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EUMETNET SRNWP-EPS EFI/SOT Software: From Research to Operations in AEMET-γSREPS

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ABSTRACT

The EUMETNET Short Range Numerical Weather Prediction - Ensemble Prediction System (SRNWP-EPS) EFI/SOT software is a result from the EUMETNET SRNWP-EPS 2019 to 2023 project. It computes the Extreme Forecast Index (EFI) and Shift of Tails index (SOT) for the different EUMETNET Member States Limited Area Modelling - Ensemble Prediction Systems (LAM-EPS). The software, implemented in Python 3, has been developed from scratch within a multiprocessor Linux environment: the European Centre for Medium-Range Weather Forecasts (ECMWF) ATOS High Performance Computer Facility (HPCF). The software has been developed testing on EFI and SOT indices for a wide variety of meteorological variables such as accumulated precipitation (AccPcp), accumulated snow (AccSnw), 2 m maximum and minimum temperature (T2mMax and T2mMin) and 10 m maximum wind gust (G10m).

In order to overcome the computational limitations derived from LAM-EPSs in terms of constructing a large and robust EPS-climatology through an expensive re-forecast with the last LAM-EPS version, the software follows methods from Météo-France that consists of temporal and spatial relaxation techniques that include neighboring data in space and time to enrich the small available dataset used to construct the EPS-climatology. Additionally, the software introduces a land-sea mask that aims at applying physically-based restrictions to the grid points included by the spatial relaxation methods. Specific extreme weather events have been selected to showcase the software with some EUMETNET Member States LAM-EPSs. Moreover, an already operational implementation of the EUMETNET SRNWP-EPS EFI/SOT software is showcased in AEMET-γSREPS, the LAM-EPS developed and operationally run at AEMET, the Spanish Meteorological Agency. The software provides products similar to the ones from the European Centre for Medium-Range Weather Forecasts Ensemble (ECMWF ENS), and are currently available for AEMET forecasting offices.

1. Introduction

a. EUMETNET SRNWP-EPS project

Under the current context of global climate change, the improvement in the prediction of High Impact Weather (HIW) events has become an important issue for the different meteorological services across Europe. The EUMETNET Short Range Numerical Weather Prediction - Ensemble Prediction System (SRNWP-EPS) project was born within the EUMETNET Numerical Weather Prediction (NWP) Cooperation Programme with the main goal of enhancing and coordinating the cooperation on developing reliable

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mesoscale short-range convection-permitting ensemble systems in Europe and, at the same time, grouping efforts developing tools that can be smoothly applied to any Limited Area Modelling - Ensemble Prediction System (LAM-EPS).

The 2019 to 2023 phase of the EUMETNET SRNWP-EPS project aimed at advancing in the LAM-EPSs capabilities related to HIW forecasting by focusing on extreme events (EUMETNET, 2023). One of the so-called Research to Operations (R2O) applications to be developed by the end of the 2019 to 2023 phase is the tool presented in this paper: the EUMETNET SRNWP-EPS EFI/SOT software (hereafter, EFI/SOT software), which calculates the Extreme Forecast Index (EFI) and Shift of Tails index (SOT) for the different EUMETNET Member States LAM-EPSs. Because the EFI/SOT software has been designed to be implemented on LAM-EPSs (most of them, with about 2.5 km of grid spacing), the resulting EFI/SOT product offers a higher spatial resolution than the European Centre for Medium-Range Weather Forecasts Ensemble (ECMWF ENS) currently running at 9 km of grid spacing. In addition, it is important to remember that LAM-EPSs are especially developed to perform forecasts in the short-range, while the ECMWF ENS focuses its forecasts on the medium-range. Therefore, the EFI/SOT software is expected to help forecasters to point to potential HIW events localised in small areas in the short-range that may have not been forecasted by the lower resolution of the ECMWF EFI/SOT.

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

The Extreme Forecast Index (EFI) was first defined in the European Centre for Medium-Range Weather Forecasts (ECMWF) by François Lalaurette, in 2002. It was conceived as a tool to provide forecasters and users of the medium-range forecasts with an objective early warning (Lalaurette, 2003).

The mathematical EFI definition used in this paper is the one revised by Zsoter (2006):

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

where $F_f\,(p)$ is the proportion of EPS members lying below the LAM-EPS climate p quantile. The term $1/\sqrt{p}(1-p)$, which takes its minimum for p=0.5 and its maximum at both ends of the probability range, is used to give more weight to the tails of the distribution (Dutra et al., 2013).

The EFI is a dimensionless index defined in such a way that it can only take values between –1 and 1. An EFI equal to 1 means that all EPS-members' forecasting values are larger than the maximum EPS-climate (called M-Climate, Model Climate by the ECMWF) quantile (p=1). On the other hand, EFI reaching –1 corresponds to the case where all EPS-members' forecasting values lie below the minimum EPS-climate quantile (p=0). Finally, the case where EFI equals 0 represents two scenarios: the first, where the Cumulative Distribution Function (CDF) from the EPS-climate and EPS-forecast are indistinguishable (this happens when the forecast spread is so large that it covers all possible outcomes from the EPS-climate); the second, where the EPS-forecast has high certainty, generating a CDF that is very close to what is climatologically normal (p=0.5 in the EPS-climate CDF) for a particular place. To figure out which scenario applies, one should look at CDFs from the model climate and forecast.

The EFI gives a general outlook about the departure of the EPS-forecast CDF from the EPS-climate CDF; it is a useful summary tool to interpret the extreme characteristics of the whole EPS-forecast distribution (Zsoter, 2006). However, the EFI does not measure the degree of abnormality of the most extreme EPS-forecast members. For this reason, and to complement the information provided by the EFI, Zsoter defined in 2006 a new index called Shift of Tails (SOT) that compares the tails of the EPS-forecast and EPS-climate CDF. This comparison can be performed either for the upper tail or the lower tail of the CDF. For instance, the latter would be useful in extreme cold events, where SOT would provide information about the exceptionality of the lowest temperatures forecasted by an EPS. The SOT index is thus sensitive to extreme forecasts only (Boisserie et al., 2016b). For the upper tails, the SOT is expressed as:

$$\mathrm{SOT}_{+}(p) = -\frac{Q_f(p) - Q_c(100)}{Q_c(p) - Q_c(100)} \tag{2}$$

where $Q_f\,(p)$ refers to the EPS-forecast p quantile, and Q_c (100) is the highest quantile of the EPS-climate. In this paper, the EPS p quantile considered in the SOT_{+} (p) expression is the 90^{th} (hereafter, SOT90), which is also the value used by the ECMWF in the ENS EFI/

SOT product, publicly accessible in ECMWF (2023a).

In a similar fashion, the SOT expression for the lower tails of the EPS distribution, $SOT\_(p)$, can be obtained by replacing Q_c (100) with Q_c (0). In this case, the considered EPS p quantile is the 10th (hereafter, SOT10), also following the main lower reference quantile from the ECMWF.

Even though the SOT90 and SOT10 definitions presented above are the ones defined in scientific literature — and the one used in the EFI/SOT program — ECMWF considers Q_c (99) and Q_c (1) (instead of Q_c (100) and Q_c (0)) in the definitions of SOT_+ (p) and $SOT\_(p)$, respectively, in order to improve the statistical robustness of their SOT index.

