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New EFI parameters for forecasting severe convection

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New EFI parameters for forecasting severe convection

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Forecasting severe convection is a challenging task for meteorological services as its prediction is inherently difficult. It is also a very important task since the impacts of severe convection on society can be substantial. For example, a series of convective storms affected western and central Europe during the first half of June 2014. At least 6 people died in Germany, and the storms are estimated to have caused economic losses totalling more than 2 billion euros in France, Germany and Belgium.

A strategic goal of ECMWF is to provide reliable forecasts of severe weather throughout the medium range (3–10 days) to national meteorological services. To this end, in 2003 ECMWF developed the Extreme Forecast Index (EFI), which provides indications of severe events and is based on the ECMWF ensemble forecast (ENS). The range of parameters to which the index is applied will soon be widened to include dedicated indicators of severe convection. The new EFI parameters have been shown to discriminate well between severe and non-severe convection in the medium range.

How the EFI works

The EFI provides specialised forecast guidance for severe weather events, such as heavy precipitation, strong winds, heavy snowfall, extreme temperatures, and, for the marine community, for unusually high ocean waves. The EFI varies from -1 to 1 and measures the difference between the ENS and model climate (M-climate) distributions. The latter are derived from a set of re-forecasts that comprises ensemble forecasts based on data going back 20 years. For more details see Box A. In addition, ECMWF has designed the Shift of Tails (SOT) index, which complements the EFI by providing information about how extreme an event could potentially be. It specifically compares the tails of the ENS and M-climate distributions (Box A). For the various weather parameters, the EFI and SOT are computed for intervals of various lengths up to day 15.

In the context of recent improvements in parametrizing deep convection in ECMWF's Integrated Forecasting System (IFS) (*Bechtold et al.*, 2014) and of a forthcoming increase in the horizontal resolution of the IFS, ECMWF has tested a number of options for providing guidance on the risk of severe convection. In particular, the aim was to select suitable parameters to which the EFI and SOT concepts could be usefully applied.

New EFI parameters

Deep moist convection (DMC) is the fundamental breeding ground for severe convective hazards such as hail, extreme rainfall, lightning, tornadoes and severe 'straight-line' winds produced by thunderstorm downdrafts. DMC requires three ingredients: conditional instability, moisture and a source of lift (*Doswell III et al.*, 1996). Convective available potential energy (CAPE) accounts for two of these: instability and moisture. Large CAPE is generally found where low-level moisture combines with steep lapse rates in the lower and middle troposphere. Indeed, CAPE is very sensitive to the temperature and dew point of the parcel that is ascending. When calculating CAPE, it is important to know which parcel is being notionally lifted in the computation. Details of the CAPE parameter that is computed and disseminated by ECMWF are given in Box B.

The likelihood of severe weather and its level of intensity tend to increase with increasing organisation of convection. Supercells are the most prominent example of organised DMC. They are chiefly found in mid-latitudes. They tend to form in the presence of strong vertical wind shear, which can occur even when CAPE is not extremely high. Strong vertical wind shear tilts the storm's updraught, allowing the downdraught and the updraught to occur in separate regions, which leads to long-lived storms. Most occurrences of large hail and tornadoes are associated with supercells.

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Extreme Forecast Index (EFI) and Shift of Tails (SOT)

A

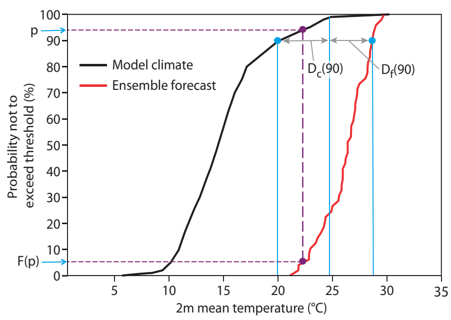
The Extreme Forecast Index (EFI) has been developed at ECMWF to inform users about how extreme an ensemble forecast is, by comparing the forecast distribution to the model climate (M-climate) distribution. It is computed as:

