Earlier awareness of extreme winter precipitation across the western Iberian Peninsula

Article

Published Version

It is advisable to refer to the publisher's version if you intend to cite from the work. See Guidance on citing.
Published version at: http://dx.doi.org/10.1002/met.1727
To link to this article DOI: http://dx.doi.org/10.1002/met.1727

www.reading.ac.uk/centaur

Meteorological
Applications   RMetS

Earlier awareness of extreme winter precipitation across the western Iberian Peninsula

David A. Lavers[1] | David S. Richardson[1] | Alexandre M. Ramos[2] | Ervin Zsoter[1,3] |

Florian Pappenberger[1] | Ricardo M. Trigo[2]

[1]Forecast Department, European Centre for Medium-Range Weather Forecasts (ECMWF), Reading, UK

[2]Instituto Dom Luiz, Faculdade de Ciências, Universidade de Lisboa, 1749-016 Lisboa, Portugal

[3]Department of Geography and Environmental Science, University of Reading, Reading, UK

Correspondence
David A. Lavers, European Centre for Medium-Range Weather Forecasts (ECMWF), Shinfield Park, Reading RG2 9AX, UK.
Email: david.lavers@ecmwf.int

Funding information
Fundação para a Ciência e a Tecnologia, Grant/Award Numbers: SFRH/BPD/84328/2012, WaterJPI/0004/2014; H2020 Environment, Grant/Award Numbers: 641811, H2020; Grant/Award Number: 700099

Extreme winter precipitation across the western Iberian Peninsula is frequently connected to atmospheric rivers, which are bands of intense water vapour transport (integrated vapour transport, IVT). Recent research over Western Europe has shown that by using the IVT forecasts in the form of the extreme forecast index (EFI), a tool that identifies anomalous conditions, it is possible to provide earlier awareness of extreme precipitation events than by using the precipitation EFI directly. The aim of the present paper is to assess these findings further by identifying the regions of Iberia where such IVT forecasts are skilful and for what lead times. Employing the EFI on the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System ensemble for winters 2015/2016 and 2016/2017 and using high-density daily surface precipitation observations, the IVT EFI is shown to have slightly more skill (than the precipitation EFI) in discriminating extreme precipitation anomalies across the western Iberian Peninsula (Portugal and northwestern Spain) from forecast day 11 onwards. The reasoning is that the higher IVT predictability means that the IVT EFI is more able to detect the approximate location of extreme events at earlier lead times than the precipitation EFI. In contrast, for shorter forecast lead times, the precipitation EFI is more skilful. Also, when considering the entire Iberian Peninsula, the precipitation EFI is more skilful and more appropriate to monitor for potential extremes even at longer lead times.

KEYWORDS

atmospheric rivers, extreme forecast index (EFI), extreme precipitation, Iberian Peninsula, water vapour transport

1 | INTRODUCTION

The European Centre for Medium-Range Weather Forecasts (ECMWF) uses the extreme forecast index (EFI) (Lalaurette, 2003; Zsoter, 2006; Zsoter et al., 2014) to identify regions that experience anomalous weather conditions in a forecast. It is calculated by comparing the ECMWF forecasts and the model climate, and this method is applied to many variables, for example, 2-m temperature,

precipitation, wind speed and convective parameters. Recent research has investigated the possibility of also employing the EFI on vertically integrated horizontal water vapour transport (integrated vapour transport, IVT) (Lavers et al., 2016; Lavers et al., 2017). The IVT, particularly in the form of an atmospheric river within an extra-tropical cyclone, is a key contributor to extreme winter precipitation and flooding in western North America (e.g. Ralph et al., 2006), the United Kingdom (Lavers et al., 2011) and the Iberian

Peninsula (Ramos *et al.*, 2015). Results have shown that the IVT EFI can provide earlier awareness of extreme precipitation (compared with using the precipitation EFI) in Western Europe (Lavers *et al.*, 2016, 2017) and western North America (Lavers *et al.*, 2017) from about forecast day 10 onwards. It is the large-scale nature and, thus, higher predictability of the IVT field that leads to the IVT being more skilful at these lead times.

