Early Warnings of Severe Convection Using the ECMWF Extreme Forecast Index

IVAN TSONEVSKY
ECMWF, Shinfield Park, Reading, United Kingdom

CHARLES A. DOSWELL III
Doswell Scientific Consulting, Norman, Oklahoma

HAROLD E. BROOKS
NOAA/NSSL, Norman, Oklahoma

(Manuscript received 15 February 2018, in final form 5 April 2018)

ABSTRACT

ECMWF provides the ensemble-based extreme forecast index (EFI) and shift of tails (SOT) products to facilitate forecasting severe weather in the medium range. Exploiting the ingredients-based method of forecasting deep moist convection, two parameters, convective available potential energy (CAPE) and a composite CAPE–shear parameter, have been recently added to the EFI/SOT, targeting severe convective weather. Verification results based on the area under the relative operating characteristic curve (ROCA) show high skill of both EFIs at discriminating between severe and nonsevere convection in the medium range over Europe and the United States. In the first 7 days of the forecast ROCA values show significant skill, staying well above the no-skill threshold of 0.5. Two case studies are presented to give some practical considerations and discuss certain limitations of the EFI/SOT forecasts and how they could be overcome. In particular, both convective EFI/SOT products are good at providing guidance for where and when severe convection is possible if there is sufficient lift for convective initiation. Probability of precipitation is suggested as a suitable ensemble product for assessing whether convection is likely to be initiated. The model climate should also be considered when determining whether severe convection is possible; EFI and SOT values are related to the climatological frequency of occurrence of deep, moist convection over a given place and time of year.

1. Introduction

The threat to life and property posed by severe thunderstorms make the forecasting of these events important. Forecasts can provide decision-makers and users with the opportunity to take protective action. As a result, in the United States for example, the National Weather Service puts significant effort into this activity. A major part is played by the Storm Prediction Center (SPC), which takes primary responsibility for forecasting at time scales from greater than an hour out to 8 days in advance. The time scale of their forecasts means that the forecasts are not intended as calls to take immediate action by individuals to save their lives, but to make sure they are prepared for later forecasts and to allow for community emergency management and broadcast groups to prepare for and inform people about the approaching hazards.

In Europe most of the national hydrometeorological services share their weather warnings including warnings of severe thunderstorms for the benefit of the whole European community via Meteoalarm, an initiative coordinated by the European Meteorological Services Network (EUMETNET). The European Commission also puts considerable effort into providing information for emergency responses to various types of disasters, including meteorological hazards through the Copernicus Emergency Management Service. In addition, the European Severe Storms Laboratory (ESSL) supports the effort to improve the forecasting of severe convective storms over Europe. An important activity in this effort has always been to develop tools and methods suitable for early warnings of different meteorological

Denotes content that is immediately available upon publication as open access.

Corresponding author: Ivan Tsonevsky, ivan.tsonevsky@ecmwf.int

DOI: 10.1175/WAF-D-18-0030.1

hazards in which the European Centre for Medium-Range Weather Forecasts (ECMWF) has been actively involved.

At the heart of the long-range (beyond day 2) forecasting efforts is an ingredients-based approach to forecasting (Doswell et al. 1996). Ingredients-based forecasting is premised on the physical understanding of what the state of the atmosphere has to be to support the weather event of interest and, if the ingredients are not currently in place, what processes might be present to bring the ingredients together. Although ingredients-based forecasting could be applicable to any phenomenon, it has been most successfully applied in the severe thunderstorm arena.

Following Doswell et al. (1996), deep, moist convection is associated with buoyancy, requiring a conditionally unstable environmental lapse rate in the midtroposphere, enough boundary layer moisture for a parcel of air to have a level of free convection, and some process to lift that parcel to the level of free convection. The first two components (the lapse rates and moisture) can be combined to calculate the CAPE of a vertical profile in the atmosphere. The lifting process typically is associated with sub-synoptic-scale processes that are not always well resolved in both observing systems and numerical weather prediction models and, as such, the details of determining the locations of lift with precision can be challenging.

In addition to buoyancy needed for convection, organization of the convection is needed in order to produce severe thunderstorms. Environmental wind shear over the lowest several kilometers of the atmosphere has been shown to be a good discriminator between nonsevere and severe thunderstorms (Rasmussen and Blanchard 1998). In particular, Brooks et al. (2003) used the magnitude of the difference of the winds from the surface to 6 km as a description of the tropospheric wind shear. The combination of the CAPE and the 0–6-km shear was shown to be reasonably good at identifying conditions associated with severe thunderstorms. This combination has been applied to reanalysis products, soundings, and climate model forecasts (Brooks et al. 2003; Brooks 2009, 2013; Allen et al. 2011; Gensini et al. 2014; Púčik et al. 2015; Westermayer et al. 2017). In a crude sense, its application mimics the process of forecasting environments favorable for severe thunderstorms on time scales of more than a few hours: namely identify regions where the ingredients, with the exception of the lifting mechanism, that are necessary for severe thunderstorms will be present.

ECMWF has been providing operationally the ensemble-based extreme forecast index (EFI) and shift of tails (SOT) as tools for forecasting severe weather since 2003. Based on an ingredients-based approach to forecasting deep, moist convection, two parameters, CAPE and a combination of CAPE and deep-layer wind shear, have been added recently to the existing EFI/SOT operational parameters, to provide a focus on severe convection. Forecasting severe convection and accompanying weather phenomena such as tornadoes, strong wind gusts, large hail, lightning, and heavy rainfall is an inherently challenging task at all time scales. The EFI and SOT presented in this paper aim to facilitate forecasting outbreaks of severe convection especially in the medium range (beyond day 2) by providing signals of the presence of anomalous values of both convective parameters compared to the model climatology. In the ECMWF's Integrated Forecasting System (IFS), for example, convective wind gusts could be significantly underestimated as a result of resolution and model constraints. A striking case of such underestimation of severe convective wind gusts was shown by Tsonevsky (2015) in which even short-range forecasts failed to give any sign of strong gusts while the EFI/SOT for both convective parameters, CAPE and CAPE–shear, presented here provided a very strong signal of a possible outbreak of severe convection 6 days in advance.

The paper is organized as follows. Section 2 provides a definition of the EFI and SOT as well as a description of both convective parameters. Verification results of the EFI for both convective parameters are presented in section 3. Two case studies are shown in section 4, where some practical considerations and limitations of the EFI and SOT are discussed. The paper concludes with a discussion of important aspects of the proposed EFI and SOT products.

2. EFI and SOT

The EFI has been developed at ECMWF as a measure of the difference between ensemble forecast and model climate (M-climate) cumulative distribution functions (CDFs; Lalaurette 2003). It is computed as

$$\mathrm{EFI} = \frac{2}{\pi}\int_0^1 \frac{p - F(p)}{\sqrt{p(1-p)}}\,dp\,, \tag{1}$$

where $F(p)$ gives the proportion of the ensemble members lying below the pth percentile of the M-climate (Fig. 1). The denominator $\sqrt{p(1-p)}$ gives more weight to the EFI toward the extremes because the term under the square root sign being a quadratic function of p has its minimum at the tails of the M-climate distribution. From a practical point of view, we can assume that if the forecast is extreme compared to the M-climate, the real weather is likely to be extreme or abnormal as well. The index takes values between -1 and 1. The closer the EFI values are to either end of the M-climate range, the more abnormal the ensemble forecast is.

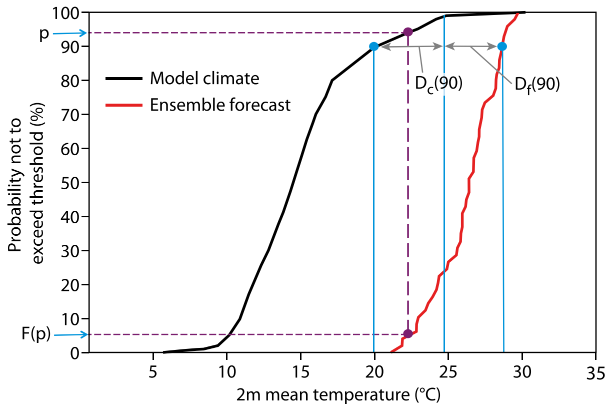

FIG. 1. CDFs of the M-climate (black curve) and real-time ENS (red curve) for 2-m mean temperature. The M-climate percentile p and ENS percentile $F(p)$ are shown, with the vertical dashed line representing the difference $[p - F(p)]$ in the EFI definition. Differences $D_f(90) = P_c(99) - P_f(90)$ and $D_c(90) = P_c(99) - P_c(90)$ define the SOT, where $P_f(90)$ is the 90th percentile of the real-time ENS distribution, and $P_c(90)$ and $P_c(99)$ are the 90th and 99th percentiles of the M-climate distribution, respectively.