Still, it is noteworthy that the EFI/SOT software allows the user configure the p quantiles to be used for the SOT_+ (p) and $SOT\_(p)$.

2. Data

a. EUMETNET SRNWP-EPS database

Within the framework of the EUMETNET SRNWP-EPS project, an off-line database of European convection-permitting LAM-EPS ensembles has been established at the ECMWF, which archives convection-related parameters mainly close to the surface (Callado et al., 2021). This database aims at enhancing the collaboration between the different European LAM-NWP consortia in LAM-EPS improvement and development, as well as other fields such as post-processing. The Met Office, United Kingdom (MOGREPS-UK), Météo-France, France (AROME-EPS), Met Éireann, Ireland (IREPS), the Danish Meteorological Institute, Denmark (COMEPS), the Italian Aeronautica Militare, Italy (ITEPS) and AEMET, Spain (AEMET-γSREPS) are currently and continuously archiving their data since 1 June 2020. This database, which consists of General Regularly-distributed Information in Binary form (GRIB) files with data for the cycles up to the last lead time run by the operational systems of each member institution, has been used to develop and test the EFI/SOT software for a number of case studies, as shown in section 4.

b. AEMET-γSREPS database

As will be described in section 5, the EFI/SOT software has been successfully implemented in AEMET-γSREPS (hereafter, γSREPS), the LAM-EPS of AEMET. In this case, the historical dataset used to construct the γSREPS-climatology were taken from the γSREPS GRIB local archive, which is saved in the ECMWF's File Storage system (ECFS). This archive, which contains data for a larger number of meteorological variables and years than the EUMETNET SRNWP-EPS database, is appropriate for building the γSREPS-climatology.

3. Methods

a. Constructing the EPS-climatology

Because the EFI is, conceptually, a comparison between the EPS-forecast and EPS-climate CDFs, it becomes clear the importance of having a robust and reliable EPS-climatology: the more robust and consistent the EPS-climatology is, the higher the reliability of the EFI. This reliability can depend, at least, on two factors. First, the level of noise in the EFI estimate — the larger the EPS-climate is, the lower the noise. And second, the EFI capability to robustly discriminate HIW — the larger the EPS-climate is, the better this discrimination should be — which can be objectively evaluated following the methods proposed in Boisserie et al. 2016 and Raynaud et al. 2018, for instance.

According to the World Meteorological Organization (WMO), climate is a dataset that collects meteorological statistics for, at least, the past 30 y. However, obtaining a historically consistent EPS-climatology is challenging given that EPSs undergo numerous updates and modifications during their lifetime that introduce heterogeneities. ECMWF overcomes this limitation by running an expensive 20-y reforecast system to obtain the EPS-climate for the construction of their ENS EFI/SOT product (ECMWF, 2023b). However, there are circumstances around LAM-EPSs that hinder the implementation of a reforecast system. On the one hand, LAM-EPSs are recent systems where the focus has been primarily on developing well-performing operational systems, rather than reforecast systems. On the other hand, reforecast systems are computationally very demanding, thus, preventing the weather centers from running these systems to engage efforts in developing and running it over large historical periods. This is the case of the EUMETNET member states, where it was decided to circumvent this problem by using the available LAM-EPS archives stored in the EUMETNET SRNWP-EPS database (containing consistent LAM-EPS data covering the last two or three years) to feed the construction of the EPS-climatology, but enriched via relaxation techniques. This approach is based on that described by Raynaud et al. 2018 in the context of the development of the AROME-EPS EFI/SOT software.

The temporal relaxation technique consists in setting a temporal window around the EFI/SOT forecast date, and then assuming that all days within such a window share the same climatology. The width of the temporal window — which is symmetrical around the target date — is configurable by the user. Regarding this temporal relaxation, the EFI/SOT software provides three options:

- *Automatic* mode: the temporal window is centered around the EFI/SOT target date for the running year and the previous ones, from the starting year configured by the user. For the running year, the three closest days within the temporal window are not considered, as the data may be correlated to the meteorological situation characterizing the EFI/SOT forecast date.
- *Seasonal* mode: given that an operative use of the automatic mode would imply a daily recalculation of the EPS-climate, and once the authors were at the point of running the EFI/SOT software operatively in AEMET-γSREPS, it was decided to create a computationally costless EPS-climate. That was the reason for defining the temporal relaxation seasonal mode, where the temporal window is centered around the 15th day of the running month for a collection of years configurable by the user. With this mode activated, the γSREPS-climate was only calculated once a month.
- *Manual* mode: there is no default temporal window, so the user has to define explicitly the list of dates that will conform the EPS-climatology.

Temporal relaxation is a resource used by the ECMWF, as well, for the construction of their ENS-climate, M-climate, as it is described in ECMWF, 2023b.

The spatial relaxation technique, which is more unusual, is based on the construction of a circular neighboring area centred at the grid point where EFI/SOT are calculated, and including for the EPS-climatology all grid points within such region. The rationale for this is the assumption that the meteorological data contained is spatially homogeneous enough to be considered to have the same climatology. In the EFI/SOT software, the user can configure the size of the neighborhood setting the radius, expressed in units of grid points. After performing some sensitivity tests (not shown here), the authors decided to set the radius equal to 4 grid points, which is equivalent to 10 km for a 2.5 km EPS grid spacing, as the operative setting of the EFI/SOT software for AEMET-γSREPS. It is noteworthy to remark that the spatial relaxation technique is implemented in the collection of the EPS-forecast data, as well.

In addition, and following Raynaud et al. 2018, the software includes a random selection filter as an optional setup. This consists in the random subsampling of a number of grid points within the circular neighborhood, in case the user wants to ameliorate spatial correlation effects. The software lets the user configure the percentage of grid points to be selected randomly. Still, in this paper this option is not used with the idea that the minimum scale at which meteorological information from NWP models have value is precisely in that neighborhood, rather than in single grid points. Therefore, we consider that including all grid points within the region can lead to a more robust EPS-climate with more data.

In this regard, the software introduces a new functionality to the original methods described in Raynaud et al. 2018: the implementation of a land-sea mask that aims at applying physically-based restrictions to the grid points included by the spatial relaxation methods. This filter tries to work around a limitation commented by Raynaud (personal communication) in the EFI/SOT performance close to land-sea boundaries. The land-sea filter discards, for a given circular neighborhood, those grid points laying over a different type of surface, either land or water/sea, from the central grid point. This is especially useful when considering meteorological variables such as temperature close to the sea, given its different behaviour over land and over water bodies. This situation can be observed in Fig. 1, where the implementation of the land-sea filter over 24h-T2mMin EFI/SOT has a noticeable impact over coastal grid points. Concretely, it leads to extreme EFI values (more negative) in comparison with the case where the filter is not activated. In this case, the coastal grid points present smoother EFI values because the calculation of the EPS-climate and forecast CDFs considers, not only the data associated to the grid points falling on earth, but also those over sea that are contained within the spatial relaxation circle. In the same vein, an orographic filter that tries to homogenise spatial relaxation so as not to combine data from locations with very different model orography could also be developed. Because the EFI/SOT software— which is running operatively in AEMET-γSREPS