One region of Western Europe with a strong link between the IVT and extreme precipitation is the Iberian Peninsula, and this has been shown by Ramos *et al.* (2015) for the large international river basins located in western Iberia (i.e. the Minho, Tagus and Duero river basins). In previous research using the IVT EFI (Lavers *et al.*, 2017), it was hypothesized that the skill obtained by using the IVT EFI could be increased by only considering an area with a significant link between the IVT and precipitation (compared with using a pan-European domain). As these areas with the strongest relationship between the IVT and precipitation are smaller in size, the availability of a high-resolution data set is essential to account for the reduced sample. The aim of this study is to use high-density gauged precipitation observations across the Iberian Peninsula to evaluate the forecast skill of the IVT and precipitation EFI in capturing extreme precipitation. This will show whether the IVT EFI skill can be raised by only considering a region where the IVT is a main driver of extreme events.

2 | DATA

This section gives a brief overview of the data sets and methods, as further details can be found in Lavers *et al.* (2017). The 51 ensemble members (with forecasts out to 15 days) from the ECMWF Integrated Forecasting System (IFS) ensemble (ENS) were retrieved for the 0000 UTC initialization for two winter seasons, November 1, 2015, to February 29, 2016; and October 20, 2016, to February 28, 2017 (253 forecasts). The dates differed in the two seasons because the experimental model version was used from October 20 to November 21, 2016 (this became the operational model on November 22, 2016), which increased the sample size and provided a constant model version for winter 2016/2017. Daily total surface precipitation was retrieved, and the magnitude of the water vapour transport (IVT) was calculated (e.g. Neiman *et al.*, 2008) using the specific humidity and zonal and meridional winds at 300, 400, 500, 700, 850, 925 and 1,000 hPa.

The ECMWF also produces re-forecasts with the same horizontal resolution as the ENS to generate a model climate; this climate can then be compared with the ENS. The re-forecasts have 11 ensemble members and have been run twice a week for the past 20 years. As with the ENS, the

daily total surface precipitation was retrieved and the IVT was calculated. The model climate was constructed using nine re-forecast dates centred on the forecast of interest, which provides a climate of 1980 members (9 dates × 20 years × 11 members).

Daily gauged precipitation data for Spain were obtained from the National Spanish Meteorological Service (AEMET) archives for the 2015/2016 and 2016/2017 winters (Vicente-Serrano *et al.*, 2017). These data correspond to 24 hr precipitation totals measured at 0700 UTC. For Portugal, the daily precipitation data were obtained from the Portuguese Meteorological and Oceanic Institute (IPMA) for the same two winters and the daily precipitation was accumulated between 0000 UTC and 2359 UTC. Note that this analysis did not change the Spanish observations to a 0000 UTC–2359 UTC period; the day with the longest time coverage was considered as the day when the precipitation fell. The average number of gauges available across the Iberian Peninsula on each day was 2,146. Extreme observed precipitation events were identified as exceedences over the 99th percentile of the model climate precipitation at the closest grid point to the gauge (as in Lavers *et al.*, 2017). This approach guards against the loss of stations due to them not having enough data to generate a gauge climatology. The model climate precipitation used was taken from forecast day 7 from the model climate nearest the middle of the month.

3 | METHODS

Using the ECMWF forecasts and model climate, the EFI (Lalaurette, 2003; Zsoter, 2006; Dutra *et al.*, 2013; Zsoter *et al.*, 2014) was used to determine how extreme a forecast was by comparing the probability distribution of the ENS and the model climate.

The EFI was calculated as:

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

where $F(p)$ is the proportion of ensemble members that lie below the pth percentile of the model climate. The EFIs ranged from −1 to 1, where −1 are extremely low and 1 are extremely high values compared with the model climate. The EFI was calculated for the November 1, 2015, to February 29, 2016 and for the October 20, 2016, to February 28, 2017 (253 dates) forecasts for each forecast day (1–15) for the IVT and precipitation.