At ECMWF the EFI is computed from the ECMWF ensemble forecast (ENS; Molteni et al. 1996). Currently, the ECMWF ensemble comprises 50 perturbed members and one control forecast. Since 19 November 2013 the vertical resolution of the ENS has been increased from 62 to 91 vertical levels; this was followed by a horizontal resolution upgrade on 8 March 2016 when it increased from 32- to about 18-km grid spacing. The recent vertical and horizontal resolution upgrades as well as the changes in the convection parameterization scheme (Bechtold et al. 2014) of IFS led to better representations of deep, moist convection in the ECMWF operational forecasts.

The M-climate is derived from the ECMWF reforecasts (Vitart 2014) that comprise 10 perturbed members and one control forecast. They have been run twice a week, every Monday and Thursday, for the past 20 years. The reforecast model version is identical to the operational real-time model, which ensures compatibility between the M-climate and the real-time forecasts. Therefore, the EFI is a postprocessed product that by design negates the effects of model biases. Moreover, the ERA-Interim/Land dataset (Balsamo et al. 2015) is driving land-only simulations at the resolution of the ENS. The data from these simulations are used to provide land initial conditions to the reforecasts, ensuring as much consistency as possible between the reforecasts and real-time forecasts. It is important for the EFI computation to use a robust climatology that provides a good representation of the climatological distribution of the meteorological parameter of interest including climatological extremes in the tails of the M-climate. Hence, all the reforecasts within a 4-week time window centered on the preceding Monday or Thursday that is closest to the initial date of the real-time ensemble forecast are used to compute the M-climate.

In addition, the SOT has been implemented to complement the EFI by providing information about how extreme an event could potentially be. It specifically compares the tails of ENS and M-climate CDFs. For the upper tail, the SOT is given by

$$\mathrm{SOT}(90) = -\frac{D_f(90)}{D_c(90)}, \tag{2}$$

where $D_f(90)$ is the difference between the 99th M-climate percentile and the 90th percentile of the ENS distribution, and $D_c(90)$ is the difference between the 99th and 90th M-climate percentiles (Fig. 1). Positive values of the SOT signify that at least 10% of the ensemble members are beyond the M-climate extreme (i.e., greater than the 99th M-climate percentile). The bigger the SOT, the further these 10% are from the M-climate.

Based on an ingredients-based approach (Doswell et al. 1996), two EFI parameters have been tested and implemented operationally with the aim of helping users forecast severe convection. The first one is for CAPE.

CAPE is defined as the vertical integral of the buoyancy between the level of free convection (LFC) and the equilibrium level (EL):

$$\mathrm{CAPE} = g\int_{z_{\mathrm{LFC}}}^{z_{\mathrm{EL}}} \frac{T_v - T_{ve}}{T_{ve}}\, dz, \tag{3}$$

where T_v is the virtual temperature of the lifted parcel, T_{ve} is the virtual temperature of the environment, g is the acceleration of gravity, z_{LFC} is the level of free convection, and z_{EL} is the equilibrium level.

In the IFS, however, the most unstable CAPE in the lowest 350 hPa is computed and provided as a model output field using the following approximation due to computational constraints:

$$\mathrm{CAPE} \approx \int_{z_{\mathrm{LFC}}}^{z_{\mathrm{EL}}} g\left(\frac{\theta_{ep} - \overline{\theta}_{es}}{\overline{\theta}_{es}}\right) dz. \tag{4}$$

In (4), $\theta_{ep} = T(p_0/p)^{R_d/c_p}\exp(L_v r/c_p T_p)$ is the equivalent potential temperature of the lifted air parcel, where T is its temperature, p is the air pressure, $p_o = 1000$ hPa is the reference pressure, $R_d = 287\,\mathrm{J\,kg^{-1}\,K^{-1}}$ is the gas constant for dry air, c_p is the heat capacity at constant pressure, L_v is the latent heat of vaporization, r is the mixing ratio, and $\overline{\theta}_{es}$ is the environmental saturated equivalent potential temperature (Betts and Dugan 1973), which is a function of the environmental temperature only. In the

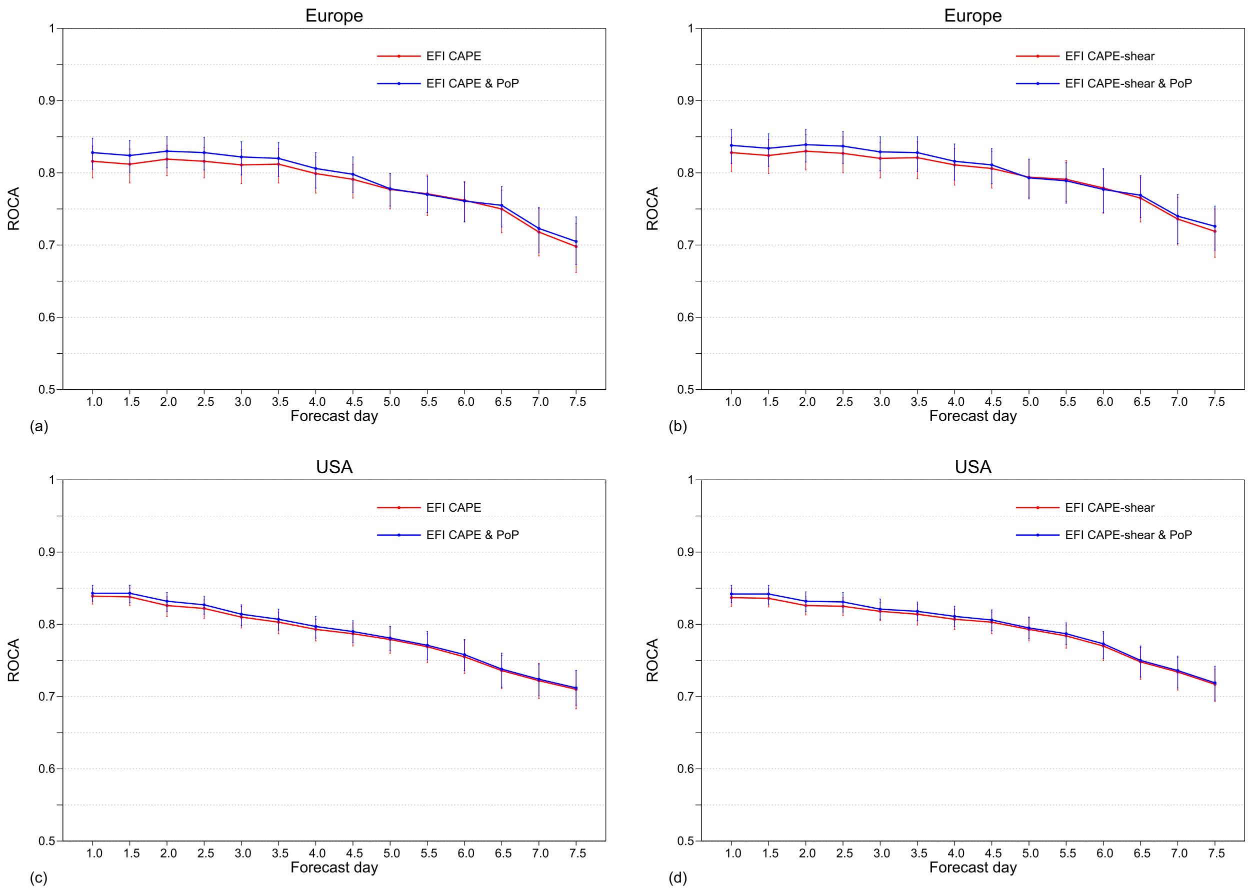

FIG. 2. ROCA comparison between the EFI only and the EFI–PoP for (a) CAPE over Europe, (b) CAPES over Europe, (c) CAPE over the United States and (d) CAPES over the United States. Reports of tornadoes, large hail, and strong wind gusts (wind gust reports flagged as nonconvective have been filtered out) are retained from ESWD for the best compatibility between the ESWD and SPC datasets of severe weather reports. A threshold of 5% is chosen for PoP. Error bars denote 90% confidence intervals drawn from a bootstrap resampling technique with 1000 random samples.

computation of CAPE from (4), the mixing of the parcels with the environment is not taken into account; that is, the ascent is considered to be adiabatic, and therefore no mass and energy are exchanged between the ascending air parcel and the environment. It is also assumed that all condensed water is instantaneously removed by precipitation; that is, the air parcel ascent is pseudoadiabatic. Overall, the processes of mixing and water loading decrease the CAPE. Furthermore, the processes of freezing and sublimation, which are also not accounted for in (4), generally slightly increase CAPE. The values of CAPE estimated by (4) are on average roughly 25% larger than those obtained by (3). The EFI products presented in this paper though are not affected by the use of the approximation in (4) because the EFI is a relative measure of the difference between the CAPE in the real-time forecast and in the M-climate.

