SEVERE CONVECTIVE STORMS IN EUROPE

Ten Years of Research and Education at the European Severe Storms Laboratory

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The European Severe Storms Laboratory studies severe weather, climate, and forecasting; organizes forecaster training; and manages a large database of severe weather reports.

During the second half of the twentieth century, research on convective storms was relatively scarce and uncoordinated in Europe compared to efforts in the United States (Dotzek et al. 2009; Antonescu et al. 2016). Scientific and forecasting practice was hampered by the fragmentation of research by national borders and a lack of awareness of the frequency and intensity of convective hazards among forecasters, researchers, and the public. Severe convective storms could, and often were, considered to be freak events. By the late 1990s, several researchers started to raise awareness that hazards such as tornadoes occur throughout Europe, and they took action. This awakening would lead to the founding of the European Severe Storms Laboratory (ESSL), a nonprofit research organization dedicated to severe convective storm research and education.

Given that ESSL has just celebrated its 10-yr anniversary, we felt that now was the time to look back

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Table 1. Key events in the history of ESSL.

1–4 Feb 2000	Vision of ESSL first presented by Nikolai Dotzek at ETSS Conference in Toulouse, France
11 Nov 2004	ESWD, version 1.00, released online at European Storm Forecast Experiment website
28 Sep 2006	Founding assembly of the European Severe Storms Laboratory e. V.: founding members Nikolai Dotzek, Alois Holzer, Bernold Feuerstein, Pieter Groenemeijer, Dario Giaiotti, Maria-Carmen Llasat, Romualdo Romero, Martin Setvák, Fulvio Stel, and Jenni Teittinen; ESSL is located at DLR in Oberpfaffenhofen, near Munich, Germany
1 Jan 2007	DWD becomes ESSL's first institutional full member
11 Aug 2007	First third-party-funded research project
1 Jan 2010	First project funded by the European Union
29 May 2010	Unexpected passing of Director Nikolai Dotzek
4 Jun 2012	First ESSL Testbed at the newly opened ESSL Research and Training Centre in Wiener Neustadt, Austria; this is ESSL's second office and the seat of ESSL's Austrian subsidiary
15 Dec 2015	Release of the EWOB app
1 Jul 2016	Celebration of tenth anniversary of ESSL; ESWD contains 100,000 severe weather reports

at its history, the reasons for its founding, and its successes. Specifically, the successes of ESSL include the first pan-European database of severe weather reports, convective-storm-parameter climatologies from reanalyses, support to operational forecasting, and damage assessments. This article concludes with the prospects for ESSL for the next 10 years and beyond.

Fig. 1. Dr. Nikolai Dotzek (1966–2010), founder of ESSL.

THE FORMATION OF ESSL.

An important first step in fostering European collaboration was the European Conference on Tornadoes and Severe Storms in Toulouse, France, held in 2000 (Table 1). The conference was organized by Dr. Jean Dessens of the French Laboratoire d'Aérologie of the Centre de Recherches Atmosphériques, and Dr. John T. Snow, dean of the Department of Geosciences, University of Oklahoma. The conference brought together scientists from different European countries, many of whom presented national climatologies of tornadoes and hail, demonstrating the significance of convective storm hazards in Europe.

A key person attending this conference was Dr. Nikolai Dotzek (Fig. 1), a scientist from the Institut für Physik der Atmosphäre of the Deutsches Zentrum für Luft- und Raumfahrt (DLR). Dotzek saw the clear need for international collaboration, both within Europe and with colleagues from overseas, in order to further severe storms research. He developed contacts with experts from the United States, including Drs. Charles Doswell III and Harold Brooks at the National Oceanic and Atmospheric Administration's (NOAA) National Severe Storms Laboratory in Norman, Oklahoma. Discussions with them made clear that raising awareness and starting the coordinated collection of severe weather reports by a European "center of excellence" would be key to addressing the hazards of severe convective storms (Doswell 2003). The development and management of such a dataset—eventually becoming known as the European Severe Weather Database (ESWD)—were to become one of the statutory goals of ESSL. Dotzek, along with 10 European scientists, founded ESSL in December 2006 as a spinoff of DLR. In its first years, ESSL was run by Director Dotzek from his office at DLR, together with the executive board, which consisted of Bernold Feuerstein, Alois Holzer, and Pieter Groenemeijer. An important focus of the budding ESSL was to become involved in research projects and to attract members, providing income from grants and membership fees to support ESSL and the ESWD. Only months after being founded, the German Weather Service [Deutscher Wetterdienst (DWD)] became the first institutional member, and ESSL became partner in its first nationally funded research project. Presently, ESWD is still the only pan-European database of ground-truth severe weather reports, an effort that has continued after Dotzek's sudden passing in 2010 (Feuerstein and Groenemeijer 2011). As of ESSL's tenth anniversary in July 2016, the ESWD contained over 100,000 individual severe weather reports.

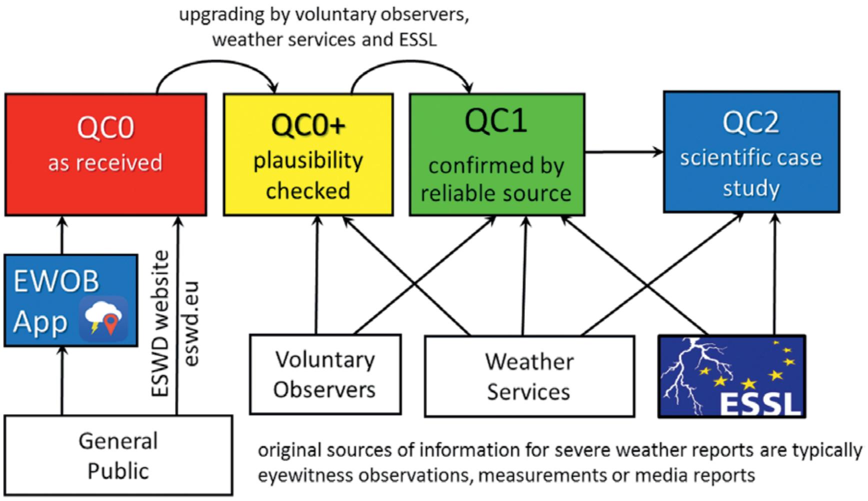

Fig. 2. Flow of severe weather data into and within ESWD. Four levels of data quality control are indicated (QC0, QC0+, QC1, and QC2).

