence of severe weather. It was established for the Prairie Provinces in 1998 and was expanded nationally in 2003.

Last, severe weather alerts in Canada have historically been issued for predefined warning regions using established thresholds for wind gust speed, hail size, and rainfall rate/accumulation (Joe et al. 1995). However, recent research has been undertaken on the use of probabilistic alerts using geo-referenced objects (Sills 2009; Joe et al. 2018) to better combine forecaster expertise with machine automation, and so-called Met-Object-based alerting is planned for implementation at the MSC in the coming years.

c. *Pan-European*

Although there was no organized system, occasional forecasts of tornadoes were made in Europe decades ago. The Dutch weatherman Joop den Tonkelaar (1926–2001) warned on an early morning radio show about the possibility of tornadoes over the Netherlands on 25 June 1967. His warning was based on the fact that the synoptic-scale pattern on 25 June was similar to the one associated with the tornadoes over France the previous day. Because the Royal Dutch Meteorological Institute (KNMI) did not want to cause any panic, the warning was changed from "possible tornadoes" to "possible severe wind gusts" (Antonescu et al. 2018). Thus, the warning issued by KNMI on 25 June 1967 was probably the first verified tornado warning ever issued in Europe (Rauhala and Schultz 2009).

A significant challenge for forecasting severe convection in Europe is the relatively small size of the forecast regions for many of the agencies and, as a result, relatively few events occurring in any one area. To address this, in 2002, a group of students began a volunteer forecasting exercise called the European Storm Forecast Experiment (ESTOFEX). ESTOFEX began after a visit by Johannes Dahl, then of the Free University of Berlin, to NSSL and the SPC. The forecasts mirrored the categorical and, later, the probabilistic forecasts issued by the SPC in the United States. It began as an exercise to see how the ingredients-based approach to forecasting could be applied in the European context and for the initial set of student forecasters to test what they had learned. Dotzek (2003) suggested it might form the basis eventually for a European Storm Prediction Center. There have been challenges to that being realized and the participants in the experiment have changed over the years, but forecasts continue to be issued and provide information that can be used by operational forecasters and decision-makers, even if on an unofficial basis. Evaluation of the forecasts has shown them to be of high quality (Brooks et al. 2011).

d. *Australia*

The Bureau of Meterology's (BoM) Severe Thunderstorm Warning Services were developed in 1989 (Bureau of Meteorology 1989). BoM began to issue severe thunderstorm "advices" (comparable to "watches") in the early 1990s, mostly by small teams in each of the states' forecasting centers.

Severe storm training sessions conducted by Dr. Charles Doswell III in the mid-1990s led to a more standardized, ingredients-based approach to forecasting, and greater focus on the importance of mesoscale meteorology for storm formation and severity. A more structured approach to national operational training was adopted and a national network of storm spotters was established. In addition, a national severe storms database was established and forecast verification commenced for each of the capital cities.

The follow up to recommendations in the aftermath of major severe storm impacts in the Sydney region in the 1990s had a significant impact on national severe storm science, services, operations, and training. The catastrophic 14 April 1999 Sydney hailstorm struck the city's eastern suburbs without warning in the early evening. A swath of giant hail caused major damage (Bureau of

Meteorology 2006). It was the costliest natural disaster in Australian history (more than 4 billion Australian dollars in today's dollars). Enquiries into the Bureau's warning performance made key recommendations on human factors, particularly operational training and procedures.

Following the hailstorm, the first Australian radar and Doppler radar training courses were developed by adapting training resources from the U.S. The ''Treloar'' hail nomograms (Treloar 1998) allowed monitoring of 50-dBZ echo height and vertically integrated liquid (VIL) to flag the onset of severe hail.

The Australian Bureau of Meteorology developed a new warning preparation tool called the Thunderstorm Interactive Forecast System (TIFS) (Bally 2004). TIFS was designed to apply advances in radar-based thunderstorm cell detection and tracking techniques to the efficient production of operational forecasts and warnings. The system ingests automated thunderstorm cell detection and tracks, allows graphical editing by forecasters, and produces graphical and text products from the edited data. The main warning graphic shows the current position of severe storms together with a 1-h nowcast based on the recent movement of the cell. This system enabled specially trained forecasters to provide a cell-based severe thunderstorm warning service in the Sydney and Brisbane areas in the early 2000s. This was later extended to other capital cities.