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

where $F(p)$ is the proportion of the ensemble members lying below the p-th percentile of the M-climate. Since IFS Cycle 41r1 implemented on 12 May 2015, the M-climate has been determined from an 11-member re-forecast ensemble that is run twice a week, on Mondays and Thursdays, from the same starting date in each of the last 20 years. A set of nine consecutive sets of the output of that re-forecast ensemble, spanning a five-week period, is used to create the M-climate. The middle week of the five is the week closest to the actual forecast run date. Extreme values of the EFI close to -1 or 1 denote a high probability of extreme weather. However, the EFI itself does not show how far beyond the M-climate extremes the ENS solutions go. The Shift of Tails (SOT) complements the EFI by specifically referencing this, comparing the tails of the ENS and M-climate distributions. It is given by:

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

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, as shown in the figure. Positive values of the SOT mean that at least 10% of the ENS members are beyond the M-climate extreme (i.e. greater than the 99th M-climate percentile). The bigger the SOT the further away these 10% are from the M-climate. More details about SOT are available on ECMWF's web pages showing EFI forecast charts and in Newsletter No. 133.



Individual convective parameters do not discriminate well between severe and non-severe events, whereas considering both instability and shear simultaneously improves the results noticeably. Based on previous studies (*Rasmussen & Blanchard*, 1998; *Craven & Brooks*, 2004) showing that the product of CAPE and vertical wind shear yields better discrimination between severe convection and ordinary thunderstorms, a parameter referred to here as the CAPE-SHEAR Parameter (CSP), has been defined as follows:

$$\mathrm{CSP} = WS_{l_1}^{l_2}\sqrt{CAPE}$$

where WS_{l1}^{l2} is the wind shear between levels l_1 and l_2. The second factor in CSP is proportional to the maximum vertical velocity in convective updrafts, w_{max}, since $w_{max} = \sqrt{2CAPE}$. CSP is thus expressed in units of specific energy (energy per unit mass), m^2/s^2. The first factor is defined as the magnitude of the vector difference between the winds at two different levels. If these levels are far apart, we can refer to this as 'bulk shear'. In operational forecasting, 0–6 km wind shear is usually used. To calculate CSP, two standard pressure levels l_1=*925 hPa* and l_2=*500 hPa* have been selected, for reasons of availability (notably in the ECMWF archive) and close proximity to the levels used in calculating 0–6 km wind shear. CSP can be expected to be strongly correlated with the probability of severe weather related to convection.

CSP is computed for calendar days using the four forecast steps available (6-hour intervals). The maximum of these four CPS values is retained. This is consistent with the EFI computation for other parameters, such as maximum wind gusts. For example, to compute the EFI for a day-2 forecast (T plus 24–48 hours), CSP is computed for T+30h, T+36h, T+42h and T+48h steps and the maximum of these values is used.

The EFI for CAPE is computed in the same way, again retaining the maximum value out of four.

Convective available potential energy (CAPE) and Convective Inhibition (CIN) in the IFS B

It is important to know what type of CAPE is provided for forecasting severe convection as air parcels at different heights have different CAPE. In the IFS, the most unstable CAPE in the lowest 350 hPa of the atmosphere is computed and provided as a model output parameter. For reasons of numerical efficiency, this CAPE parameter is computed using equivalent potential temperature θ_e instead of virtual temperature:

$$\mathrm{CAPE} = \int_{z_{LFC}}^{z_{EL}} g\left(\frac{\theta_{e,up} - \bar{\theta}_{e,sat}}{\bar{\theta}_{e,sat}}\right) dz$$

where g is the acceleration of gravity, $\theta_{e,up}$ is the updraught equivalent potential temperature, which is conserved during a pseudo-adiabatic ascent, $\bar{\theta}_{e,sat}$ is the environmental saturated equivalent potential temperature, which is a function of the environmental temperature only, z_{LFC} is the level of free convection where the air parcel becomes warmer than its environment and z_{EL} is the equilibrium level where the air parcel becomes colder than its environment.