The second EFI parameter is the CAPE–shear (CAPES) composite parameter, defined as

$$\mathrm{CAPES} = W_{925}^{500}\sqrt{\mathrm{CAPE}}, \tag{5}$$

where W_{925}^{500} is the module of the vector wind difference between the 925- and 500-hPa pressure levels, $\sqrt{\mathrm{CAPE}}$ is proportional to the maximum vertical velocity in convective updrafts, and CAPE is estimated by (4). CAPES is expressed in units of specific energy (energy per unit mass; $\mathrm{m^2\,s^{-2}}$). Vertical wind shear is an ingredient required to promote the organization of convective storms responsible for the most significant outbreaks of severe convection. Therefore, CAPES EFI tends to give a stronger signal than CAPE EFI in cases of high-shear, low-CAPE environments, which represent a significant high-impact forecasting and warning challenge (Sherburn and Parker 2014) and have been attributed to cases of primarily severe convective wind gusts across Europe (Púčik et al. 2015).

For the EFI computation, maximum values of both parameters are retained from 6-hourly model output within

TABLE 1. Reporting criteria for different severe weather phenomena used by ESSL and SPC.

	Reporting criteria	
	Europe (ESWD)	United States (SPC)
Tornado	Any	Any
Hail	Hailstone diameter at least 2 cm or smaller hailstones forming a layer at least 2 cm thick	Hailstone diameter at least 2.54 cm (1 in.)
Severe wind gusts	$25\,\mathrm{m\,s^{-1}}$ or greater measured or resulting in damage that gusts of $25\,\mathrm{m\,s^{-1}}$ would likely cause	$25.9\,\mathrm{m\,s^{-1}}$ ($58\,\mathrm{mi\,h^{-1}}$) or greater
Heavy rain	Precipitation amounts P (mm) depending on the duration t (min), according to $P(\mathrm{mm}) \geq 2\sqrt{5t(\mathrm{min})}$, or causing significant damage	Not reported
Damaging lightning	Lightning causing significant damage to aircraft, vehicles, ships, or structures, or injuring or killing people or animals	Not reported

24 h starting from a step that is 6 h after the starting step of the fixed 24-h interval. This is consistent with the computation of the EFI for other parameters such as wind gusts.

Both EFI and SOT are ensemble products implicitly encapsulating information about the forecast uncertainty. Hence, they are suitable for assisting in the provision of early warnings of high-impact weather. If the CDFs of the ENS and M-climate are close to each other, the EFI value is close to zero and thus the probability of extreme weather is low. Relatively low EFI values but high positive SOT indicate that extreme weather is possible as the tail of the ENS distribution is beyond the M-climate but the probability of an extreme event is low because of the large uncertainty in the forecast. The EFI and SOT are also climate-related products and therefore no predefined space- and time-dependent thresholds of extreme weather are necessary.

3. Verification results

The skill of the EFI is assessed operationally at ECMWF in terms of the area under the relative operating characteristic curve (ROCA; Wilks 1995). ROCA measures the ability of the EFI to discriminate between extreme and nonextreme weather. ROCA for the EFI of 10-m mean wind speed is one of the complementary headline scores that ECMWF uses to evaluate the performance of its forecasting system.

The ROCA is used in this study to assess the ability of the EFI for CAPE and CAPES to indicate outbreaks of severe convection. This assessment is performed for Europe and the United States during the spring and summer seasons (April–September) when climatologically deep, moist convection poses a serious threat. Severe weather reports from the European Severe Weather Database (ESWD; Dotzek et al. 2009) provided by ESSL and lightning data from the Met Office Arrival Time Difference Network (ATDnet) lightning detection network (Anderson and Klugmann 2014) have been used to assess the skill of the EFI over Europe. Over the United States the EFI has been verified against severe weather reports from the SPC. All scores shown in this study are valid for the year 2016.

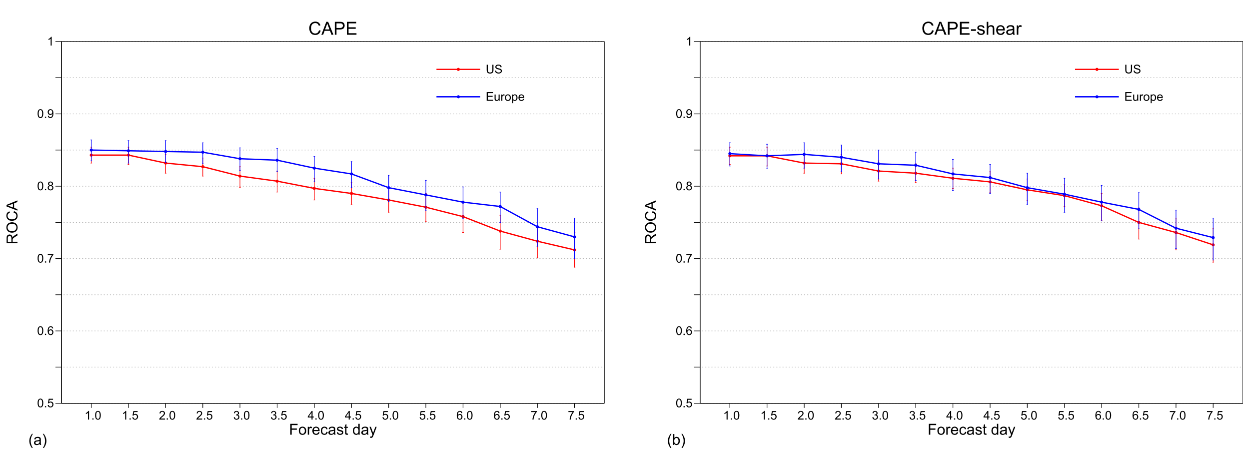

FIG. 3. ROCA skill score comparison between Europe and the United States for (a) EFI CAPE and PoP and (b) EFI CAPES and PoP. Damaging lightning and heavy precipitation reports from ESWD have been included in the verification dataset for Europe. Error bars denote 90% confidence intervals drawn from a bootstrap resampling technique with 1000 random samples.