ESWD: A PAN-EUROPEAN DATASET OF SEVERE WEATHER REPORTS. The ESWD has been used for many different purposes. As of November 2016, 67 different peer-reviewed articles reported using the ESWD. These articles included 21 climatological studies, 12 case studies, 11 studies of environmental conditions of severe weather, 8 comparisons with remote sensing products, and 2 studies on forecasting and their verification. Although the ESWD is used for forecast verification, it is not maintained by an organization responsible for forecasting severe weather, as is the case with the U.S. *Storm Data* database (Schaefer and Edwards 1999; McCarthy 2003). Instead, the ESWD relies heavily on voluntary observers, many of whom are organized in national and regional associations (e.g., national Skywarn associations). In addition, several national weather services and ESSL staff contribute new data to the dataset. Media reports are an important source of data that require careful scrutiny. For instance, media reports may not reveal whether wind damage was caused by a tornado or by straight-line winds. ESSL and its partners attempt to resolve such questions as part of their quality-control work (Fig. 2). ESWD reports have a quality flag that is set to one of four levels, depending on the quality of the data and the thoroughness of review (Groenemeijer and Kühne 2014). The quality control flags range from QC0, which applies to any report from the general public, to QC2, which signifies that the event has been a topic of an in-depth case study. In between, QC0+ denotes that a report is deemed plausible after a cursory review, and QC1 means that the report was confirmed by a reliable source (e.g., trusted spotter, weather service, ESSL staff). If the review does not clarify whether the wind damage can be attributed to a tornado or to straight-line winds, the report will be recorded as a wind event with a flag "this event may have been a tornado."

The distribution of the severe weather reports (e.g., large hail, tornadoes, convective severe wind gusts, heavy rain) shows spatial variability across Europe (Fig. 3). For all phenomena, the highest report density occurs over central Europe. Large-hail maxima occur over central Germany, northwestern Italy, and southeastern Austria, whereas tornado maxima occur over northern Germany, the Netherlands, Belgium, Luxembourg, and the United Kingdom. Because the locations of these maxima do not correspond well with maxima in favorable severe weather environments (Figs. 4a,c), underreporting of severe weather reports is likely an issue over southern and eastern Europe (e.g., Groenemeijer and Kühne 2014). Therefore, ESSL strives to gather more reports from these regions by intensifying the cooperation with both national weather services and volunteer observers. To do so, ESSL approaches people who report through the public ESWD web interface and advertises the benefits of ESSL membership to the weather services of southern and eastern European countries. To simplify the collection of reports from the general public, ESSL has recently

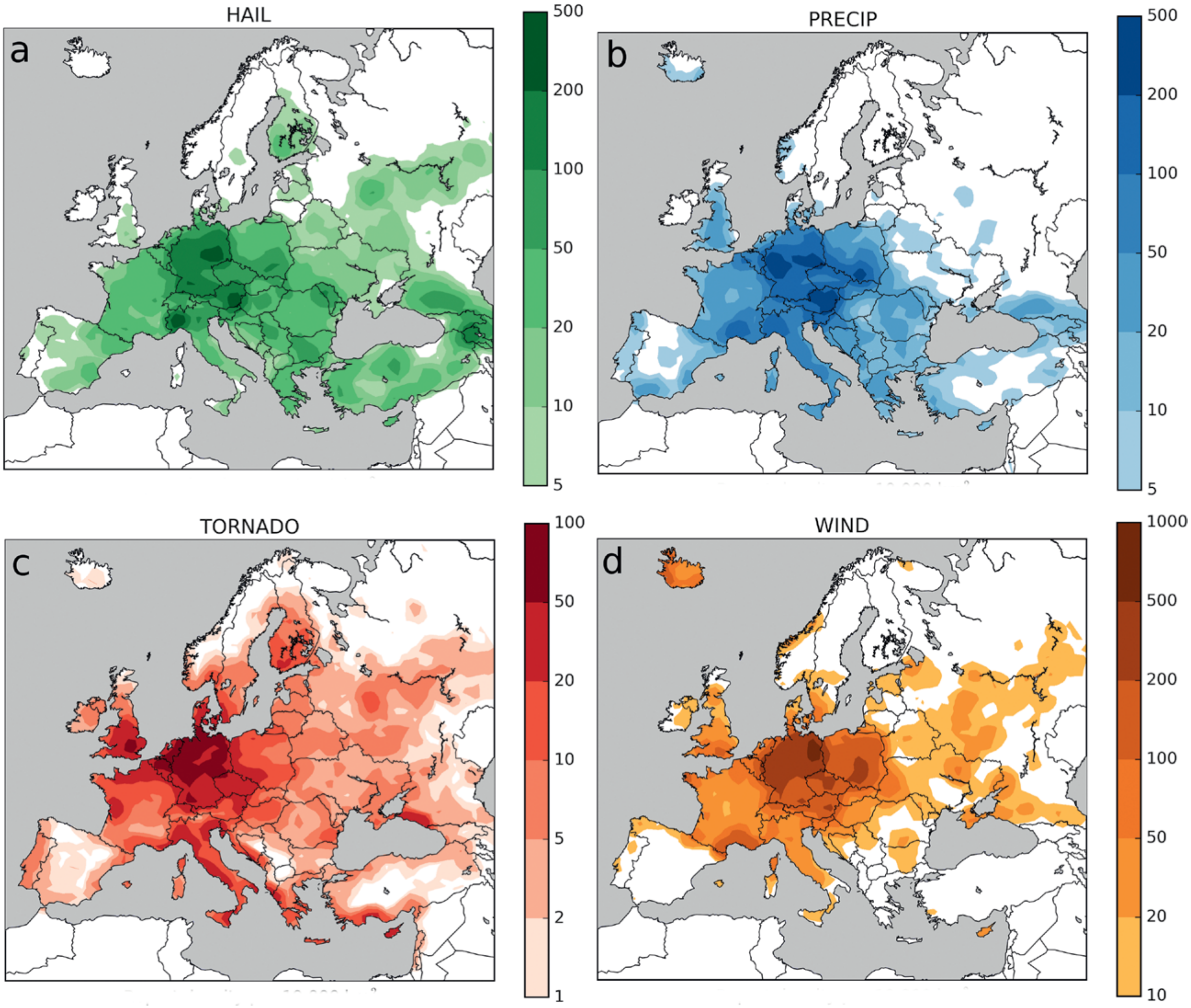

Fig. 3. Density of severe weather reports in ESWD as of Nov 2016. For every 0.5° × 0.5° grid point, all reports within 56.42 km of the point are counted. A circle with this radius has an area of 10^4 km^2.

