Application and verification of ECMWF products 2017

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1. Summary of major highlights

ECMWF output is widely used by the Met Office at many timescales, especially the week 2 period where the Met Office is particularly dependant on ECMWF output. The heaviest users of ECMWF output are the Chief and Deputy Chief Meteorologists, who provide forecast guidance across the organisation for areas around the world and hydrometeorologists at the Flood Forecasting Centre. ECMWF output also forms part of 'BestData', a multi-model blend producing site-specific forecasts available, for example, on the Met Office public website. Meanwhile, the Met Office have been actively engaged in producing some new and innovative tools to help operational meteorologists visualize ensemble output, creating and verifying regional weather regime forecasts and developing a global hazard map, which includes a focus on tropical cyclones.

2. Use and application of products

2.1 Post-processing of ECMWF model output

2.1.1 Statistical adaptation

HRES ECMWF forecasts are included in the site-specific post-processing system which is based on a Kalman Filter (KF) approach.

2.1.2 Physical adaptation

Before statistical corrections are applied some physical post-processing (e.g. accounting for height differences) is applied to the HRES ECMWF forecasts included in the site-specific post-processing.

ECMWF initial and boundary conditions have been used for initialising Unified Model (UM) limited area model (km-scale) configurations in the tropics, to gain an understanding of the impact of the driving model characteristics on the performance at the km-scale.

2.1.3 Derived fields

The Met Office automatically assigns the latest mean sea level pressure (MSLP) fields from the ECMWF medium and long range ensembles to one of 30 predefined weather patterns over Europe (Neal et al. 2016). This ensemble member weather pattern assignment is also carried out with several other global NWP models and is used to produce probabilistic weather patterns forecasts as part of the Met Office Decider product (http://www.metoffice.gov.uk/services/industry/energy/decider). The forecast guidance provided by Decider is used by Met Office operational meteorologists as well as in several commercial and public weather service (PWS) weather pattern applications, such as energy demand/supply, coastal flooding, pluvial flooding, landslides in Scotland and flow from Iceland. An example of a probabilistic weather pattern forecast from Decider using ECMWF medium range data is shown in Figure 1. Here, weather patterns have been ordered according to their wind speed anomalies (derived from ERA-Interim), which in this case shows a transition towards windier than average weather patterns in the second half of the forecast period. This transition coincided with the arrival of Storm Doris on 23 February 2017.

	Mon 13 Feb	Tue 14 Feb	Wed 15 Feb	Thu 16 Feb	Fri 17 Feb	Sat 18 Feb	Sun 19 Feb	Mon 20 Feb	Tue 21 Feb	Wed 22 Feb	Thu 23 Feb	Fri 24 Feb	Sat 25 Feb	Sun 26 Feb	Mon 27 Feb	Regime Descriptions (UK)	10mWind anomalies J/F/M
Regime 17		100	33												2	Anticyclonic E-SEly high over Denmark	-4.4 **-1.6** +1.9
Regime 18			67	98	45		2	2	2		4				2	Anticyclonic SWly, high over N France	-4.5 **-1.6** +1.8
Regime 5														2		Unbiased Sly, high over Scandinavia	-4.8 **-1.3** +3.3
Regime 6														2		Anticyclonic, Azores high ext.	-4.8 **-1.2** +2.4
Regime 12												6	2		2	Anticyclonic Sly, high over Poland	-4.1 **-1.2** +2.2
Regime 16																Anticyclonic S-SEly, high E of Denmark	-5.0 **-1.1** +2.6
Regime 25																Anticyclonic Nly, high centre Irish Sea	-4.2 **-1.1** +2.9
Regime 9															4	Anticyclonic N-NEly, high near Iceland	-4.8 **-1.0** +3.4
Regime 10						10	12				2	2		4		Anticyclonic W-SWly, slight Azores ridge	-4.4 **-1.0** +2.9
Regime 3				2	24						6		4		4	Anticyclonic SWly, ridge over N France	-4.6 **-0.9** +3.3
Regime 1											2		8		**2**	Unbiased NWly	-4.7 **-0.8** +2.7
Regime 2												2	2	2	2	Cyclonic SWly, returning Pm airmass	-4.3 **-0.7** +3.2
Regime 28													2			Cyclonic SEly, low SW of UK	-4.4 **-0.7** +3.2
Regime 7											8	6	6	12	4	Cyclonic SWly, low WNW of Ireland	-4.3 **-0.6** +2.4
Regime 22															2	Cyclonic Sly, low W of Ireland	-4.0 **-0.4** +3.0
Regime 24												2	4	4	8	Cyclonic Nly, low in N Sea	-4.0 **-0.4** +3.7
Regime 11																Cyclonic, low centred over southern UK	-3.9 **-0.3** +3.7
Regime 27	100															Anticyclonic Ely, high in Norwegian Sea	-4.0 **-0.1** +3.8
Regime 8												4	2	2		Cyclonic Wly, low near Shetland	-4.8 **0.0** +4.5
Regime 15										2	2	8		8	6	Unbiased SWly, very windy NW Britain	-3.7 **0.0** +3.5
Regime 19																Unbiased Nly, low E of Denmark	-3.8 **+0.2** +4.4
Regime 13					6	10	12	8	12	14	6	4	2	6	6	Anticyclonic NWly, high SW of Ireland	-3.2 **+0.3** +4.0
Regime 29											2	2			2	Cyclonic S-SWly, deep low W of Ireland	-4.0 **+0.3** +4.7
Regime 4					2	4			8	24	14	4	12	12	4	Unbiased Wly	-3.6 **+0.8** +4.6
Regime 14								2	6	18	18	14	14	14	8	Cyclonic N-NWly, low near S Sweden	-3.1 **+1.0** +5.2
Regime 23					24	76	75	75	51	20	4	2	2		8	Unbiased Wly, windy in N	-3.0 **+1.0** +4.7
Regime 21											2	4	10	6		Cyclonic SWly, deep low S of Iceland	-3.5 **+1.1** +5.3
Regime 30										2	4	8	10	16	12	Cyclonic W-SWly, deep low SE of Iceland	-3.1 **+1.8** +5.8
Regime 20								2	2	4	6	10	10	2	14	Cyclonic Wly, intense low near Iceland	-1.9 **+2.0** +5.8
Regime 26								12	20	18	22	24	12	10	10	Cyclonic NWly, low near Norway, windy	-2.3 **+2.1** +6.3
Total Members	51	51	51	51	51	51	51	51	51	51	51	51	51	51	51	---	---

Fig.1 The Met Office probabilistic weather pattern forecast ahead of Storm Doris on 23 February 2017. Regimes are ordered according to their ERA-Interim 10m wind speed anomalies over the UK (calmest regimes listed first).

2.2 ECMWF products

2.2.1 Use of Products

At the Met Office, ECMWF output is used alongside the Met Office's own model suite. This suite includes an hourly-cycling, convection-permitting model (UKV), a 12 member convection-permitting ensemble (MOGREPS-UK), the global model, run 4 times a day with horizontal resolution of approximately 10 km and an 18 member ensemble, MOGREPS-G.