In the early 2000s, the Bureau developed a 3D radar visualization system (Purdam 2007); this was world-class software that enabled quick and configurable access to cross sections and constant-altitude plan position indicator (CAPPI) scans that made monitoring and diagnosis of storm features much easier. It also displayed warning decision support output from radar-based algorithms trialed during the Sydney Olympics Forecast Demonstration Project.

Based on the promising performance of the Mills and Colquhoun (1998) forecasting decision tree linked to a regional NWP model, this approach the system was developed further. The new system retained some of the core science from Colquhoun's original work but took a more ingredients-based approach. The revised system, known as the National Thunderstorm Forecasting Guidance System (NTFGS) became operational in late 2003, (Hanstrum 2004; Richter 2012). The NTFGS was based on twice-daily runs of the 0.125° MesoLAPS model, Australia's mesoscale numerical weather prediction model (a mesoscale version of the Limited Area Prediction System). The NTFGS ingested raw MesoLAPS model output. It then uses fixed on/off-type thresholds to diagnose environments favorable to a range of convective phenomena. The phenomena diagnosed include surface-based thunderstorms, elevated thunderstorms, supercells, large hail, damaging/destructive winds, tornadoes, and microbursts.

As the automated surface observation network has improved, so too have human and numerical analyses. These have enabled forecasters to ''ground truth'' forecast models, thereby increasing confidence in the forecast. Forecasters use analysis and diagnostic techniques derived from morning sounding observations in combination with model forecast fields for the afternoon and evening. Hourly output from the Bureau high-resolution mesoscale model has enabled forecasters to see the evolution of wind, temperature, and humidity fields in greater detail. These fields have greatly added to forecasters' understanding of conceptual models of the atmosphere that lead to severe storm development.

8. Some new directions

Since 2000, work has grown in areas that have expanded the field of severe thunderstorm research. Some represent what might be thought as extensions on previous work because of new technological abilities. Others are, in effect, new subdisciplines or applications of ideas to completely new problems.

Radar technology, which has been so vital to our understanding of severe thunderstorms, has continued to evolve. Phased-array radars (Zrnić et al. 2007) are used for experimental purposes and could be the basis for a future network in the United States. Compared to ''traditional'' radars that have a single transmitting and receiving unit and are steered mechanically, phased-array radars have a large number of small transmitting and receiving units and are steered electronically. As a result of the electronic steering, phased-array radars can collect complete volumes of data from the atmosphere much more quickly than scanning radars. They also can utilize a variety of scanning strategies, including sampling small parts of a volume that are of particular interest (e.g., a severe thunderstorm), while maintaining surveillance of the entire volume. The electronic steering means that they can be built with no moving parts, potentially reducing mechanical failures.

The increase in the amount of data and the rapid update of the data provide great opportunities and great challenges for operational applications. More information would be available in short-fused warning applications, but the question of processing it by machines and humans is formidable. Wilson et al. (2017a) examined forecaster decision-making in the warning process using experimental phased-array data and found it led to better decisions in many cases, but also studied

issues related to workload associated with the increase in data availability (Wilson et al. 2017b).

The need to collect more and better observations in the field continues to drive development. While VORTEX and VORTEX2 pioneered surface observations, such as the mobile mesonet and StickNet systems, the results of the research based on those observations highlighted the need for better understanding of near-surface conditions in and near severe thunderstorms (e.g., Markowski et al. 2002). Collecting observations near developing tornadoes or within regions of large hail can be extremely dangerous. As a result, novel methods to take instruments to those regions have been developed. Two of them are unmanned airborne systems (UAS, popularly referred to as drones; Houston et al. 2012) and balloon-borne systems that are essentially neutrally buoyant and can deploy a number of probes that follow airflow (Markowski et al. 2018). UAS systems have an advantage of being steerable, although there may be issues at times with flight restrictions and areas of a storm with heavy rain, hail, or strong winds may still be difficult to operate in. As of the time of writing, hundreds of sensors can be tracked at the same time and, in storm situations, "swarmsondes" on the order of 50 probes have been deployed in tornadic supercells on multiple occasions. Both methods have the potential to provide theoreticians and modelers with information on scales never seen before in locations of great interest for understanding storm behavior.