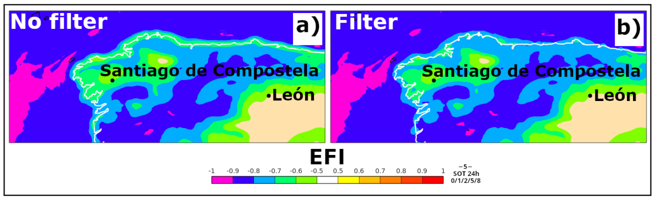

Figure 1. 24h-T2mMin EFI/SOT for γSREPS over Galicia (NW Spain) during the Philomena storm event (9 January 2021). All plots correspond to a t+24h lead time forecast, starting at 00 UTC 9 January 2021. Land-sea filter is discarded (left) and activated (right) in order to highlight the impact of this filter on EFI. *Click image for an external version; this applies to all figures hereafter.*

without orographic filtering—apparently has not shown any major artefact in EFI/SOT performance in complex orography, authors leave as future work the complete development of an orographic filter.

b. EPS-climatology for case studies

In the different case studies presented below, the EPS-climatology has been constructed from the EPS GRIB files stored in the EUMETNET SRNWP-EPS database. For all of them, the temporal relaxation configuration has been set to manual mode and a spatial relaxation circle of radius 4 (grid points) has been implemented with the land-sea filter being activated (see the corresponding columns from Table 1 for more details). These experiments have been performed as a first validation of the software for the different LAM-EPSs stored in the EUMETNET SRNWP-EPS database.

c. Operational γSREPS-climatology

As it is explained in section 5, the EFI/SOT software is currently operational — as a test product since June 2023 — within γSREPS, the LAM-EPS of AEMET. The EPS-climatology that is being used is a monthly fixed one, which means that the same climatology is used for all the days of a given month, implying a rather abrupt change in the definition of EFI/SOT indices between the last day of the previous month and the first of the next one. This corresponds to the seasonal temporal relaxation configuration mode described in section 3.a, defining a temporal window covering 30 days forward and backward, for the 2019 to 2022 period. In practice, this implies that 244 days ((30+30+1) days × 4 y) are considered to calculate the EPS-climatology of a given day. This configuration is implemented in the heat wave and cold front operational γSREPS case studies (see Table 1).

Concerning the spatial relaxation, a circular neighborhood with a radius of 4 grid points is considered, which implies that the closest 49 grid points contribute to the climatology associated with the central grid point. As mentioned above, the only spatial filter that is activated is the land-sea filter.

Note that to reduce the abrupt change between months mentioned above related to the temporal relaxation, in the midterm we at AEMET aim to implement a weekly re-calculation of the γSREPS-climatology considering weighting factors—giving more importance to data that is temporally closer to the considered week—so narrowing differences with the twice per week EPS-climate update approach implemented in the ECMWF.

4. Validation in various case studies

Three case studies are presented to validate the outcome of the EFI/SOT software. In each case study, distinct aspects and challenges of the EFI/SOT forecasts are discussed and contrasted in a number of distinct meteorological situations. Where equivalency with the ECMWF is available, a subjective comparison with the ENS EFI/SOT product is shown. Neither statistical skill assessment of the EFI/SOT product nor objective verification against the ENS EFI/SOT have been performed, mainly due to the lack of a historical EFI/SOT database (the EFI/SOT software started its operations in γSREPS in June 2023) and the differences in the spatial properties between ENS and γSREPS, respectively. This objective assessment is planned to be performed in future work, once the γSREPS EFI/SOT database becomes more robust.

a. Storm Eunice event (18–20 February 2022)

In this case study we focus on the EFI/SOT performance in an intense synoptic large low that affected a relatively large region during several days, making it a situation especially suitable for the successful application of the EFI/SOT indices developed by the ECMWF.

Storm Eunice was an extra-tropical cyclone that affected several countries of northwestern Europe between 18 and 20 February 2022. The storm, which produced heavy rainfall and snowfall, set a new record

Table 1. EUMETNET SRNWP-EPS EFI/SOT case studies summary table. It includes the temporal and spatial relaxation techniques settings.

EUMETNET SRNWP-EPS EFI/SOT CASE STUDIES SUMMARY TABLE					
Event	Synoptical storm Eunice	Mesoscale convective storm	Synoptical storm Philomena	Heat wave	Cold front
Domain	British Isles	SE England	Iberian Peninsula	Iberian Peninsula	Iberian Peninsula
LAM-EPS	IREPS	MOGREPS-UK	γSREPS / AROME-EPS	γSREPS	γSREPS
LAM-EPS members	11	18	20 / 12	10 (1)	10 (1)
LAM-EPS grid spacing (km)	2.5	2.2	2.5 / 2.5	2.5	2.5
LAM-EPS vertical levels	65	70	65 / 90	65	65
LAM-EPS LBCs	IFS-HRES	MOGREPS-G	Multi-model (2) / ARPEGE-EPS	Multi-model (2)	Multi-model (2)
EFI/SOT forecast day(s)	18–19–20 February 2022	20 July 2021	9 January 2021	18 July 2023	4 August 2023
EFI/SOT meteorological variables	24h-AccPcp, 24h-AccSnw	6h-9h-12h-15h-18h-AccPcp (starting at 12 UTC) 24h-AccPcp (starting at 00 UTC)	24h-AccPcp, 24h-AccSnw (γSREPS & AROME-EPS), 24h-T2mMax,24h-T2mMin (γSREPS)	24h-T2mMax	24h-T2mMax, 24h-T2mMin, 24h-G10m, 24h-AccPcp
ECMWF ENS comparison	YES	YES (for 24h-AccPcp)	YES (for 24h-AccPcp and 24h-AccSnw)	YES	YES
Temporal relaxation settings					
Mode	manual	manual	manual	seasonal	seasonal
Date list (3)	15 January – 15 March, 2021 to 2023 (4)	1–15 July, 2020 to 2022	15 December – 15 February, 2021 to 2023 (5)	-	-
Seasonal date (6)	-	-	-	15 July 2022	15 August 2022
Initial year (7)	-	-	-	2019	2019
Delta days (8)	-	-	-	30	30
Number of days	176	45	178	244	244
Spatial relaxation settings					
Radius (# grid points)	4	4	4	4	4
Land-sea mask filter	YES	YES	YES	YES	YES
Random filter	NO	NO	NO	NO	NO
Orographical filter	NO	NO	NO	NO	NO
Effective number of LAM-EPS climatological data associated to each grid point (# circular neighborhood grid points x # EPS-members x # climatology days)					
	94864 (49 x 11 x 176)	39690 (49 x 18 x 45)	174440 (49 x 20 x 178) / 104664 (49 x 12 x 178)	119560 (49 x 10 x 244)	119560 (49 x 10 x 244)
ECMWF ENS	1980 (20 y x 9 runs x 11 EPS-members)				

(1): γSREPS number of members was 10 instead of the usual 20 due to technical problems.
(2): IFS, ARPEGE, GFS, GSM and GEM.
(3): list of dates conforming the EPS-climatology. To be used with manual mode.
(4): excluding 16–22 February 2022.
(5): excluding 7–11 January 2021.
(6): central date (associated to the last year) to construct the temporal relaxation window. To be used with seasonal mode.
(7): initial year when the user wants to start implementing the temporal relaxation window.
(8): width of the temporal relaxation window.

for the strongest wind gust recorded in England (196 km/h) (Met Office, 2022).