Visualization of ECWMF output by Met Office operational meteorologists is via a number of mechanisms, the primary vehicles being ecCharts and ingestion of a subset of ECWMF HRES into the Visual Weather forecaster workstations. Visualization is supplemented by use of ECMWF's main products web page and some internal web-based tools and diagnostics, for example classifying ensemble members by synoptic type to objectively assess signals (this product is known as DECIDER), particularly for severe weather (Neal et al. 2016) and for coastal flood risk (Price 2017), driving a number of downstream forecasting aids for fluvial, pluvial and tidal flooding and use of multi-model ensembles in, for example, tropical cyclone forecasting (Titley and Neal 2017). Meanwhile, ECMWF model data is blended with Met Office NWP to produce what is known in-house as 'BestData', a database of site-specific forecasts for thousands of sites used for many applications including, for example, forecasts available on the Met Office public web site. In BestData, ECMWF data is the primary source of data for forecasts for week 2.

Regarding Met Office forecasting operations, over-arching, authoritative guidance for the shorter term (Day 2) is provided by the Chief Meteorologist, who has ultimate accountability for forecast output and is responsible for operational delivery of National Severe Weather Warning Service (NSWWS) impacts-based warnings. The Chief Meteorologist is supported, on shift, by two Deputy Chiefs. One focuses on UK weather on time scales from Day 2 onwards through medium range and into monthly and seasonal time scales. The other focuses on providing guidance on global forecast matters across multiple time-scales, operating in what is known as the Global Guidance Unit; here customers include Met Office meteorologists working away from the UK, UK government departments and cross-European projects such as ARISTOTLE (Rourke 2017).

Other forecast teams, for example aviation, media and marine, then use this guidance to influence their own more customer-specific output. These forecast teams are spread across the UK with some operational meteorologists based at UK military bases, some embedded with clients, for example at some UK airports and transport agencies. some at the main Operations Centre in Exeter or in the Aberdeen office. In addition, there are a number of operational teams at locations around the world (e.g. Falkland Islands). The Flood Forecasting Centre, meanwhile, comprises a team of dedicated hydrometeorologists providing advice on fluvial, pluvial and tidal flooding.

EFI and meteograms plotted with M-Climate are very popular with the Global Guidance Unit who need an efficient means of visualization severe weather potential around the world and associated climatic context. Cyclone database products (Hewson and Titley 2010) remain an effective means of visualizing extratropical cyclone details. Objective fronts and Dalmatian plots showing low pressure centres and intensity are two of the most popular elements used, especially in medium range forecasting (Figure 2). Meanwhile, diagnostics mentioned above classifying ensemble members by synoptic weather type are immensely useful in decision-making, allowing the operational meteorologist to quickly draw out the main themes and trends shown in ensemble output.

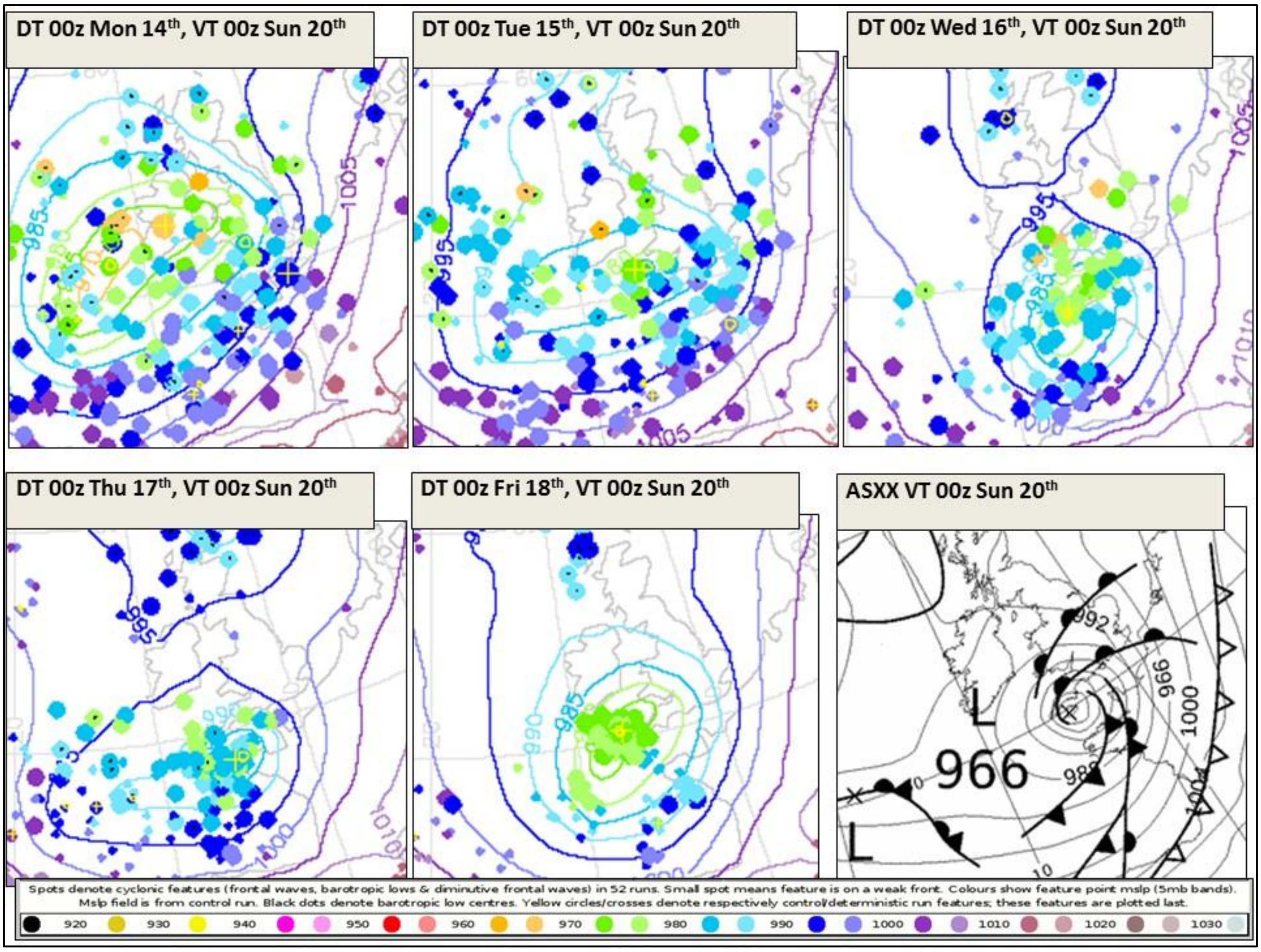

Fig.2 Series of Dalmatian plots from 00z runs of ECMWF ensemble from Monday 14th to Friday 18th November 2016 showing evolution of depression which lay near southwestern Britain 00z Sunday 20th November 2016. Verifying analysis also shown. This depression became the first windstorm of the 2016-2017 season to be named under the joint Met Office and Met Eireann storm naming project. The evolution depicted here helped inform the Met Office NSWWS warning strategy in so much as the waning trend in depression intensity mid-week resulted in some caution in naming the storm and issuing warnings.