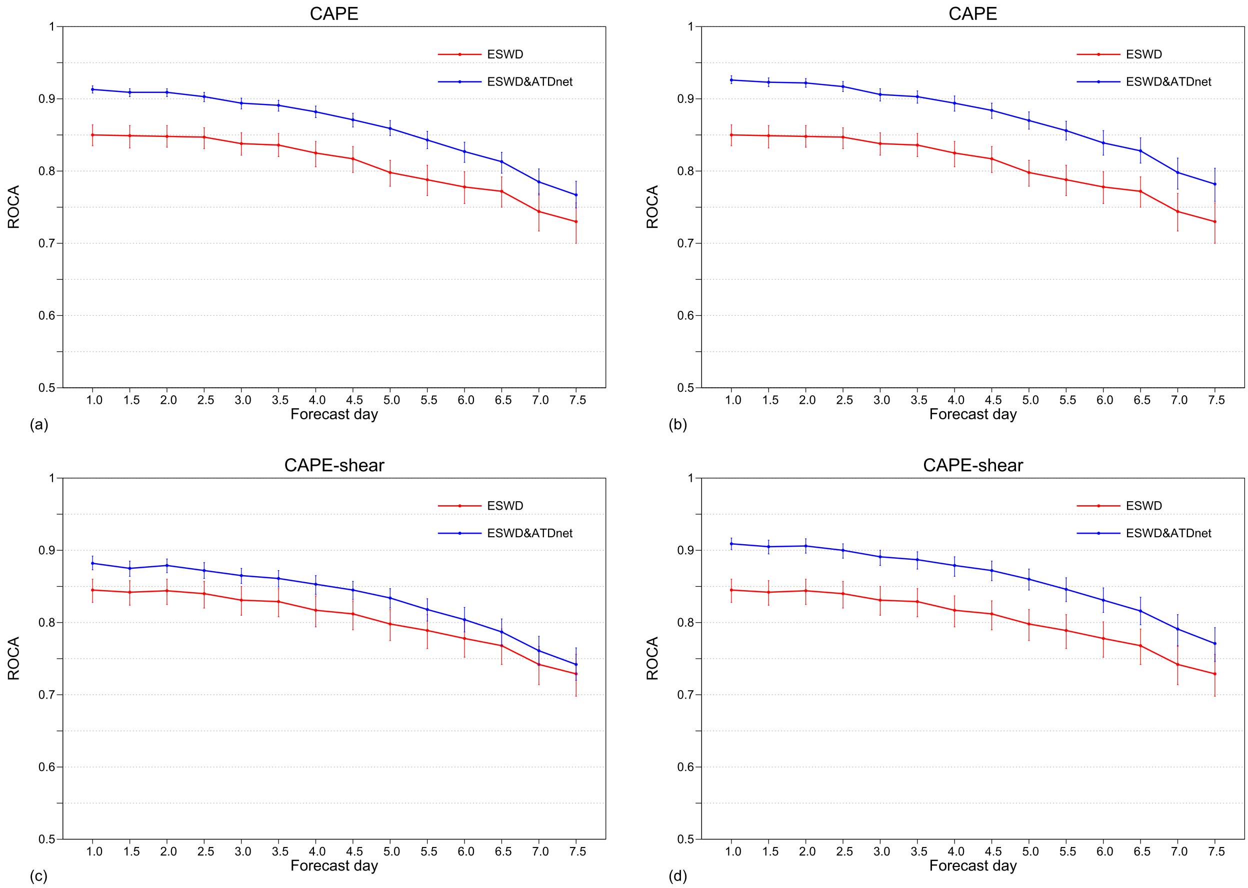

FIG. 4. ROCA comparison for Europe between datasets containing severe weather reports from ESWD only and a combination of ESWD reports and ATDnet lightning data for (a) EFI for CAPE with a lightning activity threshold of 0.2 flashes km^{-2} $(24\,h)^{-1}$, (b) EFI for CAPE with a lightning activity threshold of 0.5 flashes km^{-2} $(24\,h)^{-1}$, (c) EFI for CAPES with a lightning activity threshold of 0.2 flashes km^{-2} $(24\,h)^{-1}$, and (d) EFI for CAPES with a lightning activity threshold of 0.5 flashes km^{-2} $(24\,h)^{-1}$. ESWD reports include tornadoes, large hail, severe wind gusts, damaging lightning, and heavy convective rain. Error bars denote 90% confidence intervals drawn from a bootstrap resampling technique with 1000 random samples.

Lightning density has been computed from ATDnet data following the methodology proposed by Anderson and Klugmann (2014). ATDnet "fixes" (radio atmospheric signals emitted by lightning and detected by sensors) that occurred within 0.2° and within 1 s have been grouped together as a single flash. The lightning density data were then gridded onto the native resolution of the ENS, an octahedral reduced-Gaussian grid with 640 latitude lines between the pole and the equator (O640) (~18 km of grid spacing) using the nearest-gridpoint method. Each data file represents the lightning density by the number of flashes per square kilometer per 24 h covering the period from 0300 UTC on the verifying day to 0300 UTC the following day to account in the best way for the validity period of the EFI forecast.

Severe weather reports from ESWD and SPC have been postprocessed in the same way as the lightning data. The data files contain the number of severe weather reports closest to the nearest grid points on the O640 grid. Only land points (land–sea mask values greater than 0.5) have been retained for the verification.

EFIs for CAPE and CAPES are supposed to provide a warning of an environment in which severe convection potentially could be initiated. Sometimes high values of the EFI can indicate a very unstable atmosphere but convection does not initiate, perhaps owing to a strong capping stable layer. Probability of precipitation (PoP) forecasting could be used to filter out areas where the atmosphere is conditionally unstable but convection is unlikely to be initiated. The notion is that if the values of the EFI for CAPE and CAPES are high but PoP is very small, severe convection is unlikely. The advantage of such a combination of two ensemble products is that it is suitable for early warnings, focusing more precisely on areas under the greatest threat of severe convection. For PoP a low threshold of 1 mm $(24\,h)^{-1}$ is used. ROCA for

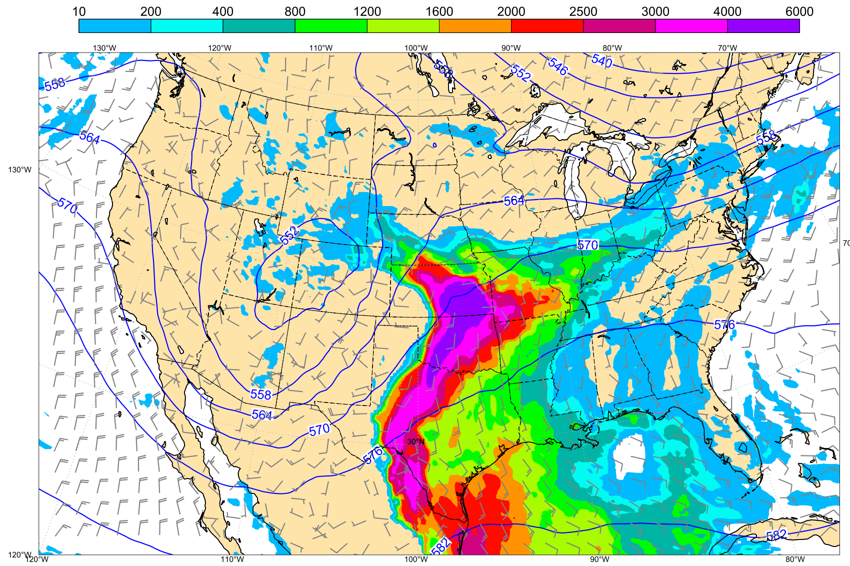

FIG. 5. ECMWF analysis at 1200 UTC 26 Apr 2016. Thick solid lines depict isohypes (dam) of geopotential height at 500 hPa. Shading represents CAPE (J kg^{-1}). Gray flags depict 10-m winds.

the combination of the EFI and PoP is evaluated for various precipitation probability thresholds (0%, 5%, 10%, 20%, . . . , 60%), and it has been found out that the 5% threshold gives the highest skill scores. ROCA skill scores for the combined product (EFI–PoP) tend to be slightly better compared to the EFI product only, especially in the short range, although the differences are relatively small and are not statistically significant (Fig. 2). Nevertheless, analysis of cases of severe convection including the ones presented in section 4 shows evidence that the PoP could be used in order to assess where deep, moist convection is more likely to be initiated. The ROCA skill scores shown hereafter refer to the combination of the EFI and PoP. The verification dataset used to compute ROCA skill scores shown in Fig. 2 includes severe reports of the following three convective hazards—tornadoes, large hail, and strong wind gusts—which are all available in both

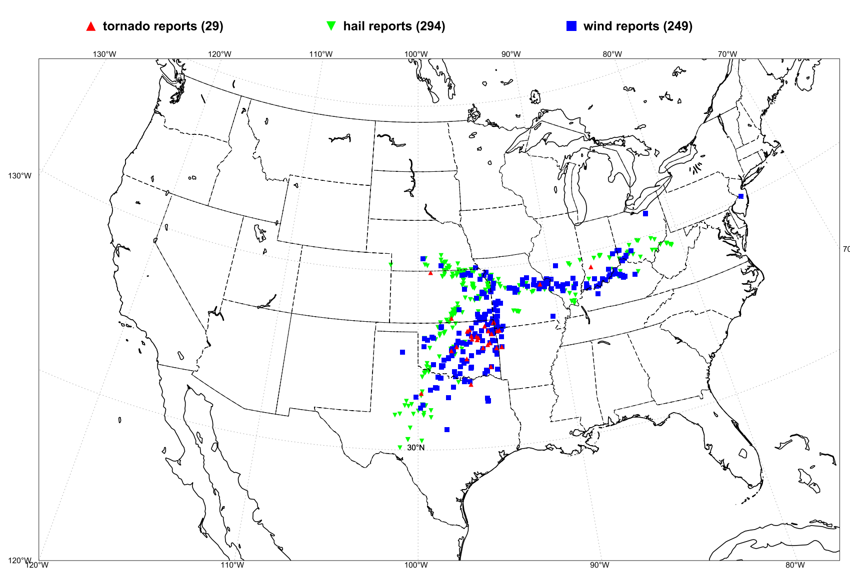

FIG. 6. SPC severe weather reports from 0600 UTC 26 Apr to 0600 UTC 27 Apr 2016.

datasets from SPC and ESWD and for which reporting criteria are fairly similar in the United States and Europe (Table 1). The skill of the EFI for both parameters, CAPE and CAPES, remains high in the medium range. The ROCA skill scores are very similar for Europe and the United States when using the same types of convective hazards.

The ESWD also collects reports of some additional convective weather hazards such as damaging lightning. Heavy rain may also accompany some severe convective storms. The criteria for reporting damaging lightning and heavy rain in the ESWD can be seen in Table 1. ROCA increases for the CAPE EFI especially if these reports of heavy rain and damaging lightning are added in the verification dataset (Fig. 3). Higher scores computed by adding additional types of convective hazards such as heavy convective rain and damaging lightning suggest that we might get better coverage of severe thunderstorms in the observation dataset, leading to better model performance. For Europe a combination of ESWD reports and ATDnet lightning data has been used to compute ROCA as well. An event is counted as severe at a particular grid point if there are one or more ESWD reports and any lightning activity or if there is no ESWD report but the lightning activity is intense. Two thresholds of flash density are used to define intense lightning activity: 0.2 and 0.5 flashes $\mathrm{km}^{-2}\,(24\,\mathrm{h})^{-1}$. These thresholds correspond roughly to the 95th and 99th percentiles of the observed lightning climatology derived from ATDnet data for April–September 2015. Kaltenböck et al. (2009) showed that high lightning activity correlates well with severe storm reports, especially with large hail and significant tornadoes (F2 or higher). Such a combined product between ESWD reports and lightning density used in climatological perspective presumably would provide better coverage of severe thunderstorms especially over sparsely populated areas and in regions where ESWD suffers from a lack of reports, and thus it would give better estimates of severe convection, as is shown in the second severe convective case in section 4. ROCA is higher when using this combined product for both EFI parameters, CAPE and CAPES, than when using just ESWD severe reports (Fig. 4).

