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RESEARCH ARTICLE

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Linking weather patterns to regional extreme precipitation for highlighting potential flood events in medium- to long-range forecasts

Doug Richardson[1,2] | **Robert Neal**[3] | **Rutger Dankers**[3,4] | **Ken Mylne**[3] | **Robert Cowling**[5] | **Holly Clements**[5] | **Jonathan Millard**[5]

[1]CSIRO Oceans & Atmosphere, Hobart, Tasmania, Australia
[2]School of Engineering, Newcastle University, Newcastle-upon-Tyne, UK
[3]Weather Science, Exeter, UK
[4]Wageningen Environmental Research, Wageningen University & Research, Wageningen, The Netherlands
[5]Flood Forecasting Centre (FFC), Exeter, UK

Correspondence
Robert Neal, Weather Science, Met Office, Exeter, UK.
Email: robert.neal@metoffice.gov.uk

Abstract
Medium- to long-range precipitation forecasts are a crucial component in mitigating the impacts of fluvial flood events. Although precipitation is difficult to predict at these lead times, the forecast skill of atmospheric circulation tends to be greater. The study explores using weather patterns (WPs) as a preliminary step in producing forecasts of upper-tail precipitation threshold exceedance probabilities for the UK. The WPs are predefined, discrete states representing daily mean sea-level pressure (MSLP) over a European–North Atlantic domain. The WPs most likely to be associated with flooding are highlighted by calculating upper-tail exceedance probabilities derived from the conditional distributions of regional precipitation given each WP. WPs associated with higher probabilities of extreme precipitation are shown to have occurred during two well-known flood events: the 2014 Somerset Levels floods in southwest England; and Storm Desmond over the northern UK in December 2015. To illustrate the potential of this WP-based prediction framework, a forecast guidance tool called Fluvial Decider is introduced. It is intended for use by hydro-meteorologists in the England and Wales Flood Forecasting Centre (FFC). Forecasts of the MSLP from ensemble prediction systems (EPSs) are assigned to the closest-matching WP, providing daily probabilistic forecasts of WPs out to the chosen lead time. Combining these probabilities with observed precipitation threshold exceedance probabilities provides a parsimonious tool for highlighting potential periods with increased risk of flooding. Model forecasts using the European Centre for Medium-range Weather Forecasts (ECMWF) EPS highlighted both flood events as being at a higher than average risk of heavy extreme precipitation at lead times of over five days.

KEYWORDS
circulation patterns, decision support, ensemble forecasts, extreme precipitation, extremes, floods, forecasting, hazards, medium range, precipitation, precipitation forecast, UK floods, weather patterns, weather types

1 | INTRODUCTION

Flooding is a recurring phenomenon that can have severe socioeconomic effects, and early warning of such events is crucial in mitigating the impacts and economic cost (Pappenberger *et al*., 2015). In England and Wales, these warnings are communicated to the public *via* the Environment Agency and Natural Resources Wales, while the Flood Forecasting Centre (FFC), an Environment Agency and Met Office partnership, provides broader flood-risk guidance at county level for core responders. The Met Office also publicly communicates extreme precipitation warnings *via* the National Severe Weather Warnings Service. These services issue warnings with a maximum lead time of between five and seven days. The FFC uses the grid-to-grid (G2G) hydrological model to support operational decisions on fluvial flood risk over five day lead times (Price *et al*., 2012). The information from the G2G is used in conjunction with hundreds of catchment- and community-specific real-time hydrological and hydraulic flood-forecasting models operated by local Environment Agency and Natural Resources Wales flood-forecasting teams. Hydro-meteorologists use information from the G2G, local models, their experience and judgement to form an assessment of the severity of potential fluvial impacts. The FFC has identified a need to develop a tool for fluvial flood prediction beyond a five day lead time. While continental- and global-scale flood-forecasting systems with longer lead times do exist (Emerton *et al*., 2016), such models require large amounts of data and are relatively expensive and time-consuming to implement. Therefore, the development of simpler approaches for longer range forecasting would be of benefit to the FFC and the wider forecasting community.

Despite recent advances in improving precipitation forecast skill (Mittermaier *et al*., 2013; Novak *et al*., 2014), it remains a challenging variable to predict, particularly at long lead times (Cuo *et al*., 2011). Large-scale atmospheric circulation variables, on the other hand, tend to be more skilfully predicted (Saha *et al*., 2014; Vitart, 2014; Lavers *et al*., 2016a, 2016b). The present study aims to exploit this difference in skill by considering the relationship between atmospheric circulation and regional UK extreme precipitation. In particular, this is achieved by characterizing the circulation using weather patterns (WPs), which are discrete states representing the broad-scale atmospheric circulation over a domain. WPs are useful for reducing the complexity of atmospheric variability and can be used to make estimates of local-scale variables such as precipitation (Huth *et al*., 2008). The WPs have often been analysed in the context of extreme precipitation and flooding, particularly in terms of how their frequencies of occurrence change during such events (Wilby, 1993; Bárdossy and Filiz, 2005; Wilby and Quinn, 2013; Prein *et al*., 2016; Eiras-Barca *et al*., 2018). A particular set (classification) of WPs, called MO30 (Neal *et al*., 2016) was developed by the Met Office and is used in the present study. MO30 has previously been used to analyse aspects of UK precipitation and drought climatology (Richardson *et al*., 2018), exploring long-term atmospheric persistence over Europe and the North Atlantic (Richardson *et al*., 2019), and investigating to what extent atmospheric circulation accounted for historical and projected European precipitation variability (Fereday *et al*., 2018).

Using the relationships between the WPs in MO30 and precipitation, an operational guidance tool for use by the FFC called Fluvial Decider is presented. This tool is intended to provide the FFC with medium- to long-range guidance, flagging prospective extreme precipitation, and hence possibly flood events, in advance of the five day lead time of the G2G. The output from the G2G model and local models determines operational forecasting decisions on whether or not to raise the flood risk and issue flood warnings. Fluvial Decider, therefore, plays the role of an advanced-warning system that allows the FFC to horizon-scan for potential flood events, and raise awareness of these with partners on a national scale, until the five day lead time at which the hydrological and hydraulic models can be used. The term "tool" is used to distinguish Fluvial Decider from a "true" forecast model, in that it is employed to highlight risk, but not to predict the exact timing, severity and extent of precipitation events (White *et al*., 2017). Given this distinction, the present study does not attempt a rigorous assessment of the skill at predicting extreme precipitation events, instead focusing on the tool's utility at providing guidance to the FFC, supported by a skill verification of the WP forecasts and assessment of the WP-precipitation climatology. Furthermore, standard forecast skill assessment is of less importance than for other decision-support tools because operational decisions, such as issuing a warning, are not taken based on Fluvial Decider. It is primarily for internal preparedness, and the user is therefore more tolerant of, for example, false alarms and missed events. In particular, missed events will, in most cases, be picked up later by the models with a shorter lead time. Nevertheless, a more comprehensive skill assessment of Fluvial Decider precipitation forecasts will be the subject of a future study once a larger sample of forecasts of extreme precipitation events is available.

Fluvial Decider is driven by forecast output from several ensemble prediction systems (EPSs), but in itself is designed to be computationally inexpensive. As such, it focuses on extreme precipitation rather than the hydrological responses (i.e. floods) directly, with the onus on expert forecasters to interpret the information. MO30 is currently used in two further Met Office operational forecast tools. The first provides the probability of a WP occurring that may result in flow originating over Iceland and entering UK airspace, something important during an Iceland volcanic episode due to the dispersion of volcanic ash and its associated impacts on aviation. The second is called Coastal Decider, a forecasting tool for flagging high-risk periods during which UK coastal sites may be at risk of flooding (Neal *et al*., 2018).

The paper is structured as follows. Section 2 provides details of the precipitation data used, together with information on how MO30 was derived, and some summary statistics of WP behaviour. Section 3 relates the MO30 WPs to extreme precipitation for several UK regions. Section 4 provides an assessment of hindcast skill for the MO30 WPs. Section 5 describes the methodology and visualizations of Fluvial Decider using two case study floods: the 2014 Somerset Levels event in southwest England and 2015's Storm Desmond, which affected northern parts of the UK. Section 6 further discusses some key aspects of the tool and its best use. Finally, Section 7 presents the conclusions and suggestions for further work.