released an Android and Apple mobile phone app called the European Weather Observer (EWOB). In the near future, reports collected through this app will be integrated into the ESWD after a quality-control step whenever they exceed the ESWD severity thresholds. In the past, efforts to complement the ESWD with several historical and national datasets (Fig. 5) and to increase the network of volunteer observers led to a steady growth in the annual number of severe weather reports (Groenemeijer and Kühne 2014; Antonescu et al. 2017). The number of wind reports has increased fastest of all event types, primarily because an increasing number of wind gust measurements have been included in addition to reported wind damage.

CLIMATOLOGY OF CONVECTIVE HAZARDS FROM REANALYSES. One of the research topics at ESSL addresses the representation of convective storms in numerical models, such as reanalyses, numerical weather forecasting, and climate prediction models. By using reanalyses, the real distribution of the convective severe weather events can be estimated by modeling how often conditions occur that favor severe storms (Brooks et al. 2003). In this way, the climatologies of severe weather environments can be compared across the globe.

As an illustration of our activities in this regard, we define a potentially severe day, equivalent to the criteria introduced by Trapp et al. (2007). A potentially severe day occurs when the product of convective available potential energy (CAPE) and 0–6-km bulk wind shear [deep-layer shear (DLS)] exceeds 10,000 m^3 s^{-3} at the same time that both factors exceed marginal thresholds (CAPE > 100 J kg^{-1} and DLS > 5 m s^{-1}) in order to rule out any days with negligible CAPE or deep-layer shear. In doing so, the ERA-Interim dataset

(Dee et al. 2011) reveals a much higher severe weather potential over the United States than over Europe (Figs. 4a,b). However, when the occurrence of precipitation (>1 mm) in the subsequent 3 h is included as an additional requirement for what we define as a severe day, the areal coverage and maximum intensity between Europe and the United States is more comparable (Figs. 4c,d). The fraction of severe days to potentially severe days (Figs. 5e,f), which we call the severe weather efficiency (after Brooks 2009), is much higher over continental Europe (mostly between 0.6 and 0.8) than over the central (below 0.2) and eastern United States (between 0.2 and 0.4). In other words, given the same potential in terms of CAPE and DLS, storms are much more likely to initiate in Europe than in the United States, consistent with the conclusion of Brooks (2009).

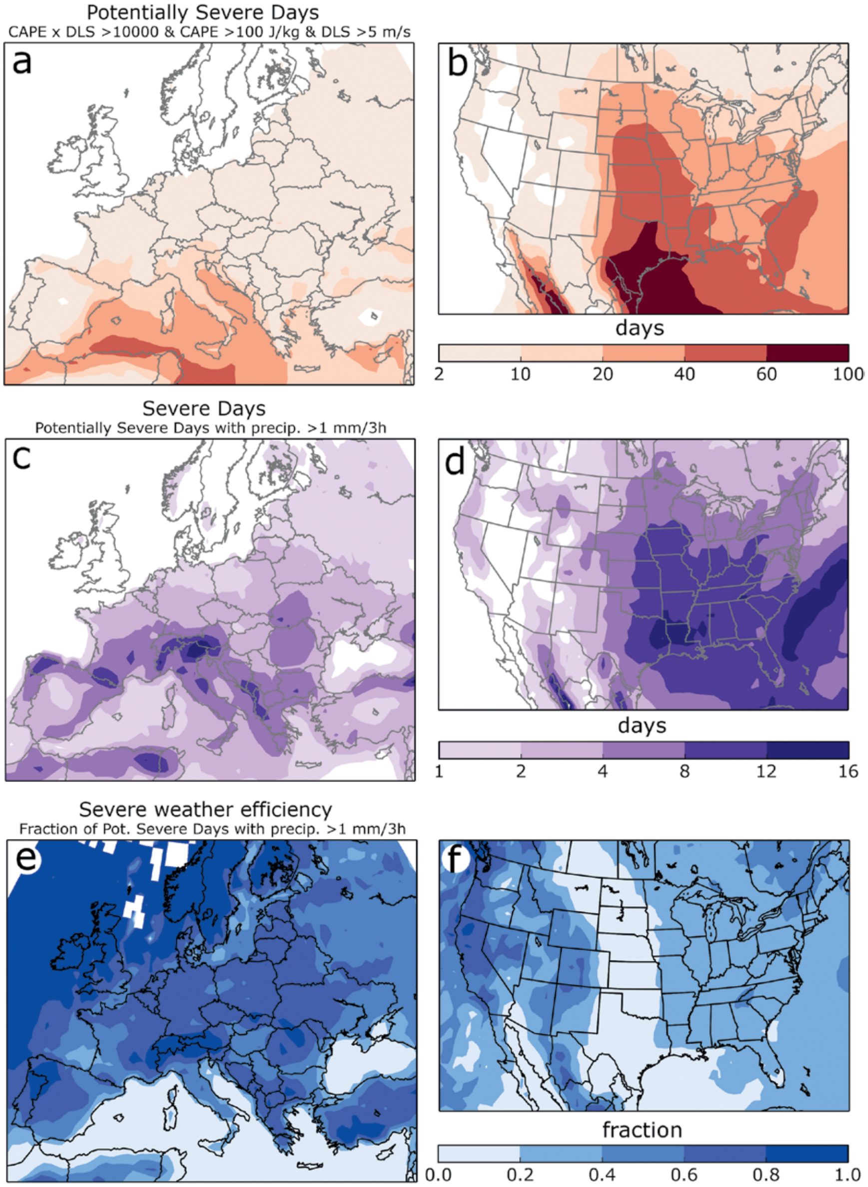

Fig. 4. (top) Annual number of potentially severe days (i.e., CAPE × DLS > 10,000 $m^3 s^{-3}$, CAPE > 100 J kg^{-1}, and DLS > 5 m s^{-1}) for (a) Europe and (b) the United States. (middle) Annual number of potentially severe days with more than 1-mm precipitation in 3 h for (c) Europe and (d) the United States. (bottom) Severe weather efficiency (as defined in the text) for (e) Europe and (f) the United States.