CAPE is computed for parcels ascending from each model level in the lowest 350 hPa. For parcels in the lowest 30 hPa, mixed layer values of θ_e are used. Finally, it is the maximum value of CAPE from all these parcels that is retained.

By analogy with CAPE, CIN is defined as the negative part of the integral:

$$\mathrm{CIN} = -\int_{z_{dep}}^{z_{LFC}} g\left(\frac{\theta_{e,up} - \bar{\theta}_{e,sat}}{\bar{\theta}_{e,sat}}\right) dz\,;\ \left(\theta_{e,up} - \bar{\theta}_{e,sat}\right) < 0$$

where z_{dep} is the departure level from which the ascent starts. The minimum positive value of CIN from all the parcels is retained. This approximation generally overestimates CIN because for simplicity CIN is computed from z_{dep} without considering the lifted condensation level z_{LCL}. It is important to note that computing CAPE and CIN using θ_e instead of virtual temperature overestimates the water vapour contribution to the buoyancy, predominantly from the lower levels.

Verification

The skill of the EFI is normally assessed in terms of 'ROC area' (ROCA – the area under a curve representing the Relative Operating Characteristic). ROCA for the 10-metre mean wind EFI is one of several complementary headline skill scores that ECMWF uses to evaluate the performance of its forecasting system. ROCA values range from 0 to 1. For a skilful forecast, ROCA should be >0.5, and the higher the value the better the ability of the EFI to discriminate between anomalous and non-anomalous weather.

For Europe, EFI forecasts for CAPE and CSP have been verified against lightning data from the UK Met Office ATDnet lightning detection system from 1 April to 31 October 2014. ATDnet detects mainly cloud-to-ground strokes. ATDnet 'fixes' (radio atmospheric signals emitted by lightning and detected by the sensors) that occurred within 0.2° and within 1s have been grouped together as a single flash. This method of converting ATDnet 'fixes' into flashes is consistent with other studies. The data has been gridded onto a regular Gaussian grid N320 with the number of flashes per day represented at each grid point using the nearest-grid-point method. Each daily data file includes all detected lightning between 0300 UTC on the verifying day and 0300 UTC the following day to account in the best way for the validity period of the EFI forecast. The verification domain covers 35ºN–65ºN and 10ºW–35ºE. Studies (e.g. *Kaltenböck et al.*, 2009) suggest that higher lightning activity correlates well with the other severe weather events that are of interest here (for which remotely sensed data is not available), and especially with large hail and 'significant' tornadoes (F2 or higher).

The main finding of the EFI evaluation for Europe is that both CSP and CAPE are able to discriminate well between severe and non-severe convection. CSP appears to be particularly good at discriminating between events of different intensity. This is illustrated by Figure 1, where the difference in ROCA for different-intensity lightning events is higher for CSP than for CAPE, by an average of 0.042 over forecast days 1–7. At the same time, ROCA for CSP in cases of high-intensity lightning is higher than ROCA for CAPE, by an average of 0.018 over forecast days 1–7. This suggests that CSP can identify very severe convective hazards better than CAPE.

A dataset of severe weather reports over the USA has been used for an additional assessment of the ability of the new convective EFI parameters to discriminate between severe and non-severe convection. All the reports of tornadoes, large hail (diameter ≥ 2.5 cm) and severe wind gusts (≥ 26 m/s) for the same mid-year period as used for Europe were considered. Severe weather reports were gridded onto a reduced Gaussian

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grid N320 using the nearest-grid-point method. Only land points (land-sea mask value > 0.5) were considered. By analogy with Europe, each daily data file includes all severe weather reports in the 24-hour period starting at 0300 UTC. The EFIs for both CAPE and CSP show good discrimination of severe convection even in the medium range (Figure 2). Consistent with the results for Europe, the EFI for CSP highlights the 'very' severe convective events better than the EFI for CAPE. On average, the values of the EFI for CSP are higher than the EFI for CAPE for severe thunderstorms producing hail at least 5 cm in diameter and/or wind gusts of 33 m/s or greater, while they are similar for tornadoes (Figure 3). The EFI values are, on average, higher for tornadoes than for hail and severe wind gusts. This is true for both CSP and CAPE.

