Hindcasting the First Tornado Forecast in Europe: 25 June 1967

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ABSTRACT

The tornado outbreak of 24–25 June 1967 was the most damaging in the history of western Europe, producing 7 F2–F5 tornadoes, 232 injuries, and 15 fatalities across France, Belgium, and the Netherlands. Following tornadoes in France on 24 June, the Royal Netherlands Meteorological Institute (KNMI) issued a tornado forecast for 25 June, which became the first ever—and first verified—tornado forecast in Europe. Fifty-two years later, tornadoes are still not usually forecast by most European national meteorological services, and a pan-European counterpart to the NOAA/NWS/Storm Prediction Center (SPC) does not exist to provide convective outlook guidance; yet, tornadoes remain an extant threat. This article asks, “What would a modern-day forecast of the 24–25 June 1967 outbreak look like?” To answer this question, a model simulation of the event is used in three ways: 20-km grid-spacing output to produce a SPC-style convective outlook provided by the European Storm Forecast Experiment (ESTOFEX), 800-m grid-spacing output to analyze simulated reflectivity and surface winds in a nowcasting analog, and 800-m grid-spacing output to produce storm-total footprints of updraft helicity maxima to compare to observed tornado tracks. The model simulates a large supercell on 24 June and weaker embedded mesocyclones on 25 June forming along a stationary front, allowing the ESTOFEX outlooks to correctly identify the threat. Updraft helicity footprints indicate multiple mesocyclones on both days within 40–50 km and 3–4 h of observed tornado tracks, demonstrating the ability to hindcast a large European tornado outbreak.

1. Introduction

The first known tornado forecast in Europe occurred on 25 June 1967 when meteorologists from the Royal Netherlands Meteorological Institute (KNMI) recognized that, following several tornadoes upstream over northern France on 24 June, the synoptic pattern was not changing overnight. Dutch weatherman Joop den

Tonkelaar appeared on an early morning radio show on 25 June and warned about the possibility of tornadoes over the Netherlands later that day. His forecast was based on a stationary synoptic-scale pattern and a similar situation in the Netherlands as in France the previous day. This insight formed the first tornado forecast based purely upon a forecast in Europe (Rauhala and Schultz 2009), although KNMI later changed the forecast from “possible tornadoes” to “possible severe wind gusts” to avoid public panic (BN DeStem 2017). den

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Tonkelaar's forecast verified with two F3 tornadoes over the Netherlands, as well as two others over France and Belgium. This kind of pattern recognition by Joop den Tonkelaar was similar to that employed by Miller and Fawbush in the first tornado forecast in the United States in 1948 (Grice et al. 1999). Although the first tornado forecasts by Miller and Fawbush drove many advances in the science of tornado prediction in the United States (Grice et al. 1999), the forecast by KNMI did not spark the same type of changes within European meteorological services, with only KNMI issuing forecasts for waterspouts as of 2015 (Holzer et al. 2015).

The KNMI forecast of 25 June 1967 was for what became the second day of the most damaging tornado outbreak in modern western European history in terms of fatalities and property damage—and second for all of Europe behind the 9 June 1984 outbreak in Russia (Finch and Bikos 2012; Antonescu et al. 2017). Combined, the outbreak of 24–25 June 1967 caused 232 injuries, 15 fatalities (Bordes 1968), and an estimated EUR 70–100 million in damages (\$68–96 million 2019 U.S. dollars) (Antonescu et al. 2017). The outbreak consisted of one F2 tornado, four F3 tornadoes, one F4 tornado, and one F5 tornado¹—one of only three documented F5s in Europe since 1900 (Groenemeijer et al. 2017). The sensitivity of the number of fatalities and buildings damaged to the specific location of the tornadoes in the outbreak has been examined by Antonescu et al. (2018). They found that transposing the seven tornado tracks from the June 1967 outbreak over a modern landscape would potentially result in 24 990 buildings being affected, 255–2580 injuries, and 17–172 fatalities.

Tornado outbreaks are defined as “multiple tornado occurrences associated with a particular synoptic-scale system” (American Meteorological Society 2017). Tornado outbreaks in the United States usually garner a lot of scientific attention, such as the numerous studies on the 3 May 1999 tornado outbreak in Oklahoma and Kansas (e.g., Thompson and Edwards 2000; Stensrud and Weiss 2002; Edwards et al. 2002; Roebber et al. 2002, as

well as others in the June 2002 Special Issue of *Weather and Forecasting*), the 4–10 May 2003 extended outbreak across the central and eastern United States (Hamill et al. 2005), and the 27–28 April 2011 outbreak in the southeastern United States (Knupp et al. 2014). In comparison, fewer studies of European tornado outbreaks exist. For example, Bech et al. (2007) discussed an outbreak of tornadoes and waterspouts that originated on a mesoscale convergence line near Barcelona on 7 September 2005, and Apsley et al. (2016) modeled an outbreak over the United Kingdom in 1981 where 104 tornado reports occurred in association with a cold front (Rowe and Meaden 1985).