Another feature that stands out is that the U.S. distribution of severe days is characterized by features with synoptic-scale dimensions, whereas the European climatology shows more uneven patterns that are strongly modulated by mountain ranges and coastlines. The mesoscale effects caused by these features (e.g., Barthlott et al. 2006) can indeed complicate convective storm forecasts. Moreover, forecasts of convective hazards are more difficult in situations of modest CAPE (<1,000 J kg^{-1}) than large CAPE (>1,000 J kg^{-1}) (Dean and Schneider 2012). Comparing the storm environments in Europe to those in the United States, Brooks (2009) showed that the environments in Europe are similar to those in the southeastern United States in winter.

SUPPORT TO OPERATIONAL FORECASTING OF SEVERE CONVECTION.

ESSL supports the forecasting community by organizing seminars and workshops for forecasters. Since 2012, ESSL has also organized the annual ESSL Testbed, which was inspired by the Spring Experiment of the NOAA Hazardous Weather Testbed (e.g., Kain et al. 2003, 2006, 2010; Clark et al. 2012; Karstens et al. 2015; http://hwt.nssl.noaa.gov/spring_experiment/). ESSL opened its Research and Training Centre in

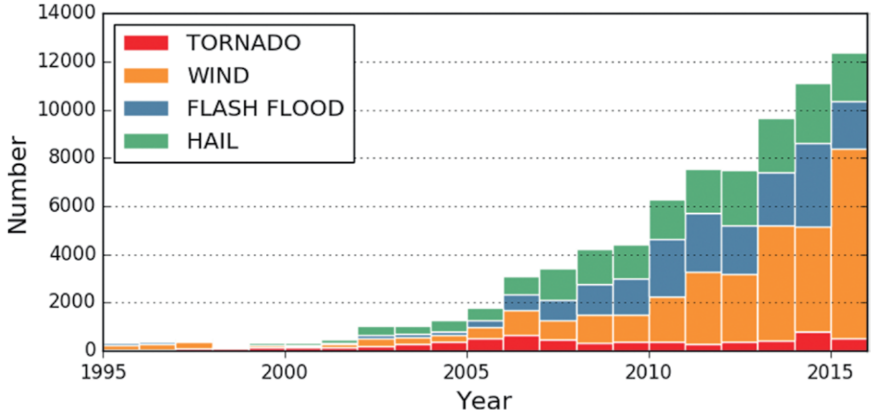

Fig. 5. Number of tornado, severe wind, flash flood, and hail reports in ESWD from Jan 1995 to Nov 2016. Tornado reports include reports of tornadoes over water (i.e., waterspouts).

Wiener Neustadt, Austria, which became the venue for the testbed. Like the Hazardous Weather Testbed, the ESSL Testbed aims to support the transfer of new forecasting and nowcasting products to operations. The testbed is supported by the weather services of Austria [Zentralanstalt für Meteorologie und Geodynamik (ZAMG)], Germany (DWD), Switzerland (MeteoSwiss), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), and Vaisala, among others. Meteorologists from various meteorological services participate and provide feedback on new products. An important achievement of the ESSL Testbed is generating interaction between forecasters and developers from different countries. During the 5 years of the testbed, 206 people from 29 countries have participated (Fig. 6), including 16 participants from the United States, who were invited to the ESSL Testbed to enhance the transfer of knowledge across the Atlantic Ocean. Despite this success, participation from a number of southern European countries and France is low. ESSL is working on establishing collaborations with meteorological services and research institutes from these countries to overcome this obstacle.

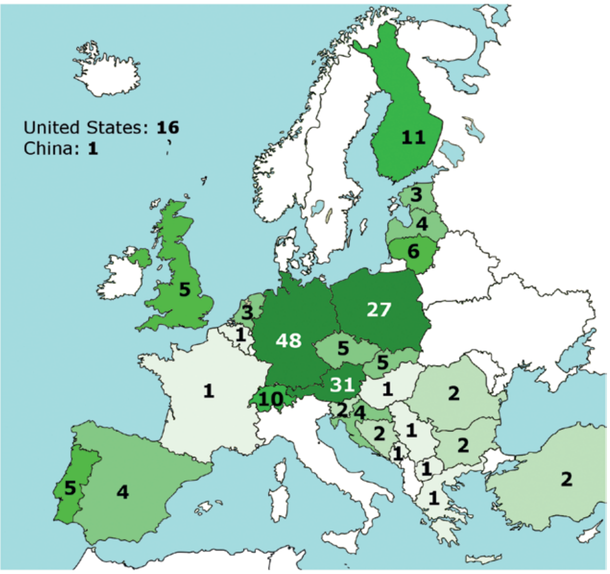

Fig. 6. Number of ESSL Testbed participants from each country.

One feature of the testbed has been evaluations of different visualizations of the 20-member convection-permitting ensemble prediction system (EPS) of the Consortium for Small-Scale Modeling model centered on Germany (COSMO-DE-EPS) provided by DWD (Doms 2011) and COSMO-E, which features 21 ensemble members and is centered on the Alps, provided by MeteoSwiss (Arpagaus et al. 2015). These evaluations have focused on how large amounts of numerical weather prediction data are optimally presented to forecasters. Various visualizations developed at NSSL (Levit et al. 2010; Kong et al. 2009) and DWD (Ben Bouallègue and Theis 2014) have been evaluated, each of them conveying different information. For instance, one visualization popular with testbed participants allows them to extract information about the shape and type of simulated storms from a map displaying where individual members exceed a threshold (Fig. 7a). Furthermore, participants liked displaying the probability of exceedance, especially when expressed relative to a 40 km × 40 km area (Fig. 7b) rather than locally (Fig. 7c). In contrast, displaying the maximum of any member was generally not regarded as useful (Fig. 7d).