For this case study, we use the EFI/SOT software on the data from the LAM-EPS IREPS (Met Éireann, 2023). EFI and SOT90 indices are forecasted for 24h-accumulated precipitation (24h-AccPcp) and 24h-accumulated snow (24h-AccSnw) on 18, 19 and 20 February 2022 (see Fig. 2). All the products are obtained from the 00 UTC IREPS cycle for each day. Concerning the IREPS-climate temporal relaxation, it collects data from the period starting at 15 January to 15 March, 2021 to 2023 (in February 2022, days 16 to 22 are not included to avoid considering meteorological correlation with the studied event, see Table 1).

For comparison purposes, ECMWF ENS EFI/SOT products for the same meteorological variables and days are also shown in Fig. 2.

A subjective verification between the EUMETNET and the ECMWF 24h-AccPcp EFI/SOT shows that the EUMETNET EFI/SOT software provides sensible results. Both products agree in identifying the most relevant EFI areas, not only in terms of geographical localization but also in intensity. Regarding the SOT90, both products partially disagree in locating some of the positive SOT90 areas. Even though an objective rigorous analysis has not yet been performed, authors suspect that the different temporal extension between the EPS-climatology used in both products—20 y for ECMWF model climate versus three years for IREPS model climate (EUMETNET)—may play its role as well as the use of Q_c (100) instead of Q_c (99) for the calculation of SOT90—an effect depicted in Fig. 7, concerning the Philomena storm event, discussed in section 4.c. Moreover, divergences between EPS-forecasts could also yield to the mentioned SOT90 discrepancies. Further investigation is left for future studies.

Similar behaviour can be observed (not shown) from the 24h-AccSnw EFI/SOT comparison between EUMETNET and ECMWF.

b. Convective storm episode over United Kingdom (20 July 2021)

In this case study we focus on the development of a short-lived mesoscale convective storm affecting a small

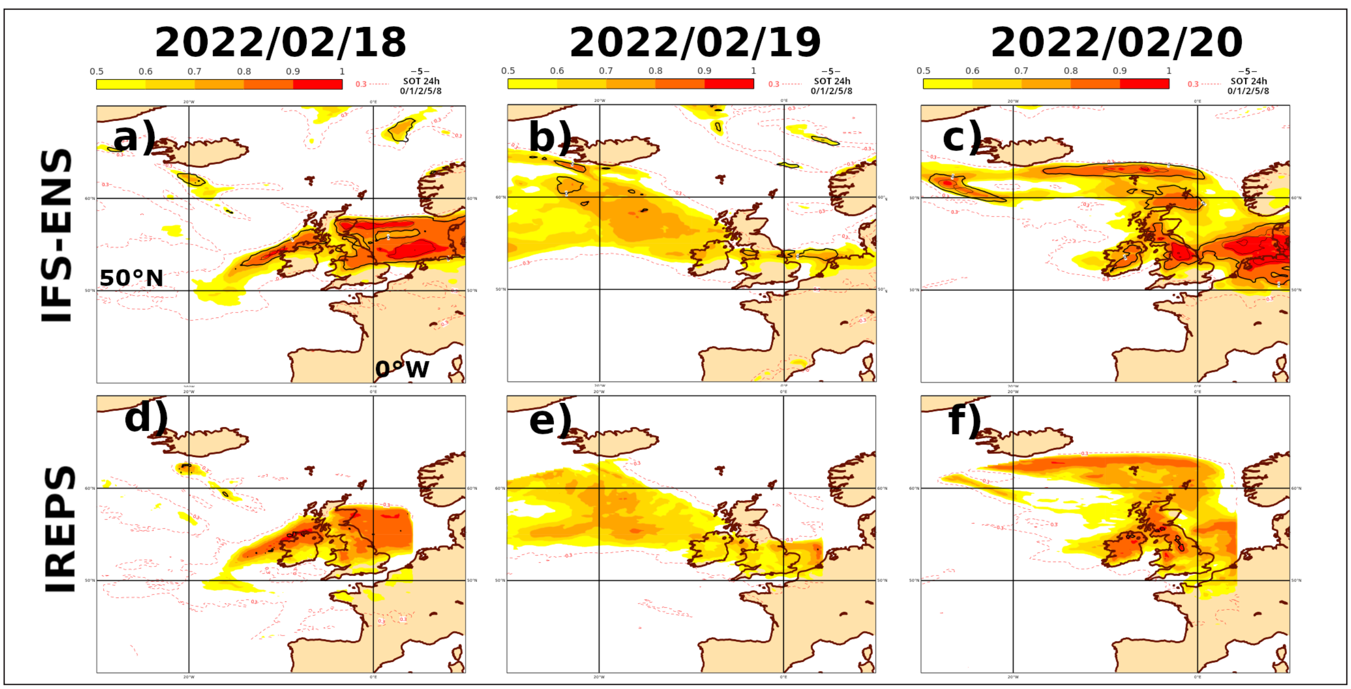

Figure 2. 24h-AccPcp EFI/SOT for global ECMWF ENS (top) and LAM-EPS IREPS (bottom) over NW Europe during the Eunice storm event (18–20 February 2022). All plots correspond to a t+24h lead time forecast, starting at 00 UTC 18 February 2022 (first column), 00 UTC 19 February 2022 (second column) and 00 UTC 20 February 2022 (third column).

region. During the 20 July 2021 afternoon, several areas in eastern and southeastern England experienced intense heavy rainfalls (in Kibworth, Leicestershire, 70 mm of precipitation was recorded in just 1 h) due to a convective storm event. Even though high pressures were dominating the United Kingdom (with many regions presenting hot, dry and sunny weather), an unstable air mass over a deep layer in the troposphere lay across eastern and southeastern England with potential for severe convection. According to an internal study performed by the UK Met Office, a small-scale upper trough disrupted into a cut-off vortex across eastern areas.

For this case study, LAM-EPS MOGREPS-UK (Met Office, 2023) is used to feed the EFI/SOT software. The EFI and SOT indices are calculated for the 24h-AccPcp forecasts as well as the corresponding ECMWF ENS product, both of them valid on 20 July 2021 (Fig. 3). The MOGREPS-UK-climate consists of data from the period 1–15 July, 2020 to 2022 (see Table 1). The radius of the spatial relaxation circle is set to 4 and the land-sea mask filter is activated.

Figure 3 reflects a nearly null signal of EFI— just little areas in southeastern England presenting EFI values higher than 0.3—thus, indicating that no extreme event associated to 24h-AccPcp is expected to take place on 20 July 2021. This result which can be, at first look, incoherent—given the floods that affected some areas in southeastern England—may have an interpretation. It is important to notice that the convective storm episode was short-lived, concentrating the huge amounts of precipitation in a few hours. For this reason, shorter accumulation periods of AccPcp were considered to see if the EFI/SOT signal experienced some changes: 6h, 9h, 12h, 15h and 18h periods are considered (from the MOGREPS-UK cycle starting at 12 UTC) (see Fig. 4). Comparison with the ECMWF is not possible in this case as the ECMWF does not produce EFI/SOT products for accumulation periods shorter than 24 h.