Because Europe experiences fewer and less damaging outbreaks, European public awareness of the risks of tornadoes is less than in the United States (Antonescu et al. 2017). Another reason is because European outbreaks often show no respect for country boundaries, and because each country is the typical size of a state in the United States, the problem of the spatial scale of the outbreaks becomes apparent. Because each country has its own national weather service responsible for its own citizens' safety, a pan-European agency with the remit to issue convective guidance or severe weather forecasts does not exist. As a result, modern European severe weather and tornado forecasts are still not produced in the same way and with the same public awareness as convective weather forecasts are in the United States (Doswell 2003; Rauhala and Schultz 2009; Doswell 2015; Miglietta and Rotunno 2016; Miglietta et al. 2017). This mentality persists even in the face of rising evidence of the risk of convective storms in general, and tornadic storms in particular, to European nations (Antonescu et al. 2017). Although organizations such as the European Severe Storms Laboratory (ESSL; Groenemeijer et al. 2017) and European Storm Forecast Experiment (ESTOFEX; <http://www.estofex.org>) exist, they are independent and not tied to any specific countries or weather services. Furthermore, such forecasts are not tied to any systematic, pan-European communications and dissemination system with common standards, such as the communications protocols employed by the U.S. National Weather Service and media such as the Emergency Alert System and Wireless Emergency Alerts. Nevertheless, official services exist that collate all meteorological warnings from European meteorological services (e.g., Meteoalarm, <http://www.meteoalarm.edu>), and there is also an effort to implement “common alerting protocol” across all weather institutes in Europe. Even the best forecasts, however, are of limited use without reaching an audience who can use them and knows how to use them. So, we ask the following questions: If the outbreak of 24–25 June 1967 were

¹ Three additional tornado reports exist over France on 25 June that are described in the European Severe Weather Database (Dotzek et al. 2009; Groenemeijer and Kühne 2014) as “very likely strong tornado during the severe tornadic episode of June 24 and 25th 1967.” These reports occurred at Merck-Saint-Liévin, Boulogne-sur-Mer, and Bergues (<http://www.keraunos.org/climatologie/les-tornades-en-france/liste-tornades/liste-des-tornades-en-france-en-1967.html>). These are not well documented tornado reports (i.e., the translation reads, “cases for which strong presumptions are present, but where certain validation criteria are missing or suffer from uncertainty”), so how they determine the EF ratings on this website is unknown. We have not found any other information pertaining to these tornadoes. For these reasons, we have not discussed them further in this article.

to repeat itself, would we be able to forecast it today using modern methods? What would a convective outlook look like for a tornado outbreak of this magnitude? Would simulated reflectivity provide a reasonable analog to what the pan-European radar network would show? Are we able to use numerical modeling limited by coarse gridded reanalyses as input conditions to perform a hindcast to represent features that would potentially spawn tornadoes?

This study answers these questions through an analysis of historical meteorological observations and other damage information in conjunction with a numerical model simulation nested from synoptic to convection-resolving scales. The model output is used in three ways. First, the model output from domains on the synoptic scale is provided to an ESTOFEX forecaster to create a realistic convective outlook. Second, simulated radar reflectivity and surface winds from the convection-resolving domain are used to make a radar mosaic plot akin to that shown by the Operational Programme for the Exchange of Weather Radar Information (OPERA) network (Huuskonen et al. 2014) that could be used to generate a nowcast to determine if and when features that could indicate tornadoes appear. Third, footprints of rotating updrafts are produced from model output from the convection-resolving domain (Roebber et al. 2002; Kain et al. 2008) to compare to the reported tornado tracks. By using the model output in these three ways, the effectiveness of the model simulation can be assessed. In addition, the quality of the simulation will reveal how sensitive the model forecast is on the mesoscale and storm-scale to being initialized from synoptic-scale reanalyses.

The structure of this paper is as follows. Section 2 discusses the synoptic setting and historical observations of the event from surface and upper-tropospheric charts, past literature, and storm reports. Section 3 discusses the setup of the convection-resolving model simulation used to reconstruct the event. Section 4 shows the synoptic-scale model simulation and describes how it would be used by ESTOFEX and other organizations throughout Europe (e.g., the national meteorological services) to produce a convective outlook. Section 5 shows the evolution of the simulated storms on both days of the outbreak, examining their morphologies from simulated radar imagery and comparing them to observations. Section 6 discusses the simulated footprints of updraft helicity to provide a comparison to the historical tornado tracks. Section 7 concludes this article.

2. Observed synoptic overview and convective storms

Although the outbreak of 24–25 June 1967 has been studied previously (Bordes 1968; Wessels 1968; Weston

1970; Dessens and Snow 1989; Stensrud 2001), these analyses mainly focus on either the French tornadoes on 24 June (Bordes 1968; Dessens and Snow 1989) or the Belgian and Dutch tornadoes on 25 June (Wessels 1968; Weston 1970). As with Stensrud (2001) and Antonescu et al. (2018), this present study views the outbreak as a whole over both days. This integrated approach is facilitated by the synoptic setting being remarkably similar on both days and the resulting tornadic storms being only a few hundred kilometers apart. In fact, the nearly stationary pattern was recognized by KNMI for the potential to produce tornadic storms on 25 June and led to the first European tornado forecast. The similarity in the synoptic setting will also allow us to examine the details that made the evolution of the event and parent storms of the tornadoes different on the two days.

a. Synoptic analysis

The surface analysis at 1200 UTC 24 June 1967 (Fig. 1a) shows a strong cyclone southeast of Ireland. (All geographic locations mentioned in the text appear in Fig. 2.) Associated with this low was a long cold front extending equatorward to Spain. Southerly surface winds over most of France brought warm air from the Mediterranean to a strong stationary front just north of 50°N (Fig. 1a). This front was characterized by a strong temperature gradient, with Brussels at 20°C being 7°C colder than Paris, 260 km to the south-southwest. As the cyclone center slowly moved southeastward, the stationary front began moving northward, becoming a warm front. The cold front proceeded eastward, cutting across France by 1200 UTC 25 June (Fig. 1b). The cold front also possessed a remarkable temperature gradient, with a 9°C difference between Clermont–Ferrand at 28°C and Tours at 19°C, about 250 km to the west (Fig. 1b). Prefrontal flow across much of France remained light and southerly.