Verification results clearly show that both EFIs for CAPE and CAPES distinguish very well between severe convective events and nonevents in the medium range. EFI and SOT forecasts for CAPE and CAPES are currently computed up to day 7, which is consistent with all other EFI parameters but there is evidence that they may be useful for longer ranges (beyond day 7) as well, although the EFI values generally become lower with longer lead times because of increasing uncertainty in the ensemble forecast.

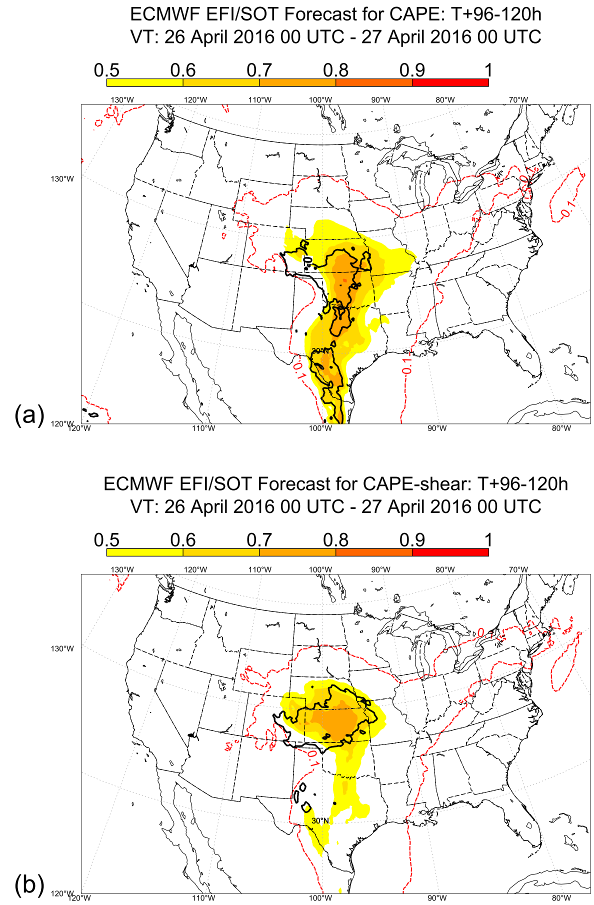

FIG. 7. ECMWF EFI/SOT T + 96–120-h forecasts for (a) CAPE and (b) CAPE–shear. Dashed red line represents EFI of 0.1. Values of EFI above 0.5 are shaded. The solid black line is the SOT zero line enclosing positive SOT values.

4. Case studies

a. *Severe convective outbreak over the United States: 26 April 2016*

During the late afternoon and night of 26 April 2016, an outbreak of severe convection occurred across parts of the southern and central Great Plains, from Texas to the north across Oklahoma and Kansas, and then to the east across Missouri, Illinois, Indiana, and Ohio.

The synoptic-scale settings played a major role in creating a favorable environment for the event (Fig. 5). An extratropical cyclone over the central and southern Rockies moved eastward toward the plains. From the triple point over Kansas a well-defined front extended

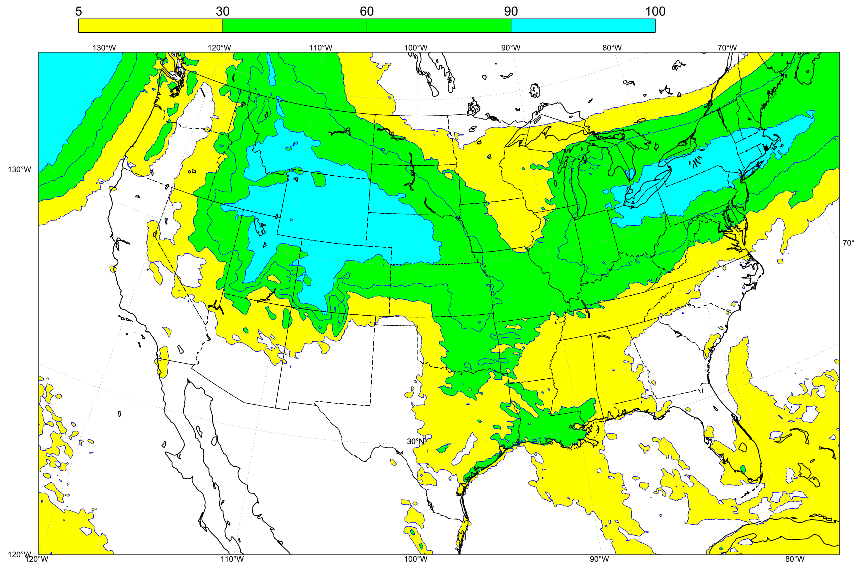

FIG. 8. ECMWF PoP for >1 mm $(24\,\mathrm{h})^{-1}$ $T + 96$–120-h forecast. Here, PoP > 5% is shaded with lines representing the 5%, 30%, 60%, and 90% probabilities.

eastward. Low-level flow advected air rich in moisture, characterized by surface dewpoint temperatures of 20°–23°C from the Gulf of Mexico to the north toward the Great Lakes, which in combination with 700–500-hPa lapse rates of about $9°\mathrm{C\,km}^{-1}$ provided unstable conditions with very high values of CAPE—between 3000 and $6000\,\mathrm{J\,kg}^{-1}$. A sharp dryline with a dewpoint temperature gradient of about 8°–10°C $(100\,\mathrm{km})^{-1}$ extended from Texas into Oklahoma and Kansas. In this environment severe thunderstorms developed, producing quite widespread large hail and strong convective wind gusts along the dryline (Fig. 6). In addition, a number of tornadoes occurred, mainly in central and eastern Oklahoma, during the warm sector of the lee cyclone. Organized convection continued to create severe weather along the quasi-stationary front from Missouri to Ohio.

The EFI for both CAPE and CAPES provided good guidance in the medium range (Fig. 7). The wider area of potential convective instability denoted by the 0.1 EFI line covers all the areas where severe convection developed. The highest values of the EFI and positive SOT highlight the regions most prone to severe thunderstorms. There is a slight difference between the two EFIs: the highest CAPE EFI values occur in an area from Texas through central Oklahoma to southern Kansas. The CAPE–shear EFI values are highest over Kansas. In both highlighted areas SOT is also positive, which means that at least 10% of the ensemble members exceed the 99th percentile of the M-climate; that is, extremely high values of both convective parameters are possible and thus significant severe storms might develop if convection initiates. Over Texas and Oklahoma, the CAPE EFI values are quite high, widely between 0.6 and 0.85, while the CAPES EFI values are lower, between 0.4 and 0.6, suggesting that very unstable air is present in a low-shear environment. This example shows that by using both convective EFIs one can sometimes better understand the convective environment and whether wind shear plays an important role in each particular case leading to more organized convection. The PoP forecast (Fig. 8) reveals that deep moist convection is highly unlikely over southern Texas as the probabilities are very low, below 5%. In fact, convection did not develop over southern Texas, and the main factor was the strong convective inhibition (CIN), which exceeded $200\,\mathrm{J\,kg}^{-1}$ in the sounding from Brownsville (Fig. 9) on that day. In comparison, the capping inversion over Norman, Oklahoma (Fig. 9), was much weaker (CIN $\sim 77\,\mathrm{J\,kg}^{-1}$) and that fact, together with very high instability [most unstable CAPE (MUCAPE) $\sim 4000\,\mathrm{J\,kg}^{-1}$], resulted in tornadic thunderstorms. Over Kansas both the CAPE and CAPES EFI values were quite high, between 0.60 and 0.79 over the areas where severe thunderstorms developed, which implies that the wind shear played a substantial role in promoting severe convection.

b. Severe convective outbreak over Europe: 18 June 2016

The synoptic-scale processes played a substantial role in the European case of 18 June 2016 as well. A midlevel