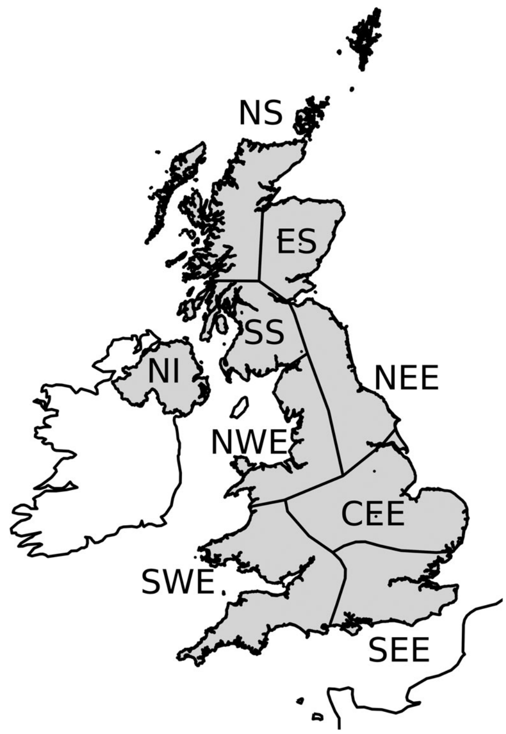

FIGURE 1 HadUKP regions: northeast England (NEE), central and east England (CEE), southeast England (SEE), southwest England and southern Wales (SWE), northwest England and northern Wales (NWE), northern Ireland (NI), southwest Scotland (SS), northern Scotland (NS) and eastern Scotland (ES)

2 | DATA

Precipitation is from the Met Office HadUKP data set (Alexander and Jones, 2000), which provides regional daily precipitation for the UK from 1931 to the present. The regions (Figure 1) are northeast England (NEE), central and east England (CEE), southeast England (SEE), southwest England and southern Wales (SWE), northwest England and northern Wales (NWE), eastern Scotland (ES), southwest Scotland (SS), northern Scotland (NS) and northern Ireland (NI). This data set is used primarily because of the large region sizes, which correspond more directly to the large-scale pressure patterns captured by the WPs. Data in the period 1931–2016 (inclusive) are selected.

MO30 was derived by clustering 154 years (between 1850 and 2003) of daily mean sea-level pressure (MSLP) anomaly data from the European and North Atlantic daily to the multi-decadal climate variability (EMULATE) data set (Ansell *et al*., 2006) into 30 distinct WPs (Neal *et al*., 2016). MO30 is shown in Figure 2; individual WPs will be referred to as WPi, for $i = 1, ..., 30$. The WPs are defined for the domain 30°W–20°E and 35–70°N with a spatial resolution of 5°, and they therefore characterize the daily atmospheric circulation over most of Europe and the North Atlantic. Daily MSLP anomaly fields are assigned to their closest matching WP (by minimizing the sum-of-squared differences between the daily field and WP definitions) between 1850 and 2003 using EMULATE, and extended to the present using 1200 UTC reanalysis MSLP data from the ERA-Interim data set (Dee *et al*., 2011). Data between 1931 and 2016 are used to align with the chosen precipitation data.

In the original derivation of MO30 (Neal *et al*., 2016), the WPs are ordered according to their historic occurrence between 1850 and 2003, with WP1 occurring the most often annually and WP30 the least often. A consequence of this ordering is that lower numbered WPs have lower magnitude MSLP anomalies and are more frequent during the summer, and vice versa for higher numbered WPs. A similar behaviour is observed when only data from 1931 onwards are considered (Figure 3). In the case of annual frequencies of occurrence, there are only slight deviations from the original ordering, in particular the increased frequency (relative to the other WPs) of WP6 and WP13, and the decreased frequency of WP16 and WP24. The seasonality is the same over both periods, with WP1–WP11 occurring more often in summer (June–August) than winter (December–February), and vice versa for the remaining WPs. These results also align with those presented by Richardson *et al.* (2018),

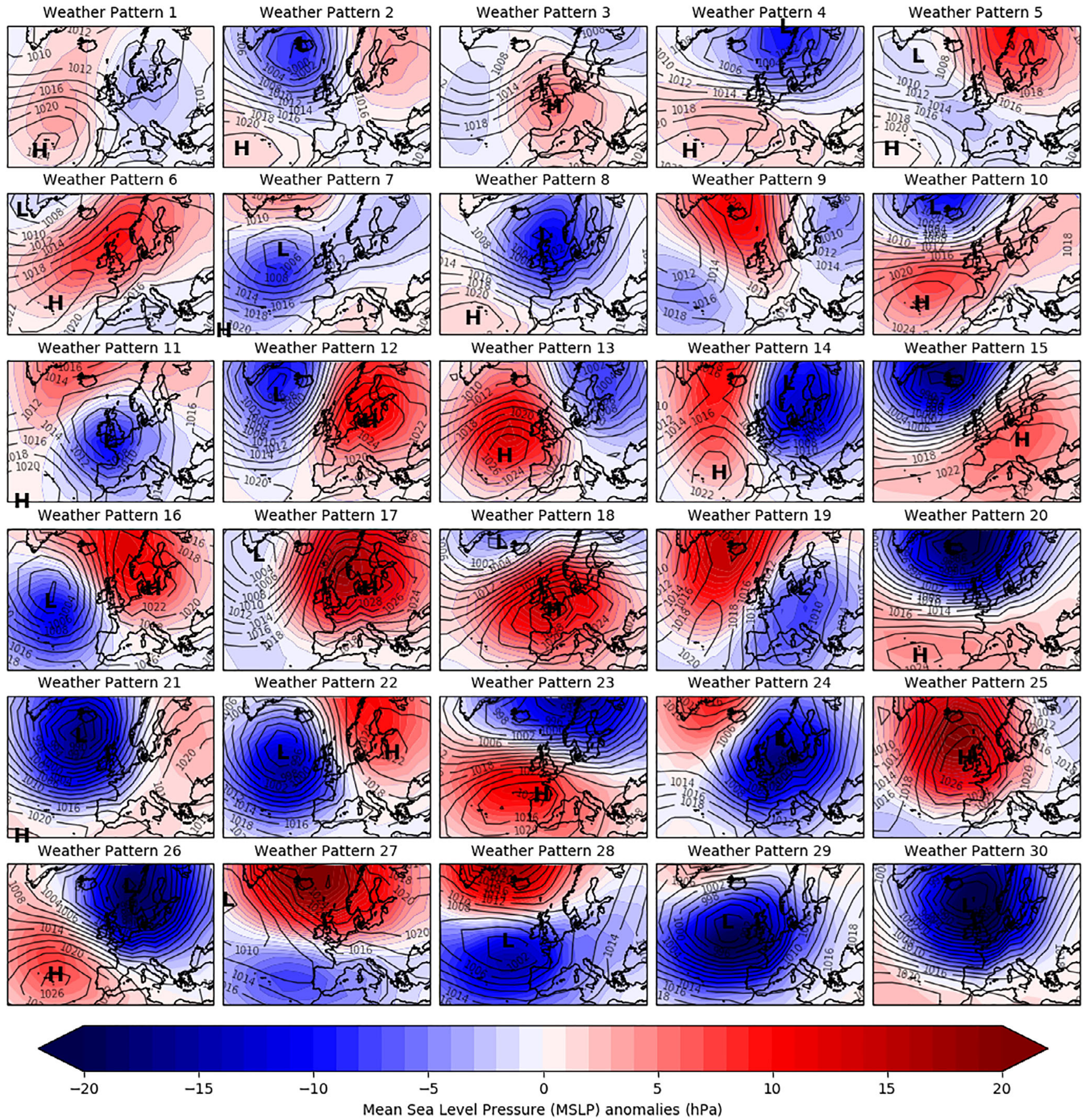

FIGURE 2 The set of 30 met Office weather patterns (MO30) showing mean sea-level pressure (MSLP) anomalies plotted as filled contours (hPa) and MSLP means plotted in the foreground (2 hPa intervals). Source: Neal *et al.* (2016, fig. 1)

who calculated the WP frequencies of occurrence based on winter and summer half-years. That study also derived the conditional distributions of HadUKP precipitation given the WPs (i.e. the distributions of precipitation that fell on days coinciding with each WP). They showed that these conditional distributions were distinct enough from each other to be suitable for UK-based precipitation analyses. However, they did not investigate the application of MO30 to extreme precipitation *via* the upper tails of these distributions, as will the present study.

3 | LINKING MO30 TO EXTREME PRECIPITATION

The WPs can be used to estimate regional precipitation by examining the conditional distributions of precipitation given each WP. These distributions can be further conditioned temporally, as the WPs will be associated with different precipitation amounts depending on the season. For the purpose of the study, the precipitation distributions are calculated for each day in the year using a 101 day centred window in order to increase the sample size and create a temporally smooth climatology. Figure 4 shows an example of regional precipitation distributions for two WPs, which are very different in terms of their MSLP anomaly definitions. Distributions are shown for WP21, which is characterized by cyclonic behaviour to the northwest of the UK and associated with strong westerly and southwesterly winds, and WP25, which features

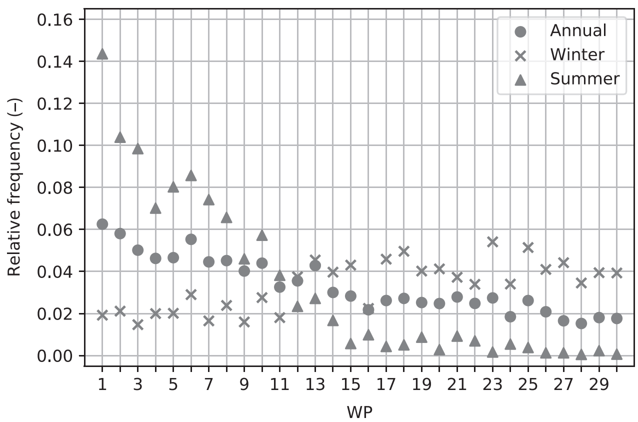

FIGURE 3 Relative frequencies of each weather pattern (WP) 1931–2016 for annual (circles), winter (December–February; crosses) and summer (June–August; triangles)

an anticyclone over the UK and is therefore likely to be associated with calm conditions. The distributions presented in Figure 4 are centred on January 1 and show that regions exposed to the westerly and southwesterly flow under the WP21 experience the highest precipitation totals (e.g. SWE, SS and NS). It is also unsurprising to see that all regions are wetter than normal under WP21 and drier than normal under WP25 during this period. Focusing on SS as an example, the climatological probabilities of exceeding different precipitation percentile thresholds are also different between these two WPs, with WP21 much more likely to be associated with exceeding those in the upper tail (Figure 5). For example, given WP21 the likelihood of exceeding the 90th percentile (around 13 mm·day^{-1}) in the 101 day window centred on January 1 is just over 25% compared with virtually 0% when WP25 is observed.