At 500 hPa on 24 June, a vertically stacked, closed low was present over the Atlantic Ocean off the coast of Ireland (Fig. 3a). By 25 June, the closed low had moved eastward (Fig. 3b). The strongest 500-hPa winds remained over France during both 24 and 25 June, maintaining strong southwesterlies aloft over the southerlies at the surface. These height and surface fields are similar to the typical summertime synoptic pattern that is conducive to tornadoes in France (Fig. 11 in Dessens and Snow 1989).

b. Convective storms on 24 June

Unfortunately, we were able to obtain only a small number of radar images for the storms associated with the severe weather events on 24–25 June 1967. Bordes (1968) provided a short description of the radar imagery from the Bourget radar on 24 June. At 1710 UTC, the observed radar echoes, with echo-top heights exceeding

FIG. 1. Excerpts from Met Office Daily Weather Summary: (a) 1200 UTC 24 Jun and (b) 1200 UTC 25 Jun 1967. Station models use standard U.K. notation with temperature ($^{\circ}\text{C}$) in the upper left of the station model; present weather to the left; pennants, barbs, half-barbs, and circles denoting wind speeds of 25, 5, and 2.5 m s^{-1} , and calm, respectively; and sky cover is described in https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/library-and-archive/library/publications/factsheets/factsheet_11-interpreting-weather-charts.pdf. (Crown copyright. Contains public sector information licensed under the Open Government Licence v1.0.)

12 km (where echo top is defined as the highest appearance of any associated reflectivity above ground level), stretched over a region southwest, west, and north of Beauvais, where the tornadoes were first reported (Davenescourt at 1810 UTC, Palluel at 1940 UTC, and Pommereuil at 2000 UTC). By 1800 UTC, the radar echoes had moved north of Beauvais (Fig. 4). After 1800 UTC, no radar images were available, and Bordes (1968) speculated that “[the] strong cumulonimbus [shown in the radar data at 1800 UTC was] at the origin of the tornadoes and other violent phenomena that

occurred between Serevillers and Pommereuil.” Given that the distance between the center of the radar echo and Pommereuil was 111 km and that the estimated speed of the storm was about 16 m s^{-1} , the storm would have reached Pommereuil sometime around 2000 UTC (Bordes 1968), which is the time the tornado hit Pommereuil.

c. Convective storms on 25 June

On 25 June, the cold front lay over northeastern France and was associated with convective storms. An F2 tornado occurred at Argoules, France, at 1145 UTC. Around 1300 UTC, wind gusts damaged Abbeville, France. Wessels (1968) provided a detailed analysis of the severe storms that occurred over Belgium and the Netherlands. By 1400 UTC, the cold front reached the border between France and Belgium, and a convective cell developed in the prefrontal airmass that produced tennis-ball-sized hail (6–7 cm) near Bergen, Belgium. At 1500 UTC 25 June, data from the Bourget radar showed a strong, isolated reflectivity maximum about 290 km northeast from the radar (Bordes 1968). The cell reached its maximum intensity (echo-top height estimated at around 14 km) and for the next two hours produced hail almost continuously. This cell was over Oostmalle, Belgium, which was hit by a tornado between 1506 and 1515 UTC. Wessels (1968) speculated that the same cell that produced the Oostmalle tornado was also associated with the tornado that hit Chaam, Netherlands, between 1527 and 1540 UTC.

Radar imagery for 25 June was also available between 1530 and 1630 UTC from the De Bilt radar in the Netherlands, located northeast of Tricht (Fig. 5). At 1530 UTC, the radar imagery showed the eastward-advancing convective line and the storms from the prefrontal region (Fig. 5a). The location of a possible supercell that produced the Chaam tornado is indicated by the red arrow in Fig. 5a. The cold front reached the western Netherlands around 1600 UTC (Fig. 5b). Weather stations along the coast reported wind gusts up to 28 m s^{-1} . A tornado first hit Nieuwaal at 1610 UTC and then damaged Tricht at 1624 UTC. Specifically, Wessels (1968) speculated that the radar data at 1630 UTC showed a hook echo corresponding with the location of Tricht (Fig. 5c). With this limited information as to the structure and evolution of the convective storms associated with the outbreak, we turn to a convection-resolving model hindcast to further explore this event.

3. Numerical model description

The model hindcast is used three ways in this study, with distinct advantages compared to using reanalyses.

FIG. 2. Map of geographical locations mentioned in the article.

First, model output at a synoptic scale provides the background for a hindcast, representing the operational global models of today. Then, nested grids within the synoptic-scale domain can resolve meso-scale and convective-scale processes, revealing meso-scale boundaries that assisted in the deepening of convection and indicated the morphologies and evolutions of the individual convective storms. Second, simulated radar reflectivity can be produced at high temporal frequency, serving as a proxy for the modern pan-European radar composites available in real time (OPERA; Huuskonen et al. 2014). Third, footprints of severe weather parameters can be generated to compare directly to the historical storm reports. Specifically, we focus on high values of updraft helicity as a measure of the potential for rotating updrafts (i.e., mesocyclones), which may precede or be associated with tornadoes. The present study uses the model output for these three purposes in the next sections.