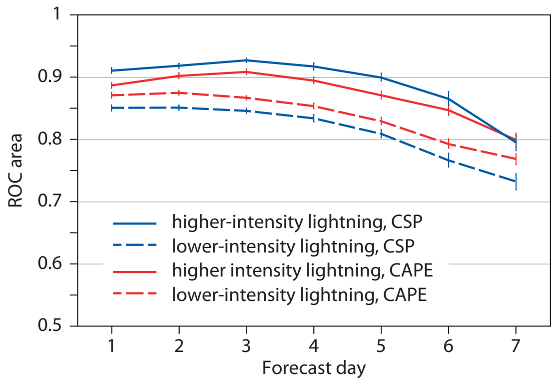

Figure 1 ROC area for the EFI for CSP (blue lines) and CAPE (red lines) over Europe (35°N–65°N, 10°W–35°E) for different intensities of lightning activity, with lower-intensity events corresponding to a frequency of 0.6% in the UK Met Office ATDnet lightning detection system dataset for the period 1 April to 31 October 2014, and higher-intensity events corresponding to a frequency of 0.04% in the same dataset. Error bars show 90% confidence intervals.

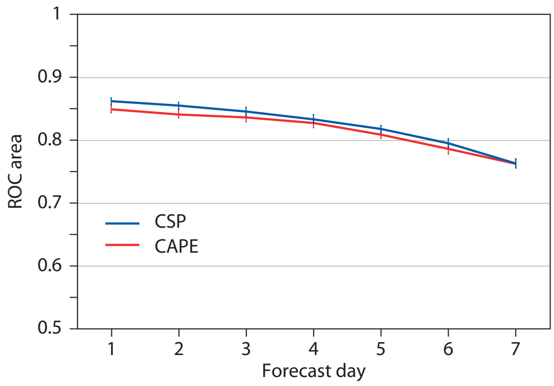

Figure 2 ROC area for the EFI for CSP and for CAPE over the USA. The EFI is verified against severe weather reports from the Storm Prediction Centre (SPC) database for 1 April to 31 October 2014. Error bars show 90% confidence intervals.