The EFI forecasts' ability to discriminate extreme precipitation (> 99th percentile) across the Iberian Peninsula was assessed using the hit and false-alarm rates, which are defined as the fraction of forecast hits with respect to the total observed events, and as the number of false alarms to total non-events respectively. These were investigated using

relative operating characteristic (ROC) curves for the EFI thresholds ranging from 0 to 1 (Wilks, 2006). The ROC area or score was also calculated; it ranged from 0 to 1, with areas > 0.5 representing a skilful forecast.

A bootstrap procedure was employed to assess the statistical significance of the differences in ROC areas between the IVT and precipitation. This process resampled with replacement the 253 forecasts (for a particular forecast day) and calculated the ROC area, and then repeated the process 1,000 times (as in Lavers *et al.,* 2017).

4 | RESULTS AND DISCUSSION

4.1 | EFI verification

This section concentrates on two sub-regions of the Iberian Peninsula to determine how the verification varies with region, thus showing the importance of regional aspects. These areas are shown by the boxes in Figure 1: (1) a sub-region of the Iberian Peninsula from the Atlantic coastline to 7°W (hereafter referred to as "7°W"), an area known to be affected by atmospheric rivers (Lavers and Villarini, 2013; Ramos *et al.,* 2015); and (2) the Iberian Peninsula from the Atlantic coastline to 1°W (hereafter referred to as "1°W"), which includes the sub-region to 7°W. Figure 1 also displays the recording gauges (black triangles) and gauges where the precipitation exceeded the 99th model climate percentile (magenta triangles) on February 12, 2016 (this event is discussed further in Section 4.2). The ROC

areas and bootstrap distributions for each forecast day calculated over the two winters studied for the IVT and precipitation EFI for the 7 and 1°W regions are shown in Figure 2a, b respectively. It is evident that the precipitation EFI is more useful (i.e. has more discriminatory power) up to about forecast day 10 for 7°W and right through the medium-range forecast horizon for 1°W. From forecast day 11, the results show that more often than not there is a slight advantage in using the IVT EFI (compared with the precipitation EFI) to discriminate extreme events in the western part of the Iberia Peninsula. However, there is overlap in the bootstrapped distributions of the ROC area differences (precipitation—IVT) from forecast day 11 (Figure 2c), which suggests some level of equality between the IVT and precipitation EFI after forecast day 11 (except on forecast day 14). In general, this confirms previous findings for Western Europe and shows larger ROC area differences (between the IVT and precipitation), and, hence, skill than those shown for Western Europe in Lavers *et al.* (2017). Therefore, the IVT EFI has potential usefulness for early awareness of extreme precipitation in this particular sub-region of Europe. For the 1°W domain (Figure 2d), the IVT EFI generally shows little added usefulness over the precipitation EFI.