Increases in computing power have also dramatically changed the capabilities on numerical models to provide information. Orf et al. (2017) modeled the 24 May 2011 supercell that produced a long-track EF5 tornado at El Reno, Oklahoma. In the center of the domain, the horizontal grid spacing was 30 m with a time step of 0.2 s. Nearly 2 billion grid points were in the model. This is in contrast to the state of the art in the early 1980s, when Weisman and Klemp (1982, 1984) described behavior of storms in terms of environmental CAPE and shear, when 1-km grid spacing was considered "high-resolution," model time steps were on the order of 10 s, and a large domain contained 150 000 grid points. Aspects of the behavior of the Orf et al. storm that are beyond our ability to observe will provide challenges for the theoreticians and observationalists of the future. It is likely that simulations such as this will provide information on processes that cannot be obtained otherwise. The challenge will be to connect that information with what can be observed to determine the fidelity of the model.

Computer power has also provided the opportunity to use models that resolve thunderstorms for short-term forecasts to provide information on storm initiation, evolution, and behavior for a few hours. The so-called Warn-on-Forecast (WoF) system (Stensrud et al. 2009) uses radar and other data to initialize an ensemble of forecasts that have the potential to provide significant information about all aspects of storms for forecasters and forecast users at scales beyond an hour. In the United States, this time frame fits between the traditional notions of watches and warnings. WoF could provide significant input into new paradigms of forecasting high-impact weather (Rothfusz et al. 2018). The challenges in taking WoF from a research activity to an operational system are formidable, from processing of the initial conditions and output to designing a robust ensemble. Progress has been made however, although there is much work to be done (Lawson et al. 2018).

At the other end of the time scale from WoF, extended-range projections of severe thunderstorms and tornadoes, ranging from a few weeks to the centennial range associated with climate change, has been an area of rapid growth. Allen (2018) has recently published an extensive review of this topic. The second has been in consideration of the societal impacts of severe thunderstorms and ways to ameliorate the impacts by assisting forecasters to make better decisions via education, communication, and descriptions of impacts of hazardous weather.

The extended-range projection work usually grows out of an application of ingredients-based forecasting (Doswell et al. 1996), with an understanding of the limitations of reporting databases discussed earlier. Griffiths et al. (1993) suggested it as an approach to estimating the true climatological distribution of events that are not well reported. Brooks et al. (2003b) applied it to the environments described by the NCAR–NCEP data to produce estimates of the global distribution of severe thunderstorms (large hail, strong winds) and tornadoes, using CAPE, shear, and lifted condensation levels as predictors, as suggested from the proximity sounding studies (Rasmussen and Blanchard 1998; Craven and Brooks 2004). Although the reanalysis was somewhat coarse (equivalent to grid spacing just finer than $2° \times 2°$) and, as a result, could not resolve important lifting mechanisms to initiate thunderstorms, and had limitations because of the parameterization of subgrid processes, it nevertheless gave a plausible large-scale picture of the global distribution. Cecil and Blankenship (2012) developed satellite estimates of the spatial distribution. The comparison of a variety of estimates of the location of strong thunderstorms in South America illustrates the general agreement from different methodologies (Fig. 18-16).