The Advanced Research version of the Weather Research and Forecast (WRF-ARW) Model (Skamarock

et al. 2008) version 3.7.1 was used to hindcast this event. The simulation was run for 48 h from 0000 UTC 24 June 1967 through 0000 UTC 26 June 1967. Four nested grids at 60-km, 20-km, 4-km, and 800-m horizontal grid spacing were specified (Fig. 6). No data assimilation was employed. The simulation used Thompson et al. (2008) microphysics, the RRTMG radiation scheme for both shortwave and longwave radiation (Iacono et al. 2008), the Mellor–Yamada–Janjić planetary boundary layer scheme (Mellor and Yamada 1982; Janjić 1994, 2002), and the Noah land surface model (Tewari et al. 2004). The Tiedke cumulus parameterization scheme (Tiedtke 1989; Zhang et al. 2011) was used on the outermost two grids only. These choices of parameterizations have been used for an operational model over Europe (ManUniCast; Schultz et al. 2015) and have demonstrated reasonable success at forecasts of convection over Europe during the past five years of real-time model operation. Atmospheric initial and boundary conditions were provided from the ERA-40 reanalysis (Uppala et al. 2005), whereas the

FIG. 3. Excerpts from NOAA Northern Hemisphere Daily Weather Map 500-hPa heights (dam) and temperature ($^{\circ}\text{C}$) analysis: (a) 1200 UTC 24 Jun and (b) 1200 UTC 25 Jun 1967. (Available at <http://library.noaa.gov/Collections/Digital-Documents/US-Daily-Weather-Maps>.)

land surface initialization was specified by the ERA-20C reanalysis (Poli et al. 2016). This combination was chosen as it provided the most accurate mesoscale reconstruction of the event in comparison to the tornadic damage tracks. This simulation is hereafter referred to as the control simulation.

4. Synoptic-scale hindcast and ESTOFEX outlook

The control simulation presents different perspectives of the tornado outbreak, depending on the resolution of each domain. In this section, we focus on the European synoptic-scale model output provided by the domain with 20-km horizontal grid spacing. We first present the hindcast in section 4a, followed by a description of the ESTOFEX forecasted outlook in section 4b.

a. Synoptic-scale hindcast

The control simulation shows 500-hPa height fields similar to what was observed (cf. Figs. 3 and 7). A 500-hPa closed low was present over the Atlantic off the coast of Ireland (Fig. 7a), which strengthened slightly overnight (Fig. 7b) before moving to the east (Fig. 7c). The closed low weakened over Ireland and the United Kingdom during the afternoon of 25 June (Figs. 7c,d). Southwesterly 500-hPa geostrophic flow occurred over France, and a strong absolute-vorticity maximum arrived onshore at 1200 UTC 25 June (Fig. 7c), which then moved eastward to the border between the Netherlands and Germany by 0000 UTC 26 June (Fig. 7d).

Most unstable convective available potential energy (MUCAPE) values exceeded 3000 J kg^{-1} at 1200 UTC on both 24 and 25 June (Figs. 8a,b). (Here, MUCAPE was calculated as the 500-m averaged parcel with maximum equivalent potential temperature in the column.) The stationary front from Fig. 1a was apparent in the model output over northern France, Belgium, the Netherlands, and Germany on 24 June (Fig. 8a), represented by a drop in simulated MUCAPE from 2500 to 0 J kg^{-1} over a distance of 50–100 km. The cold front from Fig. 1b was simulated across France on 25 June 1967 with values of MUCAPE east of the front over 1000 J kg^{-1} from just north of Spain throughout France, extending into Belgium and northern Germany (Fig. 8b).

The 0–3-km storm-relative helicity and 0–6-km bulk wind difference (commonly referred to as bulk vertical wind shear) are good indicators of tornadic potential when combined with a high-MUCAPE environment (e.g., Davies and Johns 1993; Craven and Brooks 2004; Rasmussen 2003; Anderson-Frey et al. 2016). Here, we calculate storm-relative helicity with the storm movement derived from Bunkers et al. (2000). On 24 June 1967, areas of northern France had modeled 0–3-km storm-relative helicity exceeding $300 \text{ m}^2 \text{ s}^{-2}$ (Fig. 9a). This high storm-relative helicity combined with the high MUCAPE indicates environments favorable for supercells in northern France located near the Belgium–France border and English Channel. High storm-relative helicity persisted across France on 25 June (Fig. 9b), with a secondary maximum exceeding $300 \text{ m}^2 \text{ s}^{-2}$ over Belgium, the Netherlands, and Luxembourg (BENELUX). The maximum values of 0–6-km bulk wind difference on 24 June were nearly coincident with the maxima of high storm-relative helicity, although slightly more offshore of northern France (cf. Figs. 9a and 10a). On 25 June, however, the maxima of both storm-relative helicity and bulk wind difference overlapped (cf. Figs. 9b and 10b).

Preconvective WRF-ARW soundings from the region where the storms initiated at Pommerueil on 24 June

FIG. 4. Manually drawn representation of radar echoes (solid black regions) from the Bourget radar at 1800 UTC 24 Jun 1967. Range rings are at every 20 nautical miles (37 km). (Adapted from Fig. 15 in Bordes 1968).

show MUCAPE exceeding 2700 J kg^{-1} (Fig. 11a). The winds veered strongly with height from east-southeasterly near the surface to southerly at 850 hPa and then southwesterly at 3 km. This sounding indicates an unstable atmosphere and a wind profile favorable for strong low-level rotation. Preconvective WRF-ARW soundings over the Oostmalle area on 25 June (Fig. 11b) show that the atmosphere was not quite as conducive to deep convection and rotation as 24 June, with MUCAPE of only 274 J kg^{-1} and much less veering with height than the previous day. However, MUCAPE varies a lot across this area, with Oostmalle located just northeast of a region of at least 1500 J kg^{-1} MUCAPE (Fig. 8).

b. ESTOFEX hindcasted outlook

In the United States, the SPC issues convective outlooks, a categorical product on the probability of severe weather, with separate probabilistic products for tornadoes, hail, and wind. However, there is no official pan-European organization that issues similar forecasts and products despite growing calls and awareness of this issue (Doswell 2003; Dotzek 2003; Doswell 2015; Antonescu et al. 2016; Miglietta and Rotunno 2016). To address this issue, ESTOFEX was founded in 2002 to provide a

categorical European-wide forecast to assist meteorologists in predicting severe weather hazards. ESTOFEX is a noncommercial, voluntary engagement of individuals without institutional support, which means that forecasts are not necessarily guaranteed on a daily basis. However, the ESTOFEX guidance has been, and continues to be, a reliable source of forecasts on severe convective storms in Europe (Brooks et al. 2011).