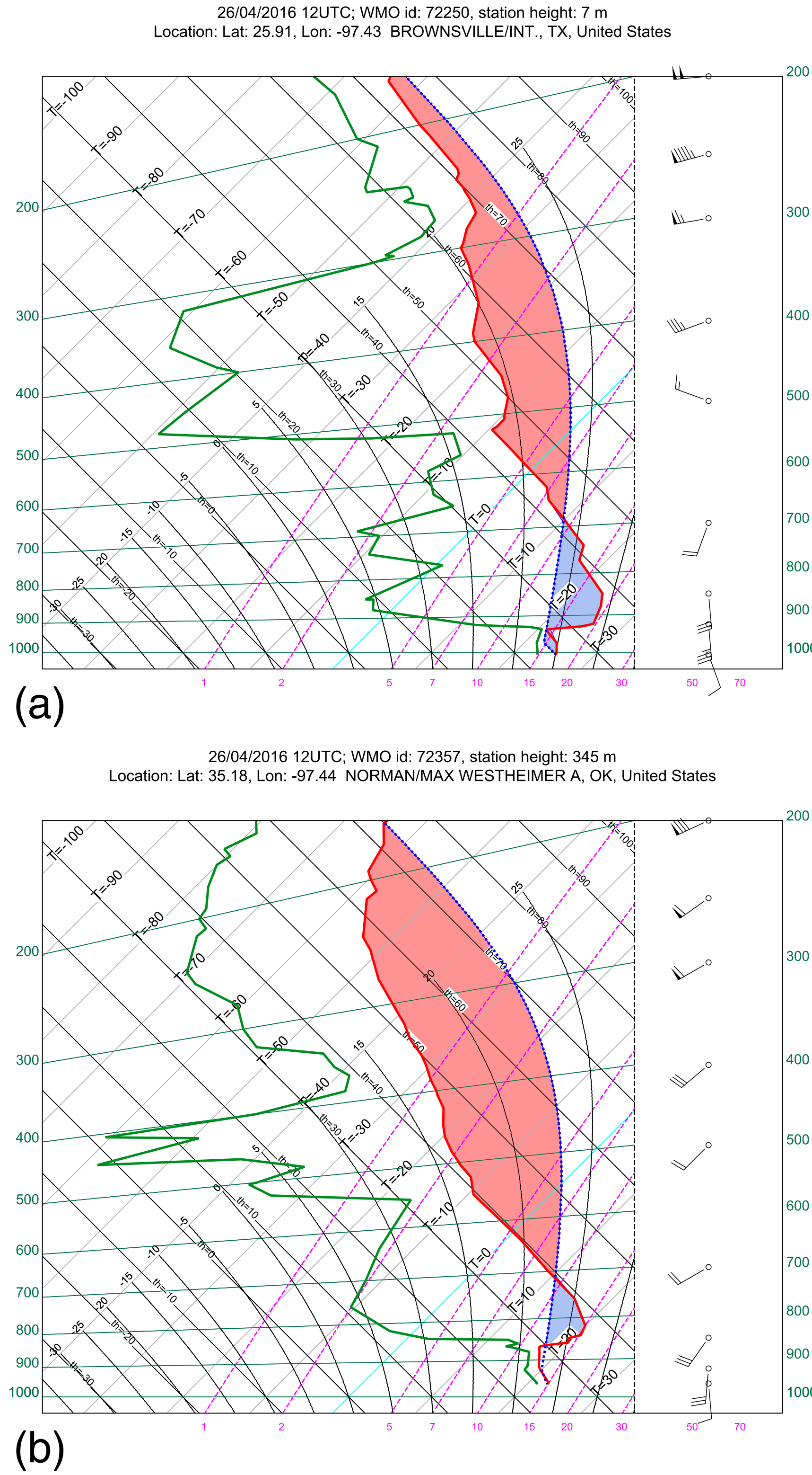

FIG. 9. Soundings for (a) Brownsville, TX, and (b) Norman, OK, at 1200 UTC 26 Apr 2016.

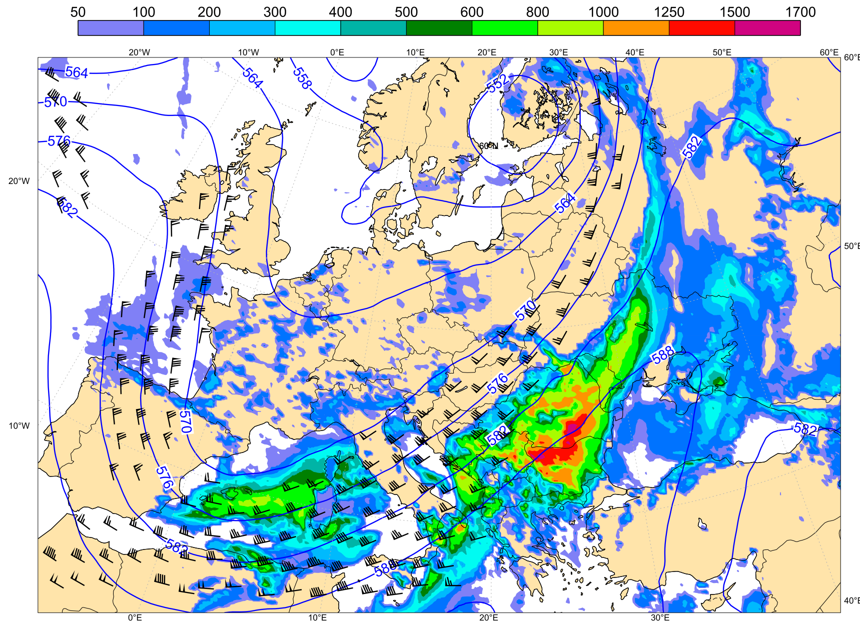

FIG. 10. ECMWF analysis at 1200 UTC 18 Jun 2016. Blue solid lines depict isohypes (dam) of geopotential height at 500 hPa. CAPE–shear values above 50 $m^2 s^{-2}$ are shaded. Flags represent 200-hPa winds above 30 $m s^{-1}$.

trough extended from the Nordic countries across western Europe, to the northern coast of Africa (Fig. 10). A well-defined slow-moving, cold front lay from the northwestern parts of Russia to the northwestern Balkans with extremely high values of CAPE–shear on the warm side over northern Bulgaria and southern Romania. A jet streak extended from the western Mediterranean to northwestern Russia. Advection of a warm and humid tropical air mass ahead of the cold front created favorable conditions for severe thunderstorms. Two clusters of

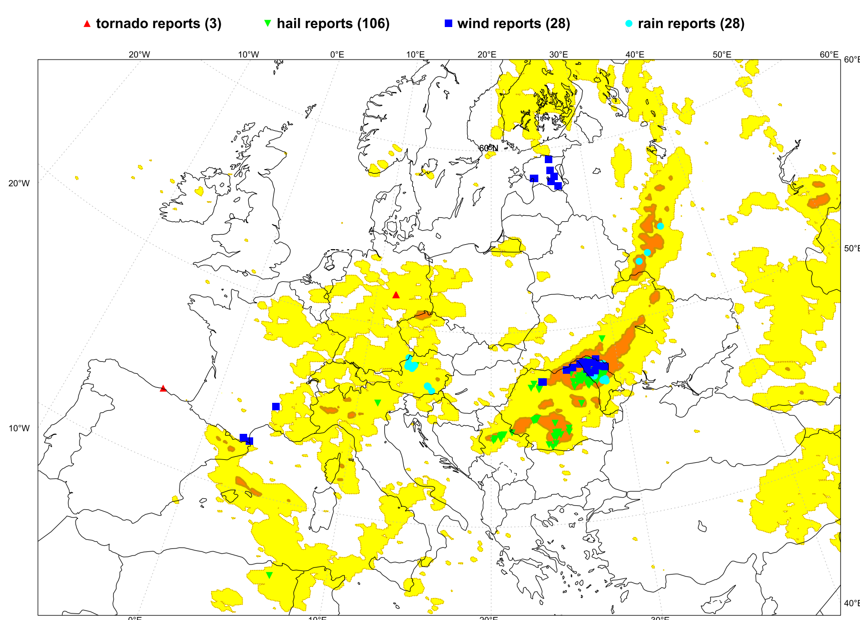

FIG. 11. ESWD reports (symbols) and ATDnet lightning activity (shading). The shading in orange denotes intense lightning activity above 0.2 flashes km^{-2} $(24 h)^{-1}$.