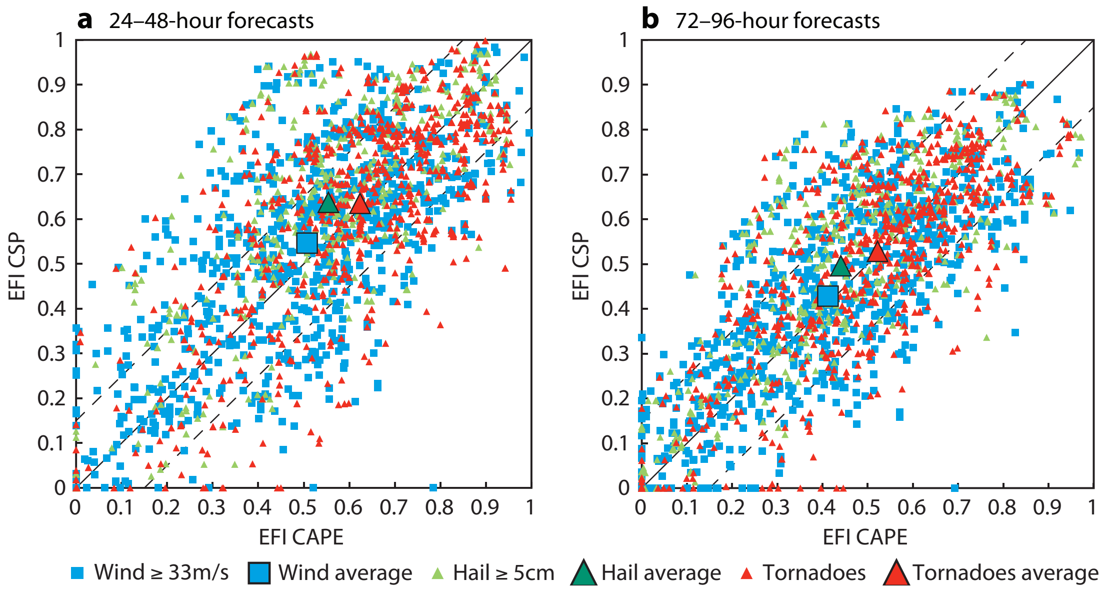

Figure 3 Scatter plot of EFI for CSP versus EFI for CAPE, for 'very' severe thunderstorms, including all reports of tornadoes, hail ≥ 5 cm in diameter and wind gusts ≥ 33 m/s from 1 April to 31 October 2014 over the USA for (a) 24–48-hour forecasts and (b) 72–96-hour forecasts. The EFI is represented by the maximum value within 100 km around each severe weather report. Dashed grey lines represent ±15% deviations from the diagonal as a threshold above which the EFIs differ significantly.

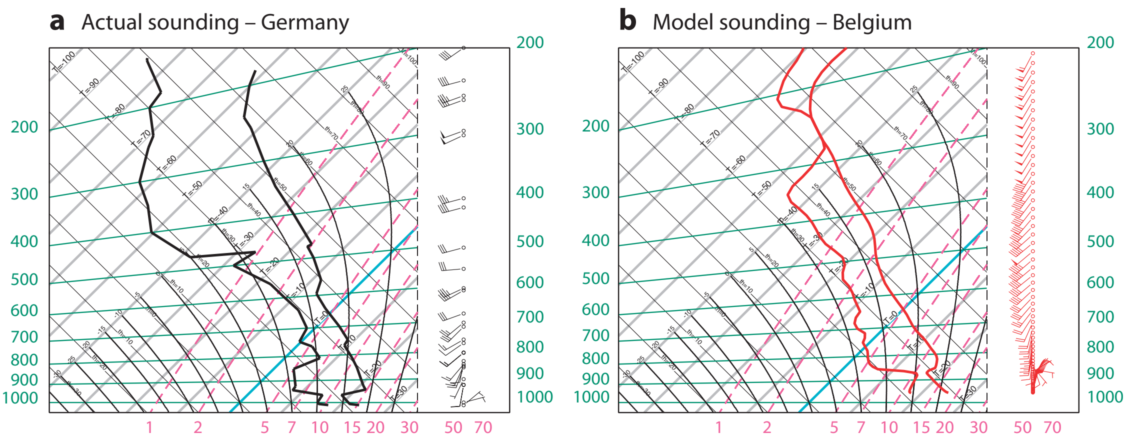

Figure 4 (a) Sounding from Bergen, northern Germany, at 1200 UTC on 9 June 2014, and (b) model tephigram for a location in eastern Belgium where the large values of CAPE were analysed at 1200 UTC on 9 June 2014 and where the severe storm that hit Germany (Figure 5a) originated.