The WPs associated with regional extreme precipitation are identified by calculating empirical exceedance probabilities from the distributions of precipitation conditional on each WP for four thresholds: the 90th, 95th, 99th and 99.7th percentiles from the precipitation distributions conditioned by season only (i.e. not also by the WP). As an example, Figures 6 and 7 show the exceedance probabilities of these thresholds for SEE, SWE and NWE for winter and summer, respectively. The WPs associated with the highest probabilities of extreme precipitation differ by region. For example, winter occurrences of WP20 have a high chance (relative to other WPs) of coinciding with precipitation exceeding each of the four thresholds, but these probabilities are greater for

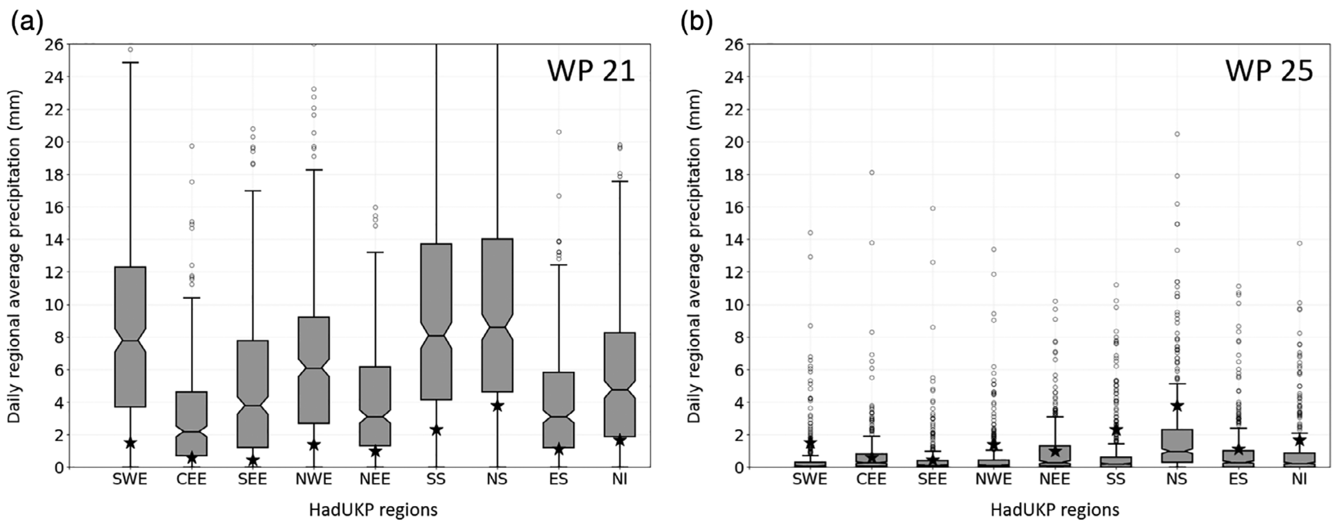

FIGURE 4 Box plots showing the regional precipitation distribution (according to HadUKP), using a 101-day window centred on January 1, for all days under WP21 (cyclonic southwesterly; left plot) and WP25 (high centred over the UK; right plot). The bottom and top of the boxes provide the 25th and 75th percentile precipitations, respectively. The centre horizontal lines in the boxes provide the median precipitations. Data points outside the tails are considered outliers. Stars provide the regional median precipitation irrespective of weather pattern. The *y*-axis is capped at 26 mm

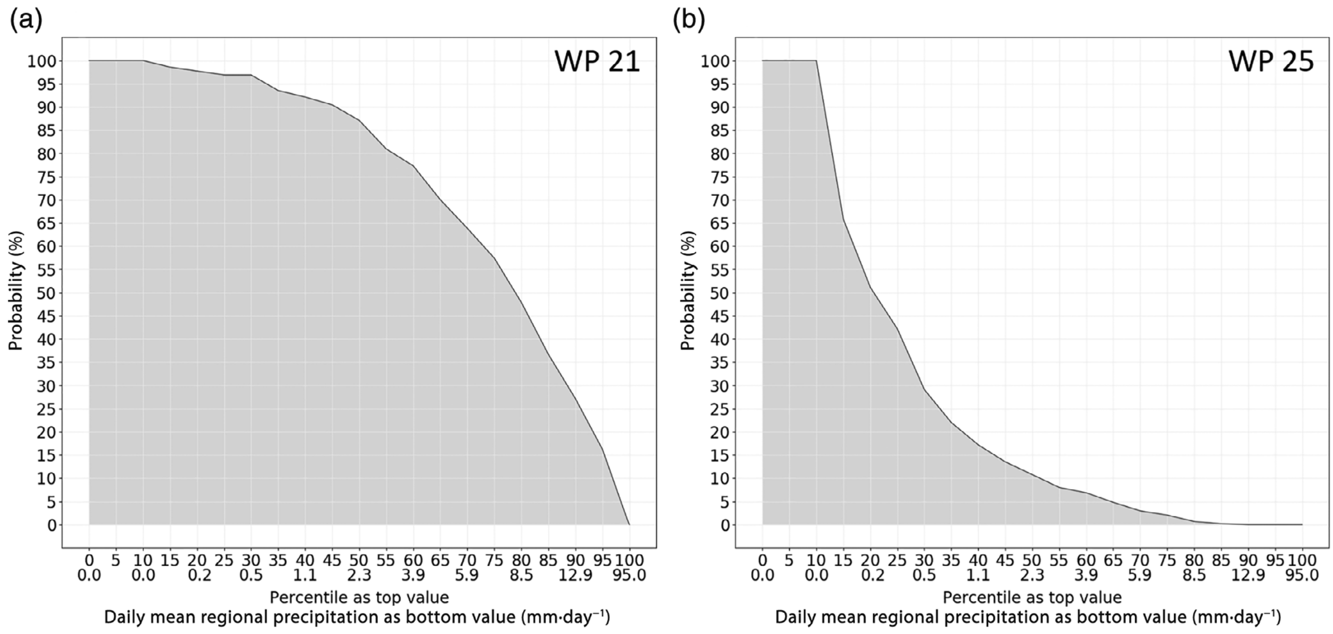

FIGURE 5 Climatological precipitation percentile exceedance probabilities (using HadUKP) for WP21 (cyclonic southwesterly; left plot) and WP25 (high centred over the UK; right plot) using a 101-day window centred on January 1 for southwest Scotland (SS)