ESTOFEX defines *severe convective weather phenomena* as hail with a diameter of at least 2 cm, any tornado, wind gusts exceeding 25 m s^{-1} , or rainfall exceeding 60 mm, whereas ESTOFEX defines *extremely severe convective weather phenomena* as hail with a diameter of at least 5 cm, wind gusts exceeding 33 m s^{-1} , or tornadoes of EF2 damage magnitude or stronger. ESTOFEX forecasts focus on a three-level severe hazard, with Level 1 representing a 5% probability of severe convective weather phenomena within 40 km of a point, Level 2 representing a 15% probability of severe convective weather phenomena, and Level 3 representing a 15% probability of extremely severe convective weather phenomena. Areas where lightning is expected are analyzed at 15% and 50% probabilities. Forecasts and outlooks are archived from the start of ESTOFEX in

FIG. 5. Radar echoes from the De Bilt radar on 25 Jun 1967 at (a) 1530 UTC, with the photograph of the radar screen taken during the Chaam tornado (approximately indicated by the red arrow), (b) 1600 UTC, and (c) 1630 UTC, with the photograph of the radar screen taken after the Tricht tornado (the red arrow shows the approximate position of Tricht). Range rings are at every 20 nautical miles (37 km). (Adapted from Fig. 5 in [Wessels 1968](#)).

2002 and more recently are compared directly with results from the European Severe Weather Database ([Dotzek et al. 2009](#); [Groenemeijer and Kühne 2014](#)). Forecasters use a collection of publicly available meteorological data, including observations, satellite, radar, and several different numerical models, to produce their forecasts.

To provide a modern analog to the hindcast of this event, ESTOFEX-associated forecaster Tomáš Púčik was contacted to produce an outlook for an unspecified date. All references to dates from June 1967 were removed from the WRF-ARW Model output on the domain with the 20-km grid spacing and provided at hourly temporal increments through a web-based interface. Fields of surface-based meteorological quantities, convective indices, and indicators of rotation (e.g., absolute vorticity, storm-relative helicity) were provided to the forecaster along with fields at standard

pressure levels of height, temperature, moisture, wind, and absolute vorticity. The forecaster was then asked to provide an outlook for the two days of model output, with 24 June 1967 referred to as day 1 and 25 June 1967 referred to as day 2. The resulting outlooks for day 1 and day 2 are shown in [Fig. 12](#). In addition to the graphical outlook, the forecaster produced a written outlook given here in full and without alteration.

Dominant synoptic scale feature is a deep trough at mid to upper troposphere over the Atlantic, moving slightly eastward from Day 1 to Day 2. Strong jet-stream surrounds the trough with $40+ \text{ ms}^{-1}$ at 300 hPa at its forward flank. Towards east, jet-stream curves around the ridge that stretches from the Central Mediterranean into Central Europe. Closer to the surface, a frontal zone runs through Spain, western France, United Kingdom into Northern Germany and Poland. Cold

FIG. 6. WRF-ARW Model configuration for the control simulation, showing the four domains with 60-km, 20-km, 4-km, and 800-m horizontal grid spacings.

frontal part of the system is forecast to advance eastwards, especially during the Day 2.

Lower-tropospheric moisture combined with mid-tropospheric lapse rates exceeding $8^{\circ}\text{C km}^{-1}$ led to CAPE [convective available potential energy] values over 1000 J kg^{-1} and locally exceeding 3000 J kg^{-1} in a wide swath from Southern France towards BENELUX, Northern Germany and further into Poland and Ukraine. At the same time, strong mid to upper tropospheric flow results in significant vertical wind shear, with 0–6-km bulk vertical wind difference values reaching $20\text{--}30 \text{ m s}^{-1}$ over much of the warm sector ahead of the cold front. Thus, CAPE–shear parameter space seems conducive to severe, well organized convection, including supercells.

Model simulates mostly isolated convective mode during both days, which is reasonable given the lack of strong synoptic scale forcing and rather slow moving frontal boundary. Any storm that develops has a high chance of becoming supercell capable of very large hail and severe wind gusts. For both days, a small scale low is forecast to develop along and/or ahead of the front with backing of the surface flow to easterly direction. In conjunction with southwesterly flow at 850 hPa reaching $15\text{--}20 \text{ m s}^{-1}$ in the evening hours over western France, BENELUX and Northwestern Germany, degree of lower-tropospheric shear is very high. As storm-relative helicity values are forecast to exceed $300 \text{ m}^2 \text{ s}^{-2}$ during both days and cloud bases stay around or below 1000 m, isolated supercells will pose significant tornado risk with strong, F2+, tornadoes well possible.

For both Day 1 and Day 2 forecasts, Level 3 is issued for regions, where ingredients look favorable for supercells capable of very large hail, strong tornadoes and where model simulates storms with high values of reflectivity and updraft helicity. Level 2 is issued for the regions with either lower probability of convective initiation and/or where the lower tropospheric shear is weaker, reducing the strong tornado risk.

The ESTOFEX outlook (Fig. 12) identifies one Level-3 region on each day, with each region possessing ingredients favorable for supercells capable of producing large hail and strong convective winds. These are the same regions that are located near the stationary front separating the warm Mediterranean air mass from the cooler air over the North Sea (Fig. 1a). The next section of this article shows the model-simulated radar imagery focusing on those two regions: northern France into Belgium on 24 June 1967 where the tornadoes in Davenescourt, Palluel, and Pommereuil occurred and BENELUX into Germany on 25 June 1967 where the tornadoes in Oostmalle, Chaam, and Tricht occurred.