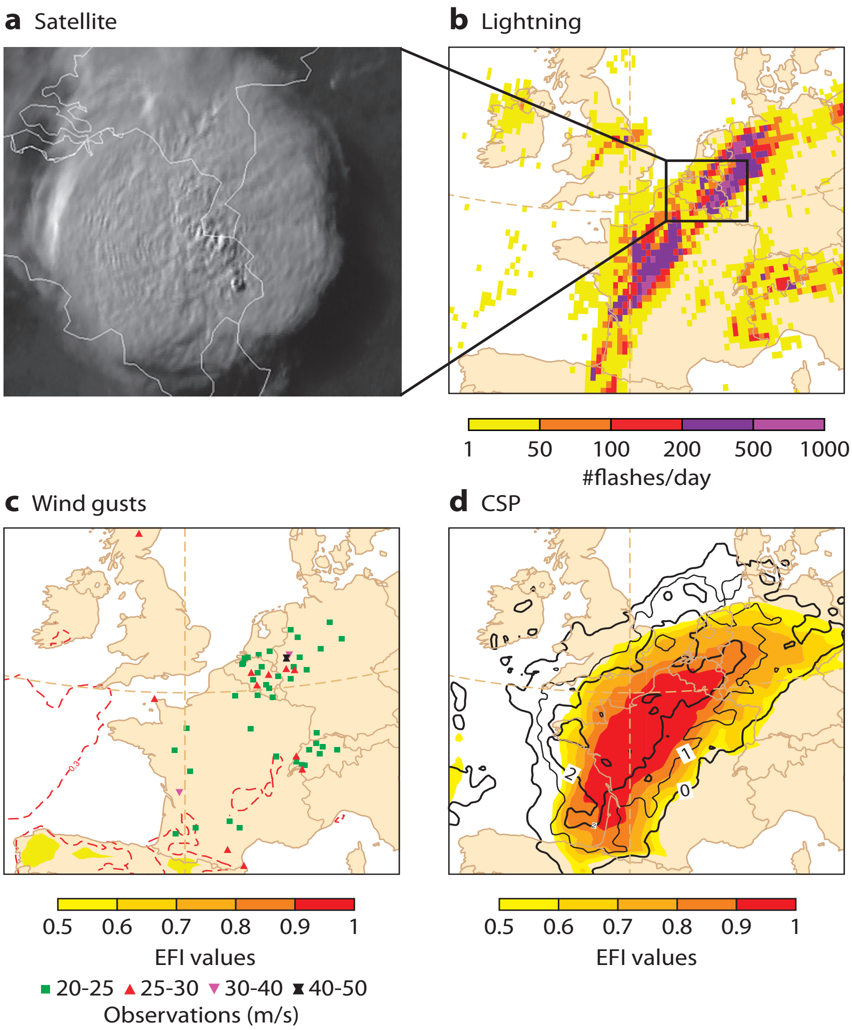

Figure 5 (a) Meteosat-10 HRV (High Resolution Visible) imagery at 1730 UTC on 9 June 2014 (source: EUMETSAT); (b) lightning activity (total number of flashes) on 9 June 2014 (source: UK Met Office ATDnet lightning database); (c) EFI for 10-metre wind gusts, T+0–24h forecast and reported maximum wind gusts (in m/s) both valid for 9 June 2014; and (d) EFI (shading) and SOT (contours) for CSP, T+120–144h forecast valid for 9 June 2014.

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Case study 1: 9 June 2014

On 9 June 2014, a hot air mass was moving north over Western Europe on the western fringe of a ridge. A quasi-stationary front could be found over the westernmost parts of the continent. Model and actual soundings showed steep lapse rates in the low to mid-troposphere with substantial low-level moisture (Figure 4). As a consequence of this, and owing also to the presence of some convective inhibition (CIN) (note the capping inversion in the lower troposphere on the tephigrams in Figure 4), very large CAPE built up. Model analysis fields suggested that CAPE values exceeded 3,000 J/kg. In addition, extreme CAPE overlapped with substantial vertical wind shear that favoured the organisation of DMC into supercells and mesoscale convective systems (MCSs).

In the event, an outbreak of severe convection affected France, the Benelux countries and western Germany with many reports received, chiefly of strong wind gusts and large hail. A violent supercell developed over western Germany in the late afternoon (Figure 5a). It uprooted many trees and caused the death of six people as well as significant damage and disruption to transport. Gusts of up to 42 m/s were recorded at Düsseldorf Airport (Figure 5c).

The EFI forecast for 10-metre wind gusts (Figure 5c) gave no indication of severe wind gusts even in the short range. The EFI for CSP, however, reached extremely high values, in excess of 0.9, giving an indication of organised DMC and suggesting that supercells might develop that day. This signal appeared in the forecast many days in advance: it is quite uncommon to see EFI values close to 1 in a day-6 forecast (Figure 5d). In addition to severe wind gusts, large hail and damaging lightning were also reported, consistent with the high EFI values. The high values of the EFI for CSP cover the areas of the most intense lightning activity, from southern France through to northern Germany (Figure 5b).