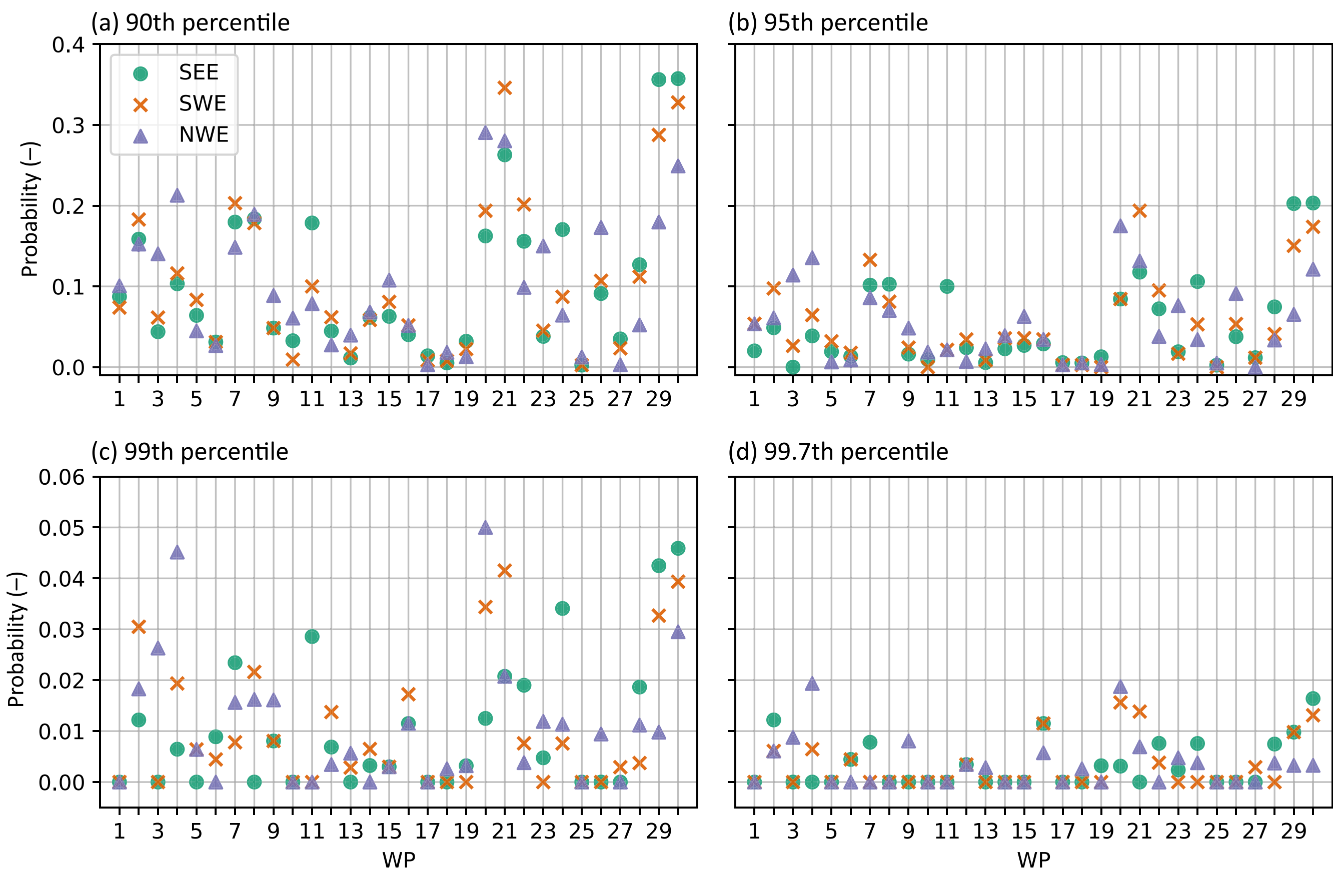

FIGURE 6 Winter (December–February) empirical precipitation exceedance probabilities for each WP for four precipitation percentiles. The regions are southeast England (SEE) (green circles), southwest England and southern Wales (SWE) (orange crosses) and northwest England and northern Wales (NWE) (purple triangles). Note the different *y*-axis scales between the top and bottom rows

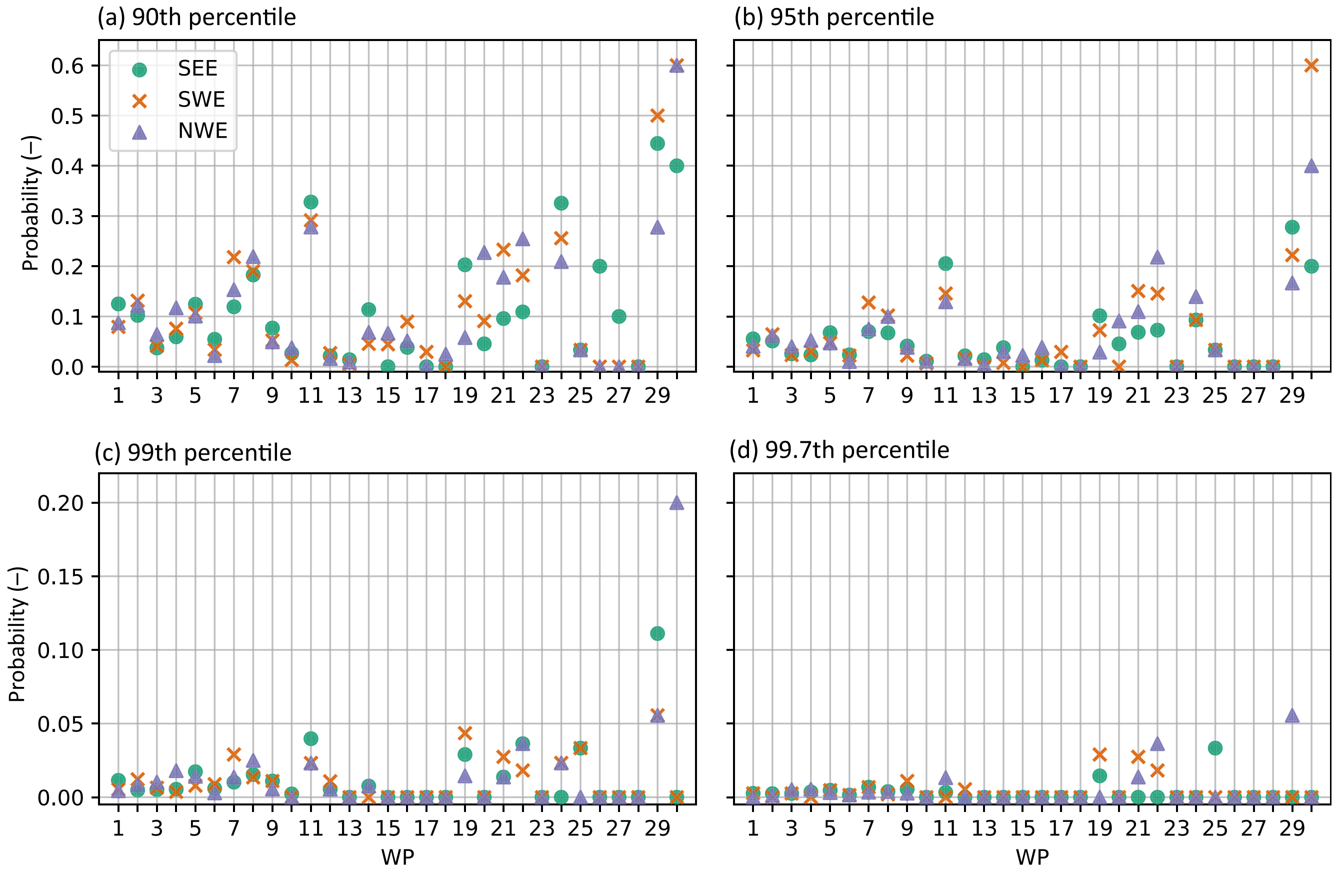

FIGURE 7 As for Figure 6, but for summer (June–August)

NWE (Figure 6). Similarly, WP21 presents a higher risk of extreme winter precipitation for SWE than the other two regions, while SEE is the most likely to experience exceedances coincident with occurrences of WP29 and WP30. The WPs typically associated with summer are capable of producing extreme precipitation in winter. WP7 and WP8 in particular feature relatively high probabilities of exceedance for all but the 99.7th percentile threshold (Figure 6). While the results indicate that the reverse (extreme summer precipitation concurrent with days featuring winter WPs) is also true (Figure 7), consider that the frequencies of occurrence of winter WPs in summer is extremely low (Figure 3). Therefore, the extremely high probabilities associated with these WPs (especially WP29 and WP30) should be treated with caution; for more discussion, see below. The regional differences in exceedance probabilities for lower numbered WPs in summer are less stark than for winter. WP7, WP8 and WP11 are the most likely to exceed the three lower thresholds, while probabilities for exceeding the 99.7th threshold are low for all summer WPs (Figure 7). It is no surprise that, for all seasons and regions, the WPs most associated with precipitation extremes are characterized by cyclonic conditions over or near to the UK (Figure 2).

4 | MO30 HINDCAST SKILL

The Met Office predicts the probabilities of occurrence of MO30 WPs using an operational post-processing system called Decider (Neal *et al.*, 2016). Driven by global EPSs, such as the European Centre for Medium-range Weather Forecasts (ECMWF) medium- to long-range EPSs (Buizza *et al.*, 2007; Vitart *et al.*, 2008) or the Met Office Global Seasonal Forecast System v.5 (GloSea5) (MacLachlan *et al.*, 2015), Decider converts daily forecasts of the MSLP to predictions of daily WPs. First, it calculates the MSLP anomaly fields for each ensemble member and day in the forecast lead time, with respect to the same climatology used in the original derivation of the MO30 WPs. These forecasts of the MSLP anomaly fields are then assigned to the closest matching WP by minimizing the sum-of-squared differences. The output therefore comprises the probability of each WP occurring (based on the ensemble frequency) for every day in the forecast lead time.

Decider's skill in predicting WP occurrences up to 15 days in advance is assessed by using the 51 member ECMWF EPS between January 1, 2010, and August 6, 2019 (Figure 8). The Brier score (BS) (Brier, 1950) is used as a metric. It measures the accuracy of probabilistic forecasts, and is given by:

$$BS = \frac{1}{N}\sum_{i=1}^{N}(f_i - o_i)^2,$$

where N is the number of forecasts; f_i is the probabilities of the forecasted events; and o_i is the binary outcomes of the events (hit or miss). Here, skill is not assessed on each WP individually, but on representative groupings (as used by Neal *et al.*, 2016, for their eight-WP classification) and so f_i and o_i represent the forecasted and observed WP groupings, respectively. This reflects the fact that some of the WPs share similarities in their MSLP patterns. The forecast probabilities (f_i) are the probability of a specific WP group occurring once or more within a three day time-window. These forecasts are considered a hit within o_i if the forecast WP group is observed once or more within the same time-window. Note that the time-window can only be two days for the first and last days in the forecast range. This time-window approach allows for temporal uncertainties in the forecast and reflects how operational meteorologists interpret medium-range forecast output presented on a daily temporal resolution. The BS is used to calculate the Brier skill score (BSS):

$$BSS = 1 - \frac{BS}{BS_{ref}},$$

where BS_{ref} is the BS of the WP climatological frequencies of occurrence. A BSS greater (lower) than zero indicates the forecast is more (less) skilful than climatology and BSS = 1 indicates a perfect forecast.