The ROC curves on forecast day 12 are given for the two study regions in Figure 2e,f. At this lead time, the slightly larger ROC area for the IVT EFI for the 7°W region indicates that the IVT EFI is more skilful in capturing extreme precipitation events than the precipitation EFI. It is thought that the large-scale characteristics of the IVT, which
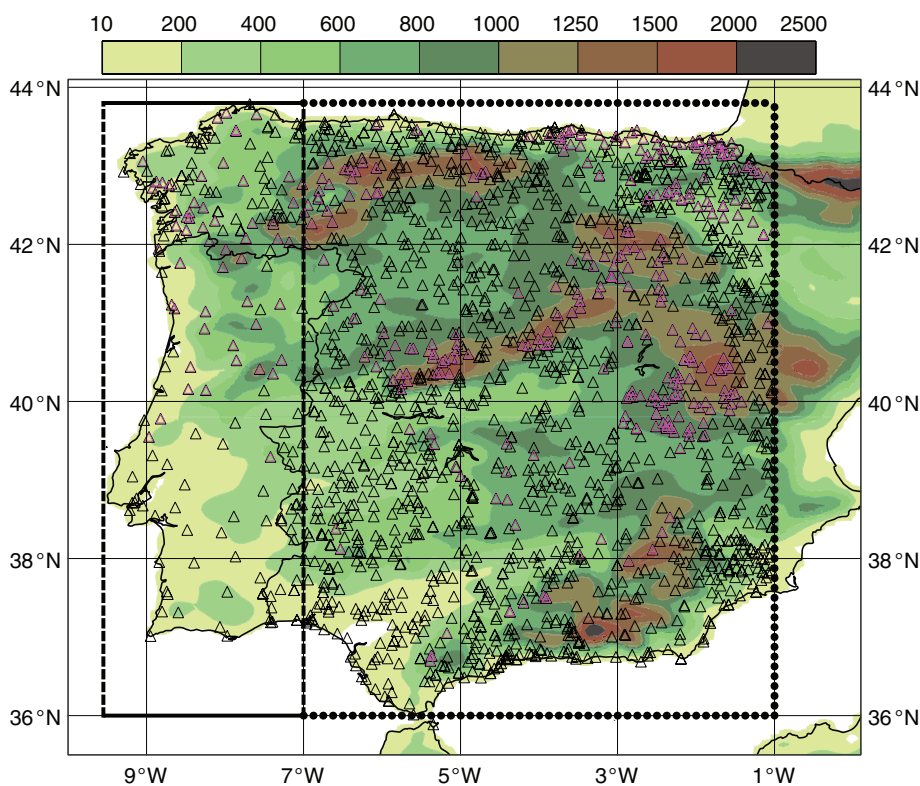

FIGURE 1 Map (m) of the Iberian Peninsula taken from the high-resolution configuration (about 9 km) of the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS). Precipitation gauges that exceeded the 99th percentile of the model climate on February 12, 2016, are plotted as lighter/magenta triangles and other reporting gauges are plotted as darker/black triangles. The study regions considered are shown; western Iberia from the Atlantic coastline up to 7°W given by the two vertical dashed lines; and Iberia from the Atlantic coastline up to 1°W given by the vertical dashed and dotted lines