Within a few years, projections based on climate model simulations began to emerge of what is likely or possible in the future. The first was carried out by Del Genio et al. (2007) for the change in distribution of severe convective parameters within a global climate

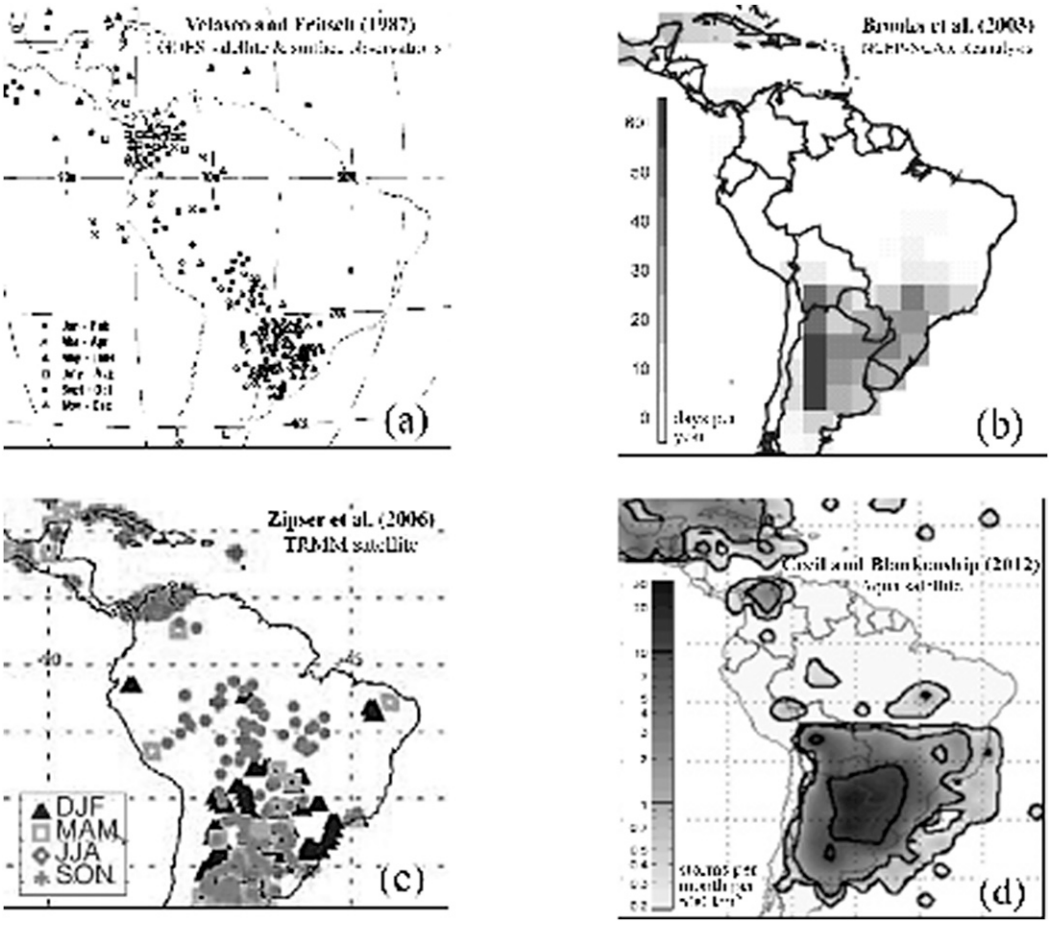

FIG. 18-16. View over South America of results from different attempts to estimate the location of strong thunderstorms. (a) Bimonthly distribution of MCCs from May 1981 to May 1983 identified by Velasco and Fritsch (1987) utilizing GOES thermal infrared imagery; (b) mean annual number of days with meteorological conditions conducive to severe convective storms based on vertical profiles from NCEP–NCAR reanalysis for the period from 1997 to 1999 (from Brooks et al. 2003b); (c) seasonal distribution of strong convective as detected by the TRMM satellite for the 1998 to 2004 period (from Zipser et al. 2006); and (d) estimated number of severe hailstorms per month and per 500 km^2 based on the period from 2003 to 2010 using the *Aqua* satellite (from Cecil and Blankenship 2012).