Field modification software (Carroll 1997) is used by the Chief and Deputy Chief Meteorologists to produce a graphical best estimate of weather conditions over the UK, a process which draws on a number of different elements of NWP, including ECMWF. Severe weather will be accompanied by the issue of National Severe Weather Warnings Service Warnings (NSWWS). This impacts-based warnings service is aimed at both the general public and resilience/emergency services and makes use of a colour-coded 4x4 matrix to communicate a sense of both likelihood and severity of weather conditions. Warnings are currently for 5 elements (or some combination thereof), namely wind, rain, snow, ice and fog (see Suri 2016 for an example). This service is set to be expanded to cover a broader range of elements within the next couple of years. ECMWF data is used alongside Met Office data in the consideration of NSWWS, and a web-based tool using ensemble output, known as EPS-W (Neal et al. 2014), can be used to generate first-guess warnings.

2.2.2 Product requests

Feedback from the Met Office forecasting community is dominated by requests for faster performance of ecCharts.

In terms of specific products, the Flood Forecasting Centre is keen to work further with David Lavers in looking at operational use of IVT, including EFI diagnostics. Meanwhile, aviation forecasting interests asked for cloud base height products in ecCharts to be expressed in terms of feet rather than metres, perhaps with customisable levels (for example levels of interest to aviation forecasters relate to TAF thresholds which are different in civil and military operations), and for these products to divide cloud into scattered and broken cloud groups.

Other product requests include products in ecCharts showing wind vector and vorticity on PV2 surfaces, vertical profiles to be made available and for Copernicus fields, for example aerosol content and dust fields, to be added to ecCharts. Requests were also made for 850 and 200 hPa velocity potential fields and stream function, 850 and 200 hPa rotational and divergent wind field to also be added to ecCharts for use in forecasting low latitude weather circulations.

3. Verification of products

3.1 Objective verification

Describe verification activities and show related scores.

3.1.1 Direct ECMWF model output (both HRES and ENS)

This is dealt with in Section 3.1.3.

3.1.2 ECMWF model output compared to other NWP models

This is dealt with in Section 3.1.3.

3.1.3 Post-processed products

e.g. Kalman-filtered products, calibrated ENS probabilities, etc.

a) Site-specific post-processed forecasts.

Figure 3 contains time series of monthly Day 1 scores for a variety of surface parameters and thresholds used to create the BestData blend (which is used to populate web forecasts). ECMWF is shown in black. All the other scores are for UM configurations, including the UK ensemble (2.2 km). The BestData blend scores are shown in red.

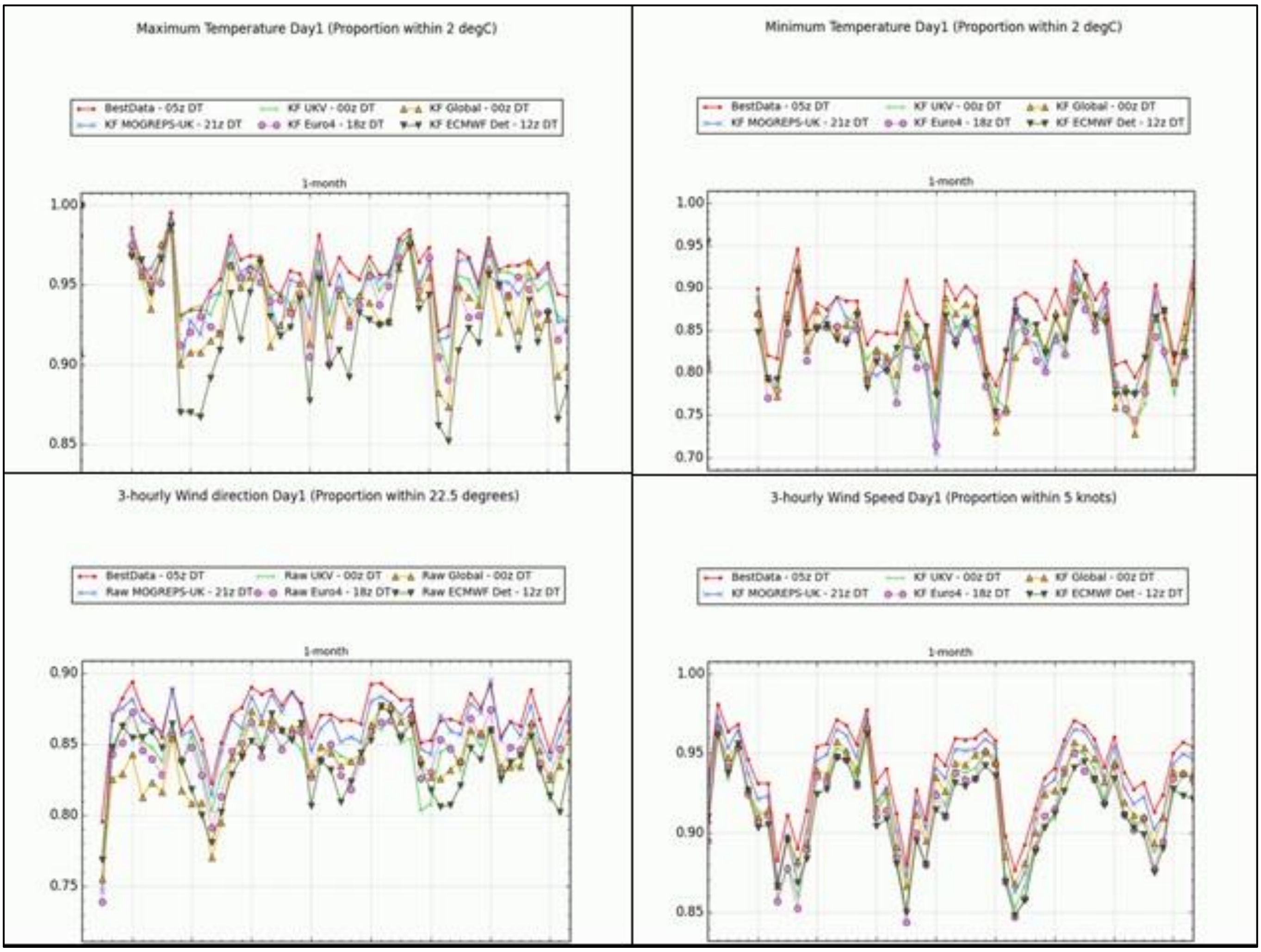

Fig.3 A selection of monthly verification statistics for Day 1 surface parameters used to create the BestData blend. The ECMWF HRES forecast is used in the blend. KF=Kalman Filter.