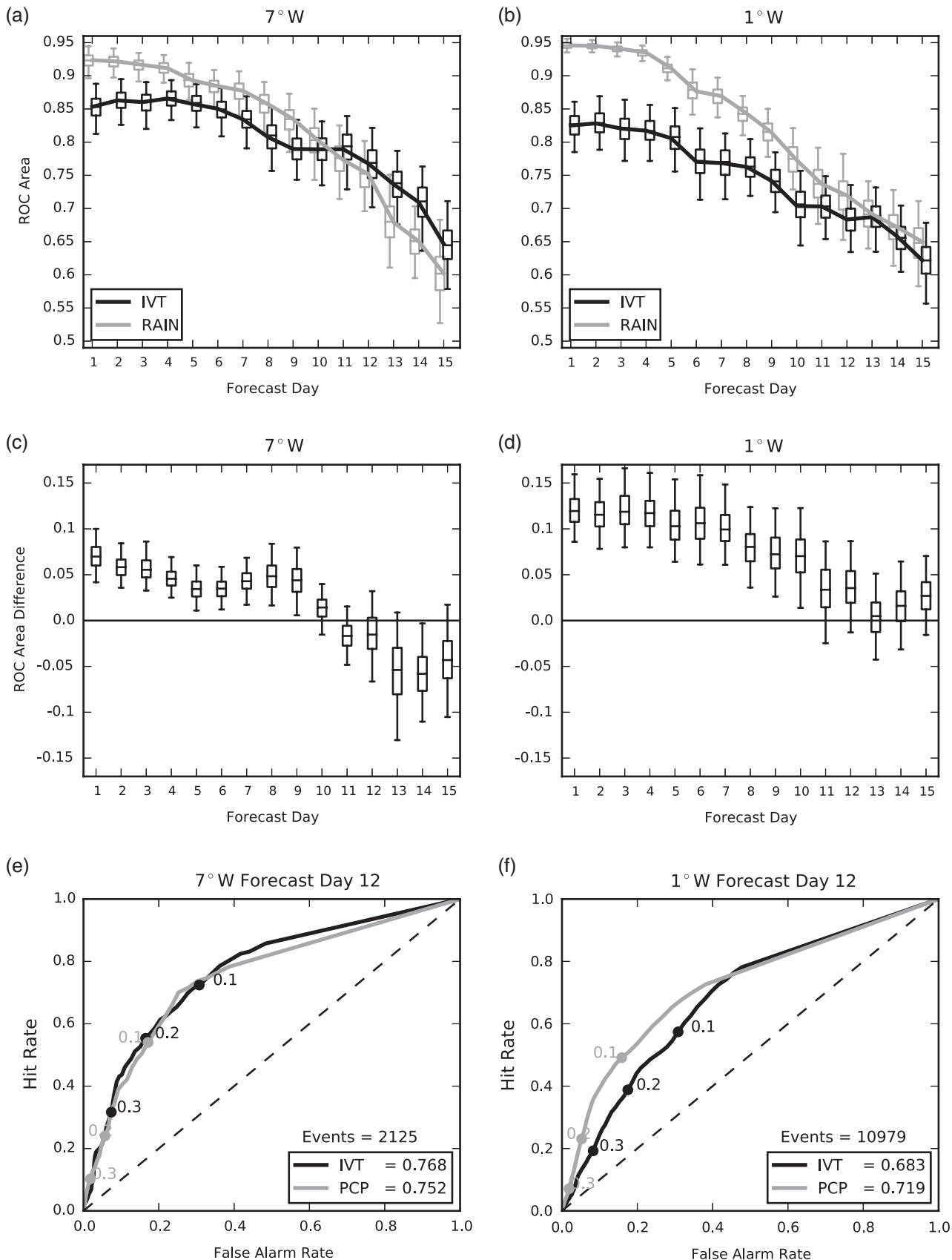
FIGURE 2 Relative operating characteristic (ROC) area with forecast day using all 253 forecasts for (a) the Atlantic coastline to 7°W; and (b) the Atlantic coastline to 1°W. Black lines are for integrated vapour transport (IVT); grey lines are for precipitation; and box plots show the distribution of the 1,000 bootstrapped samples. (c, d) The ROC area differences (precipitation—IVT) for 7 and 1°W respectively. The bottom and top of the boxes in (a–d) correspond to the 25th and 75th percentiles respectively; the line in the box is the median; and whiskers represent the 2.5th and 97.5th percentiles. (e, f) The ROC curves for the IVT (black lines) and precipitation (grey lines) for all 253 forecasts on forecast day 12 for 7 and 1°W respectively. The ROC areas are provided in the legends and the number of extreme precipitation events is also given

