WWRPWarningValueChainPro

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Warning Chain Database Questionnaire

I. Purpose

This questionnaire (template) provides for a comprehensive picture of the end-to-end production and flow of information and decision making along the warning chain during a hazardous weather event.

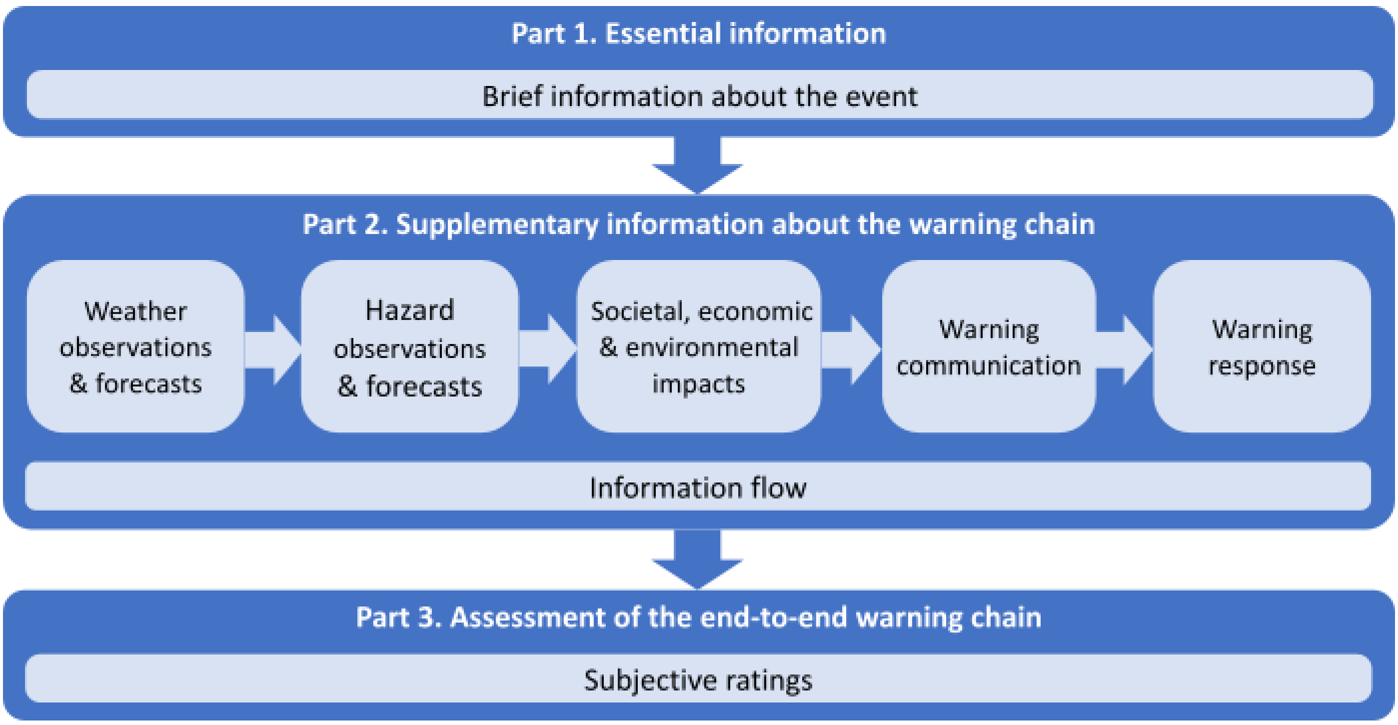
Please use this template to record as much information as possible on the end-to-end warning chain for a particular hazardous weather event. This information will:

- add to a global database of hazardous weather events with rich information covering the many components of the warning value chain,
- enable case studies and cross-cutting analysis of end-to-end warning value chains, from simple to complex, to understand effective practices,
- support the value cycle of review and learning from past events to identify improvements that would enhance future warnings.

More information about the WWRP Warning Value Chain Project can be found at http://hiweather.net/Lists/130.html.

II. Structure and format

The questionnaire consists of three main parts.



Part 1. The **essential information table** requests brief facts about a particular event, such as what happened, when, where, impacts and responses. This information will help users to filter events. Please provide numerical and short text entries. Links to this event in other databases and catalogues about this event should be provided if possible.

Part 2. The second part requests **supplementary information** about different stages in the warning value chain. This more detailed information and analysis about the weather, hazards, impacts, warning communication and warning response will help users understand what was unique about the warning chain for this event. The questions in Part 2 probe many aspects of the warning chain but are not exhaustive. Information here might include:

- Graphics (for example, forecast charts, reanalysis maps, warning graphics, photos of impacts, etc.).
- Videos (for example, from social media, weather service outlooks, etc.).
- Free-form text (for example, description of meteorology, selected extracts from reports, data analysis, tables, etc.)
- Links (e.g., to external reports, media, national archives, policy documents, protocols, meeting records, etc.)

Each section has an "additional analysis" where you can add further information not covered by the items in the questionnaire.

It is not required to complete Part 2, but please provide what information you can. Try to keep your entries brief and include references and links (URLs) to where additional information can be found. Attribute all material that may be subject to copyright (e.g., images and videos).

Many people may contribute information on this event. Where you disagree with another contributor try to provide evidence or example to support your position. You may wish to acknowledge information providers at the end of the template before Annex 1.

Part 3. The **subjective assessment** asks contributors to rate the effectiveness of the individual elements of the end-to-end warning chain, and its overall effectiveness, on a scale of 1 (poor) to 5 (excellent). This may assist users of the database in choosing cases and performing meta-analysis (recognising the large variability in contributors' judgments).

The accompanying Guide for the Warning Chain Database Questionnaire[1] provides explanation and examples of the type of information that is requested in the questionnaire.

III. How to add resources

Resources for Part 2 (e.g., reports, graphics, data, and other information not easily accessible to the public) should be stored in the event data library of the respective case study. Brief resources such as forecast maps and warning graphics should be inserted directly into the corresponding section of the template. Reports and extensive graphics are not suitable to be embedded in the template but should be referred to. Please store the resources in the event data library first and then insert as a hyperlink to the template. To do so, follow these steps:

1. Go to the event data library on Google Drive (open to anyone).
2. For an existing case study, locate the folder for the event for which you would like to add resources. If the event does not exist yet in the library, refer to the README guide to open a new case study

[1] https://docs.google.com/document/d/1xZENrxLcn3250z-cANHpqRtU9gK7OQxj/edit?usp=sharing&ouid=106255653981108702821&rtpof=true&sd=true

(project members only). If you are a project external contributor, please contact valuechain@bom.gov.au to open a new case study.

3. Place your resource in the folder and give an appropriate name so others know what it is about.
4. Right-click the file you want to embed/refer to and select 'Copy link' to retrieve the hyperlink pointing to the file.
5. In the template, use 'Insert Hyperlink' to paste the hyperlink in the appropriate place.

IV. Tips

- The Value Chain Glossary provides a common terminology.
- To assist with searching the database, please use the names of hazard types listed in *Annex 1* of this template.
- A series of prompts (i) in this template provide some quick information to assist with entering the requested data. Simply put your cursor over the information symbol i and text should pop up next to it (ignore the “Ctrl+click to follow link” instruction). *Note, that this feature is only available in the Microsoft Word App, not in the SharePoint or Google Drive browser page.* If this feature does not work for you, please consult the Guide instead.
- A single person may not be able to fill in the entire template. We encourage you to share the template with colleagues who can provide information.
- A worked example of the template is here.
- Questions on the use of this template can be directed to valuechain@bom.gov.au.

V. Completed questionnaire

The completed questionnaire should be stored in the event data library of the respective case study, or sent to valuechain@bom.gov.au.

Part 1. Essential information

Editors (Name & Institute)	Robert Neal and Helen Titley, Met Office, Exeter, UK

HAZARDOUS WEATHER EVENT		
Unique identifier i	*(This will be added by the Project Team at a later date)*	
Name of event	Storm Eunice	
When did it happen i?	Friday 18th February 2022	
Where did it happen i?	Large parts of England and Wales	☒ rural ☒ urban
Links/UIDs to other databases *(ECMWF catalogue of severe events, WMO CHE, DesInventar, EM-DAT, GLIDE, etc.)*	https://confluence.ecmwf.int/display/FCST/202202+-+Windstorm +-+Eunice	

WHAT HAPPENED – WEATHER, HAZARDS, IMPACTS, WARNINGS, RESPONSES	
Weather event type/system that caused hazards i *Refer to Annex 1*	Depression or Cyclone (Low Pressure Area)
If possible, provide more detail about weather observations & forecasts (*link to page*)	
Were any hazards forecast?	☒ yes ☐
Hazards that caused the main impacts i *Refer to Annex* 1	Large-scale wind event.
Classify hazard according to the location's climatology i	Storm Eunice was around a 1 in 10-year event. It was the most powerful storm to affect the south of the UK since a similar storm on 12th February 2014, which occurred nearly two years before the Met Office started naming storms during the 2015/16 winter.
If possible, provide more detail about hazard observations & forecasts (*link to page*)	
Were any impacts forecast?	☒ yes ☐
Main direct impacts i	Power outages, damaged and fallen trees, school and businesses closures, transport disruption (roads, rail and air), bridge closures, ferry port closures, airport closures, structural damage, large waves, storm surge.
Economic damage in USD i	$500 million USD (insured losses only) according to the Association of British Insurers.
Fatalities	Three in the UK (four if including the UK and Ireland)
If possible, provide more detail about impact observations & forecasts (*link to page*)	
Were any warnings issued?	☒ yes ☐

Main warnings issued i	The storm was named four days before the first impacts were felt and this coincided with a large ‘low likelihood of high impacts’ yellow warning being issued. This warning was later superseded by a large amber ‘medium likelihood of high impacts’ warning two days in advance. Finally, two smaller red warnings were issued. The first red warning (issued ~20 hours in advance) covered parts of south Wales and southwest England. A second red warning (issued ~6 hours in advance) covered south-east England including London.
Who issued the warnings? i	Met Office
If possible, provide more detail about the warnings & communication *(link to page)*	
Main responses to warnings i	• Many schools closed before the storm arrived in the red warning areas as well as some schools in the amber warning areas. • Many office workers chose to work from home where they could. • Refuse collections were cancelled in advance. • Non-urgent medical appointments were cancelled in many affected areas. • Many train, bus and flight services were cancelled or postponed in advance in the red and amber warning areas. • London Luton airport was closed for a short period. • The port of Dover was closed for a short period. • Both the River Severn bridges linking England to Wales were closed and the Humber bridge in northeast England was closed. • Flood defences were erected along vulnerable coastal stretches of southwest England and Wales, with one of the highest risk stretches being along the Bristol Channel.
If possible, provide more detail about responses to warnings *(link to page)*	

Part 2a. Supplementary information about weather i

Editors (Robert Neal and Helen Titley, Met Office, Exeter, UK):

Meteorological overview i

Storm Eunice was the middle of three named storms which affected the UK within the space of a week and brought with it the greatest impacts. The other two storms were named Dudley (which occurred first) and Franklin (which occurred third). This was the first time three named storms had occurred within a week since storm naming was introduced by the Met Office during the 2015/16 winter.

Two very rare red weather warnings were issued for Storm Eunice, which was the most severe and damaging storm to affect England and Wales since February 2014 (based on a post-event historical analysis by the Met Office National Climate Information Centre / Mike Kendon). Official Met Office site observations showed that winds gusted at over 70 kts (81 mph) in exposed coastal locations and a gust of 106 kts (122 mph) was recorded at Needles Old Battery, Isle of Wight, setting a new England gust speed record. Winds also gusted widely at over 60 kts (69 mph) across southern England which is unusual for this area.