Figure 4 shows how the EFI/SOT signal weakens as the accumulation period increases. The 6h-AccPcp EFI/SOT plot clearly identifies an area in southeastern England where an extreme precipitation event has high probability to occur. This is an example that reflects how sensitive the EUMETNET EFI/SOT product is with the accumulation period for a short-lived convective system. Although a given precipitation amount is more extreme for a shorter accumulation time window, further analysis would be required to explain the difference in the EFI forecasts for all the different time windows presented in Fig. 4, which is out of the scope of this paper.

c. Storm Philomena episode (9 January 2021)

In this case study, we challenge the EUMETNET EFI/SOT to an unusual event, an extreme snowfall over the Iberian Peninsula. In addition, the geographical localization of the event makes it possible to perform

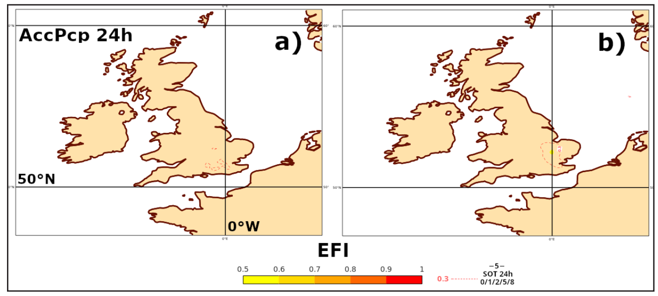

Figure 3. 24h-AccPcp EFI/SOT forecasted by LAM-EPS MOGREPS-UK (left) and ECMWF ENS (right) over the British Isles valid at 00 UTC 21 July 2021 (starting cycle at 00 UTC 20 July 2021, lead time t+24h), when a convective storm event took place in that afternoon in southeastern England.

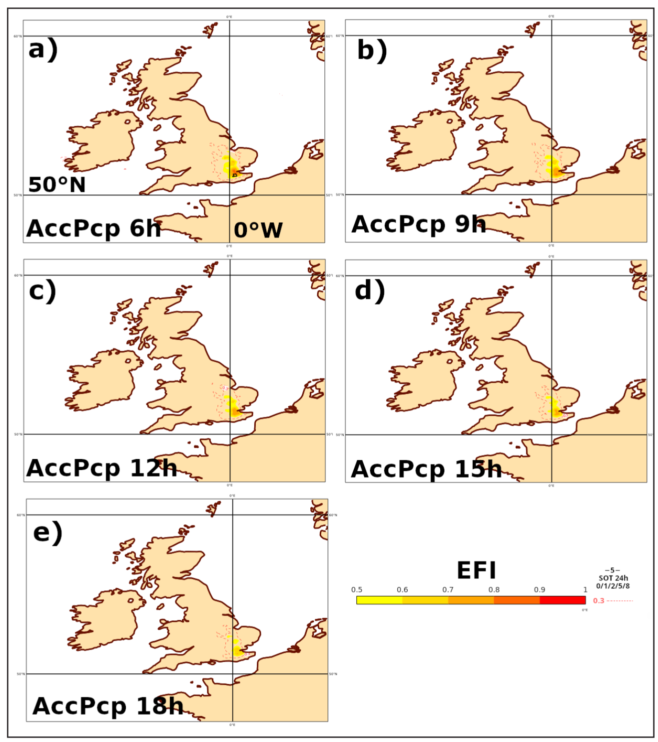

Figure 4. EFI/SOT in MOGREPS-UK for AccPcp in different accumulation periods (all of them starting at 12 UTC 20 July 2021). Time periods of 6h, 9h, 12h, 15h and 18h are considered over the British Isles during a convective storm event in SE England.

the analysis using data from γSREPS (Frogner et al., 2019) and AROME-EPS (Bouttier et al., 2016) for comparison purposes.

Philomena is the name of an extra-tropical storm that hit the Iberian Peninsula during the first days of January 2021. It produced extreme snowfall in the centre and eastern half of the Iberian Peninsula — especially noticeable in Madrid, where 50 cm of snow were registered — as well as heavy rains, intense wind gusts and a posterior drop of temperatures (AEMET, 2021).

For this case study, LAM-EPSs γSREPS and AROME-EPS have been used separately to run the EFI/SOT software. Given that both LAM-EPSs share an overlapping area in their domains, it is interesting to evaluate the consistency of the results obtained for both LAM-EPSs.

To study this episode, the EFI and SOT indices are calculated for the 24h-AccPcp, 24h-AccSnw for γSREPS and AROME-EPS (see Fig. 5), and 24h-T2mMax and 24h-T2mMin for γSREPS (Fig. 6), all valid on 9 January 2021. The EPS-climatology contains the period from 15 December to 15 March, 2021 to 2023, and the radius of the circular spatial relaxation neighborhood is set to 4. The land-sea mask filter is activated, as well (see Table 1 for details).

The results of the EFI/SOT software using γSREPS and AROME-EPS are fairly consistent: both LAM-EPSs are in good agreement in identifying the areas where the heaviest precipitation events took place — central and eastern Spain registered extreme quantities of precipitation and snowfall. Moreover, the subjective verification between the γSREPS results with the ones obtained from the ECMWF (included in Fig. 5) suggests that the EFI/SOT software performs reasonably well despite the fact that the γSREPS-climatology is temporally short (taking data from only 3 y, whereas the ECMWF ENS climate covers 20 y). This agreement could be partially explained by the application of both temporal and spatial relaxation methodologies, which create a γSREPS-climatology with 174440 records (49 neighborhood points × 178 days × 20 EPS-members), more than the 1980 records from the ECMWF ENS climatology (20 y × 9 runs × 11 EPS-members) (see Table 1). However, it is noteworthy to clarify that these sampling strategies do not replace the quality of a 20-y EPS-climate based on reforecast data as it is the case of the ENS climatology. They are techniques that enlarge the EPS-climatology in order to avoid noise in the computation. This case clearly exemplifies how the temporal and spatial relaxation techniques proposed by Raynaud et al. 2018 and applied in the EFI/SOT software seem to be suitable to calculate EFI/SOT when only a short historical LAM-EPS database is available.

Given that the SOT90 divergences between both products—previously mentioned in section 4.a—are more evident in this case study, concretely for 24h-AccPcp SOT90, it is decided to re-calculate γSREPS SOT90 product, using the Q_c (99) percentile in the SOT90 definition, in the same way as does the

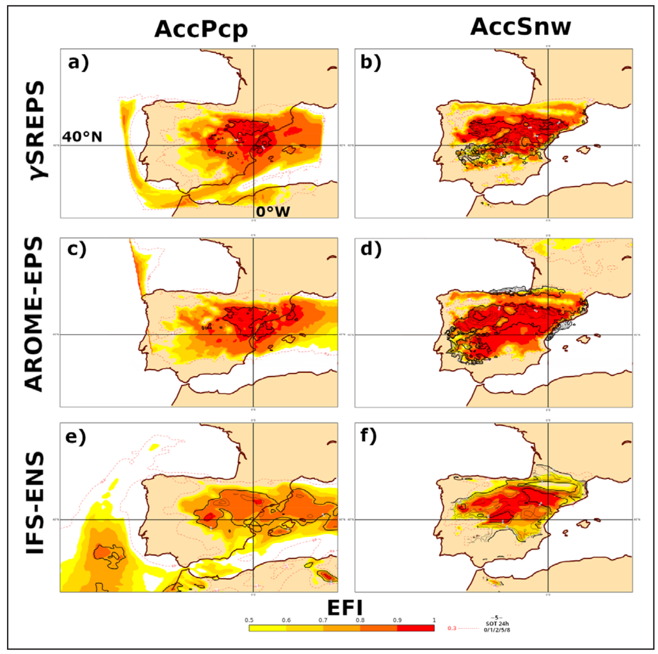

Figure 5. 24h-AccPcp (left) and 24h-AccSnw (right) EFI/SOT in LAM-EPSs γSREPS (top row), AROME-EPS (middle row) and global ECMWF ENS (bottom row) over the Iberian Peninsula on 9 January 2021, during the Philomena storm. All plots correspond to a lead time forecast t+24h starting at 00 UTC 9 January 2021.