results in higher predictability, means it is more likely to detect the location of extreme events. In contrast, the precipitation is linked to more local-scale processes, such as those associated with the land surface topography, and is therefore less able to discriminate extremes at these longer lead times. For the 1°W domain the precipitation EFI is more skilful as seen by the precipitation ROC curve generally being closer to the top left corner of the plot. This suggests that when considering all gauges up to 1°W, there are processes other than the IVT that are important to the generation of extreme precipitation. Note that other domains were considered across the Iberian Peninsula, and as the domain was extended to the east, the advantage of using the IVT EFI was gradually reduced. This is related to the fact that western Iberian precipitation is more closely associated with synoptic-scale low-pressure systems that come from the North Atlantic than the eastern sector (Cortesi *et al.,* 2013; Cortesi *et al.,* 2014) and, in particular, the impact of atmospheric rivers in extreme precipitation is very small in Spanish provinces close to the Mediterranean (Lavers and Villarini, 2013; Ramos *et al.,* 2015).

4.2 | Example of the EFI over the Iberian Peninsula on February 12, 2016

On February 12, 2016, an atmospheric river affected the Iberian Peninsula resulting in extreme precipitation and flooding. A large number of stations recorded precipitation in excess of the 99th percentile of the model climate (their location is depicted by lighter/magenta triangles in Figure 1). The EFI and mean sea level pressure (MSLP) ensemble mean forecasts for this event are shown on
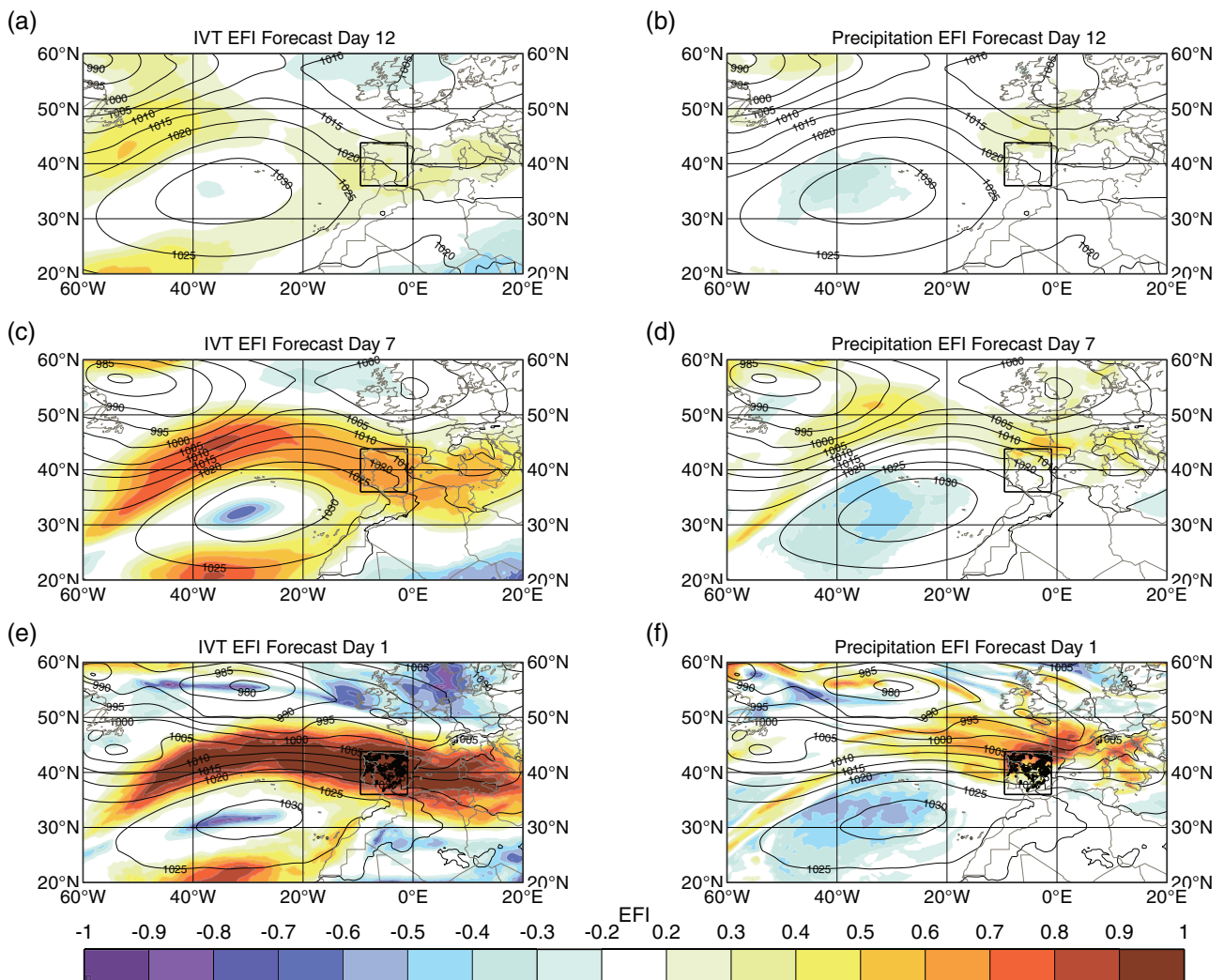