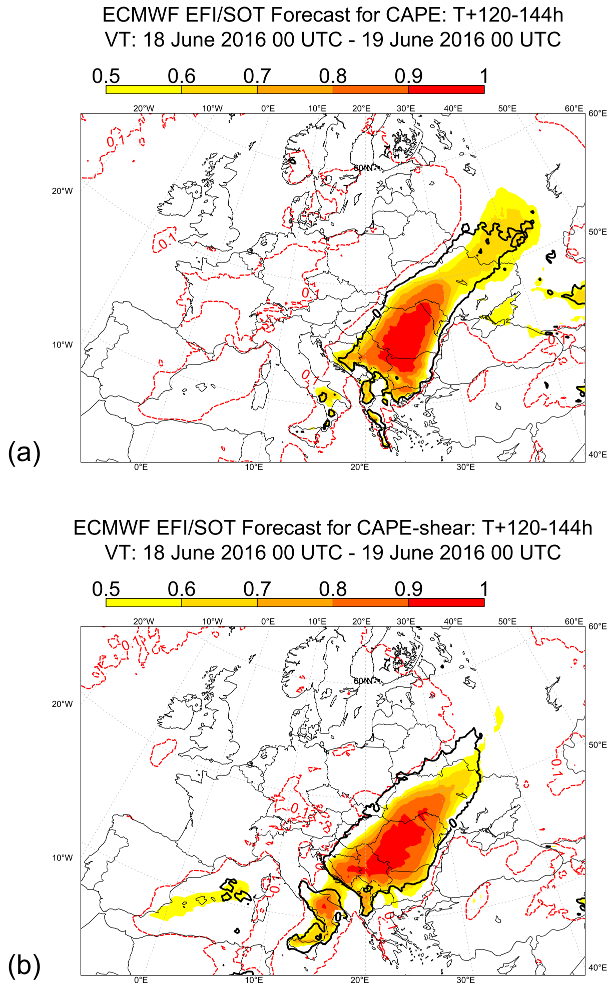

FIG. 12. ECMWF EFI/SOT T + 120–144-h forecasts for (a) CAPE and (b) CAPE–shear. Dashed red line represents EFI of 0.1. The values of the EFI above 0.5 are shaded. The solid black line is the SOT zero line enclosing positive SOT values.

severe weather reports, chiefly of large hail, appear in Romania and Moldova (Fig. 11). These clusters correlate quite well with intense lightning activity. Farther north over Russia, there is another area of intense lightning activity where, in the ESWD, there are just a few reports of heavy rain. In other areas (e.g., in Austria), there are severe weather reports with relatively modest lightning activity. These examples suggest that combining different imperfect sources of data (ESWD reports and ATDnet lightning) facilitates a better determination of the areas of hazardous weather.

It is rather striking in this case that very high values (above 0.9) of both CAPE and CAPES EFI (Fig. 12) appeared over the affected areas 6 days before the event. Such a strong signal does not happen often at this forecast time range. The fact that both EFIs reached high values roughly over the same area indicates that very high instability is coupled with substantial deep-layer shear, especially on the eastern side of the jet streak, and therefore highly organized convection might be expected. Well-organized convection including supercells indeed developed over Romania and Moldova on that day. Additionally, positive SOT is a sign that the instability reached extremely high values for at least 10% of the ensemble members. The biggest challenge for this event is in determining whether and where the convection will be initiated within the large area of high EFI values, especially over southern Romania and northern Bulgaria, where PoP value is rather small (Fig. 13). The Bucharest sounding from 1200 UTC 18 June shows very large instability, with a surface layer very rich in moisture characterized by a surface dewpoint temperature of 22°C and steep lapse rates in the lower and midtroposphere with 700–500-hPa lapse rates of about $8°\mathrm{C\,km}^{-1}$ (Fig. 14a). During the evening hours, severe thunderstorms developed to the west of Bucharest over the Danube plain in southern Romania (Fig. 14b), producing large hail, while over a major part of northern Bulgaria, storms failed to develop despite large instability.

5. Discussion and conclusions

A global forecasting system, such as the ECMWF IFS, is unable to fully capture all the processes and details at convective scales, but it is capable of forecasting relatively accurately the ingredients necessary for triggering severe convective outbreaks. The ensemble forecasting methodology can extend the predictability of such events in the medium range by providing information about forecast uncertainty. ECMWF implemented operationally two new ensemble-based products—the EFI for CAPE and CAPES—that provide skillful pointers to outbreaks of severe convection in the medium range. Alongside the strengths of these products, forecasters need to be aware of some limitations as well.

First of all, the EFI is a climate-related product and abnormal weather is defined with respect to the model climate. Therefore, climatology is essential for determining whether a particular event being abnormal is also hazardous. In the case of convection, severe thunderstorms are highly unlikely even if the EFI shows high positive values but the climatological values of CAPE or CAPES are very low (e.g., in high latitudes during winter). To prevent high but insignificant EFI values from showing up, very low values of CAPE ($\leq 10\,\mathrm{J\,kg}^{-1}$) are filtered out when computing the model climatology and

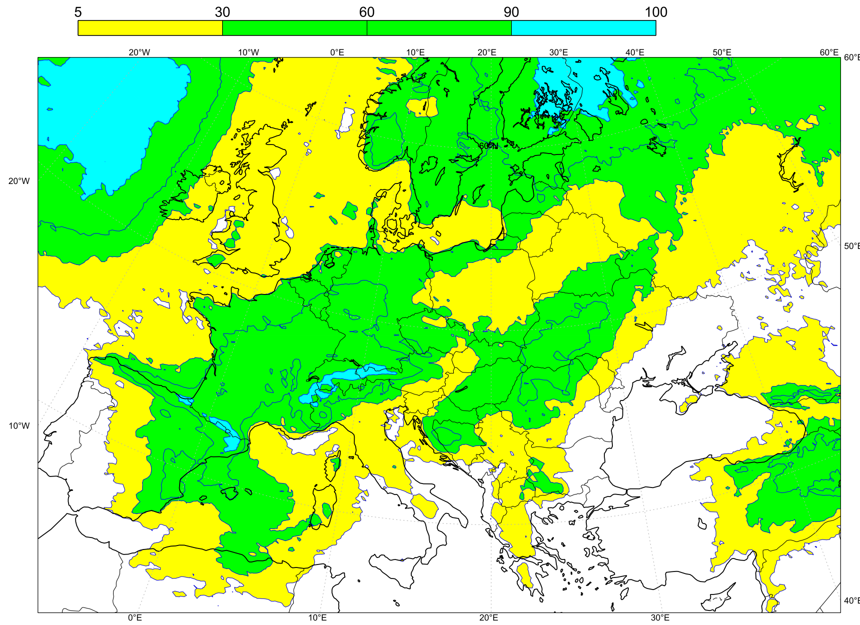

FIG. 13. ECMWF PoP for >1 mm $(24\,\mathrm{h})^{-1}$ T + 120–144-h forecast. Here, PoP > 5% is shaded with lines representing the 5%, 30%, 60%, and 90% probabilities.

the EFI. This rule is applied to CAPES as well. Nonetheless, the EFI and SOT products should be used in conjunction with the M-climate in order to determine whether a strong signal of abnormal convection could be severe. The standard EFI charts on the ECMWF website, for example, display selected quantiles of the M-climate for reference. On the other hand, if climatological values are rather high (e.g., over the Great Plains of the United States in spring), a severe convective outbreak is possible even if the EFI and SOT values are not particularly high.

Both convective EFIs provide guidance where convection could become severe, conditional on whether or not it initiates. High EFI and SOT values do not necessarily mean that severe thunderstorms are likely to happen, as convection might not be able to develop. For the case studies in this paper, another ensemble-based product, PoP, is used to reduce the number of false alarms.

While in many cases the CAPE and CAPES EFI forecasts are similar over a given geographical area, sometimes they can differ substantially depending on the type of severe convective environment. The CAPE EFI could highlight high-CAPE, low-shear environments while CAPES EFI might give higher values in low-CAPE, high-shear environments.

To compute the M-climate, EFI, and SOT, instantaneous 6-hourly forecast values for CAPE and CAPES from ECMWF ENS are used. The impact of this discretization can be noticed as stripy structures in the EFI charts in cases of fast-moving squall lines. Replacement of these values with the maxima derived from an hourly model output will be tested in the near future.

The EFI and SOT results for CAPE and CAPES presented in this paper show skill in predicting the environments associated with outbreaks of severe convection in the medium range up to day 7 with the possibility of extending these products beyond this time range. Some important tips on the best use of these products have been presented as well concerning two case studies of severe convective outbreaks. One of the most challenging questions involves knowing whether deep, moist convection will be initiated once enough instability and moisture is present. It has been shown that PoP could be used alongside the EFI and SOT to give guidance where convection is more likely to be initiated.

The EFI/SOT approach to forecasting extreme weather can be applied to parameters for which the likelihood of extreme weather increases with increasing or decreasing values of those parameters. For this reason, some convective indices such as CIN or the bulk Richardson number are not suitable to be used as EFI/SOT parameters while other indices such as the significant tornado parameter and supercell composite parameter could be tested within the EFI/SOT framework.