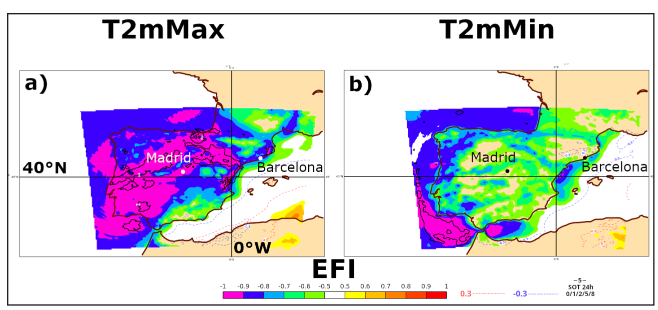

Figure 6. 24h-T2mMax and 24h-T2mMin EFI/SOT in γSREPS over the Iberian Peninsula on 9 January 2021, during the Philomena storm. Forecast lead time is t+24h starting at 00 UTC 9 January 2021.

ECMWF. This test is performed to see the sensitivity of SOT90 with the Q_c (p) parameter and, at the same time, reduce the divergences between both products. Figure 7 depicts this comparison, where it is observed the high sensitivity of the SOT90 index from a slight modification of the Q_c (p) parameter: from Q_c (100) to Q_c (99). As it can be seen in Fig. 7, this leads to a remarkable extension of the positive SOT90 areas, thus obtaining a result that resembles the ECMWF ENS 24h-AccPcp SOT90 product.

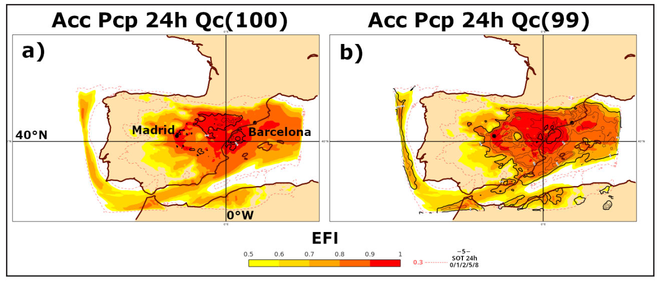

Figure 7. 24h-AccPcp EFI/SOT in γSREPS over the Iberian Peninsula on 9 January 2021, during the Philomena storm event, using Q_c (100) (left) and Q_c (99) (right) in the SOT90 definition. Forecast lead time is t+24h starting at 00 UTC 9 January 2021.

5. Implementation of the EUMETNET SRNWP-EPS EFI/SOT software in the AEMET-γSREPS

a. AEMET-γSREPS

γSREPS is an EPS that consists of 20 high-resolution members (2.5 km grid step), non-hydrostatic, convection-permitting, multi-boundary conditions and multi-model (Frogner et al., 2019 and González et al., 2020). It is running twice a day (at 00 and 12 UTC) since 2016 and currently up to 72 h lead time implemented over three independent domains: the Iberian Peninsula, Canary Islands, and Antarctica (only during the austral summer across Antarctica).

γSREPS accounts for initial condition and synoptic scale uncertainty using boundary conditions provided by five different global-scale deterministic models: ECMWF (IFS), Météo-France (ARPÈGE), National Centers for Environmental Prediction-NCEP (GFS), Japan Meteorological Agency-JMA (GSM) and Canadian Meteorological Centre-CMC (GEM).

The model and mesoscale uncertainty is accounted for by considering four different high-resolution NWP models: HIRLAM (HARMONIE-AROME), ALADIN (HARMONIE-ALARO), NCAR (WRF-ARW) and NCEP (NMMB).

The combination of the four mesoscale NWP models with the five global deterministic NWP models' boundary conditions results in the 20 members that conform γSREPS.

b. EFI/SOT in AEMET-γSREPS

Due to AEMET forecasting offices interest to have an EFI/SOT product in γSREPS, in June 2023 the software was implemented within the ECMWF ecFlow suite of γSREPS, running operatively for the two γSREPS cycles (00 and 12 UTC). Since then, successive upgrades have been applied to the software and therefore also implemented in γSREPS. In addition, the software still has to run under different meteorological situations during at least a full year period, meaning the product is in an ongoing testing phase. Feedback from AEMET forecasters has been requested and it is expected to provide useful information to validate and maybe improve the EFI/SOT product. Figure 8 shows a snapshot of the γSREPS internal website displaying one of the several EFI/SOT products available.

As commented in section 3.c, the γSREPS-climatology used to calculate EFI and SOT indices consists of four years from 2019 to 2022. It has been obtained for the three γSREPS domains, and for a quite complete set of meteorological variables: total precipitation (AccPcp), snowfall (AccSnw), convective available potential energy (CAPE), convective inhibition (CIN), 10 m maximum wind gust (G10m), precipitable water (PrecWat), 2 m relative humidity (RH2m), 2 m temperature (T2m), 2 m maximum and minimum temperature (T2mMax and T2mMin), 850hPa temperature (T850hPa), 10 m wind speed (W10m) and water vapour flux (WVF). Although γSREPS currently has a lead time of 72 h, these climatologies are available for lead times up to 48 h—as this was the maximum lead time for γSREPS until the end of 2022—in intervals of 12 and 24 h. For this reason, γSREPS EFI/SOT is not currently available for lead times beyond 48h. However, once the historical γSREPS dataset increases, it will be possible to generate an EPS-climate for lead times between 48h and 72h.

We have taken care to include most of the ECMWF ENS EFI/SOT products and to plot them with a coherent style (same intervals, color-scales, etc.), which allows forecasters to use both simultaneously. This is aimed