model for all locations east of the Rockies in the United States. They worked on the native grid of the global model and found, in general, a shift to higher energy available for storms and lower values of shear in the environment. Soon after, Trapp et al. (2009) used a regional climate model embedded in a global climate model to look at regional trends in the United States in CAPE and deep-layer shear and the combination thereof. In general, for most of the United States east of the Rocky Mountains, the frequency of high CAPE was projected to increase over the twenty-first century with shear decreasing. They projected that the frequency of severe thunderstorm days would increase under a warming climate. Soon, additional sophistication was added. Diffenbaugh et al. (2013) used an ensemble of global models and investigated different seasons of the year. The models agreed on projections of an increase in severe thunderstorm days in the springtime in the United States, but did not agree even on the sign of change in the summertime, particularly in the central plains, where some model solutions favored more frequent seasonal droughts and others did not. Although much of the work has focused on the United States, Púčik et al. (2017) described expected increases in severe thunderstorms for Europe, based on environmental conditions from an ensemble.

The Brooks et al. (2003b) reanalysis and work by Trapp et al. (2009) and Diffenbaugh et al. (2013) represent statistical downscaling as an approach to estimating the distribution of storms. Robinson et al. (2013), Gensini and Mote (2014), and Chan et al. (2018) used

dynamical downscaling in which a large-scale model is used to initialize models with grid spacing on the order of a few kilometers that are similar to those used in day-to-day forecasting. Currently, the primary limitation to dynamic downscaling is the computational costs associated with the high- resolution simulations. However, the tools that have been developed to estimate proxies of weather hazards can then be used as with weather forecasting. Gensini and Mote (2014) found an apparent increase in variability of severe thunderstorm occurrence in the springtime in the United States in the latter part of the twenty-first century compared to the latter part of the twentieth century. It is tempting to view this as consistent with an observed increase in tornado variability (Brooks et al. 2014; Elsner et al. 2015), but the time scales are sufficiently different not to have complete confidence in the relationship.

Attempts to forecast seasonal severe thunderstorm activity in relation to climatological frequency have met with limited success, in large part because of the inherent variability and a difficulty in even defining what should be forecast (e.g., total number of events, total number of days with many events, total number of events exceeding some threshold.) As an example, the environmental conditions that lead to one exceptionally large tornado outbreak are likely to be different than those that lead to the same number of tornadoes spread over many days. Because of the difficulty in forecasting the distribution of environments on that time scale, large-scale patterns that support favorable environments have been the primary emphasis. Most of the work (Allen et al. 2015; Cook et al. 2017) has focused on El Niño–Southern Oscillation and shows promise for future development. For shorter time scales out to a few weeks, recent emphasis has been on the state of the Madden–Julian oscillation, or a related quantity, the global relative angular momentum. Barrett and Gensini (2013), Barrett and Henley (2015), Gensini and Marinaro (2016), and Gensini and Allen (2018) found that outbreaks of hail and tornadoes and the most intense tornadoes were more likely in some phases of the Madden–Julian oscillation than in others, depending on time of year, as a result of changes in the large-scale weather patterns in midlatitudes. To the extent that the phase of the oscillation can be predicted or, at the very least, the timing between phases and pattern changes over North America, it is possible that such work could lead to extension of forecasts beyond current limits.