These storms formed part of a turbulent spell of wet and windy weather for the UK, associated with a powerful jet stream. Storm Eunice was an example of explosive cyclogeneses, with the central pressure dropping by approximately 30 hPa within 18 hours while the storm developed to the west of Ireland. The storm interacted with upper winds in the jet stream blowing more than 200 mph (Source: Met Office National Climate Information Centre / Mike Kendon).

================================== Weather forecast ===================================

Special/non-traditional observational data used in the weather forecast or assimilated into NWP i

No special or non-traditional observational data was used with the operational NWP forecasts used.

Comment on the adequacy of the observations available for the weather forecast i

Satellite derived observations were used within the initialisation of the NWP forecasts and were deemed adequate for use by the deterministic and ensemble-based predictions. Some of these observations were also used by forecasters when deciding how much confidence they had in the deterministic models based on how well the pseudo satellite imagery from the models matched with real imagery for developing cyclones – the ability to do this operationally is available within the Met Office meteorologist tool set.

Weather models (short- and long-range) i

Name	**Horizontal resolution**	**Ensemble size**	**Forecast length**
ECMWF medium-range	18 km	51 members	15 days
ECMWF extended-range ensemble	18 km to day 15 36 km to day 46	51 members	46 days

MOGREPS-G (Met Office)	20 km	18 members every 6-hours, with products generated from a 36-member time-lagged ensemble	8 days
GEFS (NCEP)	25 km	31 members	16 days
MOGREPS-UK (Met Office)	2.2 km	3 members every hour, with products generated from an 18-member time-lagged ensemble	5 days
UKV (Met Office)	1.5 km	NA; deterministic forecast	5 days

Post-processing/calibration applied to weather model output i

IMPROVER: Seamless blended multi-model forecasts for use at short- to medium-range lead times

Met Office nowcasting, deterministic and ensemble models are blended in a seamless forecasting approach within a gridded post-processing system called IMPROVER, which stands for "Integrated Model Post-Processing and Verification". IMPROVER became operational in spring 2022 but forecast output was available to operational meteorologists at the time of Storm Eunice. IMPROVER provides frequently updated probabilistic gridded forecasts, as well as forecasts for point locations, for input into automated forecast generation and for users such as operational meteorologists (Moseley *et al.*, 2022).

Moseley, S., Rust, F., Evans, G., Ayliffe, B., Hurst, K., Howard, K., Wright, B., and Jackson, S.: IMPROVER : A probabilistic, multi-model post-processing system for meteorological forecasts, EGU General Assembly 2022, Vienna, Austria, 23–27 May 2022, EGU22-8706, https://doi.org/10.5194/egusphere-egu22-8706, 2022.

Medium- to extended-range lead times

The Met Office weather pattern forecasting tool (called Decider; Neal *et al.,* 2016) objectively assigns ensemble members to the closest matching weather pattern definition (using a set of 30 predefined weather patterns for the UK and surrounding area) allowing the probability of each weather pattern to be derived. This post-processing is done for the medium and extended range global ensembles in order to identify the most likely weather pattern transitions at these lead times, which can then be related to changes in weather impacts.

Neal, R., Fereday, D., Crocker, R., Cromer, R.E. (2016) A flexible approach to defining weather patterns and their application in weather forecasting over Europe. Meteorological Applications, 23, 389-400, https://doi.org/10.1002/met.1563

The Met Office also carries out objective storm tracking within two global ensembles in a forecasting tool called the Cyclone Database (Hewson and Titley, 2010). This tool is run operationally at the Met Office (using MOGREPS-G) as well as at the ECMWF (using their own ensemble), and objectively identifies fronts and cyclonic features in the extra-tropics. The database has a tracking algorithm which tracks cyclones across all members, enabling several probabilistic products to be generated which are suitable for assessing the most likely tracks of Atlantic storms.

Hewson, T., Titley, H. (2010) Objective identification, typing and tracking of the complete life-cycles of cyclonic features at high spatial resolution. Meteorological Applications, 17, 355-381, https://doi.org/10.1002/met.204

Weather forecast outputs and examples i

The ECMWF medium-range ensemble is one of several global ensembles used by Met Office meteorologists in producing forecasts covering a range of lead times (from a few hours ahead out to two weeks). Figure 1 shows the evolution of wind gust forecasts from this model for Reading (a large town located west of London in central-southern England – just on the western edge of the second red warning area). It shows that even from a 15-day lead time, the forecast wind gust distribution for 18th February 2022 was slightly higher than the model climate distribution for the same time of year. This persisted for every forecast update leading up to 18th February 2022. The median wind gust from the full ensemble distribution became higher than the maximum model climate value two to three days before the event and >25% of members exceeded this value in the three to four days before the event. The persistence from the ensemble in having wind gust forecasts higher than model climatology from as far out as 15-days ahead helped flag this period early on to forecasters – this was particularly apparent from some of the hazard forecasting tools shown in a following section.

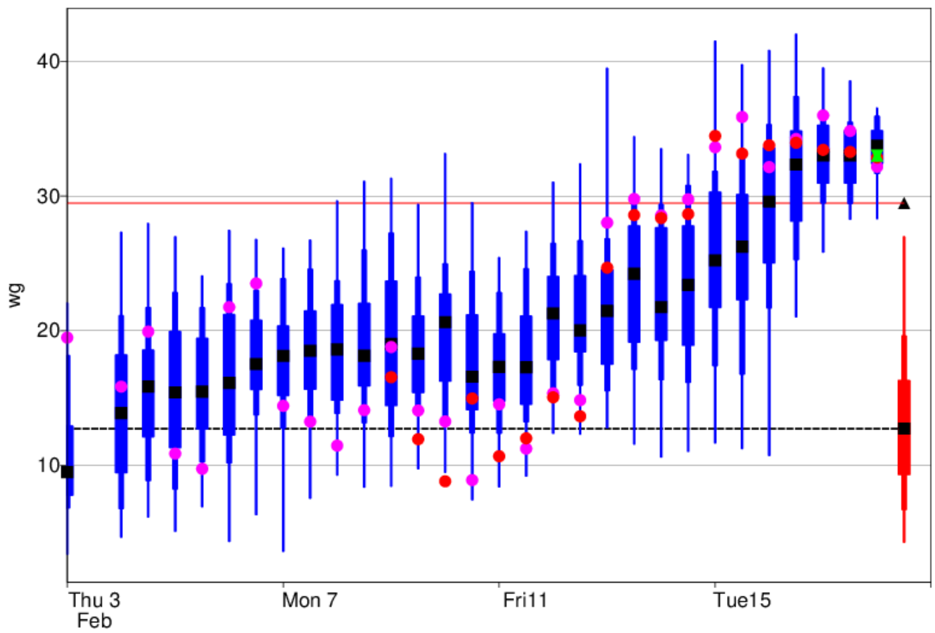
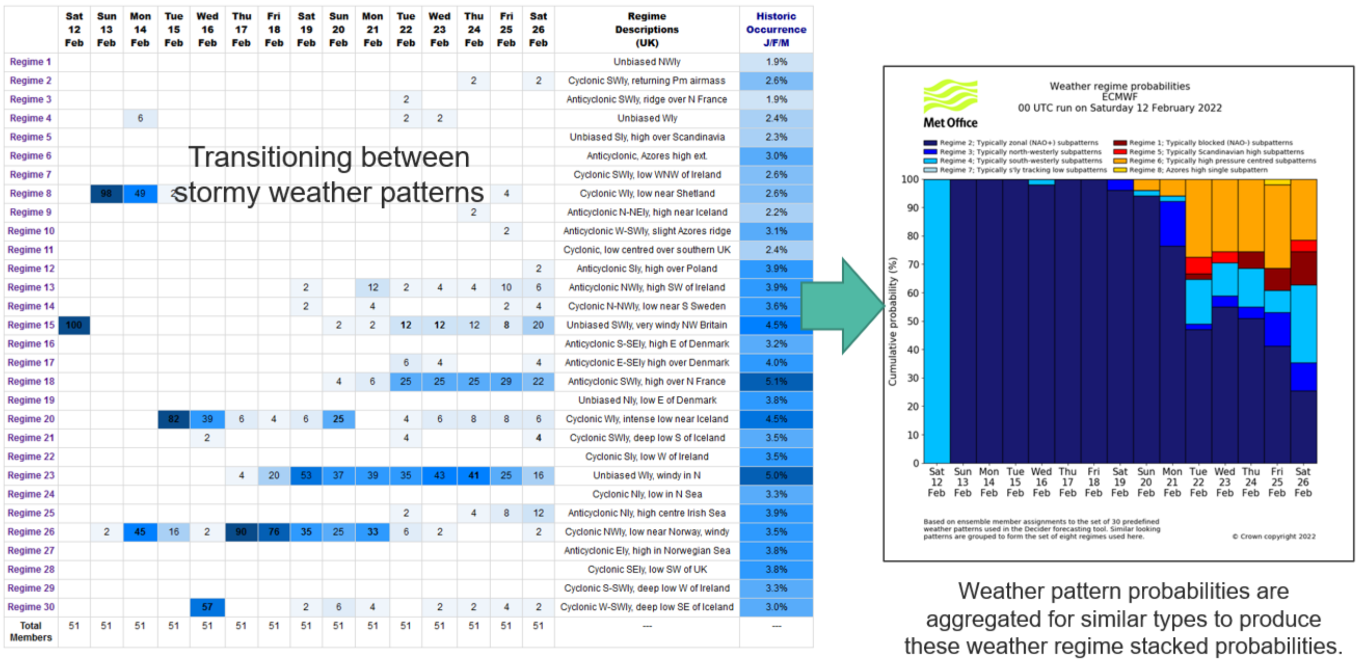


Figure 1. The ECMWF ensemble forecast evolution for max 24-hour wind gust near Reading on 18th February 2022 (00 to 00 UTC), in m/s. Max observation (from RAF Odiham) in green, HRES deterministic forecast in red, ensemble control forecast in purple, ensemble distribution in blue and model climate distribution in red. Maximum in model climate (from 1200 fields) marked as triangle. Source: ECMWF Severe Event Catalogue at https://confluence.ecmwf.int/display/FCST/202202+-+Windstorm+-+Eunice / Linus Magnusson.

The Met Office probabilistic weather pattern forecasting tool (Decider) has output driven by several global ensembles. Figure 2 shows the forecast weather pattern transitions driven by the ECMWF ensemble initialised on 12th February. Here, the most likely weather pattern transitions are shown (Figure 2; left plot), which translates into a persistence of stormy cyclonic westerly types potentially right through to the end of the month (Figure 2; right plot). This was also backed up by weather pattern forecast probabilities from MOGREPS-G and GEFS (Figure 3) adding to confidence in the forecast and generally flagging this period as being unsettled. Weather pattern 26 (cyclonic north-westerly type) was observed on 18th February 2022 and this was also the most likely forecast type (Figure 2; left plot). This weather pattern is also the windiest type climatologically for the UK at this time of year (based on an assessment of ERA5 climatologies), with climatology maps available to meteorologists within the forecast display. Although the weather pattern forecast probabilities cannot be used to identify a specific day at risk of a storm, they can be used to identify general periods at greatest risk.