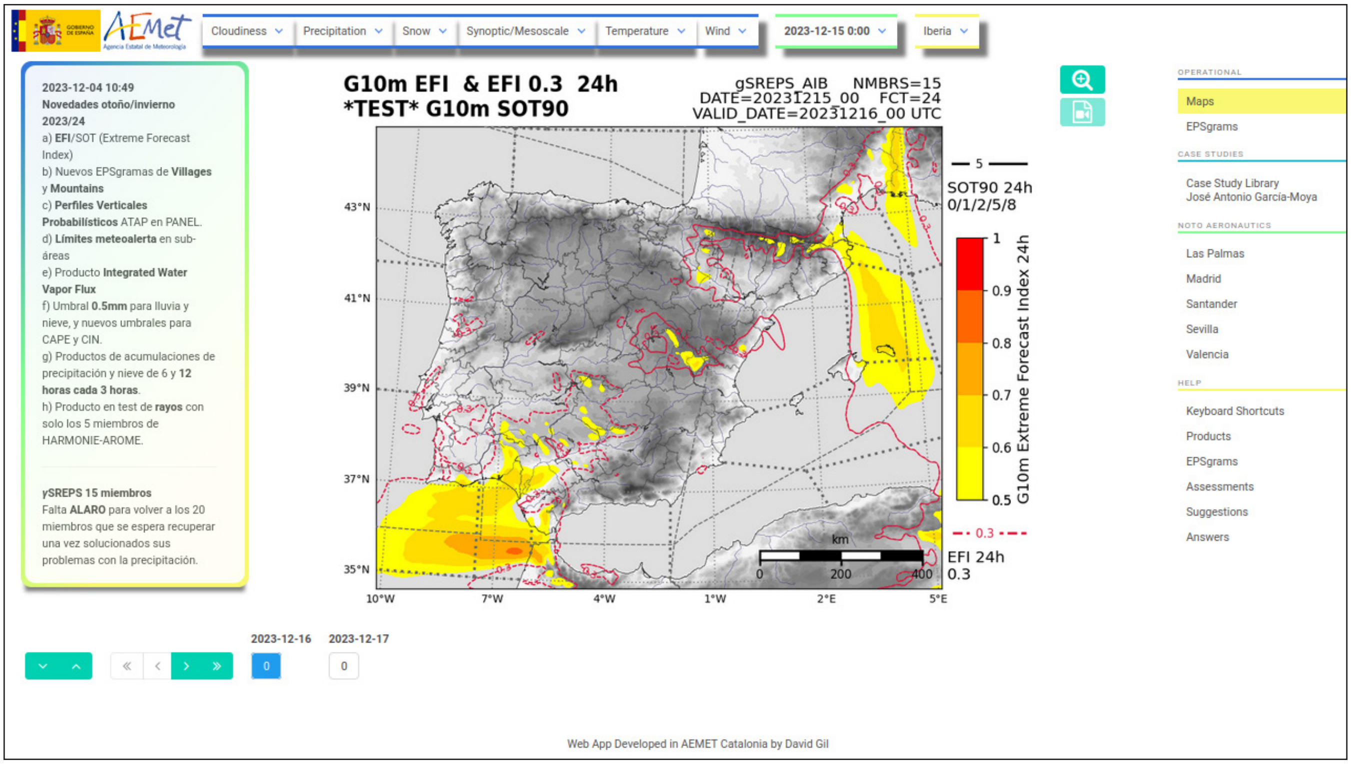

Figure 8. Example of AEMET-γSREPS internal website for the weather forecaster offices displaying the 24h-G10m EFI/SOT valid for 15 December 2023.

at facilitating the use of products from different NWP systems when deciding whether to issue warnings or not.

The authors have collected some comments from an AEMET forecaster (personal communication), in Barcelona, who is currently using the γSREPS EFI/SOT product in conjunction with the one from the ECMWF. He claims that the product is useful when considering possible alerts from the AEMET meteorological warning system, especially when the situation has to do with high temperature episodes. Concerning the degree of coherence between γSREPS and ECMWF EFI/SOT, some divergence between both products is noticed, though not remarkable. For instance, the ECMWF temperature EFI values tend to be higher than the γSREPS ones. In comparison with the ECMWF ENS, γSREPS has a temporally shorter EPS-climatology, more recent and, thus, hotter due to the effects of global warming.

c. AEMET-γSREPS EFI/SOT case studies

Since the implementation of the EFI/SOT software within the AEMET-γSREPS in June 2023, different types of meteorological events have taken place. Two of them have been selected to showcase the applicability of the γSREPS EFI/SOT product under different meteorological situations (see corresponding columns in Table 1 for more details). In all these cases, the ECMWF ENS EFI/SOT product is also presented, for validation purposes by comparison.

1) HEAT WAVE EPISODE (18 JULY 2023)

July 2023 in Spain has been the fifth hottest July in the 21st century. Several heat episodes with short temporal extension — covering 2 or 3 days — were reported (AEMET, 2023a). One of these episodes was the heat wave that affected most of the Iberian Peninsula during the period from 17 to 19 July. Some AEMET weather stations broke records in registering maximum daily temperature in July: Lleida (43.2ºC on 18 July), Toledo (42.9 ºC on 17 July), Ceuta (40.8 ºC on 19 July), and Teruel (40.6 ºC on 18 July) (AEMET, 2023a).

Subjective verification between γSREPS and ECMWF ENS 24h-T2mMax EFI/SOT products (see Fig. 9) shows that both agree in identifying eastern Spain as the area where extreme high temperatures were most

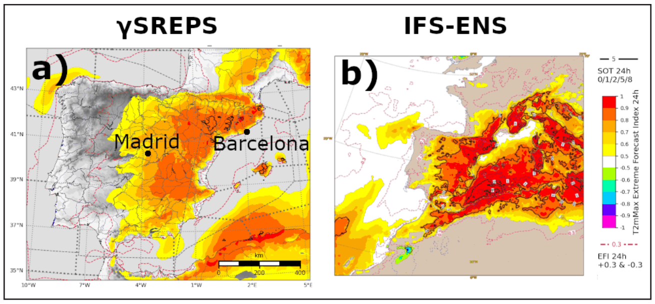

Figure 9. 24h-T2mMax EFI/SOT in *γ*SREPS and ECMWF ENS over the Iberian Peninsula on 18 July 2023, during a heat wave episode. Forecast lead time is t+24h starting at 00 UTC 18 July 2023.

probable to be registered on 18 July 2023. However, some differences can be distinguished between both products. In terms of EFI, it is observed that values ranging between 0.9 and 1 are spatially more extended in the ENS product than in *γ*SREPS, where this range of values is only reached in little localised areas, reflecting the high-resolution of our product. Similar behaviour can be found for SOT90: positive SOT90 values span larger areas in the ENS than in *γ*SREPS. As was mentioned in section 4.a, the discrepancies regarding EFI and SOT intensity could be partially explained in terms of the large difference in the temporal extension between both EPS-climates. Any recent extreme in the climate record is likely to be less-statistically-anomalous in *γ*SREPS because it has a shorter climatology. The latter EFI/SOT divergences between ENS and *γ*SREPS could provide useful information to forecasting offices to issue more valuable warnings of heat waves. Regarding the SOT90 discrepancies, it is important to recall the sensitivity of the SOT90 index with the Q_c (p) parameter, discussed in section 4.c.

2) COLD FRONT EPISODE (4 AUGUST 2023)

When the full Iberian Peninsula was immersed in the hottest period of the year, a synoptic configuration characterised by the displacement of an upper-level trough across northern Spain enhanced the flux of northerly winds, that for a few hours, produced a decrease in temperatures in the northern half of the Iberian Peninsula.

Table 2 (AEMET, 2023b) depicts the intense drop of temperatures in different regions of Spain during the northerly winds episode. The evolution of the daily maximum temperature in Teruel is especially remarkable, where a decrease of almost 13 ºC was registered in just 48 h.

24h-T2mMax and 24h-T2mMin *γ*SREPS EFI/SOT products (see Fig. 10) predicted a noticeable decrease of temperatures affecting the northern half of Iberian Peninsula. A similar scenario is presented in the ECMWF ENS EFI/SOT products (included in Fig. 10). This prediction was later confirmed by the observations, as it can be shown in Table 2.