Considering year-round forecasts (Figure 8a), Decider has high skill for the first few days, steadily declining as lead time increases. The skill is greatest for the North Atlantic Oscillation (NAO) WP groups, possibly because these groups contain some of the WPs with the greatest-magnitude MSLP anomalies, and the model is therefore more certain about whether or not they will occur. This

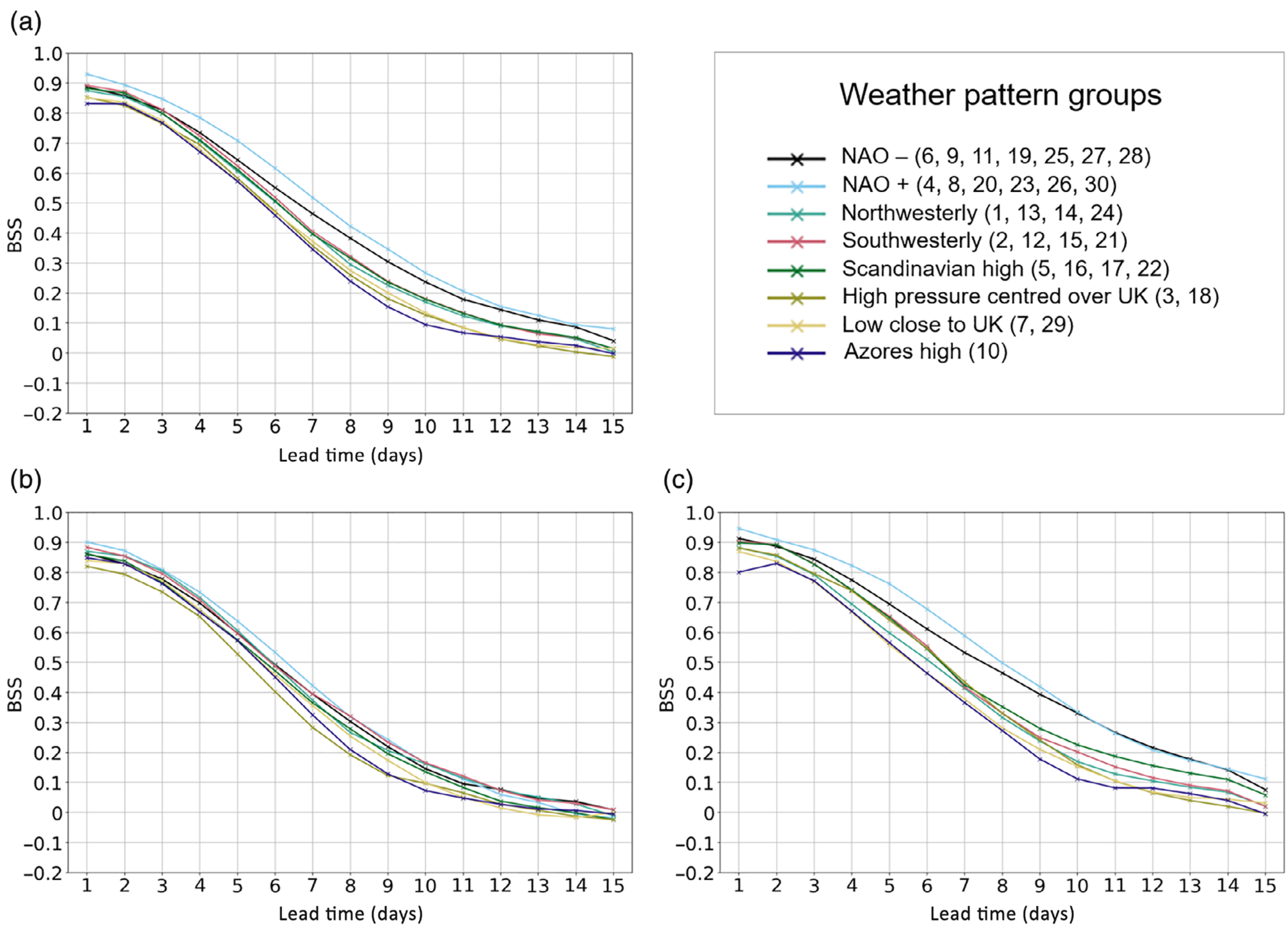

FIGURE 8 Brier skill scores (BSS) for eight weather pattern groups: (a) annual scores; (b) April–September scores; and (c) October–March scores. "NAO" stands for the North Atlantic Oscillation. Based on the verification of the 51 member European Centre for Medium-range Weather Forecasts (ECMWF) 15 day ensemble between January 1, 2010, and August 6, 2019

is supported by the relative reduction in these groups' forecast skill in summer (Figure 8b), when they are less common (Figure 3). Skill in winter is greater than summer, with the NAO groups maintaining at least respectable skill throughout the 15 days (Figure 8c). Indeed, aside from day 15, the skill in forecasting all WP groups is greater than climatology.

5 | FLUVIAL DECIDER METHODOLOGY AND VISUALIZATIONS

Decider forms the basis of three Met Office operational WP applications, where each application is based on probabilities of impacts conditioned on MO30 WPs. Fluvial Decider is the latest application and has a key methodological difference. Both other applications provide probabilities of "high-risk" WPs occurring, while ignoring other WPs. To determine the probability of flow over UK airspace originating from Iceland, the high-risk WPs were defined subjectively by Met Office operational meteorologists. In Coastal Decider, the high-risk WPs were defined objectively using wave hindcasts and historical skew-surges, and so vary by coast (Neal *et al*., 2018). Fluvial Decider instead considers the probabilities of all WPs in its guidance because there are many WPs associated with extreme precipitation, especially in winter (Figures 6 and 7). Storm surges and high-wave events, on the other hand, are more restricted to a limited set of WPs coinciding with a period of spring tides. Another key difference of Fluvial Decider is that it directly provides predictions of the variable of interest, that is, precipitation threshold exceedances. By contrast, Coastal Decider primarily provides forecast probabilities of the high-risk WPs, and operational hydro-meteorologists need to estimate the expected storm surge or wave height from the forecast pressure anomaly or wind speeds in the original EPS forecasts.

In Fluvial Decider, probabilistic predictions of precipitation exceeding the four thresholds are derived for each region and day in the forecast lead time. The predictions are the empirical exceedance probabilities from the 101 day climatology (50 days either side of the forecast date) between 1931 and 2016. Note that a rolling climatology (rather than fixed seasons) is used in the operational product to avoid the sudden change in the data subset when transitioning between seasons.

The following subsections describe two case studies to illustrate the role of extreme precipitation-producing WPs during flood events, together with the forecast visualizations and best use of Fluvial Decider.

5.1 | Winter 2013/2014

During winter 2013/2014, at least 12 major storms occurred in two spells between mid-December and early January, and then from late January to mid-February. The initial impacts were from strong winds in northern regions, but from late December, the focus switched to fluvial and pluvial flooding. Widespread heavy precipitation fell on already saturated ground, causing flooding with significant impacts on the River Thames and Somerset Levels (Huntingford *et al*., 2014; Kendon and McCarthy, 2015; Muchan *et al*., 2015; Kay *et al*., 2018). For SWE, regional average precipitation on December 23 was 40 mm, and 18 days between December 23, 2013, and February 9, 2014, experienced > 10 mm·day^{-1} (Figure 9). For comparison, the maximum winter daily precipitation for SWE between 1981 and 2010 was 30 mm, while 10 mm for the same period is just below the 90th percentile. Winter 2013/2014 was dominated by the occurrences of the two least-common WPs, WP29 and WP30, followed by WP21. These three WPs accounted for roughly 75% of the total precipitation (440.9 mm) that fell during this period. They feature deep low-pressure anomalies and westerly or southwesterly flow over the UK (Figure 2), and correspondingly have amongst the highest probabilities of winter precipitation exceedance for all four thresholds (Figure 6).

An example of the Fluvial Decider guidance during that winter is shown in Figure 10. The visualizations used to summarize the forecasts must be unambiguous and concise to be effectively interpreted by the FFC (Pappenberger *et al*., 2013). Guidance is presented in two ways. The primary visualization is the likelihood compared with normal of precipitation exceeding the thresholds (Figure 10, top) and the secondary visualization is the standard probabilities of exceedance (Figure 10, bottom). These descriptions pertain to the left-hand *y*-axes, which differ by the scaling of the displayed data. Both visualizations present the same information, but in slightly different formats.