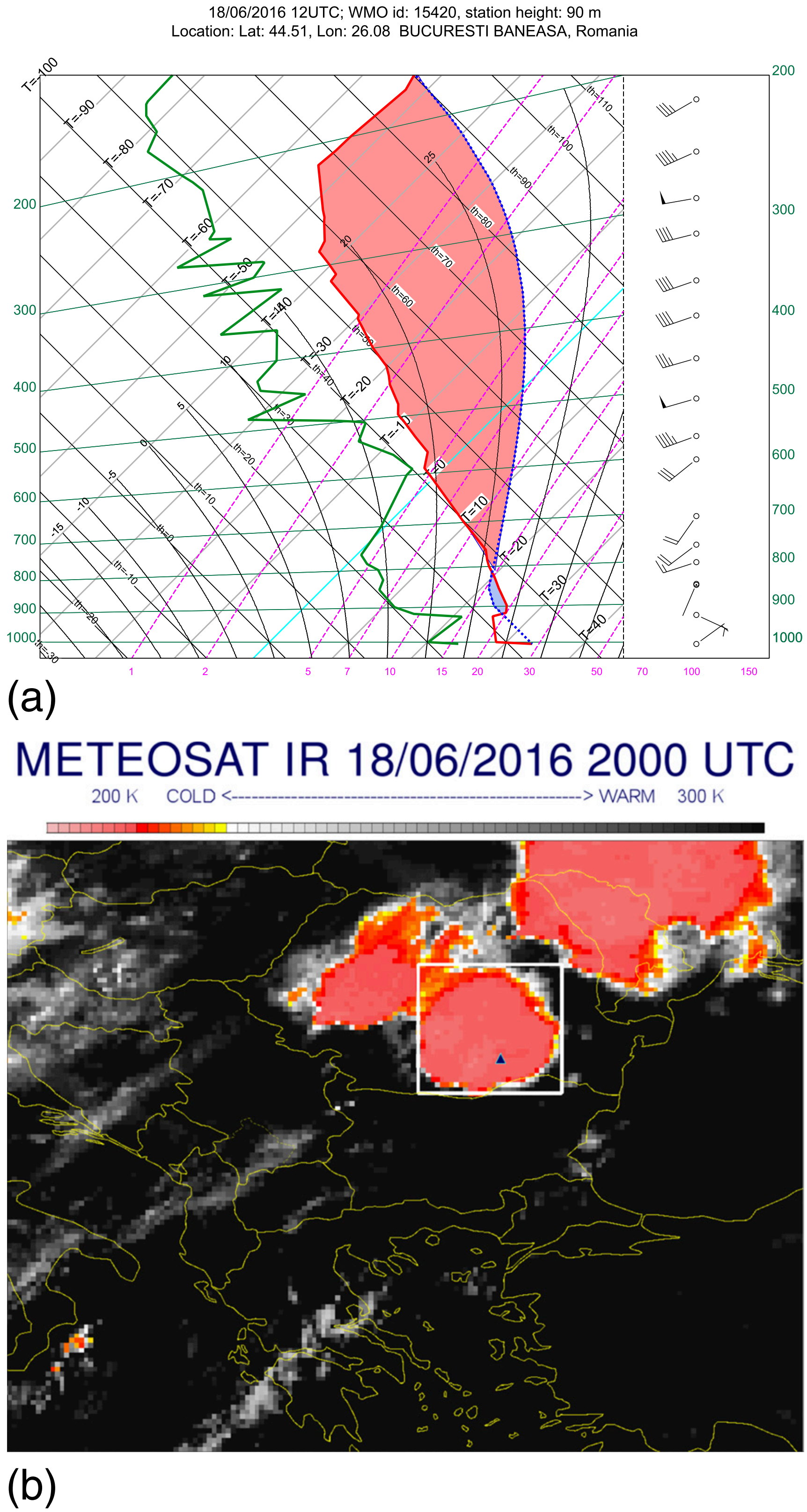

FIG. 14. (a) Sounding for Bucharest, Romania, at 1200 UTC 18 Jun 2016 and (b) Meteosat IR 10.8-μm satellite imagery at 2000 UTC 18 Jun 2016. A supercellular thunderstorm that produced large hail up to 5–6 cm according to the ESWD reports is shown inside the white rectangle. The triangle symbol within the rectangle denotes the location of the sounding in Bucharest shown in (a).

Acknowledgments. The authors thank Tim Hewson, Erik Andersson, and Florian Pappenberger from ECMWF, as well as James Correa from CIMMS/SPC and the three anonymous reviewers for their valuable comments, which led to substantial improvements in the manuscript. This work was completed as part of regular operational activities at ECMWF, and it was not associated with any grant.

REFERENCES

Allen, J. T., D. J. Karoly, and G. A. Mills, 2011: A severe thunderstorm climatology for Australia and associated thunderstorm environments. *Aust. Meteor. Oceangr.*, **61**, 143–158, https://doi.org/10.22499/2.6103.001.

Anderson, G., and D. Klugmann, 2014: A European lightning density analysis using 5 years of ATDnet data. *Nat. Hazards Earth Syst. Sci.*, **14**, 815–829, https://doi.org/10.5194/nhess-14-815-2014.

Balsamo, G., and Coauthors, 2015: ERA-Interim/Land: A global land surface reanalysis data set. *Hydrol. Earth Syst. Sci.*, **19**, 389–407, https://doi.org/10.5194/hess-19-389-2015.

Bechtold, P., N. Semane, Ph. Lopez, J.-P. Chaboureau, A. Beljaars, and N. Bormann, 2014: Representing equilibrium and nonequilibrium convection in large-scale models. *J. Atmos. Sci.*, **71**, 734–753, https://doi.org/10.1175/JAS-D-13-0163.1.

Betts, A., and F. J. Dugan, 1973: Empirical formula for saturation pseudoadiabats and saturation equivalent potential temperature. *J. Appl. Meteor.*, **12**, 731–732, https://doi.org/10.1175/1520-0450(1973)012<0731:EFFSPA>2.0.CO;2.

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

——, 2013: Severe thunderstorms and climate change. *Atmos. Res.*, **123**, 129–138, https://doi.org/10.1016/j.atmosres.2012.04.002.

——, 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.

Doswell, C. A., III, H. E. Brooks, and R. A. Maddox, 1996: Flash flood forecasting: An ingredients-based methodology. *Wea. Forecasting*, **11**, 560–581, https://doi.org/10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2.

Dotzek, N., 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.

Gensini, V. A., T. L. Mote, and H. E. Brooks, 2014: Severe thunderstorm reanalysis environments and collocated radiosonde observations. *J. Appl. Meteor. Climatol.*, **53**, 742–751, https://doi.org/10.1175/JAMC-D-13-0263.1.

Kaltenböck, R., G. Diendorfer, and N. Dotzek, 2009: Evaluation of thunderstorm indices from ECMWF analyses, lightning data and severe storm reports. *Atmos. Res.*, **93**, 381–396, https://doi.org/10.1016/j.atmosres.2008.11.005.

Lalaurette, F., 2003: Early detection of abnormal weather conditions using a probabilistic extreme forecast index. *Quart. J. Roy. Meteor. Soc.*, **129**, 3037–3057, https://doi.org/10.1256/qj.02.152.

Molteni, F., R. Buizza, T. N. Palmer, and T. Petroliagis, 1996: The ECMWF Ensemble Prediction System: Methodology and validation. *Quart. J. Roy. Meteor. Soc.*, **122**, 73–119, https://doi.org/10.1002/qj.49712252905.

Púčik, T., P. Groenemeijer, D. Rýva, and M. Kolár, 2015: Proximity soundings of severe and nonsevere thunderstorms in central Europe. *Mon. Wea. Rev.*, **143**, 4805–4821, https://doi.org/10.1175/MWR-D-15-0104.1.

Rasmussen, E. N., and D. O. Blanchard, 1998: A baseline climatology of sounding-derived supercell and tornado forecast parameters. *Wea. Forecasting*, **13**, 1148–1164, https://doi.org/10.1175/1520-0434(1998)013<1148:ABCOSD>2.0.CO;2.

Sherburn, K. D., and M. D. Parker, 2014: Climatology and ingredients of significant severe convection in high-shear, low-CAPE environments. *Wea. Forecasting*, **29**, 854–877, https://doi.org/10.1175/WAF-D-13-00041.1.

Tsonevsky, I., 2015: New EFI parameters for forecasting severe convection. *ECMWF Newsletter*, No. 144, ECMWF, Reading United Kingdom, 27–32, https://doi.org/10.21957/2t3a904u.

Vitart, F., 2014: Evolution of ECMWF sub-seasonal forecast scores. *Quart. J. Roy. Meteor. Soc.*, **140**, 1889–1899, https://doi.org/10.1002/qj.2256.

Westermayer, A. T., P. Groenemeijer, G. Pistotnik, R. Sausen, and E. Faust, 2017: Identification of favorable environments for thunderstorms in reanalysis data. *Meteor. Z.*, **26**, 59–70, https://doi.org/10.1127/metz/2016/0754.

Wilks, D. S., 1995: Forecast verification. *Statistical Methods in the Atmospheric Sciences*, D. S. Wilks, Ed., Academic Press, 255–335.