During this episode there was intense precipitation in southwestern areas of the Mediterranean Sea, especially in front of the Argelian coast (consult numerical labels contained in Fig. 10 for geographical location). The Cantabric area and the northern side of the Pyrenees (see numerical labels in Fig. 10) registered precipitation, something unusual from a cold front in summer in that region. This scenario was well captured by the 24h-AccPcp *γ*SREPS EFI/SOT product, in a similar way to ENS (both shown in Fig. 10). The most important discrepancy between both products relies on the SOT values: more intense (more positive) in the ECMWF ENS, where SOT values higher than 8 are obtained over the Mediterranean Sea. As argued in section 4.c, this discrepancy may be due to the different temporal extension of the EPS-climate used by both products, as well as the use of a different Q_c (p) parameter in the definition of SOT index.

In terms of wind, the synoptic configuration characterising this event enhanced the incoming flux of northerly winds in the Iberian Peninsula. This flux of wind partially follows its way along the Portuguese coast, another part channels through the Ebro River basin reaching the Mediterranean Sea (the so-called Cierzo wind) and part of the flux borders the Pyrenees arriving to the Mediterranean Sea (the Tramuntana wind). 24h-G10m *γ*SREPS EFI/SOT (Fig. 10) clearly reflects the existence of more intense than usual winds for the three fluxes mentioned above. The correspondence between the *γ*SREPS and the ECMWF ENS EFI/SOT product (included in Fig. 10) is, in general, satisfactory, leaving apart the SOT intensity issue.

6. Conclusions

Within the framework of the EUMETNET SRNWP-EPS project, we have developed software that calculates the EFI and SOT indices for the different EUMETNET Member States LAM-EPSs, as a new product to support forecasts of extreme or/and High Impact Weather in Europe. The goal of this software is to provide an EFI/SOT product with higher spatial resolution than the ECMWF—2.5 km versus 9 km—and more suitable in the short-range.

Table 2. Evolution of 24h-T2mMax and 24h-T2mMin in different AEMET weather stations during the period 2–5 August 2023.

Evolution of 24h-T2mMax and 24h-T2mMin (ºC)				
AEMET station	2 August 2023	3 August 2023	4 August 2023	5 August 2023
Burgos Airport	30.1 / 14.5	24.5 / 10.6	20.1 / 9.2	28.8 / 5.8
Segovia	29.8 / 16.7	25.8 / 13.0	22.7 / 10.3	29.9 / 11.6
Lleida	37.2 / 20.0	30.0 / 19.4	29.4 / 16.2	33.1 / 14.5
Teruel	37.1 / 16.4	30.4 / 14.6	24.2 / 12.4	30.2 / 8.9

The temporal and spatial relaxation techniques—presented in Raynaud et al. 2018—have proved their usefulness through the subjective verification of the EUMETNET EFI/SOT product with the ECMWF ENS EFI/SOT. Different case studies have been run to validate the consistency and performance of the EFI/SOT results. Data from four LAM-EPSs have been considered for the presented case studies: AEMET-γSREPS (AEMET, Spain), MOGREPS-UK (MetOffice, United Kingdom), AROME-EPS (Météo-France, France) and IREPS (Met Éireann, Ireland). Even though results are not presented in this article, the EFI/SOT software has also been successfully tested using data from COMEPS (Danish Meteorological Institute, Denmark) and ITEPS (Italian Aeronautica Militare, Italy). Subjective comparison with the ECMWF EFI/SOT proves that the obtained EFI/SOT results—calculated for distinct meteorological variables—are very consistent and, in consequence, it is argued that the spatial and temporal relaxations are valid methodologies to apply when only a historically limited LAM-EPS dataset is available and computationally expensive re-forecasts are not possible to implement.

In June 2023, the EUMETNET SRNWP-EPS EFI/SOT software was successfully implemented within AEMET-γSREPS, considering a monthly fixed EPS-climate that covers a four-year period (2019 to 2022). Despite the relatively short temporal extension of the γSREPS-climate, the γSREPS EFI/SOT product gives coherent and robust results from the subjective verification with the corresponding ECMWF ENS EFI/SOT product. The major discrepancy between both products relies on the intensity of the positive SOT values: for the same extreme event, SOT values tend to be higher in the ECMWF than in γSREPS. This may be attributed to the different temporal extension between the EPS-climates used in both cases (20 y extension in ECMWF ENS and 4 y in AEMET-γSREPS), as well as

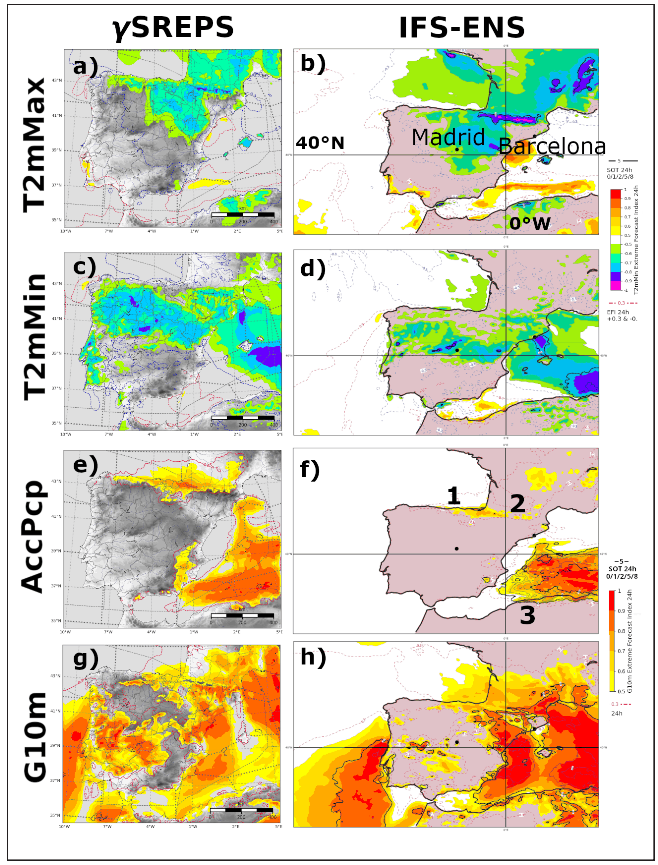

Figure 10. 24h-T2mMax (first row), 24h-T2mMin (second row), 24h-AccPcp (third row) and 24h-G10m (fourth row) EFI/SOT in γSREPS (left) and ECMWF ENS (right) over the Iberian Peninsula on 4 August 2023, during a cold front event. Forecast lead time is t+24h starting at 00 UTC 4 August 2023. The three numerical labels included in one of the panels indicate three geographical areas (1. Cantabric area, 2. Pyrenees and 3. Argelian coast) that are mentioned in the discussion of the cold front event, in section 5.

the use of a different Q_c (p) climate percentile in the definition of the SOT index—Q_c (99) in ECMWF ENS and Q_c (100) in γSREPS, for the SOT90—although further investigation must be performed to support these hypotheses. However, it can be argued that such large SOT values, especially those associated with high temperatures, might be overestimating the actual impact of such events. The final operational goal is to calculate the γSREPS-climate in weekly moving temporal window, in a way closer to the approach as implemented in the ECMWF in order to make the γSREPS EFI/SOT product as comparable as possible to the ENS EFI/SOT.

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