As explained in Sections 2.1.1 and 2.1.2 both physical and statistical correction schemes are applied to the HRES forecasts. Statistical corrections are only applied to selected parameters (e.g. wind direction at present). These results are based on the existing system which is in the process of being replaced. The new system should be running in parallel during 2018/19, with the view of retiring the old system in 2019

b) Tropical Cyclones

At the Met Office, the MOTCTracker tropical cyclone tracker (Heming, 2017) is used to identify and track tropical storms in the MOGREPS-G, ECMWF ENS and NCEP GEFS ensembles. Ensemble-based products for named storms from each model, and from the multi-model ensemble are then created (see Figure 4).

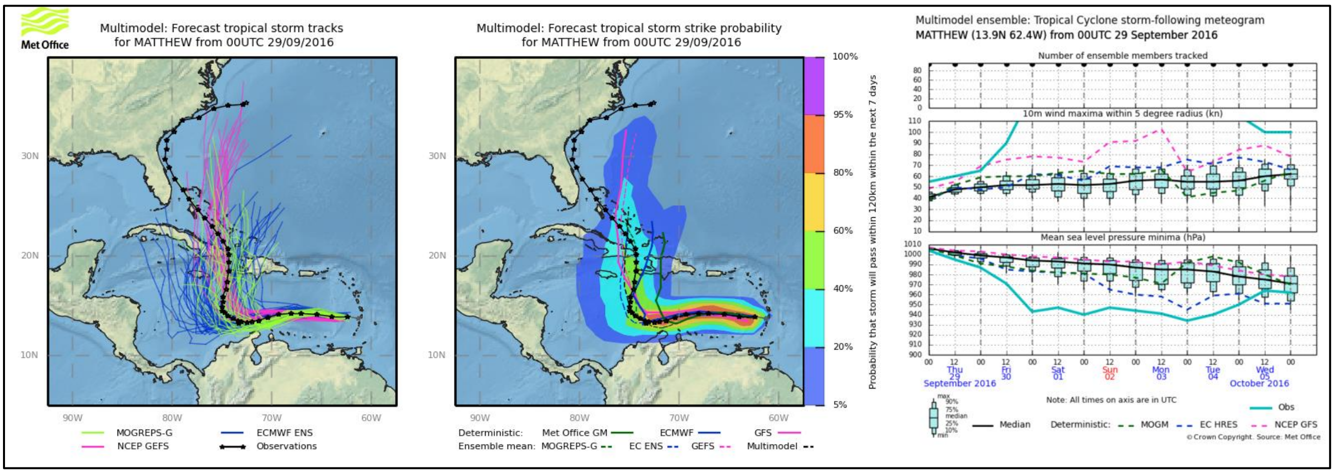

Fig.4 Multi-model ensemble forecast for Hurricane Matthew from 00UTC 29/09/2016. The tracks from each member, coloured according to the model, is on the left image, with the observed track overlain in black. The centre image shows the probability that the storm will pass within 120km in the next 7 days, with the deterministic and ensemble mean tracks overlain, and the observations again shown in black. The right image shows a storm-following meteogram which shows the spread in intensity values (mean sea level pressure minima and 10m wind maxima). The deterministic model intensities are overlain, and this time the observations are overlain in cyan.

Figure 5 shows the verification results for the strike probability forecasts from January 2016 to December 2016 using the three main operational ensembles (MOGREPS-G, ECMWF ENS and NCEP GEFS) individually, and in the various multi-model combinations. There were 81 named storms in this time, across the six tropical cyclone basins. When comparing the individual ensembles, the ECMWF ENS ensemble shows the greatest skill, reliability and value. The performance of NCEP GEFS and MOGREPS-G is very similar, with MOGREPS-G having a marginally better ROC area, but a lower relative economic value than NCEP GEFS at all cost loss ratios other than the very lowest and very highest cost loss ratios. However, the ensemble with the overall greatest skill and value is the multi-model ensemble combination of MOGREPS-G, ECMWF ENS and NCEP GEFS, showing the benefit of combining the data from the three centres in to multi-model ensemble forecast products.