In addition to working with NWP forecasts, several tools primarily based on remote sensing data have been evaluated. As an example, the NowcastMIX warning advisory system output (James et al. 2013) assigns several warning levels to convective cells detected by radar and predicts their motion in the coming hour (Fig. 8). Testbed participants evaluated the correct assignment of the warning categories, as well as the accuracy of the predicted storm motion. The participants found that warning categories were generally assigned rather well, but those participants not familiar with the warning system found it

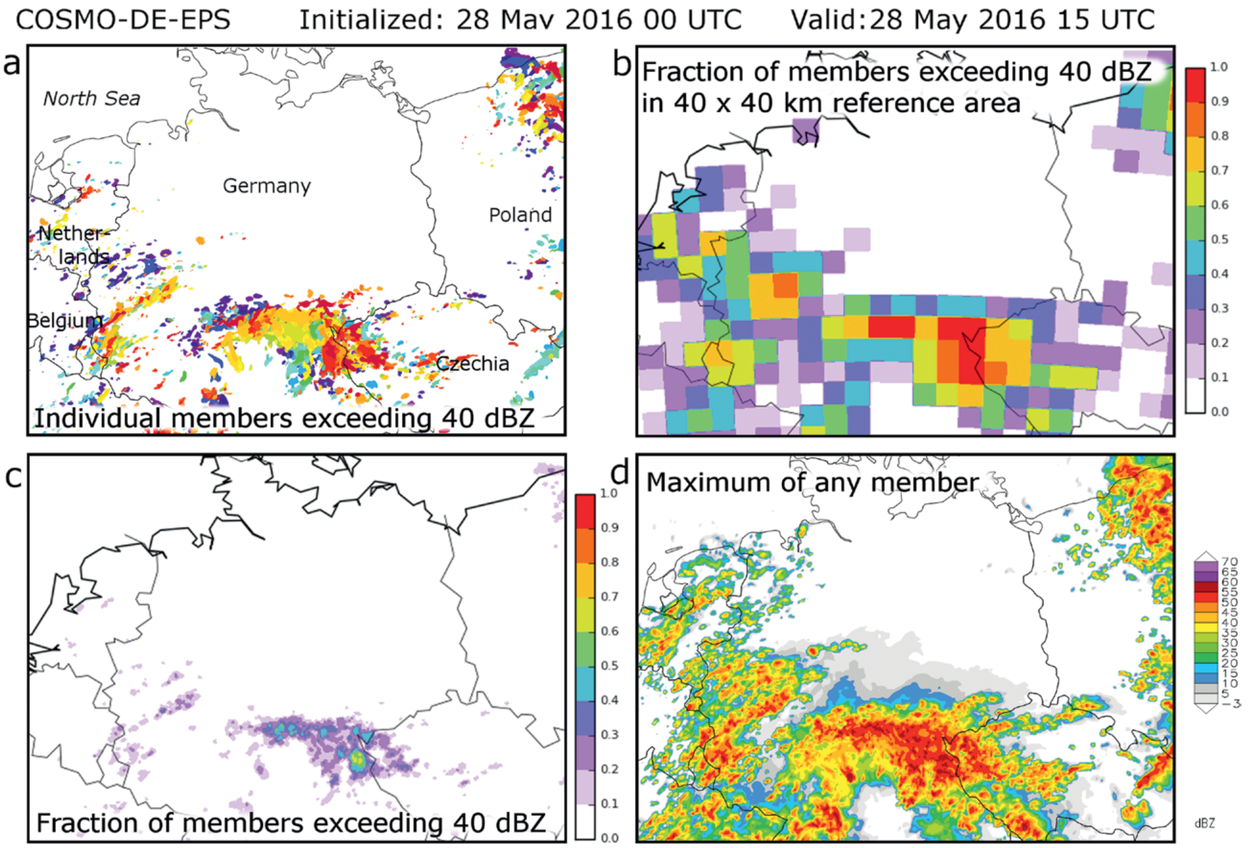

Fig. 7. Four visualizations of a 20-member COSMO-DE-EPS 15-h ensemble forecast of radar reflectivity valid 1500 UTC 28 May 2016. (a) Fraction of members exceeding 40 dBZ. (b) Individual members exceeding 40 dBZ. (c) Fraction of members exceeding 40 dBZ in a 40 km × 40 km area. (d) Maximum reflectivity from any member (dBZ).

complicated. The predicted storm motions were quite accurate, except in situations with weak lower-tropospheric winds.

SEVERE WEATHER DAMAGE ASSESSMENTS. During its 10 years, ESSL has performed damage assessments after tornado and severe wind events, frequently collaborating with experts from the United States. One of the duties of ESSL is to perform damage assessments of the most severe tornado events, in particular when there is no other experienced organization available to do this, which is the case in most countries in Europe.

On 8 July 2015, a violent tornado struck northern Italy. Using a framework laid out by Feuerstein et al. (2011), ESSL teamed up with the Regional Agency for Environmental Prevention and Protection of Veneto (ARPA-V), ZAMG, and the MeteoNetwork Association to assess the damage. The 11-km-long damage path of the tornado occurred in an area between the large cities of Venice and Padua (Fig. 9). The event led to three fatalities and severe damage to brick houses, including the total collapse of an ancient villa. Fortunately, this tornado missed the highly populated cities nearby, stressing the need for increasing the capabilities for operationally forecasting tornadoes in Italy (Miglietta and Rotunno 2016).