Related to the extended projection work, attempts to modify databases of severe weather reports to account for changes in reporting practices formed the basis for examining how aspects of severe thunderstorms have changed over time. Verbout et al. (2006) found that, in many aspects, tornadoes rated F1 or higher on the Fujita scale in the United States showed more consistency over time than using all tornadoes or those rated F2 or higher. That distinction enabled Brooks et al. (2014) and Elsner et al. (2015) to identify increases in the variability of tornado occurrence since the mid-1970s, as shown by a decrease in the number of days per year with at least one tornado, but a large increase in the number of days with many tornadoes. This was despite the fact that the long-term trend in number of F1 and stronger tornadoes per year showed little or no trend during the period. Brooks et al. (2014) also found an increase in the variability of when the 50th F1 or stronger tornado occurred in the United States. This represented approximately the 10th percentile of the typical annual number, so could be thought as related to the ''beginning'' of the ill-defined tornado ''season.'' The fact that the changes began in the mid-1970s and, at least qualitatively, occurred at the same time as global temperature was increasing, it was tempting to try to relate the changes in variability to changes in global temperature, but the physical processes that would lead to that relationship were unclear. Long and Stoy (2014) showed that the timing of the peak of tornado occurrence in the plains has shifted earlier in the year in recent decades. A unique aspect of their analysis was estimating an annual cycle for each year in the tornado record in the region of interest and then finding the timing of the peak of each season. By focusing on the timing within each year independently, the overall increase in reports from year to year would not affect their analysis. Lu et al. (2015) used a somewhat different approach to the timing, but found a similar result to Long and Stoy (2014) for timing in the plains. Importantly, they also investigated environmental variables that are favorable for tornado development and found that the change in timing closely resembled changes in wind shear related quantities, and not with thermodynamic variables. Given that the most direct effect of global warming would likely be on the thermodynamic variables, this raised the question of whether the change was a result of global warming or some other large-scale change. The lack of a well-understood physical link between warming, the environmental changes, and the tornado data led Trapp and Hoogewind (2018) to look at the relationship of summertime tornado occurrence and Arctic sea ice extent. Tornado activity, measured in a variety of ways, was lower in years with low summertime Arctic sea ice. This did not fully explain a cause-and-effect relationship, but it perhaps added another link to the chain.

The impacts of severe thunderstorms have motivated much of the research carried out over the last century, but identifying the relationship of forecasts to impacts is

an extremely difficult task. Changes in society (e.g., population, building practices, communication) are an important component of this. Brooks and Doswell (2001a, 2002) investigated ways to acknowledge those societal changes by comparing death and property damage for historical tornadoes. Death rates as a function of population in the United States dropped by an order of magnitude between the mid-1920s and 1990, but changed much more slowly before and after that. Given that the drop begins before forecasting of tornadoes began, it is clear that the nonmeteorological aspects dominate for at least part of the record (Brooks and Doswell 2001a). Disentangling the various roles of the components has not been done. Using increasing national wealth as a normalization for damage over the years led to the conclusion that the three most damaging tornadoes in the record all took place before 1930, but that there are many roughly comparable events scattered throughout the twentieth century (Brooks and Doswell 2002).

A series of fundamental studies documenting deaths in severe convective storms in the United States were carried out in the early 2000s. High winds (Ashley and Mote 2005; Ashley and Black 2008; Schoen and Ashley 2011), floods (Ashley and Ashley 2008), tornadoes (Ashley 2007), and lightning (Ashley and Gilson 2009) were all considered. Importantly, both meteorological characteristics, such as the nature of the event, and societal characteristics, such as population demographics, were included. Not surprisingly, locations with many deaths have both a relatively high chance of a hazard occurring and a large vulnerable population.

The relatively long history of forecasting severe thunderstorms in the United States has meant that much of the recent work on why and how impacts differ over time and storm has been done there. Simmons and Sutter (2011) summarize much of that work. Of particular interest is the model of tornado casualties as a function of various aspects of the tornado, the tornado warning, and the demographics of the population where the tornado occurred (Simmons and Sutter 2005). The authors are economists and, as such, used an econometric approach to developing their model. Conceptually, at least, it can allow researchers and planners to estimate the impacts of any possible tornado occurring in a location. Hoekstra et al. (2011) surveyed the public to learn about their understanding of tornado threats and their preferences in the structure and delivery of warnings from the National Weather Service in the United States. Klockow et al. (2014) and Peppler et al. (2018) explored how people understand risk in terms of location, which impacts how they respond to warning messages. Related to this, Klockow-McClain et al. (2019) studied how different displays of possible experimental tornado warning information affected public response.