FIGURE 3 The extreme forecast index (EFI) fields valid for February 12, 2016, for (a, c, e) the integrated vapour transport (IVT) and (b, d, f) precipitation. (a, b) Forecast day 12 initialized at 0000 UTC February 1, 2016; ensemble average mean sea level pressure (MSLP) from forecasts initialized at 0000 UTC February 1, 2016, valid at 1200 UTC February 12, 2016 ($T + 276$ h). (c, d) Forecast day 7 initialized at 0000 UTC February 6, 2016; the ensemble average MSLP from forecasts initialized at 0000 UTC February 6, 2016, valid at 1200 UTC February 12, 2016 ($T + 156$ h). (e, f) Forecast day 1 initialized at 0000 UTC February 12, 2016; the ensemble average MSLP from forecasts initialized at 0000 UTC February 12, 2016, valid at 1200 UTC February 12, 2016 ($T + 12$ h). The black dots in (e, f) represent the precipitation gauges that exceeded the 99th percentile of the model climate at the closest grid point to the gauge; and black boxes in all panels show the larger Iberian domain used

forecast day 12 (Figure 3a,b), forecast day 7 (Figure 3c,d), and forecast day 1 (Figure 3e,f). Visual inspection of Figure 3a,b indicates that the IVT EFI (mean EFI = 0.29; maximum = 0.35) has a stronger and, hence, earlier signal across the region for this event compared with the precipitation EFI (mean EFI = 0.15; maximum = 0.32). The IVT EFI also captures the large-scale flow across the North Atlantic (as shown by the IVT EFI pattern around the ensemble mean MSLP) due to its relationship with larger synoptic-scale processes. By forecast day 7, the signature of an atmospheric river is striking (Figure 3c), and although the signal is clearer than that shown for the precipitation EFI (Figure 3d), this comes at the expense of the IVT EFI having more false alarms over the Mediterranean. In turn, this means that the interpretation of the IVT EFI to forewarn of extreme precipitation requires regional knowledge, such as about the local topography that is known to impose a very distinct contribution, during intense IVT events, to precipitation totals in the western and eastern Iberian river basins (Ramos *et al.,* 2015). This corroborates the results presented in Figure 2a,b, which showed that on forecast day 7 the precipitation EFI is more able to discriminate which gauges will experience extreme precipitation. Similar findings occur on forecast day 1 when the large-scale IVT field not only captures the extreme events but also many surrounding gauges, thus resulting in a higher false-alarm rate and less discriminating power than the precipitation EFI. This is the reason behind the IVT EFI being less skilful up to about forecast day 10, as presented in Figure 2a.

5 | CONCLUSIONS

The aim of this study was to assess whether the integrated vapour transport (IVT) extreme forecast index (EFI) shows more usefulness (compared with the precipitation EFI) in discriminating extreme precipitation events over the Iberian Peninsula, a region with a strong connection between IVT and extreme precipitation. Using the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble forecasts from two winters and high-density gauged precipitation observations across Spain and Portugal, the results corroborate the findings of Lavers *et al.* (2017) and show that the IVT EFI is slightly more skilful in detecting extreme precipitation in Portugal and northwestern Spain (7°W region) from forecast days 11–15. By focusing on a region of Western Europe with a strong association between the IVT and precipitation, the difference in the relative operating characteristic (ROC) score (between the IVT and precipitation) was increased. At earlier lead times, however, the precipitation EFI is more skilful at identifying extreme events because the larger-scale IVT EFI fields tend to cover a broader area resulting in a higher false-alarm rate. This implies that knowledge of local topography, for example, is required for the IVT EFI to provide earlier awareness of extreme precipitation events. When considering a broader region of the Iberian Peninsula (1°W domain), the precipitation EFI was generally more skilful than the IVT EFI throughout the 15-day forecast horizon, suggesting that the IVT has less influence on extreme precipitation events farther east in Spain. These results are in agreement with previous findings that atmospheric rivers do not explain extreme precipitation over eastern regions of the Iberian Peninsula, as shown for the Ebro River basin by Ramos *et al.* (2015).

The findings herein add to the body of literature showing the potential usefulness of using the IVT EFI in the mid-latitudes during the late medium-range forecast horizon, and the most appropriate approach for implementing it operationally is being discussed.