DEVELOPMENT AND FUTURE OF ESSL. ESSL, legally an association, has grown slowly but steadily since it was founded in 2006. It has welcomed among its members the weather services of Germany, Austria, Romania, the Czech Republic, Finland, Montenegro, Slovakia, Croatia, and the Netherlands, as well as EUMETSAT and the European Centre for Medium-Range Weather Forecasts (ECMWF). Cooperation with these organizations and the World Meteorological Organization's Region VI are important in dealing with severe storm hazards and forecasting them. In the future, ESSL may not only train weather forecasters, but may also provide guidance to weather service forecasters on shift, a task similar to that which is performed by the Storm Prediction Center (SPC) within NOAA. The European Storm Forecast Experiment (ESTOFEX; www.estofex.org), which was founded in 2002, has demonstrated that a

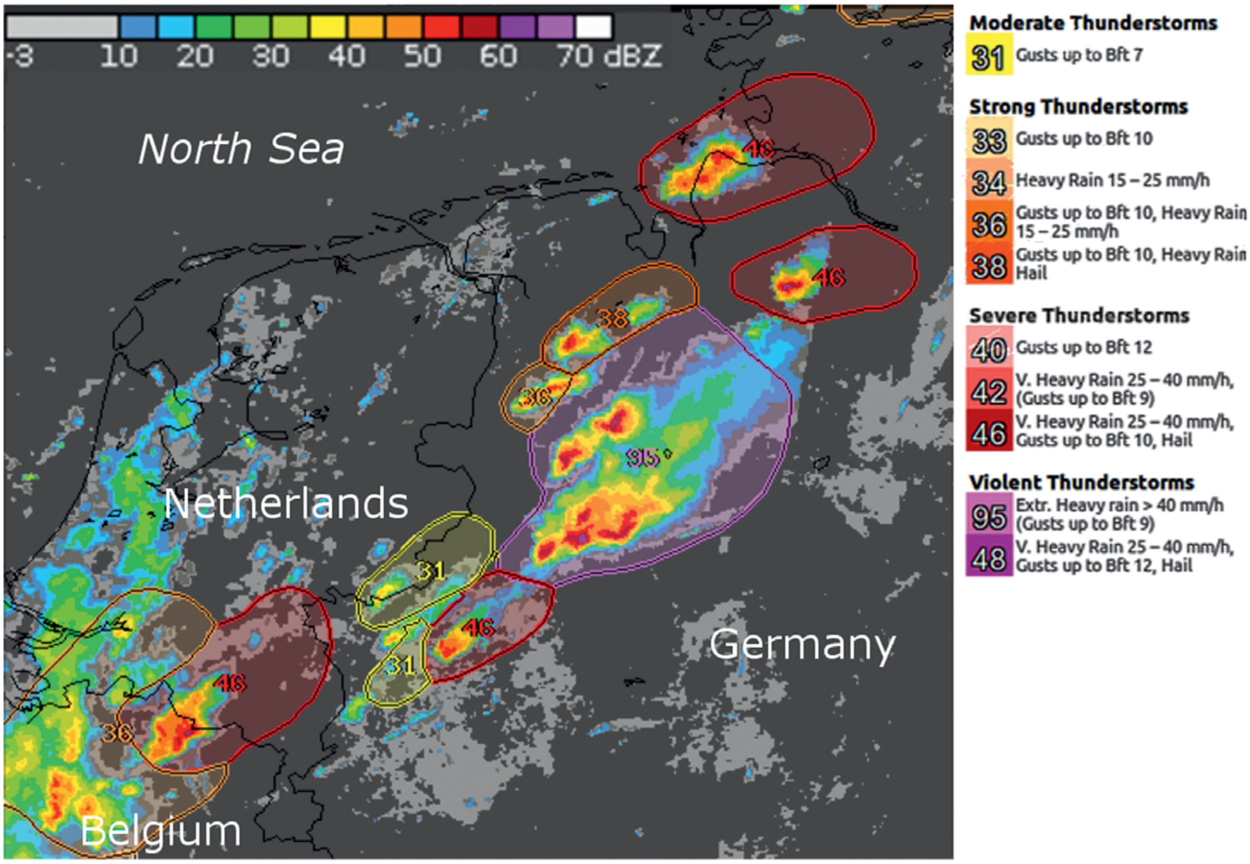

Fig. 8. Visualization of the NowcastMIX warning advisory system of DWD and radar reflectivity over northwestern Germany and adjacent areas at 1805 UTC 23 Jun 2016. (Data courtesy of DWD.)

scientific forecasting approach similar to that which is in use at the SPC can produce forecasts with considerable skill across Europe (Brooks et al. 2011). Providing guidance to regional forecasters in predicting convective hazards will be an important step in increasing Europe's level of preparedness (Dotzek 2007; Doswell 2003; Miglietta and Rotunno 2016). The pan-European nature of the convective storm problem demonstrated by the need and existence of ESSL is a strong motivation for such an effort.

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FIG. 9. Damage path of the violent tornado that occurred on 8 Jul 2015 near Dolo and Mira, Italy. Individual numbers indicate ratings of damage on the Fujita scale according to the procedure outlined by Feuerstein et al. (2011). The top-right damage photo inset shows the remains of the eighteenth-century Villa Fini. [Damage photos courtesy of A. Gobbi, MeteoNetwork Association. Map imagery courtesy of Google. Map data courtesy of GeoBasis-DE/Federal Agency for Cartography and Geodesy (Bundesamt für Kartographie und Geodäsie; BKG), Frankfurt, Germany; Google; Instituto Geográfico Nacional, Madrid, Spain; Mapa, GISrael, Tel-Aviv, Israel; and ORION Middle East (ORION-ME), Beirut, Lebanon.]

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REFERENCES

Antonescu, B., D. M. Schultz, F. Lomas, and T. Kühne, 2016: Tornadoes in Europe: Synthesis of observational datasets. *Mon. Wea. Rev.*, **144**, 2445–2480, https://doi.org/10.1175/MWR-D-15-0298.1.

——, ——, A. Holzer, and P. Groenemeijer, 2017: Tornadoes in Europe: An underestimated threat. *Bull. Amer. Meteor. Soc.*, **98**, 713–728, https://doi.org/10.1175/BAMS-D-16-0171.1.

Arpagaus, M., S. Böing, O. Fuhrer, D. Leuenberger, G. De Morsier, J. Schmidli, and A. Walser, 2015: The future high-resolution NWP systems of MeteoSwiss: COSMO-1 and COSMO-E. *33rd Int. Conf. of Alpine Meteorology*, Innsbruck, Austria, Institute of Meteorology and Geophysics, University of Innsbruck. O1.1, www.uibk.ac.at/congress/icam2015/abstracts_oral_presentations.htm#O12.2.