	Sat 12 Feb	Sun 13 Feb	Mon 14 Feb	Tue 15 Feb	Wed 16 Feb	Thu 17 Feb	Fri 18 Feb	Sat 19 Feb	Sun 20 Feb	Mon 21 Feb	Tue 22 Feb	Wed 23 Feb	Thu 24 Feb	Fri 25 Feb	Sat 26 Feb	Regime Descriptions (UK)	Historic Occurrence J/F/M
Regime 1																Unbiased NWly	1.9%
Regime 2													2		2	Cyclonic SWly, returning Pm airmass	2.6%
Regime 3											2					Anticyclonic SWly, ridge over N France	1.9%
Regime 4			6								2	2				Unbiased Wly	2.4%
Regime 5																Unbiased Sly, high over Scandinavia	2.3%
Regime 6																Anticyclonic, Azores high ext.	3.0%
Regime 7																Cyclonic SWly, low WNW of Ireland	2.6%
Regime 8		98	49	2										4		Cyclonic Wly, low near Shetland	2.6%
Regime 9													2			Anticyclonic N-NEly, high near Iceland	2.2%
Regime 10														2		Anticyclonic W-SWly, slight Azores ridge	3.1%
Regime 11																Cyclonic, low centred over southern UK	2.4%
Regime 12															2	Anticyclonic Sly, high over Poland	3.9%
Regime 13								2		12	2	4	4	10	6	Anticyclonic NWly, high SW of Ireland	3.9%
Regime 14								2		4				2	4	Cyclonic N-NWly, low near S Sweden	3.6%
Regime 15	100								2	2	12	12	12	8	20	Unbiased SWly, very windy NW Britain	4.5%
Regime 16																Anticyclonic S-SEly, high E of Denmark	3.2%
Regime 17											6	4			4	Anticyclonic E-SEly high over Denmark	4.0%
Regime 18									4	6	25	25	25	29	22	Anticyclonic SWly, high over N France	5.1%
Regime 19																Unbiased Nly, low E of Denmark	3.8%
Regime 20				82	39	6	4	6	25		4	6	8	8	6	Cyclonic Wly, intense low near Iceland	4.5%
Regime 21					2						4				4	Cyclonic SWly, deep low S of Iceland	3.5%
Regime 22																Cyclonic Sly, low W of Ireland	3.5%
Regime 23						4	20	53	37	39	35	43	41	25	16	Unbiased Wly, windy in N	5.0%
Regime 24																Cyclonic Nly, low in N Sea	3.3%
Regime 25											2		4	8	12	Anticyclonic Nly, high centre Irish Sea	3.9%
Regime 26		2	45	16	2	90	76	35	25	33	6	2			2	Cyclonic NWly, low near Norway, windy	3.5%
Regime 27																Anticyclonic Ely, high in Norwegian Sea	3.8%
Regime 28																Cyclonic SEly, low SW of UK	3.8%
Regime 29																Cyclonic S-SWly, deep low W of Ireland	3.3%
Regime 30					57			2	6	4		2	2	4	2	Cyclonic W-SWly, deep low SE of Iceland	3.0%
Total Members	51	51	51	51	51	51	51	51	51	51	51	51	51	51	51	---	---

Figure 2. Probabilistic weather pattern forecasts using the 0000 UTC ECMWF ensemble initialised on 12th February 2022 (left), with corresponding stacked probabilities for a reduced set of eight weather pattern groups (right). Source: Met Office / Robert Neal.

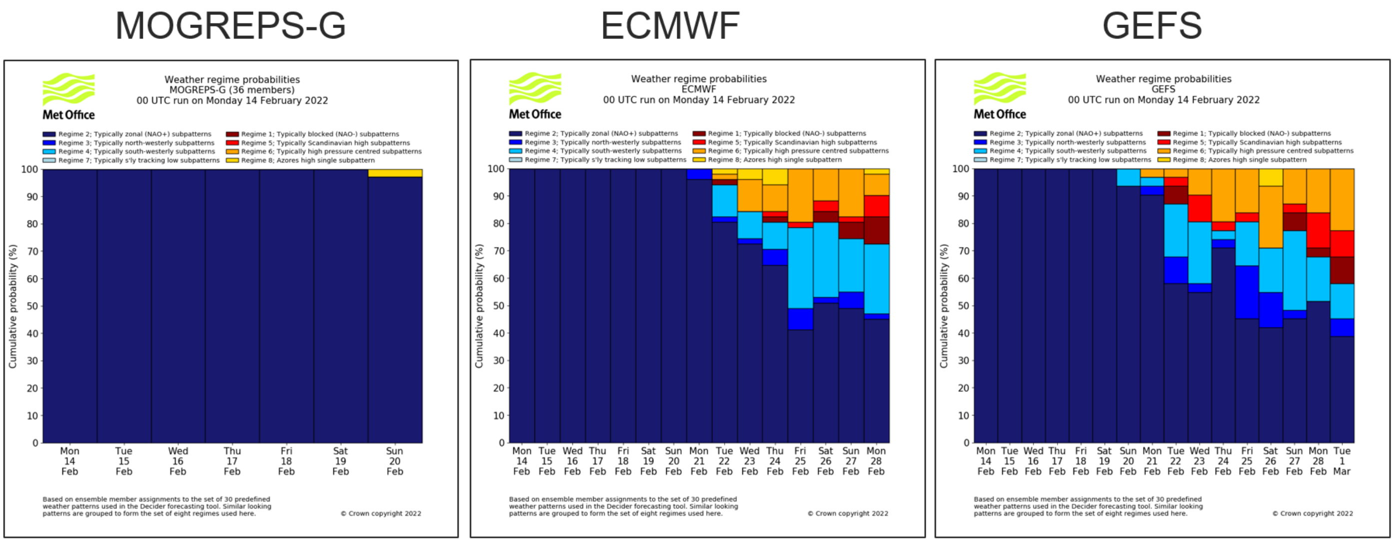


Figure 3. Forecast probabilities for a set of 8 weather pattern groups, based on global ensemble output from MOGREPS-G (left), ECMWF (middle) and GEFS (right). All forecasts use the 00:00 UTC initialisation time on 14th February 2022, providing a 5-day lead time for Storm Eunice. Source: Met Office / Robert Neal.

Although models were good at predicting a general unsettled spell a week or more in advance (e.g., Figures 1, 2 and 3), it wasn't until four to five days in advance that forecast confidence started to become high enough for the issuance of warnings and naming of the storm. This was due to the explosive cyclogenesis of Storm Eunice and the uncertainties associated with a storm that only forms a few hours or days before it reaches the UK. As a result, the first warnings were issued four-days in advance on 14th February 2022. This followed two or three consecutive ensemble runs (from several models) where the majority of members had a deep low tracking across the UK. However, there were still uncertainties in the specific track and intensity as illustrated by the PMSL postage stamps at the relatively short lead time of 54 hours (Figure 4 for MOGREPS-G, Figure 5 for ECMWF, and Figure 6 for GEFS).

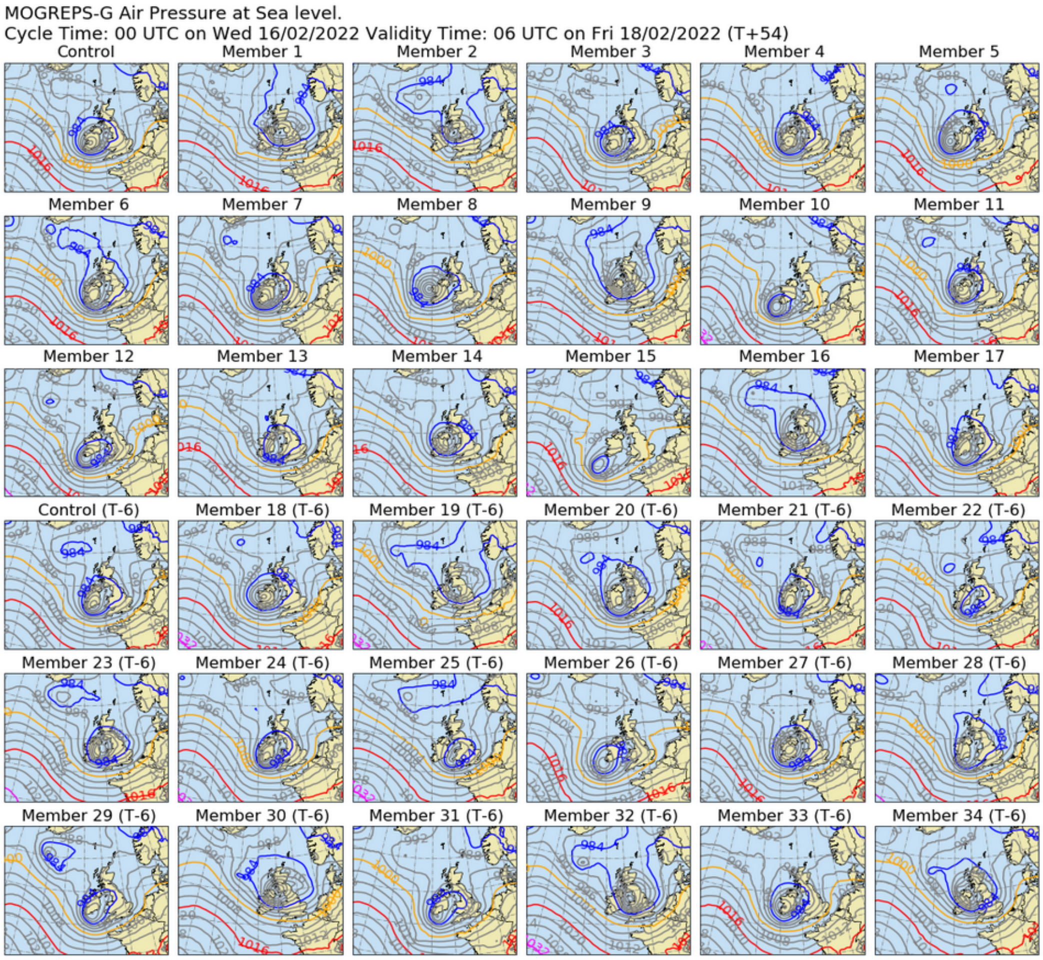


Figure 4. MOGREPS-G PMSL postage stamps for Storm Eunice, providing a 54-hour forecast. Source: Met Office.