For the likelihood compared with normal visualization (Figure 10, top), the data are presented relative to each threshold's "normal" probability (i.e. based on the percentile it represents for the 101 day climatology of interest), with the absolute probabilities on the right *y*-axis. It is intended as the default visualization and presents a quick overview of expected periods with a higher or lower than normal likelihood of exceeding one or more precipitation thresholds. The standard probability visualization (Figure 10, bottom), on the other hand, shows the absolute probabilities of threshold exceedances, with the right *y*-axis presenting the likelihoods compared with normal for each threshold

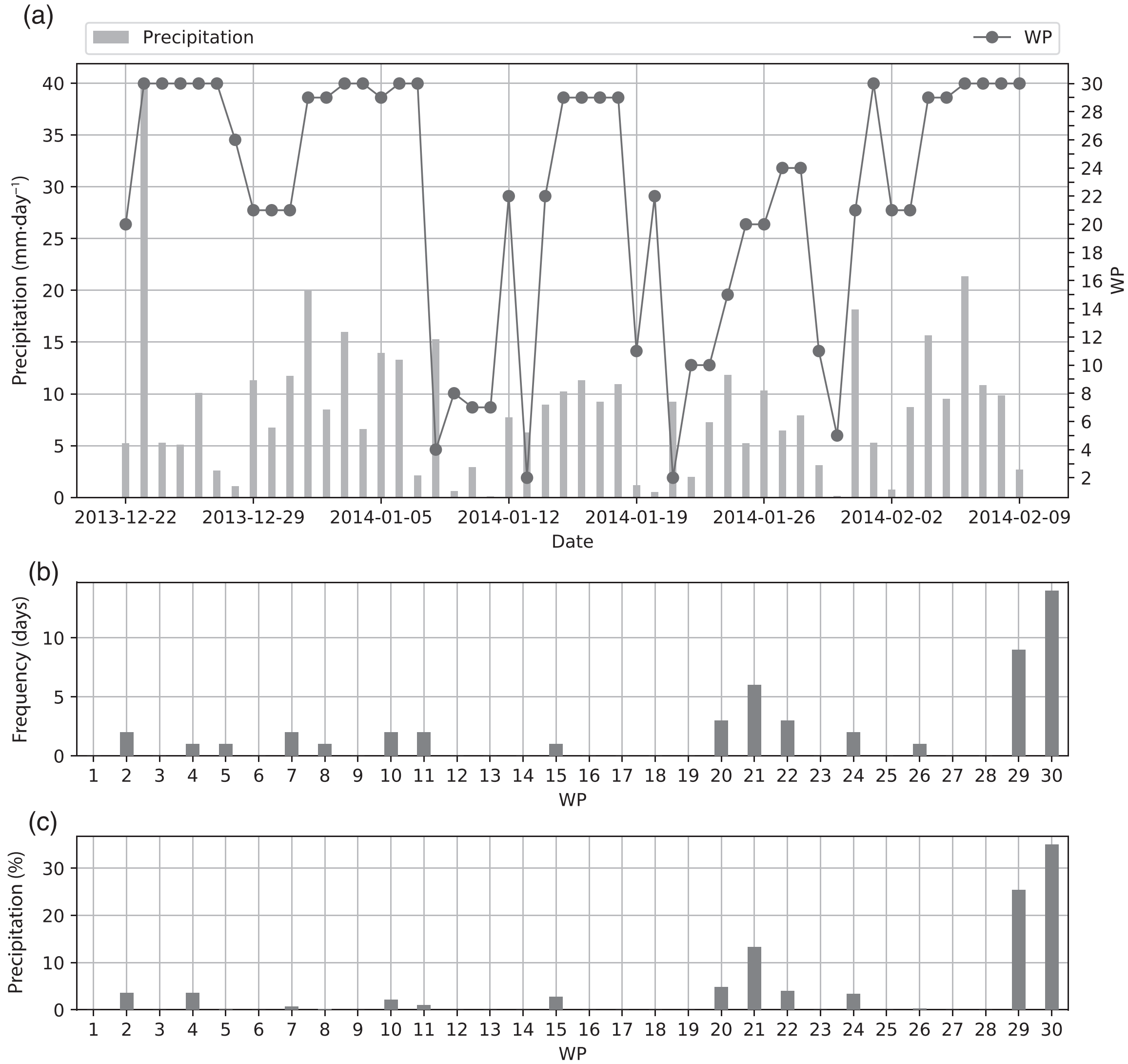

FIGURE 9 (a) Winter 2013/2014 (including Somerset Levels floods) time series of weather patterns (WPs) and southwest England and southern Wales (SWE) precipitation; (b) WP frequencies; and (c) each WP's percentage contribution to the period's total precipitation of 440.9 mm

exceedance. It provides a visual summary of the actual probabilities involved, and serves as a reminder to the forecasters that a higher than normal chance may still be small in absolute terms. Shading is added to this visualization, highlighting when the probabilities are greater than the climatological probability. Note in Figure 10 how the left *y*-axis in of the top panel is the same as right *y*-axis of the bottom panel, and the right *y*-axis of the top panel is the same as left *y*-axis of the bottom panel. The difference is that the plotted data are scaled to the left *y*-axis of each plot.

Figure 10 shows how, for a forecast issued on January 30, 2014, Fluvial Decider clearly highlights SWE as being particularly at risk during the full two week forecast lead time suggesting no respite from the wetter-than-normal conditions. This is shown by the probabilities of threshold exceedances being far higher than normal, and high in absolute terms, throughout the forecast period. The factor by which predicted exceedances are more likely than normal being greatest for the 99.7th percentile. This matches well with the observed precipitation, which was substantial in SWE during this period (Figure 9). For this forecast, Decider provided accurate predictions of the WPs for the first five days in the lead time (Supporting Information Figure S1). Beyond this, the ensemble members were split between WP30 (the observed WP), WP20, WP21 and WP29. The incorrect prediction of WP20, WP21 and WP29 by some members during this period is not surprising as they are similar to WP30 in terms of their MSLP anomaly definitions (Figure 2). Furthermore, due to the similar threshold exceedance probabilities of the four WPs (Figure 6), there was seemingly no detrimental impact to the resulting precipitation forecasts.

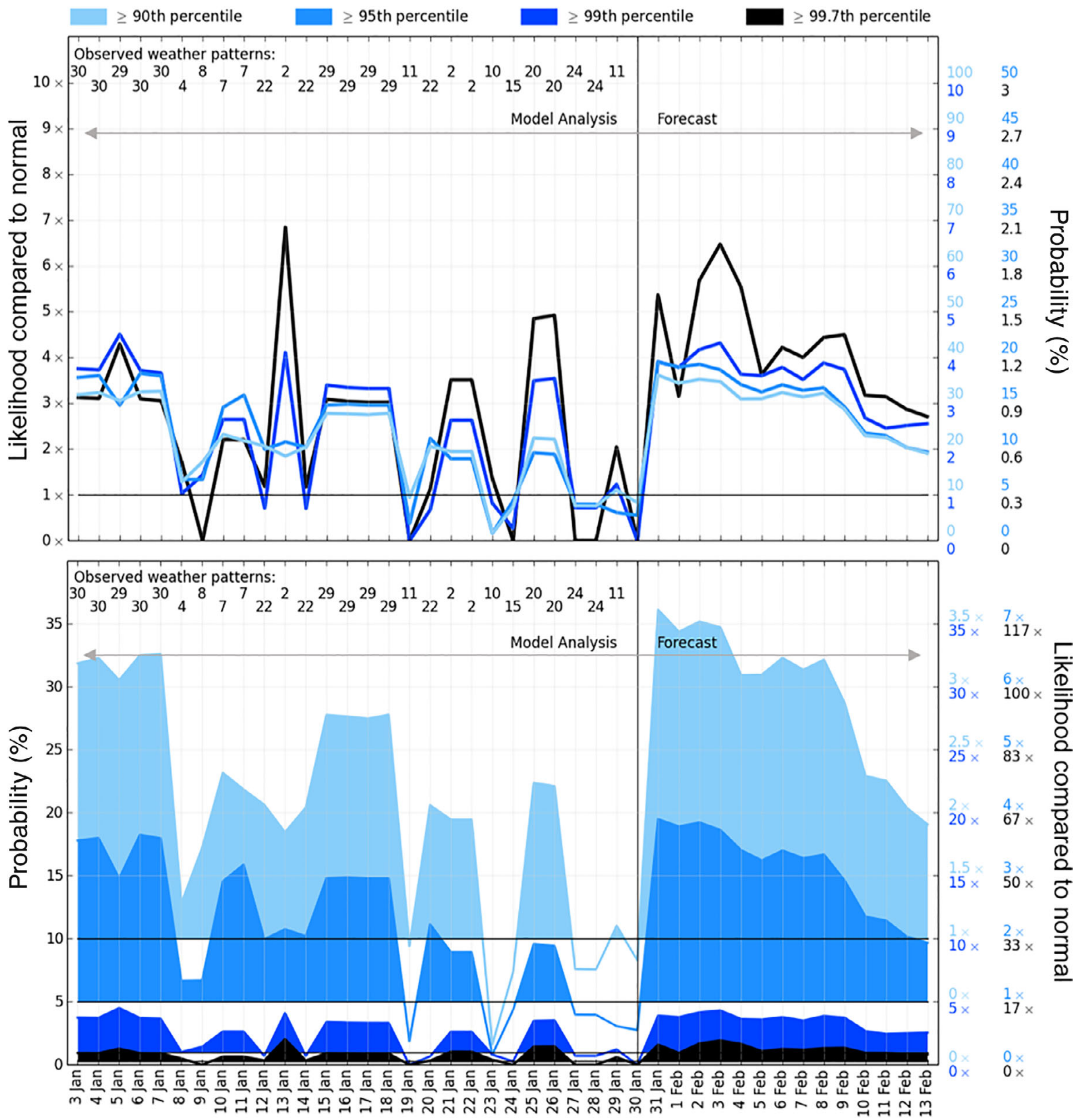

FIGURE 10 Fluvial Decider visualization for the forecast initialized at 0000 UTC on January 30, 2014, using the European Centre for Medium-range Weather Forecasts (ECMWF) 15 day ensemble prediction system. Precipitation data are for southwest England and southern Wales (SWE). The top panel shows the likelihood of exceeding four precipitation thresholds (represented by different colours) relative to their climatological likelihood, with the absolute probabilities on the right-hand axis. Data are shown for the observations ("model analysis") and the forecast, to the left and right of the vertical grey line (i.e. the forecast initialization date), respectively. The horizontal black line at 1 indicates climatological relative likelihood. The observed weather patterns are shown near the top of the model analysis. The bottom panel is very similar, but instead has the absolute probabilities on the left-hand axis, with the relative probabilities on the right. Horizontal black lines for each threshold indicate the climatological exceedance probabilities, with values exceeding climatology shaded in the relevant colour