Barthlott, C., U. Corsmeier, C. Meißner, F. Braun, and C. Kottmeier, 2006: The influence of mesoscale circulation systems on triggering convective cells over complex terrain. *Atmos. Res.*, **81**, 150–175, https://doi.org/10.1016/j.atmosres.2005.11.010.

Ben Bouallègue, Z., and S. Theis, 2014: Spatial techniques applied to precipitation ensemble forecasts: From verification results to probabilistic products. *Meteor. Appl.*, **21**, 922–929, https://doi.org/10.1002/met.1435.

Brooks, H. E., 2009: Proximity soundings for Europe and the United States from reanalysis data. *Atmos. Res.*, **93**, 546–553, https://doi.org/10.1016/j.atmosres.2008.10.005.

——, J. W. Lee, and J. P. Craven, 2003: The spatial distribution of severe thunderstorms and tornado environments from global reanalysis data. *Atmos. Res.*, **67–68**, 73–94, https://doi.org/10.1016/S0169-8095(03)00045-0.

——, and Coauthors, 2011: Evaluation of European Storm Forecast Experiment (ESTOFEX) forecasts. *Atmos. Res.*, **100**, 538–546, https://doi.org/10.1016/j.atmosres.2010.09.004.

Clark, A., and Coauthors, 2012: An overview of the 2010 Hazardous Weather Testbed Experimental Forecast Program Spring Experiment. *Bull. Amer. Meteor. Soc.*, **93**, 55–74, https://doi.org/10.1175/BAMS-D-11-00040.1.

Dean, A. R., and R. S. Schneider, 2012: An examination of tornado environments, events, and impacts from 2003–2012. *26th Conf. on Severe Local Storms*, Nashville, TN, Amer. Meteor. Soc., P6.0, https://ams.confex.com/ams/26SLS/webprogram/Paper211580.html.

Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, https://doi.org/10.1002/qj.828.

Doms, G., 2011: A description of the nonhydrostatic COSMO-Model. Part I: Dynamics and numerics. COSMO-Model 5.1 Rep., Consortium for Small-Scale Modelling, 153 pp., www.cosmo-model.org/content/model/documentation/core/cosmoDyncsNumcs.pdf.

Doswell, C. A., III, 2003: Societal impacts of severe thunderstorms and tornadoes: Lessons learned and implications for Europe. *Atmos. Res.*, **67–68**, 135–152, https://doi.org/10.1016/S0169-8095(03)00048-6.

Dotzek, N., 2007: Proposal for a European storms prediction centre. *Severe Storms over Europe—A Cross-Border Perspective of Disaster Reduction*, H.Schmitz-Wenzel et al., Eds., DKKV Publications Series, Vol. 36, Deutsches Komitee Katastrophenvorsorge e.V., 31–32, www.dkkv.org/fileadmin/user_upload/Veroeffentlichungen/Publikationen/DKKV_36_Severe_Storms_over_Europe.pdf.

——, P. Groenemeijer, B. Feuerstein, and A. M. Holzer, 2009: Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD. *Atmos. Res.*, **93**, 575–586, https://doi.org/10.1016/j.atmosres.2008.10.020.

Feuerstein, B., and P. Groenemeijer, 2011: In memoriam Nikolai Dotzek. *Atmos. Res.*, **100**, 306–309, https://doi.org/10.1016/j.atmosres.2011.02.005.

——, ——, E. Dirksen, M. Hubrig, A. M. Holzer, and N. Dotzek, 2011: Towards an improved wind speed scale vs. damage description adapted for central Europe. *Atmos. Res.*, **100**, 547–564, https://doi.org/10.1016/j.atmosres.2010.12.026.

Groenemeijer, P., and T. Kühne, 2014: A climatology of tornadoes in Europe: Results from the European Severe Weather Database. *Mon. Wea. Rev.*, **142**, 4775–4790, https://doi.org/10.1175/MWR-D-14-00107.1.

James, P., S. Trepte, B. Reichert, and D. Heizenreder, 2013: NowCastMIX—Automatic integrated warnings from continuously monitored nowcasting systems based on a fuzzy-logic approach with optimized estimates of storm cell vectors. *Seventh European Conf. on Severe Storms*, Helsinki, Finland, European Severe Storms Laboratory, www.essl.org/ECSS/2013/programme/poster/65.pdf.

Kain, J. S., P. R. Janish, S. J. Weiss, R. S. Schneider, M. E. Baldwin, and H. E. Brooks, 2003: Collaboration between forecasters and research scientists at the NSSL and SPC: The Spring Program. *Bull. Amer. Meteor. Soc.*, **84**, 1797–1806, https://doi.org/10.1175/BAMS-84-12-1797.

——, S. J. Weiss, J. J. Levit, M. E. Baldwin, and D. R. Bright, 2006: Examination of convection-allowing configurations of the WRF Model for the prediction of severe convective weather: The SPC/NSSL Spring Program 2004. *Wea. Forecasting*, **21**, 167–181, https://doi.org/10.1175/WAF906.1.

——, and Coauthors, 2010: Assessing advances in the assimilation of radar data and other mesoscale observations within a collaborative forecasting–research environment. *Wea. Forecasting*, **25**, 1510–1521, https://doi.org/10.1175/2010WAF2222405.1.

Karstens, C., and Coauthors, 2015: Evaluation of a probabilistic forecasting methodology for severe convective weather in the 2014 Hazardous Weather Testbed. *Wea. Forecasting*, **30**, 1551–1570, https://doi.org/10.1175/WAF-D-14-00163.1.

Kong, F., and Coauthors, 2009: A real-time storm-scale ensemble forecast system: 2009 Spring Experiment. *23rd Conf. on Weather Analysis and Forecasting/19th Conf. on Numerical Weather Prediction*, Omaha, NE, Amer. Meteor. Soc., 16A.3, http://ams.confex.com/ams/23WAF19NWP/techprogram/paper_154118.htm.