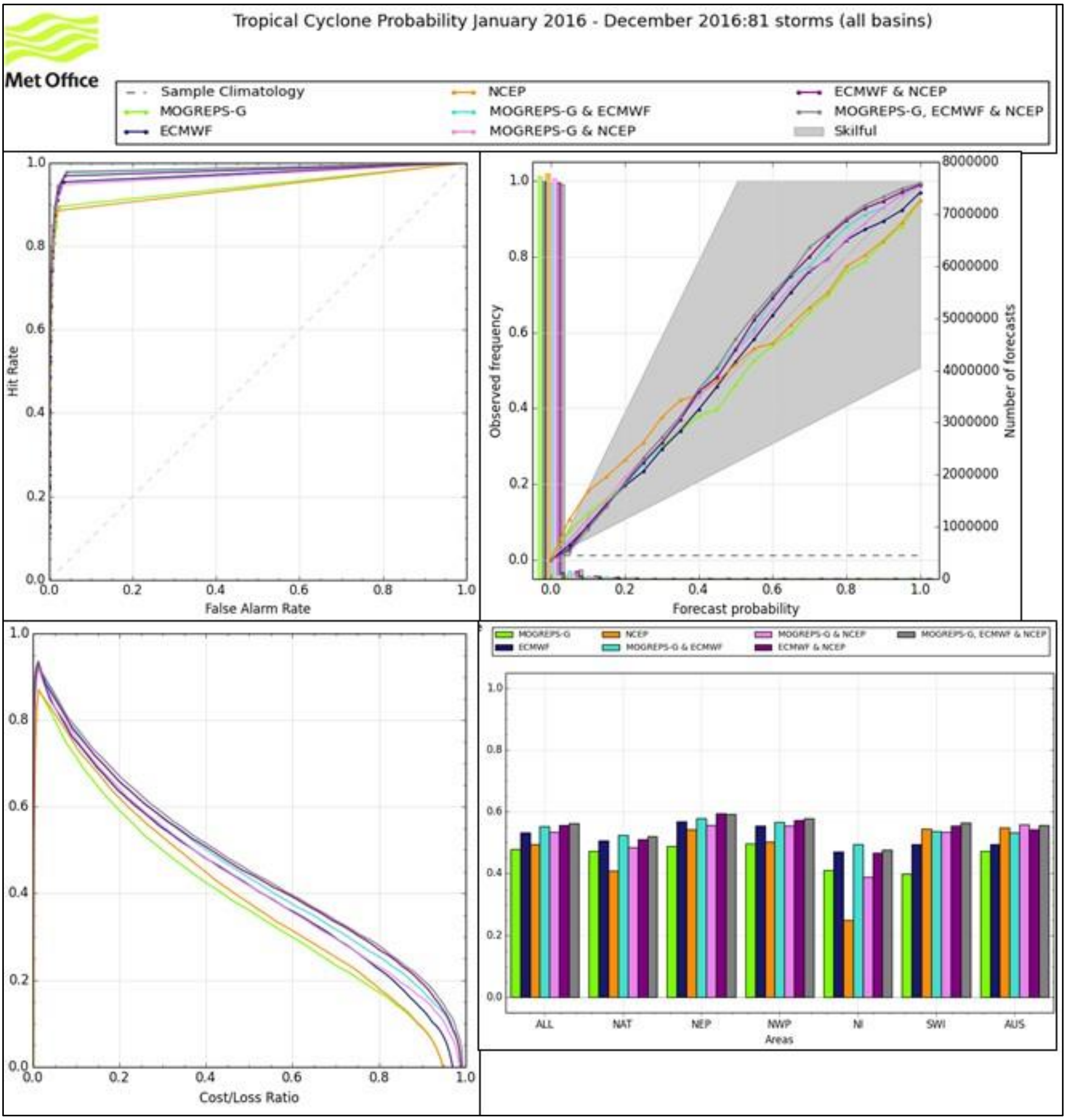

Fig.5 Verification plots comparing strike probability forecasts from January 2016 to December 2016 in 7 different ensemble models or multi-model combinations. Relative Operating Characteristic (ROC) plot (top left) assesses the skill of the forecast. A forecast with perfect skill would produce a curve from bottom left to top left to top right. The points along the curve are the corresponding hit rates and false alarm rates for each probability bin. Reliability plot (top right) displays how well the predicted probabilities correspond to their observed frequencies. Perfect reliability would be a diagonal line from (0, 0) to (1,1). Economic value plot (bottom left) indicates the relative improvement in economic value between the sample climatology and a perfect forecast for all cost loss ratios. Brier Skill Score for each basin, using CLIPER Climatology and Persistence forecasts as the reference in the skill score.

c) Global Hazard Map

The Met Office Global Hazard Map (GHM) aims to forecast the probability of high-impact weather across the globe over the coming week and is primarily used by operational forecasters in the Global Guidance Unit of the Met Office. The GHM currently uses MOGREPS-G and ECMWF ENS forecast data, which are available separately or in a multi-model ensemble forecast. Forecast layers are currently available for tropical cyclones, precipitation, wind gust, snowfall, heat wave and cold wave. A key feature of the GHM is the symbol and polygon-based summary map (Figure 6) which provides an "at-a-glance" view of forecast high-impact weather for the week ahead. In addition to forecast layers, GHM also provides the option to visualise vulnerability and exposure layers such as population density, fragile states index and antecedent rainfall, in conjunction with the probabilistic forecast layers and recent geo-hazards. The precipitation, snowfall and wind gust layers display the probability of the 24hr precipitation accumulation / snowfall accumulation / maximum wind gust exceeding the 99th percentile of the ECMWF M-Climate forecast climatology. Additional absolute thresholds of 10mm for precipitation and 14 m/s for wind gust are applied to ensure that the values are meaningful in areas of very low rainfall or wind gusts. Figure 7 illustrates an example of each of the layers. The development of the heat wave and cold wave forecast layers are based on methods outlined by Nairn and Fawcett (2015). In their approach heat waves are defined as heat-impact events using a new index, called the Excess Heat Factor (EHF), which is intended to capture heat wave intensity as it applies to human health outcomes.

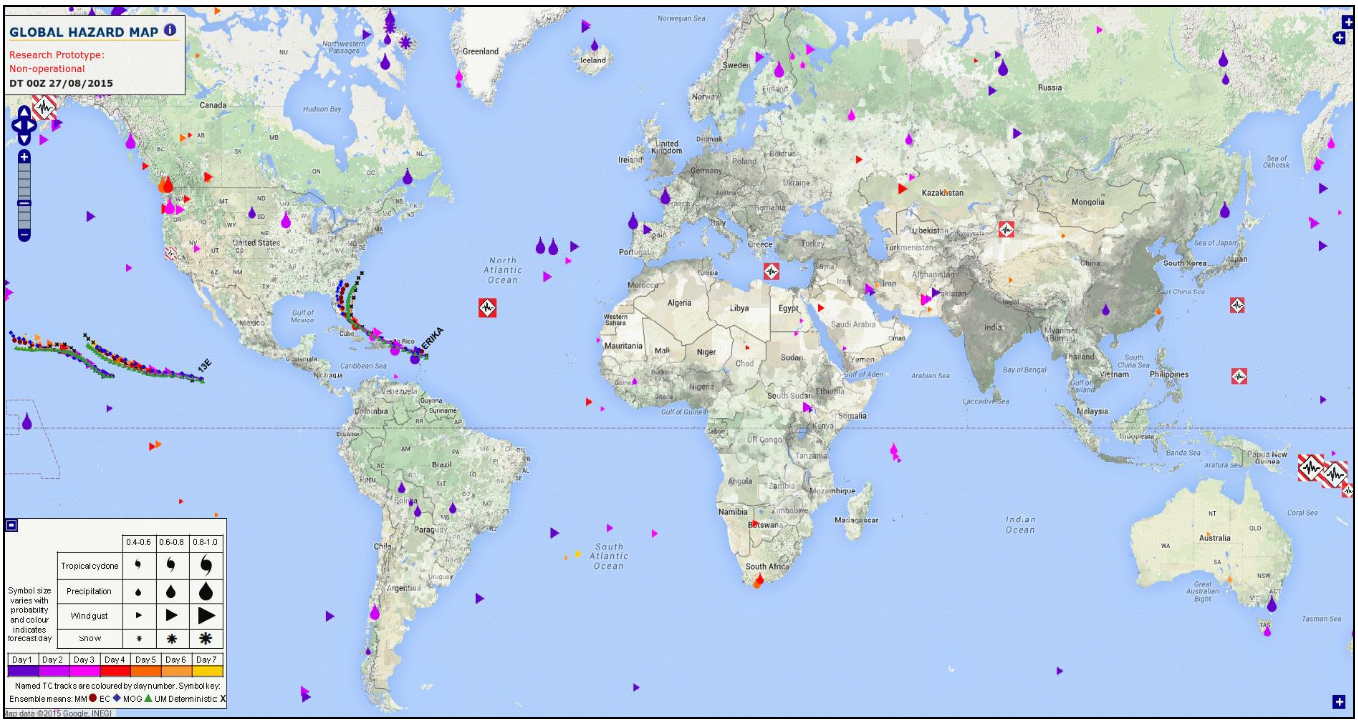

Fig.6 GHM symbol-based summary map showing an 'at-a-glance' view of forecast high-impact weather for the week ahead. Symbols are sized based on probability and coloured based on lead time.