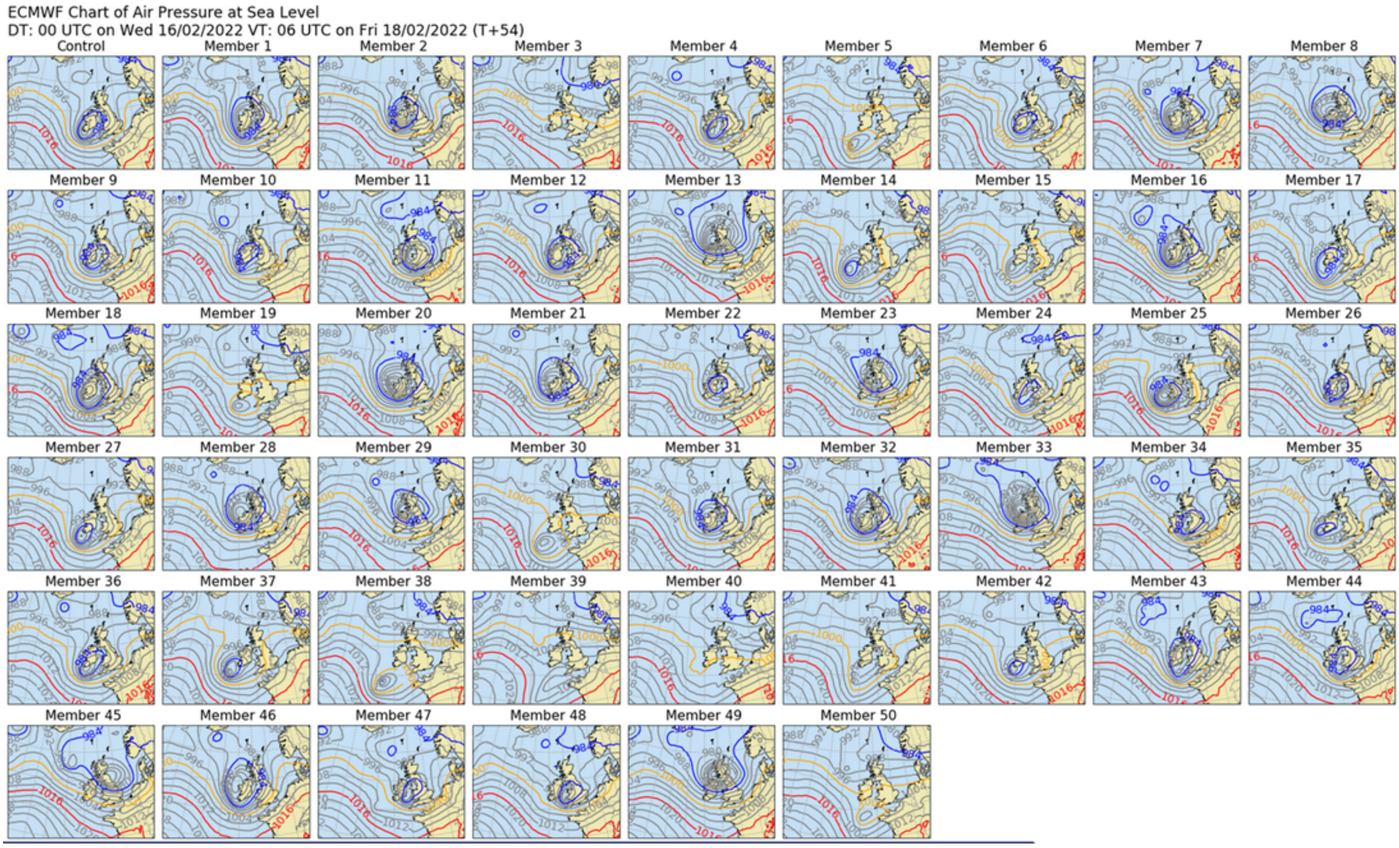


Figure 5. ECMWF PMSL postage stamps for Storm Eunice, providing a 54-hour forecast. Source: Met Office.

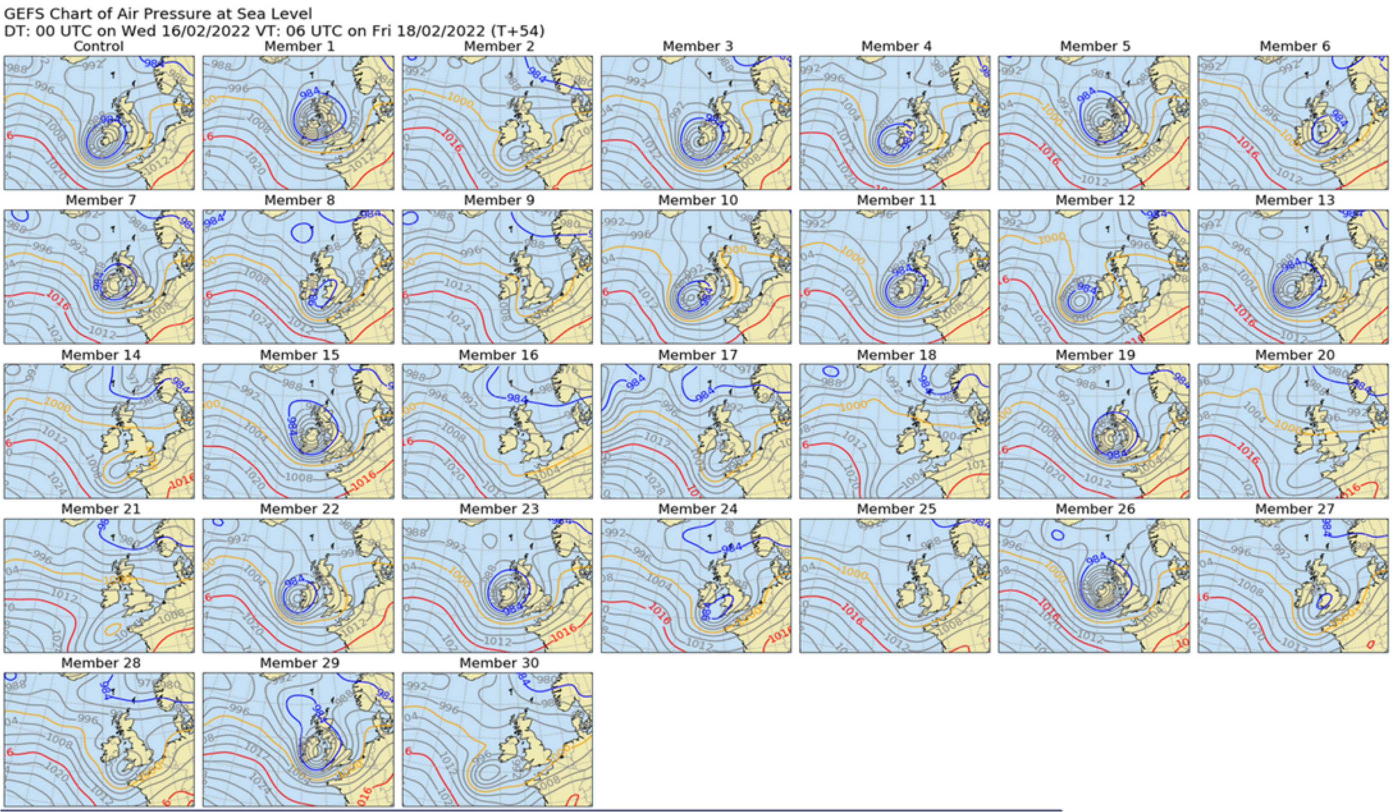


Figure 6. GEFS PMSL postage stamps for Storm Eunice, providing a 54-hour forecast. Source: Met Office.

The uncertainties in the position of the low shown in the postage stamps (Figures 4, 5 and 6) can be shown more clearly in the Cyclone Database (Figures 7 and 8). Here, we focus on output from the MOGREPS-G ensemble and look at strike probabilities (Figure 7) and individual member tracks (Figure 8). The strike probabilities are created by scanning for strong cyclone tracks across a spatial and time window, yielding higher probability values further ahead of the event than would be seen on traditional 'at-a-point' probability forecasts. As the strike probabilities are reflective of the track of the storm, the strongest surface winds are found to the south of these storm tracks. The 6-to-7-day lead time plot for strike probabilities (from the 00 UTC run on 12th February 2022; Figure 7) has the most likely track of the storm over Scotland with relatively low probabilities – this is also reflected in the MOGREPS-G 6-day first guess warnings from EPS-W (Figure 19). However, strike probabilities using runs from 13th February 2022 onwards move the track south (with the highest probabilities correctly across northern parts of Wales and England) and with minimal jumpiness from run to run. The relatively low spatial spread in the individual member tracks at a 24-hour lead time (Figure 8) also highlights the increasing forecast confidence at shorter lead times. This additional graphic also has the benefit of showing uncertainties in the timing of the storm which was forecast to reach the west coast in the early hours of 18th February 2018 at a 24-hour lead time.

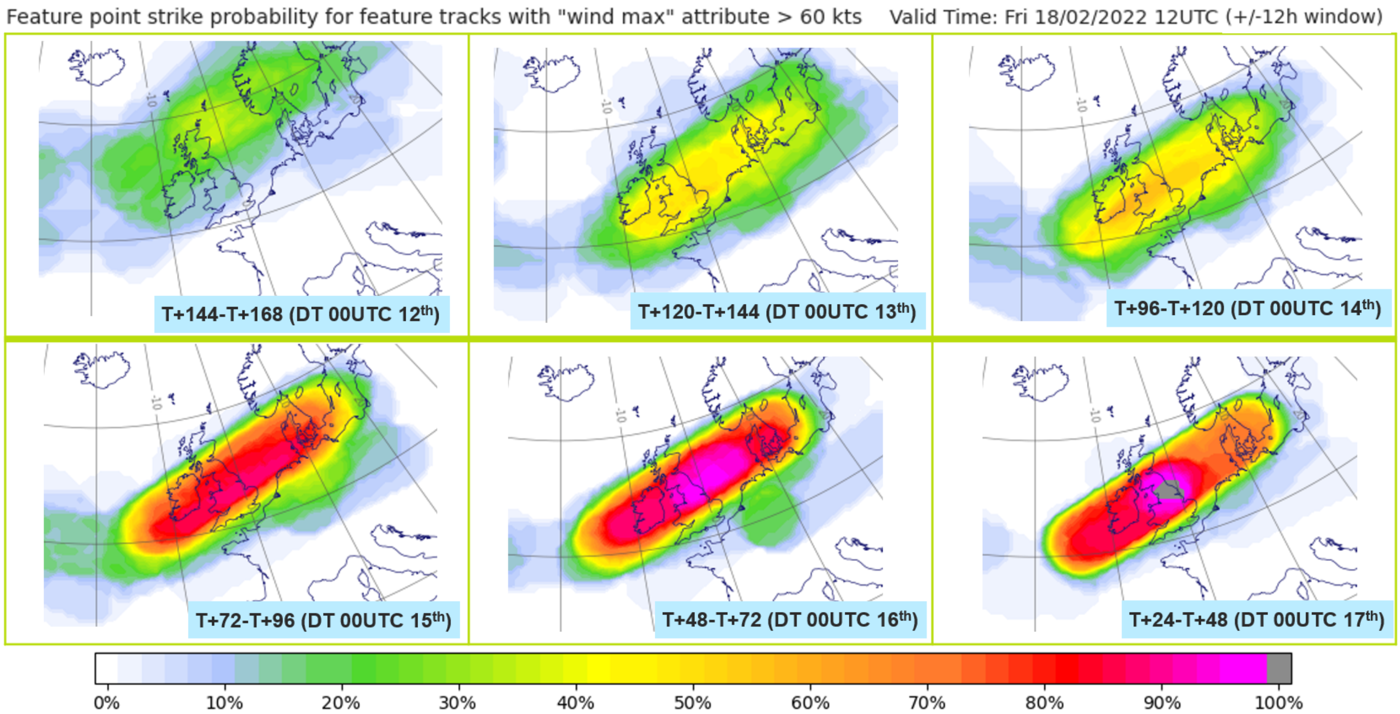


Figure 7. MOGREPS-G probability of a cyclonic feature tracking within 300 km of each point in a 24-hour period, only considering members with max 1 km wind speed > 60 knots. The multiple maps show the forecast evolution valid on 18th February 2022 (the day of Storm Eunice). Source: Met Office / Helen Titley.