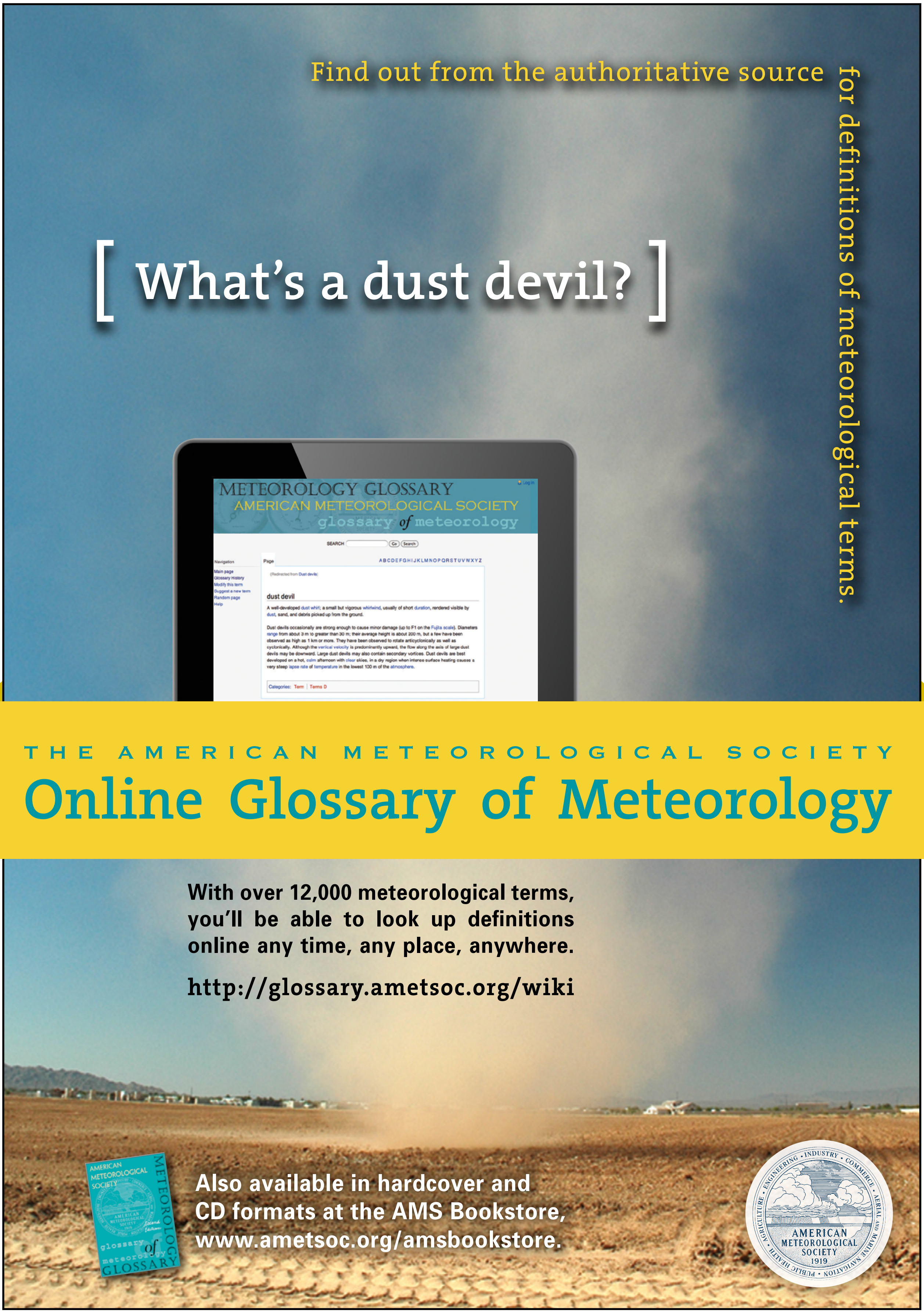
Levit, J. J., and Coauthors, 2010: The NOAA Hazardous Weather Testbed 2008 Spring Experiment: Technical and scientific challenges of creating a data visualization environment for storm-scale deterministic and ensemble forecasts. *24th Conf. on Severe Local Storms*, Savannah, GA, Amer. Meteor. Soc., P10.5, https://ams.confex.com/ams/pdfpapers/141785.pdf.

McCarthy, D. W., 2003: NWS tornado surveys and the impact on the National Tornado Database. *First Symp. on F-Scale and Severe Weather Damage Assessment*, Long Beach, CA, Amer. Meteor. Soc., 3.2, https://ams.confex.com/ams/pdfpapers/55718.pdf.

Miglietta, M., and R. Rotunno, 2016: An EF3 multivortex tornado over the Ionian region: Is it time for a dedicated warning system over Italy? *Bull. Amer. Meteor. Soc.*, **97**, 337–344, https://doi.org/10.1175/BAMS-D-14-00227.1.

Schaefer, J., and R. Edwards, 1999: The SPC tornado/severe thunderstorm database. Preprints, *11th Conf. on Applied Climatology*, Dallas, TX, Amer. Meteor. Soc., 603–606.

Trapp, J., N. S. Diffenbaugh, H. E. Brooks, M. E. Baldwin, E. D. Robinson, and J. S. Pal, 2007: Changes in severe thunderstorm environment frequency during the 21st century caused by anthropogenically enhanced global radiative forcing. *Proc. Natl. Acad. Sci. USA*, **104**, 19 719–19 723, https://doi.org/10.1073/pnas.0705494104.



Find out from the authoritative source for definitions of meteorological terms.

[What’s a dust devil?]

(Redirected from Dust devils)

dust devil

A well-developed dust whirl; a small but vigorous whirlwind, usually of short duration, rendered visible by dust, sand, and debris picked up from the ground.

Dust devils occasionally are strong enough to cause minor damage (up to F1 on the Fujita scale). Diameters range from about 3 m to greater than 30 m; their average height is about 200 m, but a few have been observed as high as 1 km or more. They have been observed to rotate anticyclonically as well as cyclonically. Although the vertical velocity is predominantly upward, the flow along the axis of large dust devils may be downward. Large dust devils may also contain secondary vortices. Dust devils are best developed on a hot, calm afternoon with clear skies, in a dry region when intense surface heating causes a very steep lapse rate of temperature in the lowest 100 m of the atmosphere.

Categories: Term | Terms D

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