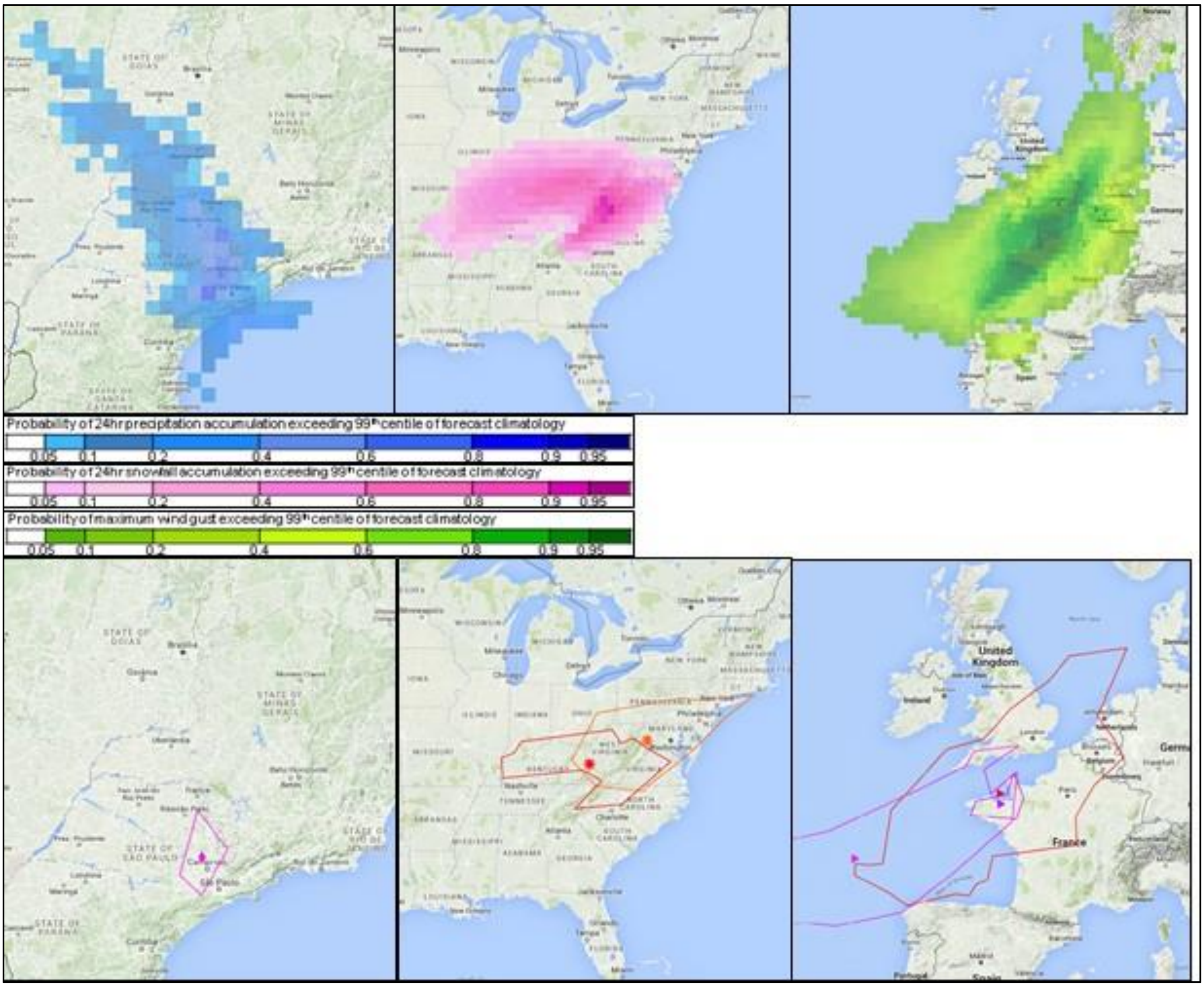

Fig.7 Examples of (A) precipitation, (B) snowfall and (C) wind gust layers in the Global Hazard Map. The figure shows the gridded probability of an "event" (an exceedance of the 99th M-Climate percentile) from a particular day's forecast (top), and the summary symbol and polygon that would have appeared on the summary sheet for this forecast (bottom).

An evaluation of the GHM forecasts has been carried out, with a primary aim of assessing how well the GHM meets its objective to identify and forecast high-impact weather with the potential to cause community impacts around the globe. This has been addressed in two ways: (1) objective verification methods which compare gridded hazard forecast data against global weather observations to create contingency based verification statistics and (2) a newly developed impact-based evaluation approach aimed at identifying how well GHM forecasts relate to records of community impacts.

The precipitation forecast layers (defined as the probability of the 24-hour precipitation accumulation exceeding the 99th percentile in the M-Climate climatology) were verified against observations at 3315 sites worldwide, with observed events defined as where the observed 24-hour precipitation exceeded the 99th percentile in the SEEPS climatology at that site). Figure 8 shows a comparison of the area under the ROC curve for each of the three model precipitation layers available in Global Hazard Map (ECMWF ENS, MOGREPS-G and the multi-model ensemble) at each forecast day. The plot shows that the skill, as defined by the area under the ROC curve, is greatest for the multi-model at all lead times, confirming that using the multi-model ensemble fields to create the summary layers is a sensible choice. As you would expect, the area under the ROC curve decreases as the lead time increases, as the hit rate lowers and the false alarm rate grows. The drop off in skill in all models is fairly steady to day 4, and then drops off slowly from there to day 7. However, there is good skill shown throughout the forecast period in the GHM gridded precipitation forecasts.

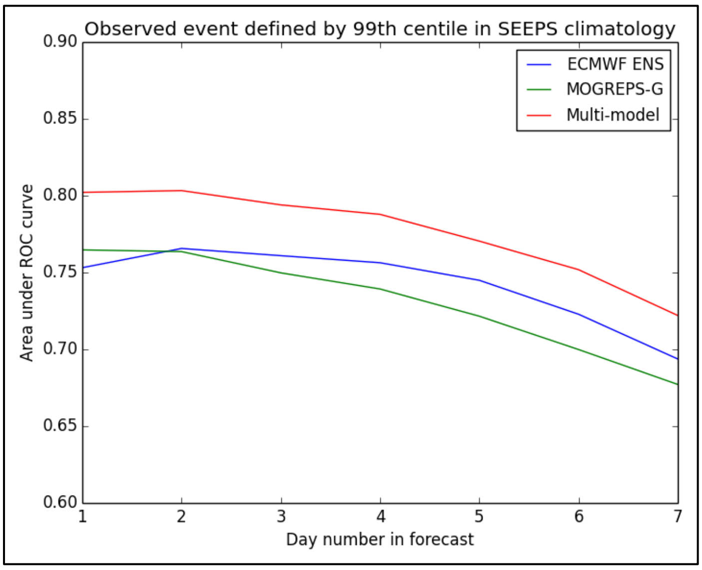

Fig.8 Area under the ROC curve for the three ensemble forecast models for 24-hour precipitation exceeding the 99th percentile of the M-Climate climatology for each day in the forecast. Verification is carried out against station-based observations at 3315 sites for the period 4th February 2015 - 31st December 2015, with the observed event defined by the 99th percentile in the SEEPS climatology.