Case study 2: 13 May 2015

The EFI for both CAPE and CSP is supposed to provide indications of potentially anomalous convection and in particular of severe convective outbreaks in mid-latitudes in the warm part of the year. The EFI shows the area where the given convective parameter is anomalous compared to the model climatology. On many occasions this area is much bigger than the area where severe convection actually occurs. In this sense the new EFI parameters show where the convection could be severe if it is initiated.

The example below aims to suggest to users how the area of severe convection might be specified more precisely several days in advance, using the EFI and other forecast fields. The day-4 EFI forecast from 10 May 2015 0000 UTC shows a wide area, ranging from northern Iberia through France, Switzerland and southern Germany to Hungary, where CAPE and CSP reach extremely high values (Figure 6a and 6c). This suggests that convection, if it is initiated, could be well-organised and would be capable of producing large hail, severe wind gusts and even tornadoes. The positive SOT values show that at least 10% of ENS members forecast values of CAPE and CSP exceeding the 99th percentile of the M-climate (see Box A). The M-climate is shown for reference in Figures 6b and 6d.

Figure 6e shows the probability of convective precipitation greater than 1 mm from ENS, together with the large-scale flow forecast represented by the ensemble mean of 500-hPa geopotential. The highest probability of rain was forecast for easternmost France, Switzerland, southern Germany and parts of Austria and Hungary. For the rest of the area covered by the EFI the probabilities are very low, suggesting that DMC is very unlikely there. In the event, severe storms did develop over the aforementioned areas on 13 May, producing large hail and severe wind gusts in the evening hours with a tornado reported over southern Germany. Analysis of other cases similar to this one suggests that viewing the EFI for CAPE and CSP alongside the probability of convective rain can provide the forecaster with more precise guidance on where severe convection is likely to occur in the medium range – in this particular case that means 4 days in advance (T+72–96h).