ORCID

David A. Lavers iD http://orcid.org/0000-0002-7947-3737

REFERENCES

Cortesi, N., Gonzalez-Hidalgo, J.C., Trigo, R. and Ramos, A. (2014) Weather types and spatial variability of precipitation in the Iberian Peninsula. *International Journal of Climatology*, 34, 2661–2677. https://doi.org/10.1002/joc.3866.

Cortesi, N., Trigo, R., Gonzalez-Hidalgo, J.C. and Ramos, A. (2013) Modeling monthly precipitation with circulation weather types for a dense network of stations over Iberia. *Hydrology and Earth System Sciences*, 9, 665–678.

Dutra, E., Diamantakis, M., Tsonevsky, I., Zsoter, E., Wetterhall, F., Stockdale, T., Richardson, D. and Pappenberger, F. (2013) The extreme forecast index at the seasonal scale. *Atmospheric Science Letters*, 14, 256–262. https://doi.org/10.1002/asl2.448.

Lalaurette, F. (2003) Early detection of abnormal weather conditions using a probabilistic extreme forecast index. *Quarterly Journal of the Royal Meteorological Society*, 129, 3037–3057.

Lavers, D.A., Allan, R.P., Wood, E.F., Villarini, G., Brayshaw, D.J. and Wade, A.J. (2011) Winter floods in Britain are connected to atmospheric rivers. *Geophysical Research Letters*, 38, L23803. https://doi.org/10.1029/2011GL049783.

Lavers, D.A., Pappenberger, F., Richardson, D.S. and Zsoter, E. (2016) ECMWF extreme forecast index for water vapor transport: a forecast tool for atmospheric rivers and extreme precipitation. *Geophysical Research Letters*, 43, 11852–11858. https://doi.org/10.1002/2016GL071320.

Lavers, D.A. and Villarini, G. (2013) The nexus between atmospheric rivers and extreme precipitation across Europe. *Geophysical Research Letters*, 40, 3259–3264. https://doi.org/10.1002/grl.50636.

Lavers, D.A., Zsoter, E., Richardson, D.S. and Pappenberger, F. (2017) An assessment of the ECMWF extreme forecast index for water vapor transport during boreal winter. *Weather and Forecasting*, 32(4), 1667–1674. https://doi.org/10.1175/WAF-D-17-0073.1.

Neiman, P.J., Ralph, F.M., Wick, G.A., Lundquist, J.D. and Dettinger, M.D. (2008) Meteorological characteristics and overland precipitation impacts of atmospheric rivers affecting the west coast of North America based on eight years of SSM/I satellite observations. *Journal of Hydrometeorology*, 9(1), 22–47.

Ralph, F.M., Neiman, P.J., Wick, G.A., Gutman, S.I., Dettinger, M.D., Cayan, D.R. and White, A.B. (2006) Flooding on California's Russian River: role of atmospheric rivers. *Geophysical Research Letters*, 33, L13801. https://doi.org/10.1029/2006GL026689.

Ramos, A.M., Trigo, R.M., Liberato, M.L.R. and Ricardo, T. (2015) Daily precipitation extreme events in the Iberian Peninsula and its association with Atmospheric Rivers. *Journal of Hydrometeorology*, 16, 579–597. https://doi.org/10.1175/JHM-D-14-0103.1.

Vicente-Serrano, S.M., Tomas-Burguera, M., Beguería, S., Reig, F., Latorre, B., Peña-Gallardo, M., Luna, M.Y., Morata, A. and González-Hidalgo, J.C. (2017) A high resolution dataset of drought indices for Spain. *Data*, 2(3), 22. https://doi.org/10.3390/data2030022.

Wilks, D.S. (2006) *Statistical Methods in the Atmospheric Sciences*. 2nd edition. Burlington, MA: Academic Press.

Zsoter, E. (2006) Recent developments in extreme weather forecasting. *ECMWF Newsletter*, 107, 8–17.

Zsoter, E., Pappenberger, F. and Richardson, D. (2014) Sensitivity of model climate to sampling configurations and the impact on the Extreme Forecast Index. *Meteorological Applications*, 22, 236–247. https://doi.org/10.1002/met.1447.