5.2 | December 2015

The second case study is the Cumbria floods of December 2015. Storm Desmond occurred on December 5–6, resulting in the flooding of thousands of homes and businesses in Cumbria, northwest England. Precipitation during this storm was record-breaking in places (Met Office, 2016), and followed a wet November (Figure 11). The WP that coincided with Storm Desmond was WP20, again a cyclonic type. WP20 is associated with the highest probabilities of exceedance for all thresholds except the 99.7th percentile (for which its probability is only just second, behind WP4) for precipitation in NWE (Figure 6). However, WP23 was the largest contributor of precipitation in NWE for the 38 day period between November 5 and December 12 (Figure 11), predominantly because it coincided with the wettest day in the period on November 14 and another very wet day on December 9. This WP, along with the third highest contributor, WP15, actually features positive MSLP anomalies for much of the UK, but it is also characterized by strong westerly and southwesterly winds, possibly explaining the reasonably high probabilities of precipitation threshold exceedance in NWE (Figure 6).

For a forecast issued one week before Storm Desmond, Fluvial Decider predicted above-average probabilities of exceedance for the majority of days in the two week lead time (Figure 12). Observed precipitation was correspondingly high (Figure 11), although towards the end of the hindcast period the model did not predict some high-precipitation days on December 9 and 12. The Storm Desmond event itself (December 5) does not particularly stand out in the forecast relative to the other days, although at a lead time of eight days the likelihood of exceeding all four thresholds is greater than normal (Figure 12, top). The likelihood of extreme precipitation on this day is more obvious in the absolute probability visualization (Figure 12, bottom), as the shading clearly indicates heightened risk of exceeding the 90th and 95th percentiles, a feature that is somewhat obscured when looking only at the likelihoods compared with normal (Figure 12, top).

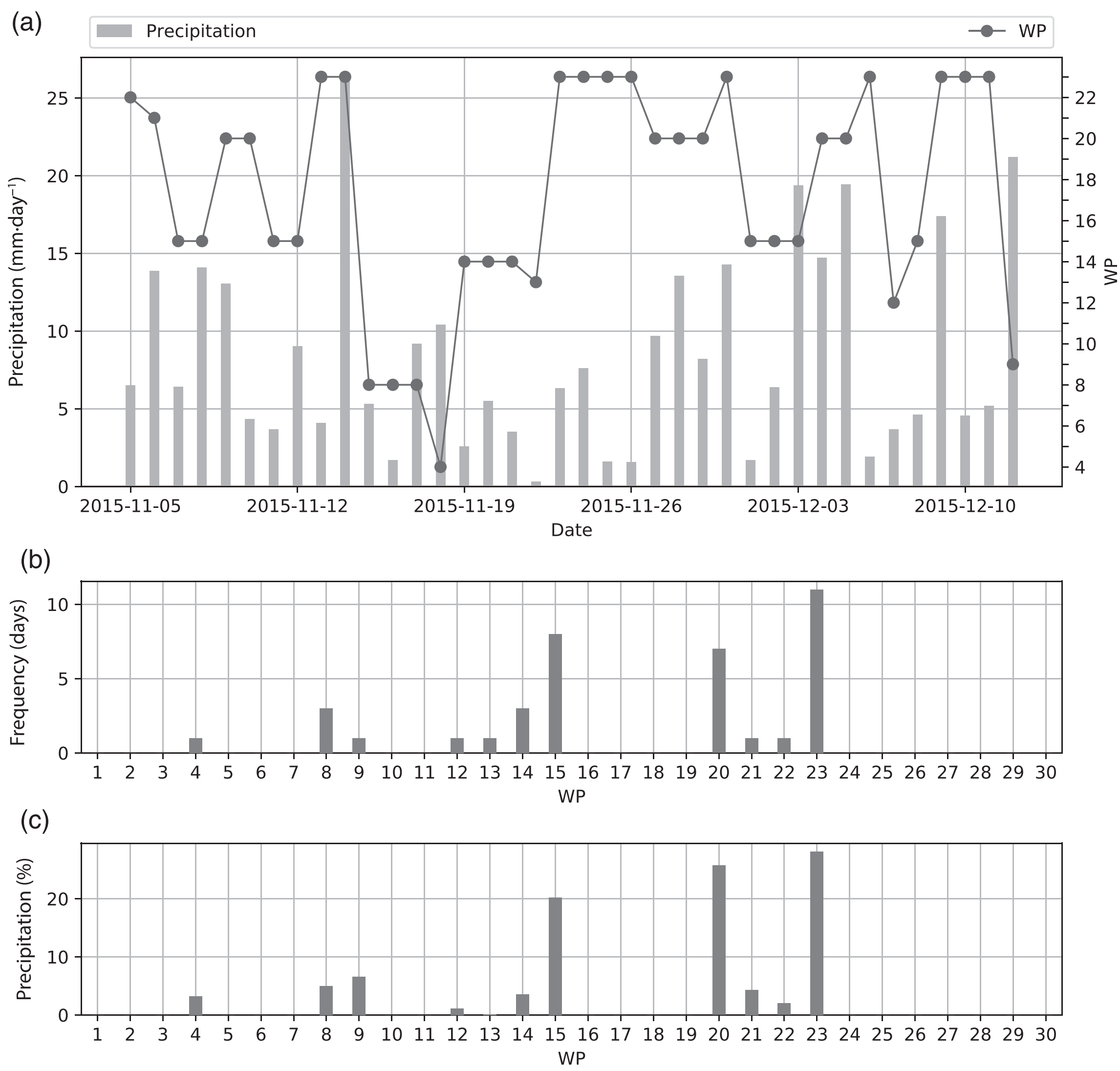

FIGURE 11 (a) December 2015 (including Storm Desmond on December 5–6) time series of weather patterns (WPs) and northwest England and northern Wales (NWE) precipitation; (b) WP frequencies (middle); and (c) each WP's percentage contribution to the period's total precipitation of 322.5 mm (bottom)