Work on measuring public understanding of weather threats has been growing in other countries. Notably, Silver (2015) investigated forecasts in Canada and found that the majority of respondents in their sample actively sought weather forecast information to help make pragmatic decisions about things such as clothing choice, but that they were not always clear about the meaning terms used in forecast. Keul et al. (2018) carried out survey work in eight different countries with a variety of threats, population characteristics, and forecasting emphases to examine public understanding of their threats. Keul et al. (2018) found a wide variety of attitudes toward risk and preparedness between countries. Even with the sample population lacking weather-related education and negative weather encounters, both cultural and sociodemographic factors were found to influence their weather risk perception, fear, and preparedness. More economically developed nations appeared to have populations who viewed themselves as better prepared for weather hazards, in part because those countries tended to have more robust forecasting activities and more resources to cope with disasters. This work allows for comparison of commonalities and differences in the different countries.

Ripberger et al. (2015) investigated the impacts of forecast errors on perceptions by the public of the quality of the warnings and the trust in the system. They found that both missed events and false alarms had negative impacts on the perceptions of quality, but the trade-off between the two was difficult to assess. Work of this kind provides an opportunity to shape physical science research priorities. If the impact of errors on future response to warnings can be measured, it could provide a basis for setting performance goals for a warning system. How far the existing system at any time is from those goals could, in turn, identify areas of possible improvement. Currently, there is no guidance on how to set those goals.

In the aftermath of the large death toll from tornadoes in the United States in 2011, the realization that improvements in outcomes required coordinated consideration of both physical and social aspects of the problem. To that end, a workshop made recommendations about physical and social science work, both individually and collaboratively, that needed to be addressed (Lindell and Brooks 2013). Subsequently, the VORTEX-Southeast field program scheduled for 2016–18 included physical science and social science priorities. Mason et al. (2018) investigated the particularly challenging problem of

communicating actionable information on tornadoes during the night by surveying residents of Tennessee about if and how they receive warnings. Ashley (2007) had pointed out the particular problem of nocturnal tornadoes in the southeastern United States because of the juxtaposition of demographic characteristics and the reception of information problem. The relatively high rural population density there, with high rates of poverty and mobile home residence, in combination with the difficulty of gathering and communicating information overnight makes the challenge of tornado safety particularly difficult there.

9. Conclusions

Severe thunderstorm research and forecasting was an almost unknown field a century ago. The combination of improved observational capabilities and numerical modeling has driven an amazing increase in our understanding of weather and the ability of national meteorological services to provide information to protect lives and property from severe thunderstorms. A century ago, we as a community did not even have any way to quantify instability in the atmosphere, let alone understand its critical role in severe thunderstorms. We had no idea about the airflow within severe thunderstorms or the fluid mechanics of tornadogenesis. It could be argued that the severe thunderstorm research/forecasting community has a more intimate interrelationship than many other areas within meteorology. The same high temporal and spatial resolution observations needed to make accurate and useful forecasts are also invaluable to researchers attempting to understand how the atmosphere works. Our field faces the challenges of expanding the time horizon of forecasts and of working toward making forecasts more useful, a task that requires both physical and social scientists. There is no reason to believe that next century will not continue the trend of improved observational capabilities intended to answer questions that remain, such as details about convective initiation, tornadogenesis, tornado decay, and the creation and use of more effective forecasts to protect life and property. Those answers will undoubtedly lead to additional questions that we cannot even think of at this time. The growth of international collaboration, assuming political activities do not impose limits, should spread existing knowledge and generate a better understanding of how the atmosphere really works.

Our story also highlights the importance of individual scientists in the process. Much of our progress has been the result of imaginative individuals asking interesting questions in new ways, collecting or using old data, and devising tools to collect new data. There are people in our history that have made substantial contributions by being in the right place at the right time asking new questions.

Acknowledgments. First and foremost, we owe a debt to the thousands of scientists who have contributed to the field. Their work made this project both fascinating and frustrating, as difficult choices had to be made as to what to include and what, unfortunately, not to include. We are aware that important material has not been covered and that, in another process to produce this manuscript, different choices would have been made. We thank the anonymous reviewers for their exceptionally hard work in the arduous task of reviewing. The final product is substantially better than the initial submission. Note that some material regarding Canada's contribution was first published in "From Pioneers to Practitioners: A Short History of Severe Thunderstorm Research and Forecasting in Canada" (Sills and Joe 2019). We are encouraging other contributors to publish their complete contributions for their countries and regions.

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