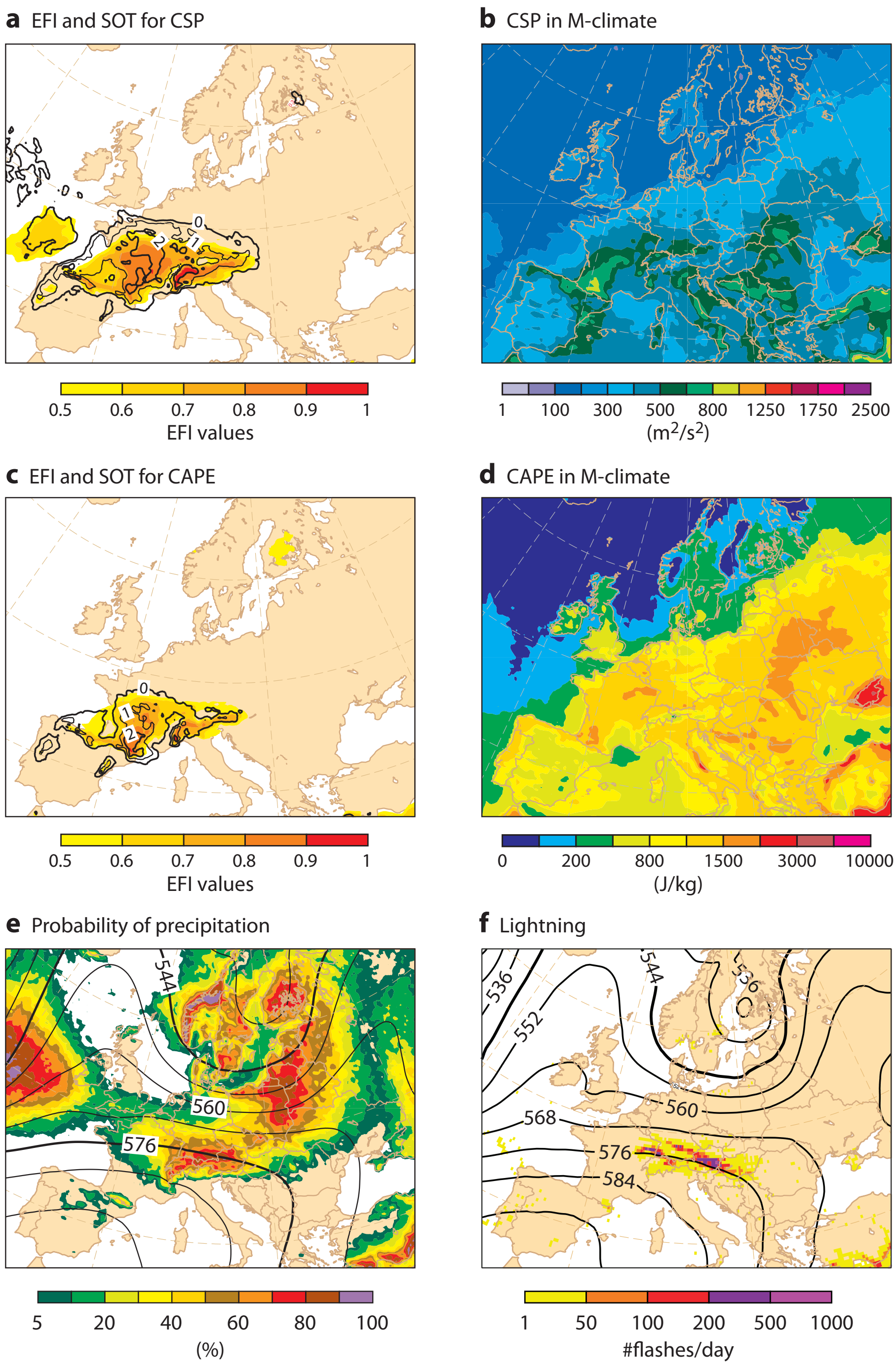

Figure 6 (a) EFI (shading) and SOT (contours) for CSP, T+72–96h forecast from 10 May 2015, (b) M-climate 99th percentile for CSP in m^2/s^2, (c) EFI (shading) and SOT (contours) for CAPE, T+72–96h forecast from 10 May 2015, (d) M-climate 99th percentile for CAPE in J/kg, (e) probability of convective precipitation ≥ 1mm, T+72–96h (in %, shading) and ENS mean of 500 hPa geopotential height (in geopotential decametres, contours), T+84h, from 10 May 2015, and (f) lightning activity (in number of flashes/day per grid box) valid for 13 May 2015 and ECMWF analysis of 500 hPa geopotential height (in geopotential decametres, contours) valid for 13 May 2015 1200 UTC.

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Practical considerations

Neither of the convective parameters presented here considers Convective Inhibition (CIN – see Box B), which is a measure of the amount of energy an air parcel needs in order to reach the level of free convection (LFC). If CIN is large, DMC is unlikely to occur even if the EFI is high.

The EFI gives an indication of the likelihood of anomalous weather relative to a baseline distribution of what ordinarily occurs in the given location at the given time of year. So in areas where even the climatological extremes of the convective index are small, e.g. in continental areas in winter, severe convective weather such as tornadoes or large hail are unlikely even if the EFI is high. Therefore, to be sure of whether severe convection is possible or not, the forecaster should always view the EFI alongside the absolute values of the given convective parameter seen in climatology (provided by the M-climate), and then use their knowledge and experience of what levels of these parameters might be needed to lead to severe convection.

The results presented in this study suggest that the EFI can be applied successfully to forecasting severe convection in the medium range. EFIs for CAPE and the combined CAPE-SHEAR parameter CSP are now available on the ECMWF website in test mode and any feedback from users is welcome.

Further reading

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