5. Analysis of simulated reflectivity

This section examines the morphology and evolution of the modeled storms on both 24 and 25 June (section 5a) and compares them to observations of radar imagery from 1967 (section 5b).

a. Nowcasting analog using simulated reflectivity

To see the storm-scale evolution, the model output from the domain with 800-m grid spacing is shown, focusing on the two Level-3 regions from Fig. 12. At 1400 UTC 24 June, the model-simulated reflectivity (Koch et al. 2005) at 1 km AGL shows initial convection organizing into a line from northern France into the middle of the United Kingdom (Fig. 13a). However, at the bottom edge of the map (circled and labeled as Cell 1), two small reflectivity maxima occur in the southerly inflow. At 1500 UTC, Cell 1 grows in conjunction with an apparent increase in low-level convergence (Fig. 13b). As the cell moves eastward with the mean winds aloft by 1600 UTC, it encounters a mesoscale convergence zone near the France–Belgium border (Fig. 13c) that is consistent with the stationary front in Fig. 1a. At this time, Cell 1 possesses a mesocyclone with rotation occurring on its southern edge heading toward Palluel (look ahead to the updraft helicity maxima in Fig. 15a). A modern nowcaster would recognize this as a storm capable of producing a tornado, especially when interpreted in the context of the storm’s local environment,

FIG. 7. The 500-hPa geopotential height (solid lines every 6 dam) and absolute vorticity ($\times 10^{-5} \text{ s}^{-1}$; shaded according to scale) from the WRF-ARW domain with 60-km horizontal grid spacing: (a) 1200 UTC 24 Jun, (b) 0000 UTC 25 Jun, (c) 1200 UTC 25 Jun, and (d) 0000 UTC 26 Jun 1967.

suggesting a warning could be issued for Cell 1. By 1700 UTC, Cell 1 also shows a well-defined hook pointing southward (Fig. 13d), indicating a possible supercell. The linear system present at 1400 UTC has nearly dissipated, leaving only the nearly discrete

mesocyclone (cf. Figs. 13a,d). Cell 1 moves across Belgium and the Netherlands during 1800–2000 UTC (Figs. 13d–g), becoming more linear with an embedded mesoscale convective vortex located toward the interior of the storm (apparent near the Netherlands–Germany

FIG. 8. Sea level pressure (solid lines every 4 hPa) and MUCAPE (J kg^{-1} ; shaded according to scale) from the WRF-ARW domain with 20-km horizontal grid spacing: (a) 1200 UTC 24 Jun and (b) 1200 UTC 25 Jun 1967. Here, MUCAPE was calculated as the 500-m averaged parcel with maximum equivalent potential temperature in the column. The large black dot indicates the location of Oostmalle, Belgium.

FIG. 9. The 0–3-km storm relative helicity ($\text{m}^2 \text{s}^{-2}$; shaded according to scale), with the storm movement calculated as in [Bunkers et al. \(2000\)](#), from the WRF-ARW domain with 20-km horizontal grid spacing: (a) 1200 UTC 24 Jun and (b) 1200 UTC 25 Jun 1967.

border at 2000 UTC, [Fig. 13g](#)) and producing strong (25–30 m s^{-1}) westerly winds ([Fig. 13h](#)).

The mesoscale evolution on 25 June ([Fig. 14](#)) is in stark contrast to that of 24 June. Whereas on 24 June one large right-moving supercell dominated the Level-3 region, on 25 June there are three separate cells (labeled

FIG. 10. The 0–6-km bulk wind difference (m s^{-1} ; shaded according to scale) from the WRF-ARW domain with 20-km horizontal grid spacing: (a) 1200 UTC 24 Jun and (b) 1200 UTC 25 Jun 1967.

as Cell 2, Cell 3, and Cell 4). Cell 2 is first identified at 1200 UTC as a small feature along a boundary between southerly winds from southern Belgium to central Belgium and more southwesterly winds in northern Belgium (Fig. 14a). Cell 2 moves eastward along this boundary through Belgium and into the Netherlands and Germany. The structure of Cell 2 indicates a mesocyclone from 1300

FIG. 11. Preconvective soundings from the WRF-ARW domain with 800-m horizontal grid spacing: (a) Davenescourt, France, at 1200 UTC 24 Jun 1967 and (b) Oostmalle, Belgium, at 1200 UTC 25 Jun 1967. The red dashed line represents the rising path of the most unstable parcel after saturation. Winds are represented by pennants, barbs, and half-barbs denoting wind speeds of 25, 5, and 2.5 m s^{-1} .

to 1400 UTC as it moves along the boundary (Figs. 14b,c; look ahead to the updraft helicity maxima in Fig. 15a). As Cell 2 moves into Germany at 1400 UTC, Cell 3 begins to form along the boundary (Fig. 14c). Cell 3 intensifies as it undertakes a similar path to the east-northeast along the boundary, reaching its maximum intensity at 1700 UTC (Fig. 14f). By 1800 UTC, the boundary moves north, and the surface winds north of the boundary become more easterly as the precipitation becomes more

FIG. 12. ESTOFEX hindcast convective outlooks for (a) 24 Jun and (b) 25 Jun 1967. Thin and thick yellow lines represent 15% and 50% probabilities of lightning, respectively.

poorly organized along the coast of the Netherlands (Fig. 14g). By 1900 UTC, another isolated cell (Cell 4) forms at the northern end of a north–south-oriented boundary with strong westerly winds behind (Fig. 14h).

b. Simulated reflectivity comparison with observations

Despite the relative lack of radar data in 1967, the single cell observed north of Beauvais at 1800 UTC 24 June (Fig. 4) appears to be comparable to the modeled Cell 1 at 1500 UTC (Fig. 13b). For day 1, the model

initiates the convection around 2–3 h before it is observed from storm reports, and Cell 1 travels north of the observed tornadoes in Davenescourt, Palluel, and Pommereuil by around 20–30 km.