The impact-based evaluation method involved collating a global heavy rainfall impacts database, using a range of media sources, and comparing entries with precipitation summary symbol polygons produced from multi-model ensemble forecasts. This newly-developed, semi-automated method of overlaying forecast hazard polygons with areas where impacts have occurred, allowed a large numbers of individual impact events to be compared with forecast data in a robust, consistent and timely manner. A heavy rainfall impact database was constructed containing 853 entries which occurred between February and December, 2015, and used to create impact polygons to allow spatial and temporal comparison with the summary polygon forecasts. A hit is identified where an impact polygon intersects with a precipitation forecast polygon, for the corresponding recording/validity times. For a detailed description of the impact-based evaluation methods see Robbins and Titley (2017). Figure 9 shows how well the precipitation summary polygons performed at forecasting heavy rainfall events which resulted in community impacts. Hit rates for all impact records, regardless of severity, range from ~40% to 60% for days 1 to 3, and taper off to between 10% and 25% at days 6 and 7.

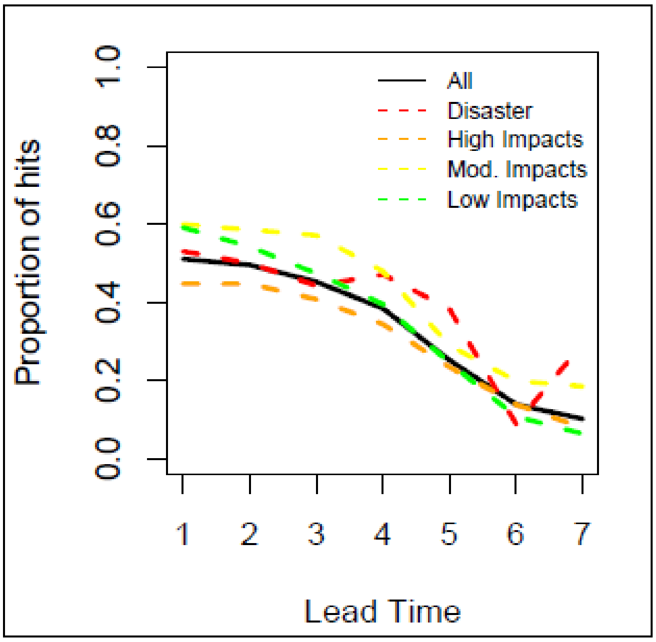

Fig.9 Plot illustrating the proportion of hits obtained by comparing intersects between heavy rainfall impact polygons and GHM forecast precipitation summary polygons, for matching occurrence ('observed') and validity ('forecast') dates. Results are split based on the impact severity of each impact record.

3.1.4 End products delivered to users

The Met Office is in the process of setting up automated verification of the probabilistic weather pattern forecasts provided by the Decider product introduced in Section 2.1.3. This verification will eventually be available for a number of global NWP models including ECMWF, GEFS, MOGREPS-G and GloSea5. Figure 10 displays the latest ECMWF probabilistic weather pattern forecast frequency bias results between 31 March 2016 and 3 May 2017. Results show that the frequency of forecasting the various patterns is not constant with lead time. Some are more prevalent at short lead times (e.g. Regime 18), whereas others are more prevalent at longer lead times (e.g.29 and 30). The sample size during this ~13 month verification period for some weather patterns is very low so more forecasts need to be accumulated before any conclusions can be drawn. It is hoped that more updates on this work will be available next year.

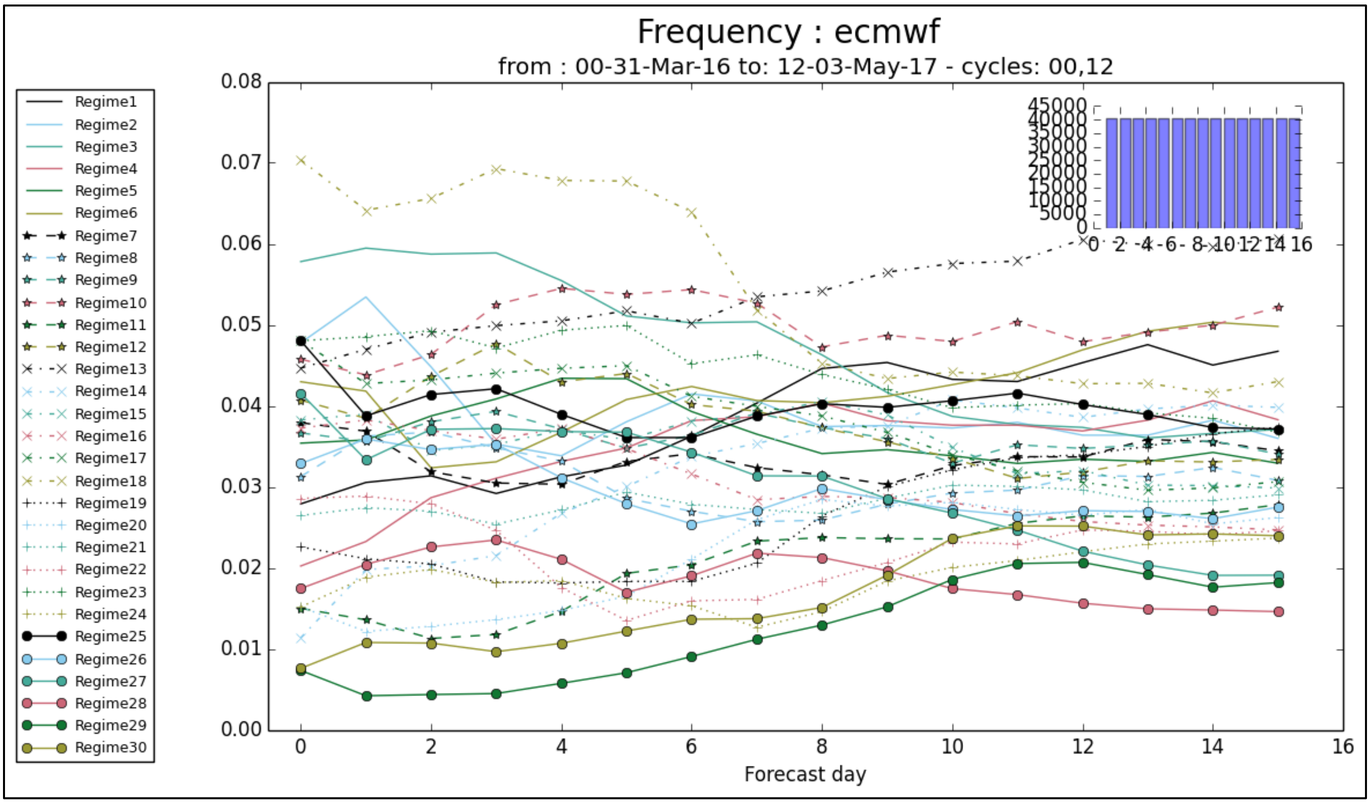

Fig.10 Probabilistic weather patterns forecast frequencies between 31 March 2016 and 3 May 2017 using the ECMWF medium range ensemble. Day 0 frequencies provide the observed frequencies for each weather pattern over the verification period.