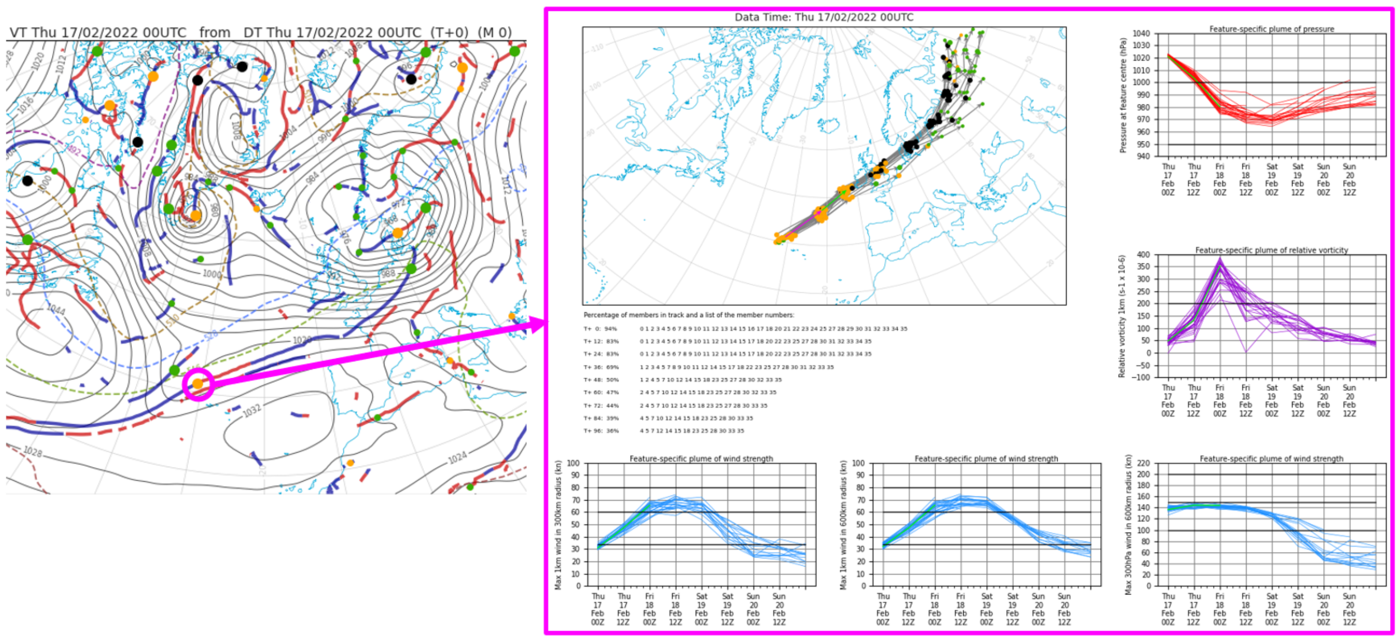


Figure 8. A screenshot of the clickable Cyclone Database feature map from the 00 UTC MOGREPS-G run on 17th February 2022 (one day before storm Eunice). Here, Storm Eunice is selected allowing the forecaster to see the track of the storm across all 36 ensemble members. The dots in the map on the right-side image represent the central positions of the storm at 12-hourly intervals. The separate line graphs in the right-side image represent different metrics for the storm, with one line for each member. These metrics include central pressure (top-right), relative vorticity (middle-right) and wind strength (bottom three). Source: Met Office / Helen Titley.

At shorter lead times (one to two days ahead), as well as refining the final track of the storm, forecasters were particularly interested in the maximum wind gusts which could be achieved. The wind gusts provided the main hazard from the storm and are covered in more detail in the hazard forecasting section of this questionnaire. However, here we look at a few short-range high resolution wind gust forecasts to get a feel for the sort of values being forecast. The UKV (Figure 9) shows an area of wind gusts in excess of 70 kts moving in off the Bristol Channel at 09:00 UTC on 18th February (providing a 54-hour forecast). MOGREPS-UK wind gust forecasts from individual members (Figure 10) can then be used to assess the uncertainty around this forecast, which show that there is uncertainty in the timing and spatial extent of the strongest wind gusts. However, feedback from operational meteorologists reveal that these high-resolution wind gust diagnostics are not given as much weight as those from the lower resolution global models. This is described well by Paul Gunderson (Met Office chief meteorologist):

> *"One thing we still lack is a reliable gust diagnostic though. For example, on Thursday night [17th February 2022], UKV/PP only had peak gusts in the 50s knots for most of SE England – this would have struggled to cause medium impacts, let alone high. Forecast gusts were better-derived from first principles analysis of model profiles (e.g., winds through/above the boundary layer, stability), noting that MOGREPS-G probabilities of say, >60 knot gusts, better fitted my estimates than UKV/PP. I've found this to be true of other windstorms too, e.g., Storm Ciara in February 2020."*

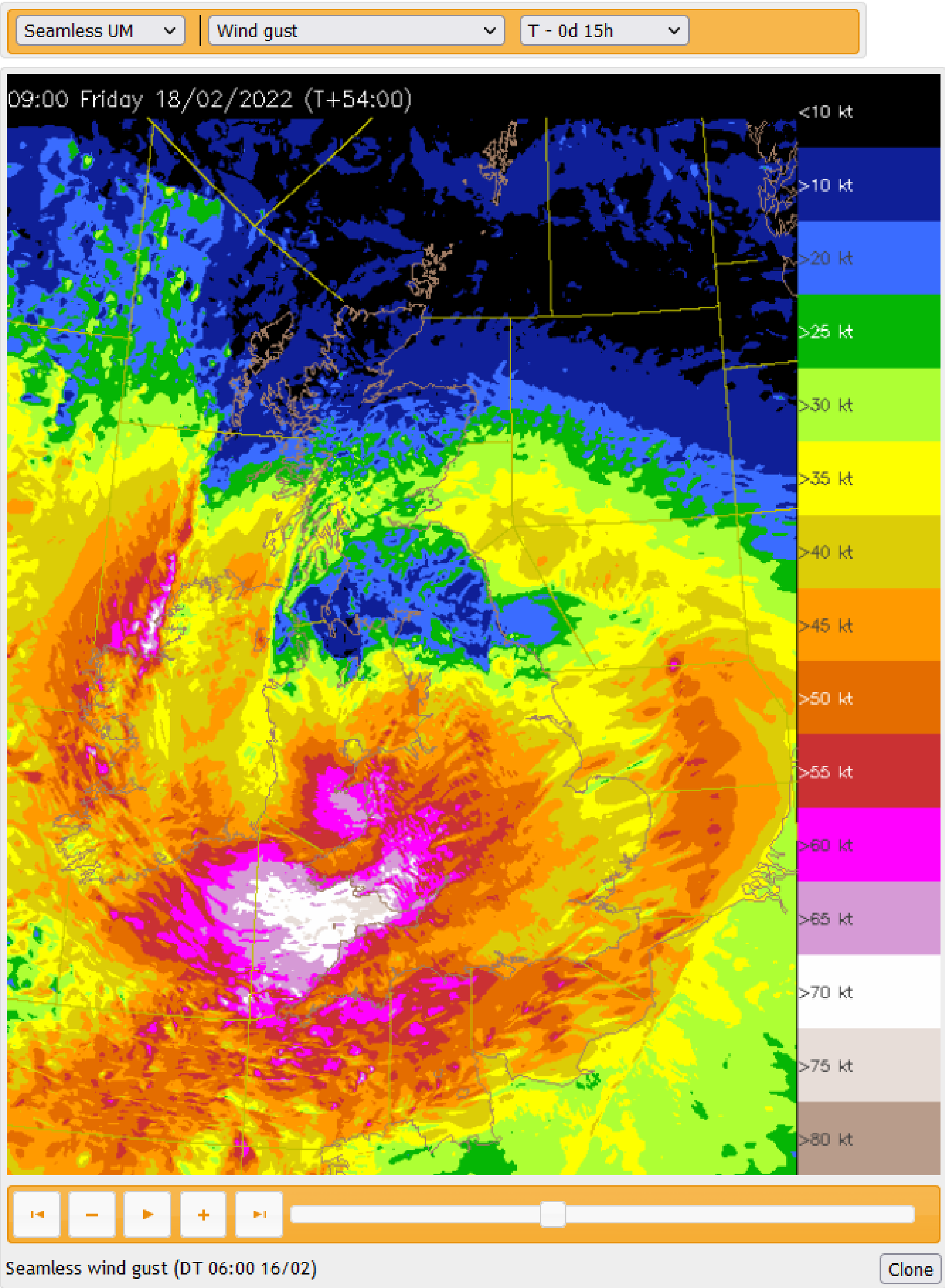


Figure 9. 54-hour high resolution UKV wind gust forecast, valid at 09:00 UTC on 18th February 2022, showing the core of the strong winds moving into the Bristol Channel / South Wales / South-west England, which later moved east across parts of England. Source: Met Office.

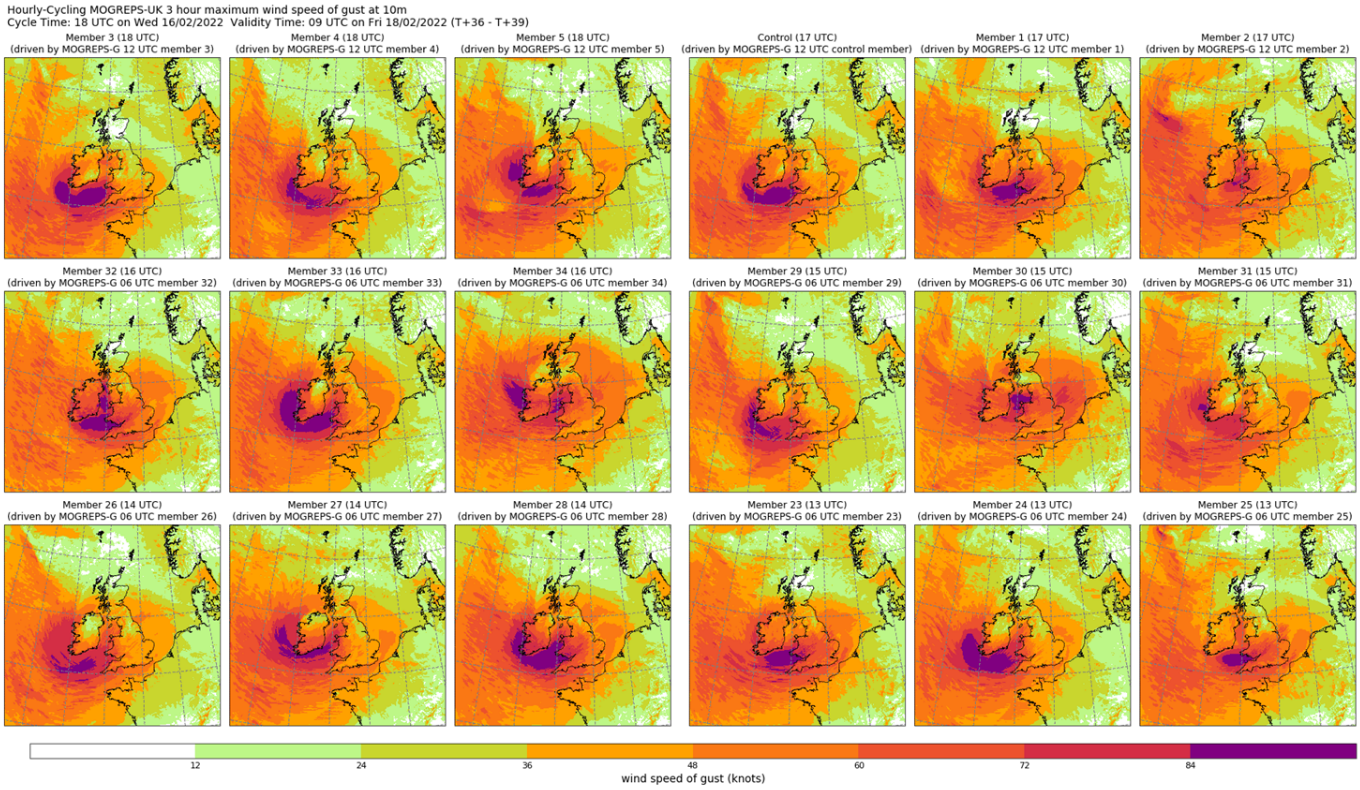


Figure 10. MOGREPS-UK wind gust postage stamps, showing the maximum 10m wind gusts between 0600 UTC and 0900 UTC on 18th February 2022 (T+36 to 39 hours), which is when the core of the strong winds started moving into parts of England and Wales. Even at these short lead times there is variation in the position, timing, and intensity of the strongest winds. Source: Met Office.