For day 2, the model shows cells that possess rotation and small hook echoes along a northward-moving convergence line, passing over Oostmalle, Chaam, and Tricht. The modeled convergence line where Cells 2 and 3 occur does not directly overlay with the reported tornadoes; the simulated boundary is 40–50 km farther south. Cell 3 occurs when the tornadoes were reported at this southern location. The time in the simulation when simulated reflectivity on day 2 best compares to observations is at 1900 UTC (Fig. 14h), which shows a similar linear feature as Wessels (1968) at 1630 UTC (Fig. 5c). This linear feature is behind Cell 4 and occurs after the time of the observed tornado reports (1615–1710 UTC).

6. Footprints of simulated rotating updrafts versus observed tornado tracks

The model output is used to calculate and plot the tracks of rotating updrafts, which represent the parent cyclonic circulations (i.e., mesocyclones) that may precede tornadoes (e.g., Fig. 11 in Roebber et al. 2002). Such plots are analogous to rotation tracks derived from radar (Miller et al. 2013). To represent these rotating updrafts, we calculate the 2–5-km updraft helicity as defined by Kain et al. (2008) (Fig. 15). For 24 June, most of the simulated maxima of updraft helicity are generated by Cell 1, which travels toward the northeast and passes north of Davenescourt, Palluel, and Pommereuil (Fig. 15a). Maximum values of 2–5-km updraft helicity frequently exceed $50 \text{ m}^2 \text{ s}^{-2}$ and have maxima over $250 \text{ m}^2 \text{ s}^{-2}$ along the path of Cell 1, with a track labeled 1 in Fig. 15a running parallel to the observed tracks. Whereas Track 1 apparently moves toward the location of the observed tornado in Palluel, a time-lapse view of the areas of Cell 1 that exceed 35 dBZ (Fig. 15b) shows the cell joining and splitting, with two centers of high radar reflectivity within Cell 1. As this cell approached the France–Belgium border, two mesocyclones were present (marked as A and B). These mesocyclones can be linked to three more tracks of high updraft helicity (Tracks 2, 3, and 4) as the storm moves across Belgium, with mesocyclone A being associated with Tracks 2 and 4 and mesocyclone B associated with Track 3. These three tracks of high updraft helicity indicate the strengthening and weakening of these two mesocyclones within the splitting/joining cell as it moves across France and Belgium. The two mesocyclones within one region of heavy

FIG. 13. Simulated radar reflectivity for 24 Jun (dBZ; shaded according to scale) and vectors of 10 m AGL wind speed from the WRF-ARW domain with 800-m horizontal grid spacing: (a) 1400, (b) 1500, (c) 1600, (d) 1700, (e) 1800, (f) 1900, (g) 2000, and (h) 2100 UTC. Cell 1 is indicated by a black circle. The magenta line in (c) represents the mesoscale convergence zone. The inset of Cell 1 is shown in (d). Wind vectors are plotted every 16 km.

FIG. 14. Simulated radar reflectivity for 25 Jun (dBZ; shaded according to scale) from the WRF-ARW domain with 800-m horizontal grid spacing: (a) 1200, (b) 1300, (c) 1400, (d) 1500, (e) 1600, (f) 1700, (g) 1800, and (h) 1900 UTC. Cell 2 is indicated by a blue circle in (a)–(c), Cell 3 is indicated by a black circle in (c)–(f), and Cell 4 is indicated by a red circle in (h). Wind vectors are plotted every 16 km.

FIG. 15. Storm footprints for 24 Jun 1967 from the WRF-ARW domain with 800-m horizontal grid spacing. (a) The 2–5-km updraft helicity maxima exceeding $50 \text{ m}^2 \text{s}^{-2}$ (colored according to scale), plotted at 5-min intervals during 1400–2000 UTC 24 Jun 1967, with four tracks of high updraft helicity highlighted (labeled 1, 2, 3, and 4). Locations of the observed Davenescourt, Palluel, and Pommereuil tornado tracks are overlain. (b) Overview of hourly simulated radar reflectivity (dBZ; colored according to scale) of Cell 1 during 1400–1800 UTC 24 Jun 1967 from Fig. 13. Mesocyclones A and B are labeled at 1700 UTC.

precipitation are consistent with the reported tornadoes in Davenescourt (1840 UTC), Palluel (1935 UTC), and Pommereuil (2000 UTC), all of which had tracks in similar northeastward directions and within 40–50 km of each other.

FIG. 16. Storm footprints for 25 Jun 1967 from the WRF-ARW domain with 800-m horizontal grid spacing. The 2–5-km updraft helicity maxima exceeding $50 \text{ m}^2 \text{s}^{-2}$ (colored according to scale), plotted at 5-min intervals during 1200–2000 UTC 25 Jun 1967, with three tracks labeled (A, B, and C). Locations of the observed Oostmalle, Chaam, and Tricht tornado tracks are overlain.

The tracks of the simulated updraft helicity on 25 June (Fig. 16) are not as easy to attribute to single precipitation features as are the results from 24 June. The maximum updraft helicity for the storms on 25 June (Fig. 16) shows rotation for all three of the cells on this day at multiple times as they proceed along the convergence line. This rotation is consistent with the storm morphologies represented by the simulated reflectivity (Fig. 14). Cell 2 and Cell 3 take similar tracks, with Track A being associated first with Cell 2 but with the highest values of updraft helicity associated with Cell 3. Cell 3 is also associated with the swath of high updraft helicity in Track B. Cell 4 (Fig. 14) is associated with Track C (Fig. 16), with Track C being similar in length to the distance from Oostmalle to Tricht. Track A and Track B are south of the reported tornadoes, whereas Track C is to the north. However, all the modeled tracks are oriented in a similar direction as the observed tornadoes, suggesting some measure of veracity between the observed tornado tracks and the modeled tracks. The control simulation produced severe storms near the actual storm reports, except no plausible simulated convection formed near the actual tornado in Argoules (not shown). Based on this model output, it would be harder to make a good tornado forecast or nowcast using the rotation tracks for 25 June compared to 24 June as the updraft helicity values were

smaller, despite the environment being favorable on both days.