3.2 Subjective verification

3.2.1 Subjective scores (including evaluation of confidence indices when available)

Subjective verification by Met Office operational meteorologists paints ECMWF output in a favourable light. Some biases/weaknesses have been noted, including:

- Visibility tending towards very dense or nothing at all.
- Convective rainfall rates appearing on the low side and general under-forecasting of extreme rainfall amounts.
- Showers can be produced unrealistically in shallow convective environments and are too numerous in polar maritime and returning polar maritime airmasses.
- Boundary layer cloud amounts often show a slight clear bias, although in spring 2017 extent of convective infill was overdone over the UK in set-ups with shallow convective boundary layers.
- Tendency for the ensemble to jump with HRES.

It is, however, recognised that, firstly, ECMWF output is not necessarily primed for forecasting some of these elements and that developments are taking place to tackle some of these issues, for example extreme point precipitation and visibility.

3.2.2 Case studies

Storm Doris was named by the Met Office on 21 February 2017 as yellow and amber warnings for wind, snow and rain were issued across the UK. Storm Doris arrived on 23 February with the final forecaster issued warnings shown in Figure 11. The Met Office has an ensemble-based first-guess warning tool called EPS-W (Neal et al., 2013), which is a regionally varying threshold-based warning tool. The first-guess warnings for wind gusts from MOGREPS-G and ECMWF are shown in Figures 12 and 13 respectively. These figures show how the first guess warnings evolved over time, with the earliest lead time (5 day) warnings having small areas of yellow marked from both models. The amber area increased as the forecast lead time reduced with both models moving the main area at risk further south. Although the main area at risk from severe wind gusts was not captured well in early lead times, the consistency between MOGREPS and ECMWF gave forecasters confidence in the changing signal towards a more southerly risk area. The medium-range ECMWF forecasts from Decider (Section 2.1.3) also provided an indication towards windier than average conditions, at over a week's lead time.

Fig.11 The final Met Office forecaster issued warnings on 23 February 2017, for the weather impacts associated with Storm Doris.

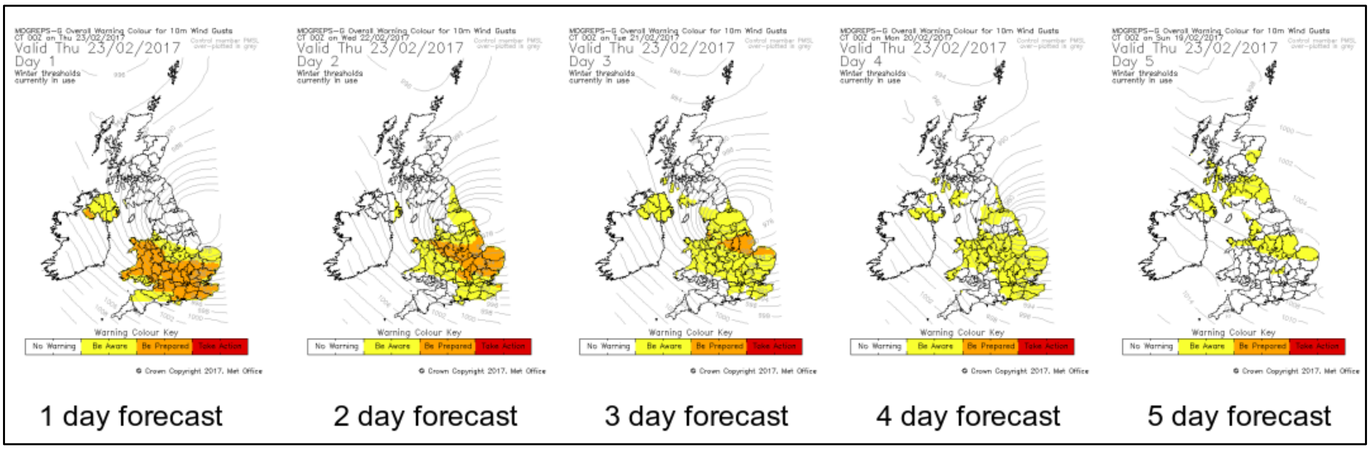

Fig.12 The evolution of first-guess warnings from MOGREPS-G using the 10m wind gust diagnostic.

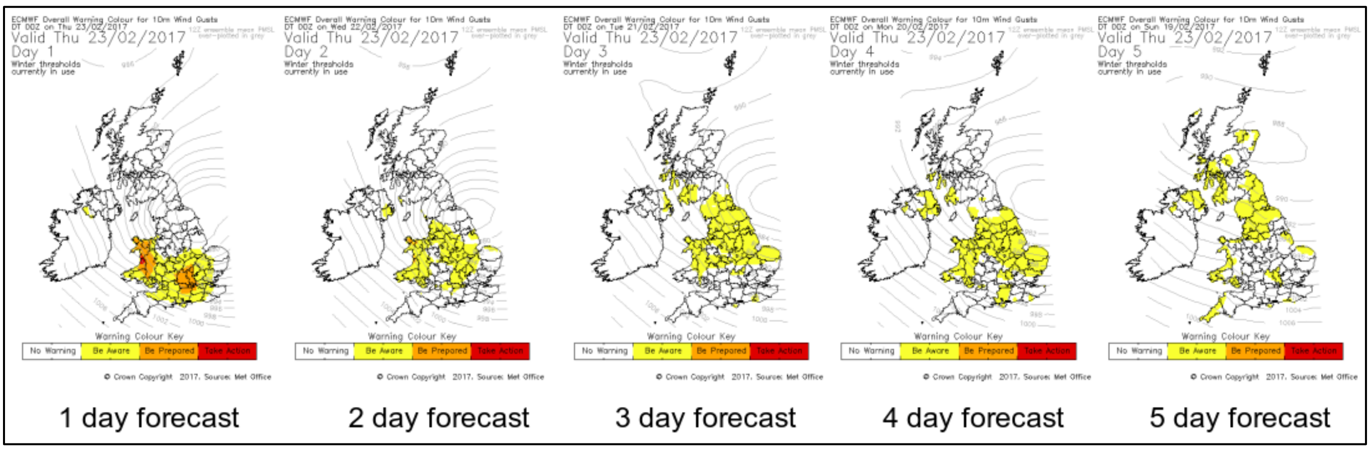

Fig.13 The evolution of first-guess warnings from ECMWF using the 10m wind gust diagnostic.

4. Feedback on ECMWF "forecast user" initiatives

The known IFS forecast issues page is something the Met Office have pushed for strongly in the past, so its creation has been welcomed and this page continues to be widely used by our operational meteorologists. The severe event catalogue is less widely used by Met Office operational meteorologists and, in view of Met Office worldwide forecasting commitments perhaps something Met Office operational meteorologists may be able to contribute to. The use of this catalogue, meanwhile, to draw out common predictive elements on different time scales as the number of cases studies grows, as illustrated by Linus Magnusson at the 2017 UEF, seems likely to yield some useful results.

5. References to relevant publications

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