Interpretation/guidance for forecast users i

Forecasters began to identify Storm Eunice with reasonable confidence in model output four to five days in advance based on an assessment of weather forecasts across several ensembles and deterministic models. However, forecast confidence in the exact track was still low at this stage but it was deemed that the storm had the potential for high impacts given the rapid development / explosive cyclogenesis that was showing in some of the model output. This resulted in the issuance of the first yellow ‘low likelihood of high impacts’ warning four days in advance, which also coincided with the storm naming.

This relatively low forecast confidence continued for several days and improved slowly, with some differences emerging between models. Helen Caughey (Met Office Deputy Chief Meteorologist) was on day shift on 16th February 2022, and she commented during her morning brief that “*the ECMWF deterministic model has a more elongated track resulting in a weaker low compared to the Met Office deterministic model*” which she suspected may have been overdoing its development slightly at the time. Helen also showed the corresponding ECMWF and MOGREPS-G postage stamps and highlighted how the MOGREPS-G members were more consistent (less spread) compared to ECMWF which had slightly more variability. For example, around 10 to 20% of members from ECMWF still had a relatively weak (although still windy) feature tracking across the UK at a 2-day lead time. This meant forecasters were still uncertain in the track of the storm and so they produced a graphic to illustrate the most likely and alternative scenario tracks (Figure 11) to help illustrate these uncertainties. This graphic helped inform the area of the first amber warning at a 2-day lead time which was issued as a ‘medium likelihood of high impacts’.

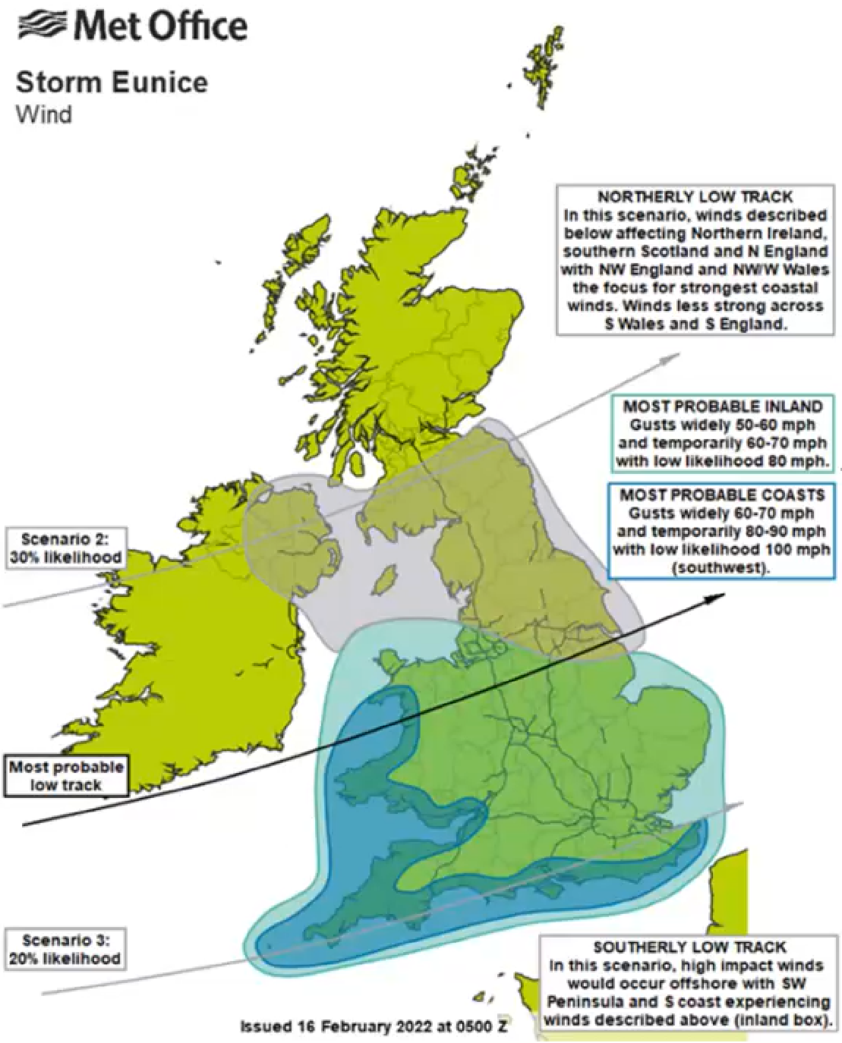


Figure 11. Schematic illustrating the most likely track of Storm Eunice, alongside two lower probability scenarios. Based on uncertainties in the ensemble output two days before Storm Eunice. This guidance was used to inform the area of the first Amber warning (low likelihood of significant impacts). Source: Met Office Chief Forecaster guidance document for internal use.

The Flood Forecasting Centre (who are responsible for issuing flood warnings in England and Wales) were also concerned by Storm Eunice as the very deep low was likely to cause a storm surge in the Bristol Channel, which on its own may not have caused too many impacts, however it was due to coincide with a spring tide and large waves. These three hazards combined had the potential to lead to the overtopping of defences in coastal stretches along the Bristol Channel (including the north coasts of Cornwall, Devon, and Somerset) as well as the south coast of Wales). Steven Stanbridge (Hydrometeorologist) was on day shift on 16th February and commented in his brief on the uncertainties in the forecast, which translated into a yellow warning for flooding being issued at a 2-day lead time for a 'low likelihood of high impacts'.

What was the level of agreement between the different forecasts? i

Models had good agreement in the general story, but there were some cross-model differences even at a 48-hour lead time as highlighted by Helen Caughey (Met Office Deputy Chief Meteorologist). Here, most members showed a stormy solution (with ECMWF generally having more spread than MOGREPS-G and GEFS), but there were still uncertainties and the timing, track and intentisty.

How reliable and accurate were weather forecasts at different lead times? i

Compared to some severe weather events, the predictability of Storm Eunice was relatively low due to it only forming a few days before it made landfall over the UK. For this reason, forecasts for the specific event did not become reliable until four to five days before. This meant that Storm Eunice was only named by the Met Office four days before (on 14th February). Considerable uncertainties still existed following this in terms of the magnitude, track, and timing of Storm Eunice, meaning that the first amber warning was only issued two days before (on 16th February 2022). Forecast confidence then increased with the first red warning being issued a day before (on 17th February 2022) for parts of south-west England and Wales. Finally, a few hours before the storm reached the UK, a second red warning was issued (on 18th February 2022) for parts of south-east England including London.

When was the potential event first detected in the models? i

The generally very stormy period during mid-February 2022 (specifically 16th to 21st February 2022 which contained three named storms) was signalled by models with relatively high confidence one to two weeks in advance (e.g., as shown by the wind gust forecasts in Figure 1 and weather pattern forecasts in Figures 2 and 3). However, due to the rapid cyclogenesis which Storm Eunice underwent, it was not forecast with sufficient confidence for warnings and naming until four to five days in advance. Considerable forecast uncertainties still remained following this with respect to the timing, track, and intensity of the storm (e.g., as shown in the postage stamps in Figures 4, 5 and 6).

================================ Weather observations ================================

Weather observations and analyses i

Storm track

Storm Eunice tracked rapidly east across central Wales and England and was centred over northern England at 12:00 UTC on 18th February 2022 (Figures 12 and 13) with the strongest winds on the southern flank of the low. The development of this storm was an example of explosive cyclogenesis, which according to official Met Office observations compiled by the National Climate Information Centre, saw the central pressure drop by approximately 30 hPa within 18 hours while the storm developed to the west of Ireland. The rapid development of the storm was accelerated through its interaction with upper winds in the jet stream blowing at more than 200 mph.

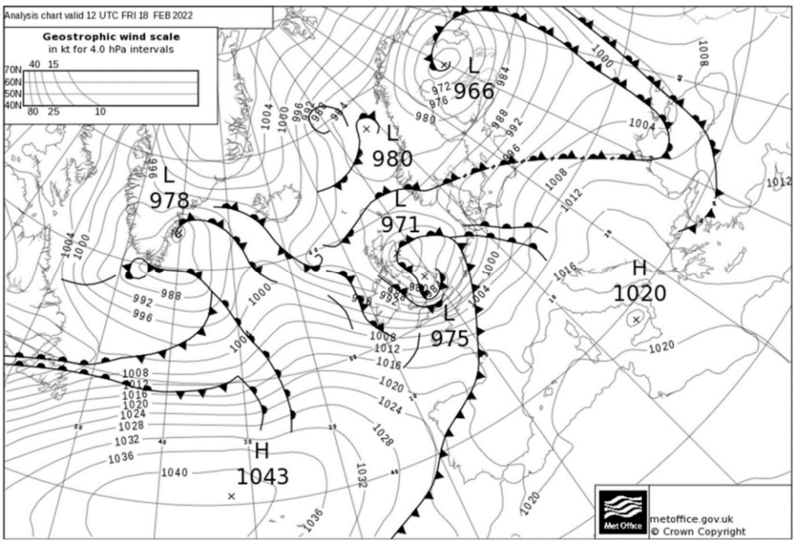


Figure 12. Analysis chart at 12:00 UTC on 18th February 2022. Source: Source: Met Office.

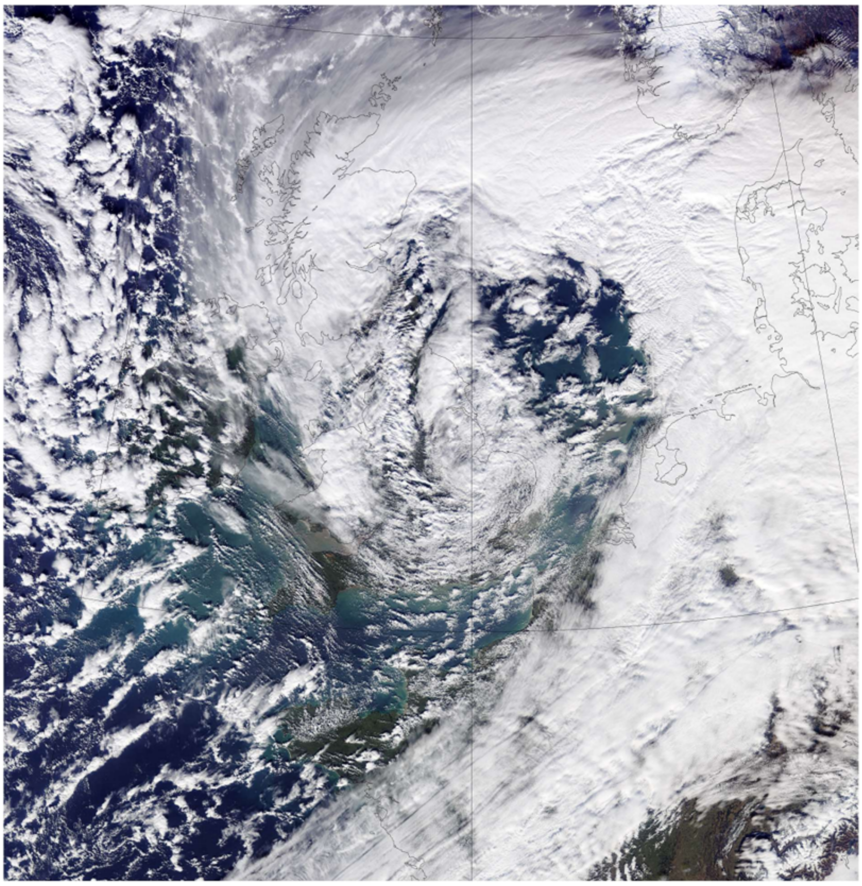


Figure 13. The satellite image at 1200 UTC on 18 February 2022 shows storm Eunice centred across eastern England with associated fronts sweeping from Scotland across the North Sea to the near continent. Image copyright Met Office / NOAA / NASA.