A reviewer of this article expressed concern that the values of updraft helicity in our control simulation are smaller than in other previously published simulations (e.g., [Loken et al. 2017](#)). For example, in the 800-m grid-spacing domain of the control simulation, maxima on 24 June exceeded $250 \text{ m}^2 \text{ s}^{-2}$ in [Fig. 15a](#) and maxima on 25 June exceeded $150 \text{ m}^2 \text{ s}^{-2}$ in [Fig. 16](#), although a few maxima do exceed $250 \text{ m}^2 \text{ s}^{-2}$. These maxima are less than maxima in 63 forecasts at 4- and 1-km grid spacing (99th percentile values $50 \text{ m}^2 \text{ s}^{-2}$ and $450\text{--}500 \text{ m}^2 \text{ s}^{-2}$, respectively) over the central United States during the NOAA Hazardous Weather Testbed Spring Forecasting Experiments (Table 3 in [Loken et al. 2017](#)). Ground truth for such values is obviously a challenge for a case from June 1967, whereas such values could conceivably be calculated from dual-Doppler wind analyses for U.S. storms. Furthermore, Table 4 of [Loken et al. \(2017\)](#) showed their model verification when thresholds for updraft helicity were set at 25, 50, 75, 100, and $125 \text{ m}^2 \text{ s}^{-2}$, whereas our minimum plotting thresholds were set at $50 \text{ m}^2 \text{ s}^{-2}$. So, our threshold for plotting fits comfortably within the thresholds for verification in [Loken et al. \(2017\)](#), even for their 1-km grid-spacing forecasts. Our experience with updraft helicity from the COSMO-DE model (2.8-km grid spacing) in the ESSL Testbed is similar to that of [Loken et al. \(2017\)](#); we frequently find maxima larger than $400 \text{ m}^2 \text{ s}^{-2}$ in high-CAPE-high-shear environments. Indeed, we expect that the maxima of updraft helicity would be larger at higher resolution, but it is unclear that the lower values in our control simulation would encompass substantially more area or be less representative of important meteorological features because of the smaller values of the maxima. If there is no updraft or vorticity in the flow field (both of which are highly localized quantities), then their product (as the integrand of the updraft helicity equation) would be small. Thus, it is not clear that the issue raised by the reviewer is a critical concern, and such a result actually should be expected.

7. Conclusions

After hearing reports of tornadoes throughout France on 24 June 1967 in the evening and recognizing the ingredients that could contribute to tornadic storm formation were going to be present over the Netherlands on the next day, KNMI issued a forecast for “possible tornadoes” on the morning of 25 June. This statement was the first known tornado forecast over Europe, and for the residents of Oostmalle, Chaam, and Tricht, it may have provided some advance knowledge of the

events to come, although no information exists on whether or not those residents received or acted upon the forecast. In the present study, we produced a hindcast of the tornado outbreak of 24–25 June 1967, discussing past observations and using numerical model output to interpret a plausible scenario for the convective storms.

The model output agreed well with the actual synoptic pattern. The event of 24–25 June 1967 was a strong synoptically forced tornado outbreak associated with a slow-moving closed low in the jet stream and a stationary–warm front at the surface. The ingredients for deep moist convection were present, with moist southerly flow leading to a high-MUCAPE, high-shear environment for Europe. In that sense, this event is strongly reminiscent of the conceptual model for convective storms offered by [Newton \(1963\)](#). This pattern recognition led to KNMI’s successful tornado forecast 53 years ago.

The convective-scale model output produced individual rotating convective storms that plausibly could have produced tornadoes within kilometers and hours of the actual storms. Although we do not expect a one-to-one relationship between the modeled storms and the actual storms from 1967, the model output was similar to what was observed. From the model output, the tornadoes of 24 June 1967 could have plausibly all come from a single cell that evolved from one to two centers of circulation, with cell mergers potentially occurring during the storm evolution.

In contrast to the single precipitation feature present on 24 June (even with potential cell mergers and splitting), our simulation revealed multiple cells from multiple discrete precipitation features that moved along the same convergent boundary on 25 June. This evolution indicates that, despite the observed tornado tracks being colinear, multiple storms may have produced the tornadoes. Although the model output produced severe storms near the actual storm reports on 24 June in France and 25 June in Belgium and the Netherlands, the model did not produce any plausible convection that caused the tornado in Argoules on 25 June.

This hindcast using a high-resolution, convection-allowing model shows that we have the ability to simulate storms with mesocyclones from modern-day reanalyses, as previous studies have also demonstrated for other historical convective storms ([Locatelli et al. 2002](#); [Shafer et al. 2009, 2010](#); [Corfidi et al. 2010](#); [Apsley et al. 2016](#)). This study shows that if a similar event to the 24–25 June 1967 outbreak were to occur today over Europe, modern severe storm forecasting techniques would be able to predict the timing and intensity of the storm reports to be useful in an operational

setting. The lead time provided by ESTOFEX-style outlooks would greatly help national meteorological organizations prepare and disseminate forecasts to the public that could potentially be affected. Enhanced now-casting abilities using radar (or simulated reflectivity) and modeled surface wind speeds at subkilometer grid spacings can also help determine potential areas where severe convection could occur. This study shows the need for further investment in these types of systems and now-casting training, as it may help forecast a similar event to this in the future.

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