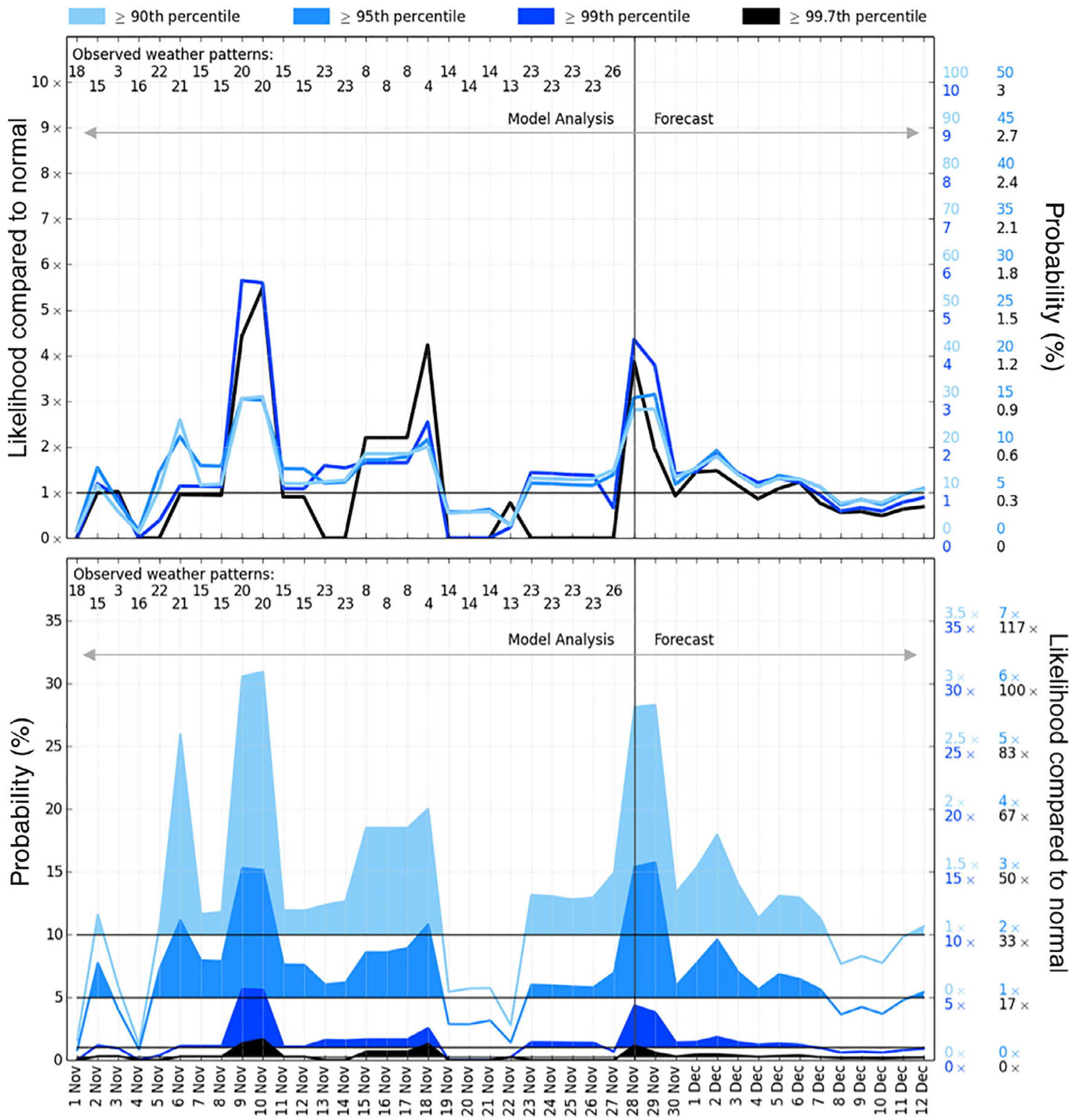

FIGURE 12 As for Figure 10, but for the forecast initialized at 0000 UTC on November 28, 2015. Precipitation data are for northwest England and northern Wales (NWE)

The reason that Storm Desmond does not stand out in the Fluvial Decider guidance issued on November 28 is because 38 of the 51 ensemble members predicted an even split between WP15, WP18 and WP20 for December 5 (with 25%, 25% and 24% probabilities, respectively) (Supporting Information Figure S2). Only WP20, which was the observed WP on this day, shows high probabilities of exceeding the four precipitation thresholds for NWE (Figure 6), while WP18 has near-zero probabilities and is characterized by an anticyclone over the southern UK (Figure 2). The ensemble spread in predicted WPs is much greater for this case study than for winter 2013/2014, particularly at lead times greater than eight days.

6 | INTERPRETATION AND BEST USE OF FLUVIAL DECIDER

The probabilistic nature of Decider is worth discussing further. The uncertainties surrounding the exact timing and magnitude of the predicted MSLP fields means that Decider may not correctly predict the timing of a WP, or might incorrectly predict a particular WP in favour of a different WP with a similar spatial pressure distribution (e.g. WP20 and WP30). This is why applications using Decider are more useful as guidance tools for multi-day periods considered as a whole. Indeed, the two case-study forecast periods discussed show some days when the resulting precipitation exceeded expectations from the forecast, such as December 9 and 12, 2015 (Figures 11 and 12). The reasons for missed events such as these could either be Decider predicting low likelihoods of the eventual observed WP (or WPs with similar probabilities of precipitation exceedance), especially at long lead times, or the eventual observed precipitation being historically unlikely given the (correctly) predicted WP. For December 9 there was a large ensemble spread, with the observed WP (WP23) predicted with 12% probability, while for December 12 the observed WP (WP9) was not predicted by any ensemble member (Supporting Information Figure S2). Furthermore, the observed NWE precipitation totals of 17.4 and 21.2 mm correspond to roughly the 99th percentile of the precipitation distributions given the WPs (WP23 and WP9, respectively) and climatological period (101 days centred on the two dates).

Fluvial Decider is more useful during the winter half-year (October–March) for three reasons. First, extreme precipitation during summer is often a result of localized convective events (Hand *et al.*, 2004), which in any case are more associated with pluvial, rather than fluvial, flood events (Archer and Fowler, 2018). Owing to the large region sizes and sparse locations of precipitation gauges used in the HadUKP data set creation (Alexander and Jones, 2000), localized downpours would be smoothed out when calculating regional precipitation averages, even if such events were captured by a gauge. Floods and extreme precipitation events in winter, on the other hand, tend to be a result of large-scale frontal systems (e.g. the Somerset Levels floods in February 2014), for which the associated circulation is better represented by the WPs, and for which the spatial extent of such events is likely to be reflected in the regional precipitation series. The second reason for Fluvial Decider's reduced usefulness in summer is because of the low historical occurrences of "wintry" WPs occurring in this season (Figure 3). This makes the associated exceedance probabilities unreliable due to a small sample size, and results in very high probabilities of threshold exceedance for some WPs (e.g. WP29 and WP30) (Figure 7). This in turn leads to "likelihood spikes" in forecast probabilities, which might be over-interpreted by users. By contrast, winter occurrences of WPs are much more evenly spread, meaning any "likelihood spikes" in the forecast may be treated as more reliable. The third reason is that model skill in predicting the WPs is greater in winter than in summer (Figure 8), particularly for the two largest WP groupings (NAO+ and NAO−).

The forecast visualizations are complemented by showing the observed WPs from the previous 27 days. This is to provide the hydro-meteorologists in the FFC with a quick reference for the observed WPs over the most recent weeks as a reminder of recent WP transitions and persistence. This then helps to provide a context for the upcoming forecast period (e.g. "last week's anticyclonic dry spell is likely to be followed by a transition to cyclonic WPs with periods of persistent and heavy rain"). The corresponding empirical probabilities of exceeding the precipitation thresholds are also shown. This allows the user a quick assessment of potential current conditions for the corresponding region, such as the saturation levels of soils or river levels that might make a potential extreme precipitation event more likely to lead to flooding. However, information on the effect of longer term antecedent precipitation that can influence these variables and affect the risk is not provided. More detailed hydrological models and real observations of soil saturation are always used by forecasters when issuing flood warnings. Ideally, these "observed" exceedance probabilities would be replaced by the HadUKP observed regional precipitation amounts, but the data set is not updated at the daily rate necessary for Fluvial Decider.

7 | SUMMARY AND CONCLUSIONS

The relationships between a European-domain weather pattern (WP) classification and regional UK extreme precipitation have been explored, with a focus on how these relationships could be useful in medium- to long-range fluvial flood forecast applications. Different WPs are associated with upper-tail precipitation threshold exceedances for different regions and seasons. Furthermore, using two case studies of UK flood events, winter 2013/2014 and December 2015, it was shown that the WPs associated with extreme precipitation in winter (Figure 6) correspond to those that occurred during the floods (Figures 9 and 11). The WP classification effectively reduces the variability of atmospheric circulation over Europe and the North Atlantic down to 30 discrete regimes. Using an ensemble prediction system (EPS), predictions of these WPs can then be used to estimate the probability that precipitation will exceed upper-tail thresholds relevant for extreme events, where the estimated probabilities are derived from historical conditional distributions of precipitation given the WPs. This forms the basis of a forecast guidance tool for potential extreme precipitation events that was introduced, intended for use by the Met Office and the Environment Agency's operational Flood Forecasting Centre (FFC). This tool, Fluvial Decider, was introduced into FFC operations in October 2017. It aims to provide advance warning of high-risk periods, beyond the short-range lead times for which hydrological flood prediction models are run. By highlighting when there are signals in the longer term forecast for an increased risk of flooding, the tool enables the government and partners (i.e. the Environment Agency and Natural Resources Wales) to plan ahead, managing resources and slowing other work to make space for mitigating and responding to potential flood events.

Case study analysis has helped to illustrate the best use of Fluvial Decider as an operational forecasting guidance tool, as forecast visualizations of parts of these events showed that an end-user could have been made aware of the likelihood of upcoming extreme precipitation two weeks in advance (Figures 10 and 12). Two particular case studies were selected to illustrate the features and use of the tool, but a wide range of case studies were analysed initially, with risk highlighted in most. There is also an understanding of the skill of the underlying probabilistic WP forecasts that provide a large input into Fluvial Decider's forecast output. The model is at least reasonably skilful for the first eight days, and always more skilful than climatology. However, before operationalizing Fluvial Decider, a highly recommended piece of (planned) future research would be to verify the skill for the probability forecasts of exceeding regional precipitation thresholds.

This could be done by comparing results based on the WP approach with the precipitation forecasts taken from EPSs directly. Fluvial Decider assumes that EPSs have higher skill in medium- to long-range forecasting of atmospheric pressure compared with directly predicting precipitation, and exploits this by first predicting the WPs and using these to estimate future precipitation. While studies have shown that some EPSs do exhibit higher skill in forecasting atmospheric variables (Lavers *et al.*, 2014; Saha *et al.*, 2014; Baker *et al.*, 2018), it would be interesting to see if this skill translates to Fluvial Decider by verifying forecasts against a benchmark of direct precipitation forecasts from other EPSs. To help with this, hindcast data sets of the mean sea-level pressure (MSLP) are available, which could be converted into WP hindcasts. However, this will be the subject of a future study. Further fine-tuning could be made to Fluvial Decider by testing other precipitation data sets. For example, Jones *et al.* (2014) argue that the HadUKP regions used in the present study are not suited to extreme precipitation. They propose a new set of regions, although the corresponding regionally averaged precipitation data are not readily available. Furthermore, as Fluvial Decider is ultimately a tool for assisting expert judgement, it is perhaps not crucial that the precipitation data set used is not the absolute optimal choice possible.

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ORCID

Doug Richardson https://orcid.org/0000-0001-5397-0201
Robert Neal https://orcid.org/0000-0003-2678-6016

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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