Wind gusts

The strongest winds were around the coast of Wales and south-west coast of England with several stations recording gusts of over 70 kts (81 mph) including 106 kts (122 mph) at Needles Old Battery (Isle of Wight) – a new England record, 78 kts (90 mph) at Isle of Portland (Dorset), 76 kts (87 mph) at Mumbles Head (West Glamorgan), 73 kts (84 mph) at Aberdaron (Gwynedd) and 72 kts (83 mph) at Pembrey Sands (Carmarthenshire) and Chivenor (Devon), as shown in Figure 14. Most stations in England south of London recorded gusts of over 60 kts (69 mph) – such as 68 kn (78 mph) at Charlwood (Surrey) and 67 kts (77 mph) at Boscombe Down (Wiltshire).

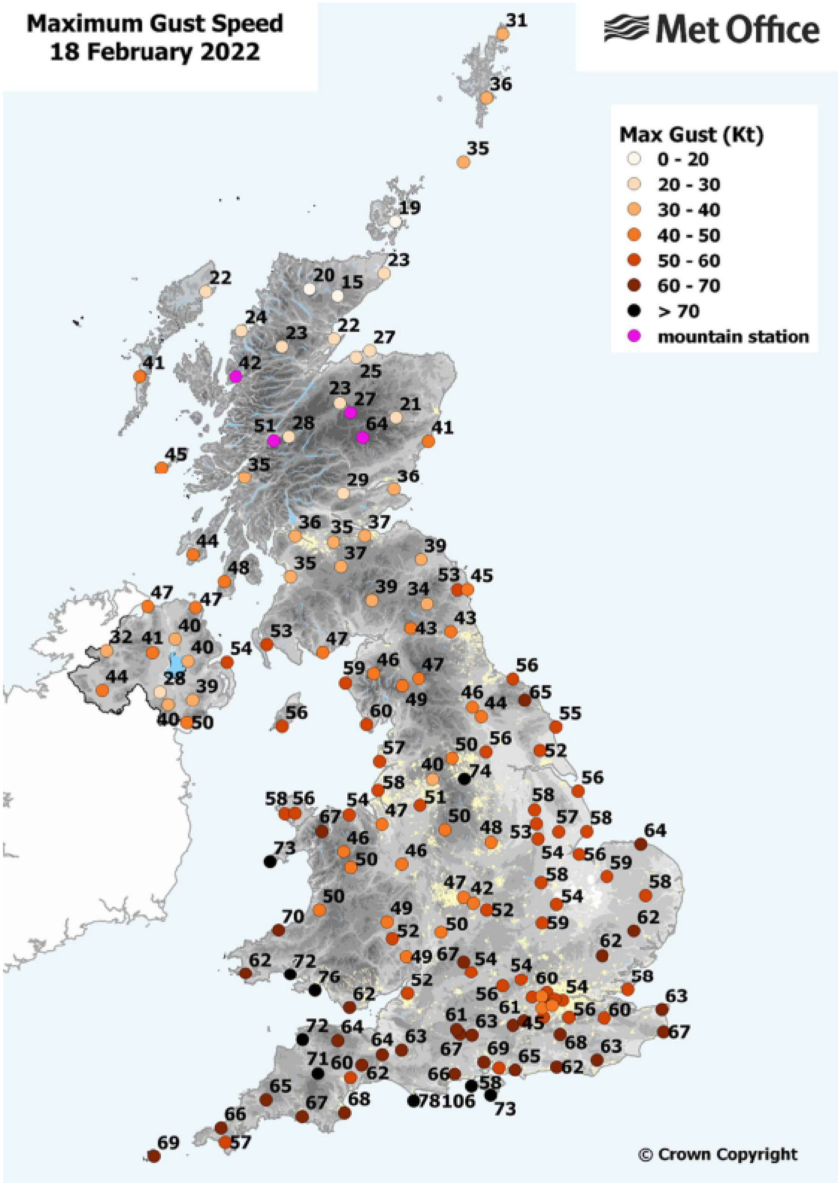


Figure 14. The maximum gust speeds (in knots) from storm Eunice on 18th February 2022. Source: Met Office National Climate Information Centre / Mike Kendon.

How did the observed weather relate to climatology and/or previous extreme events? i

Figure 15 counts the number of stations across England and Wales recording gusts ≥ 60 kts (69 mph) and ≥ 70 kts (81 mph) by date, based on observations from 1970 (i.e., over the last 50 years), using official Met Office observations compiled by the National Climate Information Centre. Presenting the data in this way helps compare Storm Eunice with storms in the observational record, taking into account a broad indication of severity and spatial extent.

During Storm Eunice, a total of 38 stations recorded gusts in excess of 60 kts, and nine stations in excess of 70 kts, both across England and Wales (Figure 15). Based on these metrics, storm Eunice was the most severe storm to affect England and Wales since 12th February 2014. This 2014 storm was one of a sequence of major storms during the 2013/2014 winter when a similar red warning was issued for wind. Storm Eunice was broadly comparable with this storm, although 12th February 2014 was more severe across parts of Wales (for example with gusts of 94 kts (108 mph) at Aberdaron, Gwynedd, 83 kts (96 mph) at Lake Vyrnwy (Powys) and 81 kts (93 mph) at Capel Curig (Gwynedd) – based on official Met Office observations.

Storm Eunice was more severe than other more recent storms, notably Storm Ciara on 9th February 2020, but Figure 15 also shows there are many more severe storms in the observational record. For example, based on data from the Met Office National Climate Information Centre, wind gusts recorded during the Burns' Day storm of 25th January 1990 were approximately 10 to 15 kts higher than Storm Eunice, and this storm resulted in widespread severe damage with 47 lives lost (Met Office case study; https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/1990/burns-day-storm---25-january-1990---met-office.pdf). Met Office observations also show that the storm on 26th February 1990 was much more severe.

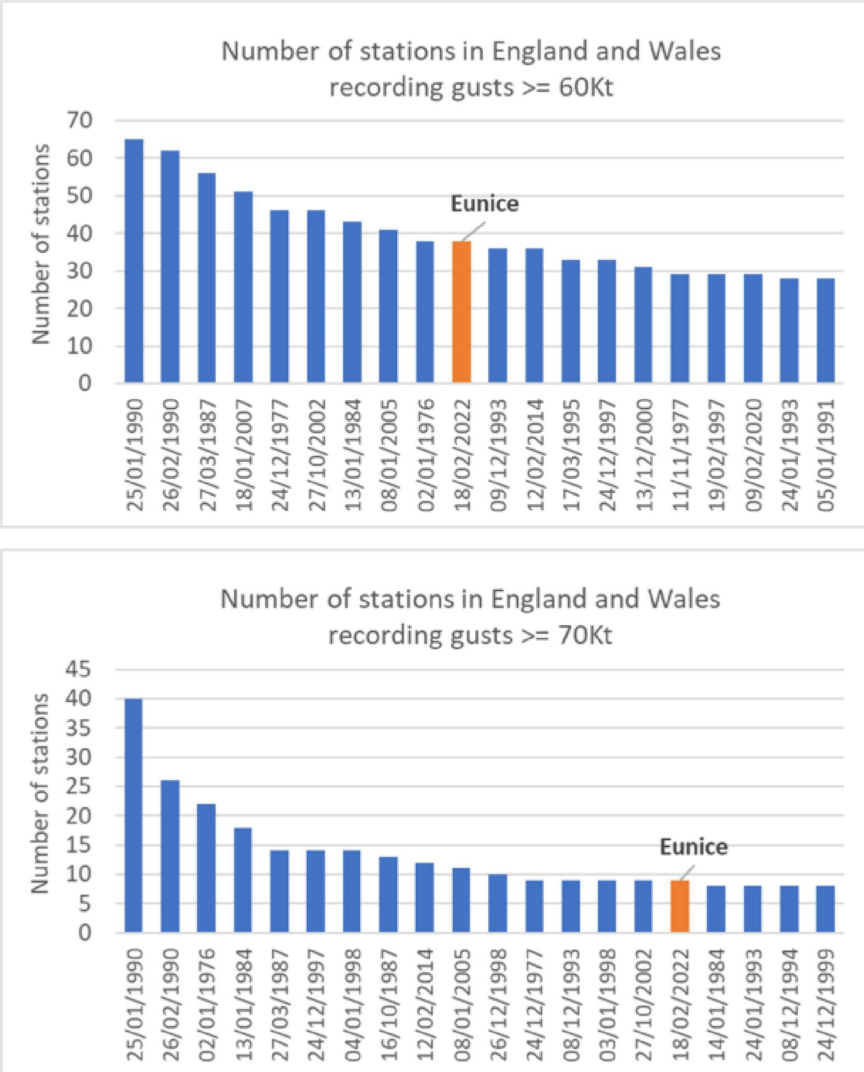


Figure 15. The number of stations across England and Wales recording gusts ≥ 60 kts (69 mph) and ≥ 70 kts (81 mph) by date, based on observations from 1970 to 2021. Source: Met Office National Climate Information Centre / Mike Kendon).

Additional analysis i

Nothing to add.

Successes/issues/challenges experienced i

There were no known issues with accessing weather observations.

Part 2b. Supplementary information about hazards i

Editors (Robert Neal and Helen Titley, Met Office, Exeter, UK):

Brief overview of the hazard event(s) i

The main hazard was the wind footprint associated with Storm Eunice, which saw a swathe of exceptionally strong winds on the southern flank of the low-pressure system. These winds predominantly affected western and southern parts of Wales as well as central and southern parts of England. Also, a multi-hazard event caused by a combination of large waves and a storm surge resulted in localised coastal flooding impacts. The storm surge caused by the low-pressure system was also amplified due to it coinciding with a spring tide. Note: This warning value chain questionnaire will focus on the wind hazard only in order to reduce its scope and keep the length manageable.

================================ Hazard forecast ==================================

Observational data used in the hazard forecast or assimilated into the hazard model i

Here we focus on the wind hazard associated with Storm Eunice and forecasting tools which specifically identify the storm as a significant feature or provide a hazard footprint for extreme wind. Met Office forecasting tools which meet this criterion, and which were available to operational meteorologists in the lead up to Storm Eunice are described below. These forecasting tools are all driven by output from ensemble forecasting systems and require no specific observational input other than that derived by data assimilation within the NWP process.

Comment on the adequacy of observations available for the hazard forecast i

As stated above, the hazard forecasts described below were derived from NWP ensemble output. As such, observations used are fully integrated within the NWP data-assimilation process. These would have included sources such as satellite and surface-based observations.

Hazard prediction models/tools i

Name	**Resolution**	**Ensemble size**	**Forecast length**
IMPROVER wind gust percentiles and probability maps	2 km (All forecasts are regridded from their native resolution to a 2km standard grid)	Forecasts are based on a seamless blended multi-model, which includes nowcasting, deterministic and ensemble models. The models used in IMPROVER at the time of Storm Eunice were all from the Met Office, including nowcasting models, the UKV, MOGREPS-UK, MOGREPS-G and the global deterministic model.	8 days (which is the maximum lead time of MOGREPS-G)
Ensemble prediction system first-guess warnings (EPS-W) driven by MOGREPS-G	20 km	36 time-lagged members by merging two 18-member cycles	7-days
Ensemble prediction system first-guess warnings (EPS-W) driven by MOGREPS-UK	2.2 km	18 time-lagged members by merging six 3-member cycles	5-days

Met Office Global Hazard Map – Multi-model version using MOGREPS-G and ECMWF	33 km for MOGREPS-G and 18 km for ECMWF	36 time-lagged members for MOGREPS-G and 51 members for ECMWF	7-days
ECMWF Extreme Forecast Index (EFI)	18 km	51-members	It is driven by the 15-day ECMWF ensemble, although the EFI product is capped at 7-days due to increasing uncertainties beyond this range.

Hazard forecast outputs and examples i

IMPROVER

Note: For background information on IMPROVER please see the 'calibration' subheading under the 'weather forecasts' section. The 24-hour lead time wind gust percentile maps from IMPROVER (Figure 16), although not providing physical solutions of the model, can be useful in showing the spread of solutions. For example, for a given grid point, the 5th percentile could be considered a reasonable best-case scenario and the 95th percentile could be considered a reasonable worst-case scenario, with the medium in the middle. The yellow shading in these plots highlights grid points in excess of 64 kts (over 70 mph) and maximum grid point values are given by the overplotted numbers. This reveals gusts as high as 75 kts (86 mph) for the 50th percentile and 84 kts (97 mph) for the 95th percentile in one or two exposed locations. The number of grid points exceeding 64 kts at the 50th and 95th percentiles also extend across large areas of central and southern England as well as large parts of Wales, which shows a potentially very large hazard footprint.

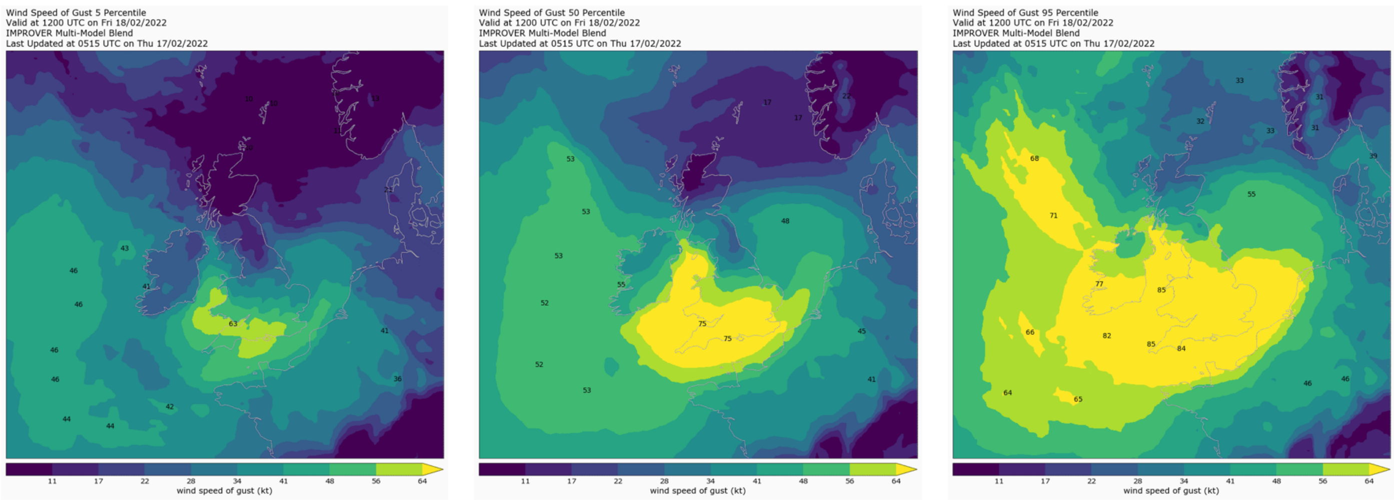


Figure 16. IMPROVER maximum 10m wind gust percentiles (5th left; 50th middle; 95th right), which will be based on a blend of the UKV and MOGREPS-UK. Based on a blend time of 05:15 UTC on 17th February 2022 and valid between 1100 and 1200 UTC on 18th February 2022. Source: Met Office.

IMPROVER data is also perfect for presenting as probabilities of threshold exceedance. Figure 17 shows the probability of exceeding 70 mph (left plot) and 80 mph (right plot) which are deemed thresholds where wind impacts can be experienced (based on an assessment of past wind events). These forecasts again provide a 24-hour lead time and clearly show the hazard footprint moving in off the Irish Sea and through the Bristol Channel towards central and southern Wales and England where there is a high population density.

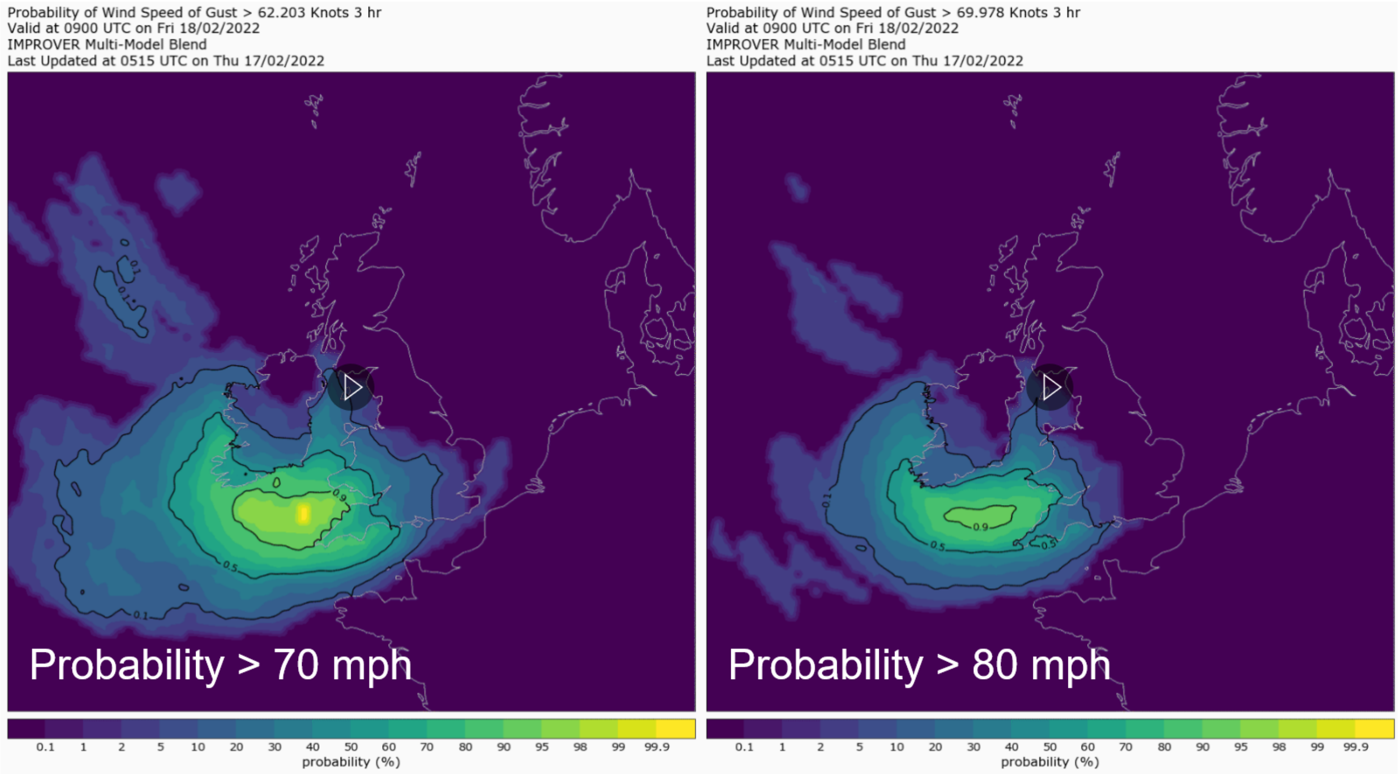


Figure 17. IMPROVER probability of 10m wind gusts > 70mph (left) and 80mph (right) valid at 0900 UTC on 18th February 2022. Based on the blend time of 0515 UTC on 17th February 2022. Source: Met Office.

Ensemble prediction system first-guess warnings (EPS-W)

The Met Office has a forecasting tool called "EPS-W", which stands for Ensemble Prediction System first-guess Warnings (Neal et al., 2014).

> *Neal, R., Boyle, P., Grahame, N., Mylne, K., Sharpe, M. 2014. Ensemble based first guess support towards a risk-based severe weather warning service. Meteorological Applications, 21, 563-577, https://doi.org/10.1002/met.1377*

EPS-W post-processes ensemble data into a format which mimics the National Severe Weather Warning Service (NSWWS) colour states of yellow, amber, and red and presents these first-guess warnings at daily time-steps out to a week in advance. First-guess warnings are based on a combination of likelihood and impact as illustrated in the NSWWS weather impact matrix (Figure 18). Numbers in the weather impact matrix reflect priority when calculating an overall warning status and position within the matrix, whereby impact takes priority over likelihood. The priority given in EPS-W for deriving the overall warning status (yellow, amber, or red) may not be suitable for all customers and warning events; however, this approach does provide a reasonable compromise between prioritising both likelihood and impact.

EPS-W uses a set of guideline proxy impact thresholds (low, medium, and high) for each parameter and likelihoods (derived from ensemble forecasts) of the three impact levels are combined to derive an overall warning status at each grid-point (yellow, amber, or red). Like other parameters, the wind gust thresholds used by EPS-W vary by region, taking account of varying levels of impact of severe weather for different parts of the UK. For example, in winter these are set to 60 mph (low impact), 65 mph (medium impact) and 75 mph (high impact) in south-east England including London. Whereas in the less populated south-west England where strong winds are also more common these thresholds are set to 65 mph (low impact), 70 mph (medium impact) and 80 mph (high impact). These guideline proxy impact thresholds do not fully take account of non-weather issues which might affect the impact level. For example, first-guess warnings might need to be modified depending on (1) the time of day and/or time of year (2) antecedent conditions and (3) major outdoor events in the area.

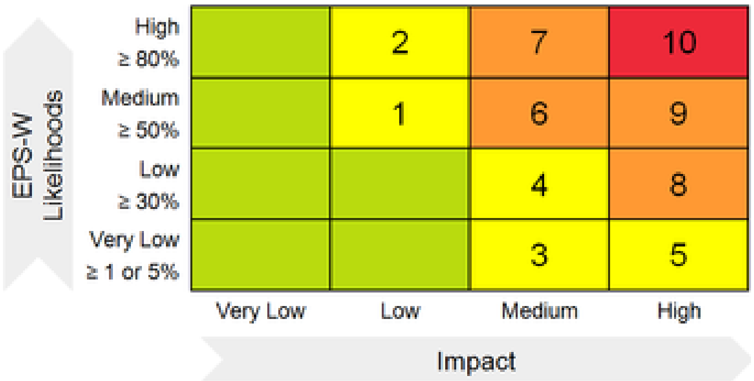


Figure 18. NSWWS weather impact matrix. Probability thresholds shown are used by EPS-W only. Source: Met Office / Robert Neal.

The MOGREPS-G driven version of EPS-W first highlighted a yellow warning covering the affected area at a 5-day lead time (Figure 19); however, this warning area was slightly larger than what was eventually issued by forecasters one day later. The first-guess warning area was reduced slightly in its northern extent by a 4-day lead time which is when Storm Eunice was first named and when the first forecaster-issued yellow warning was issued. Amber warning areas were first shown in the correct area (Wales and central/southern England) at a three-day lead time; however, the first forecaster-issued amber warning was not put out until a two-day lead time. The amber warning area in the MOGREPS-G version of EPS-W remained fairly consistent between a three- and zero-day lead time, helping to provide more confidence in the warning area and colour. MOGREPS-G also showed very rare red warning areas covering south-east England and parts of London from a one-day lead time, although the red shading in south-west England and south Wales is less extensive than issued by the forecasters at the same lead time.

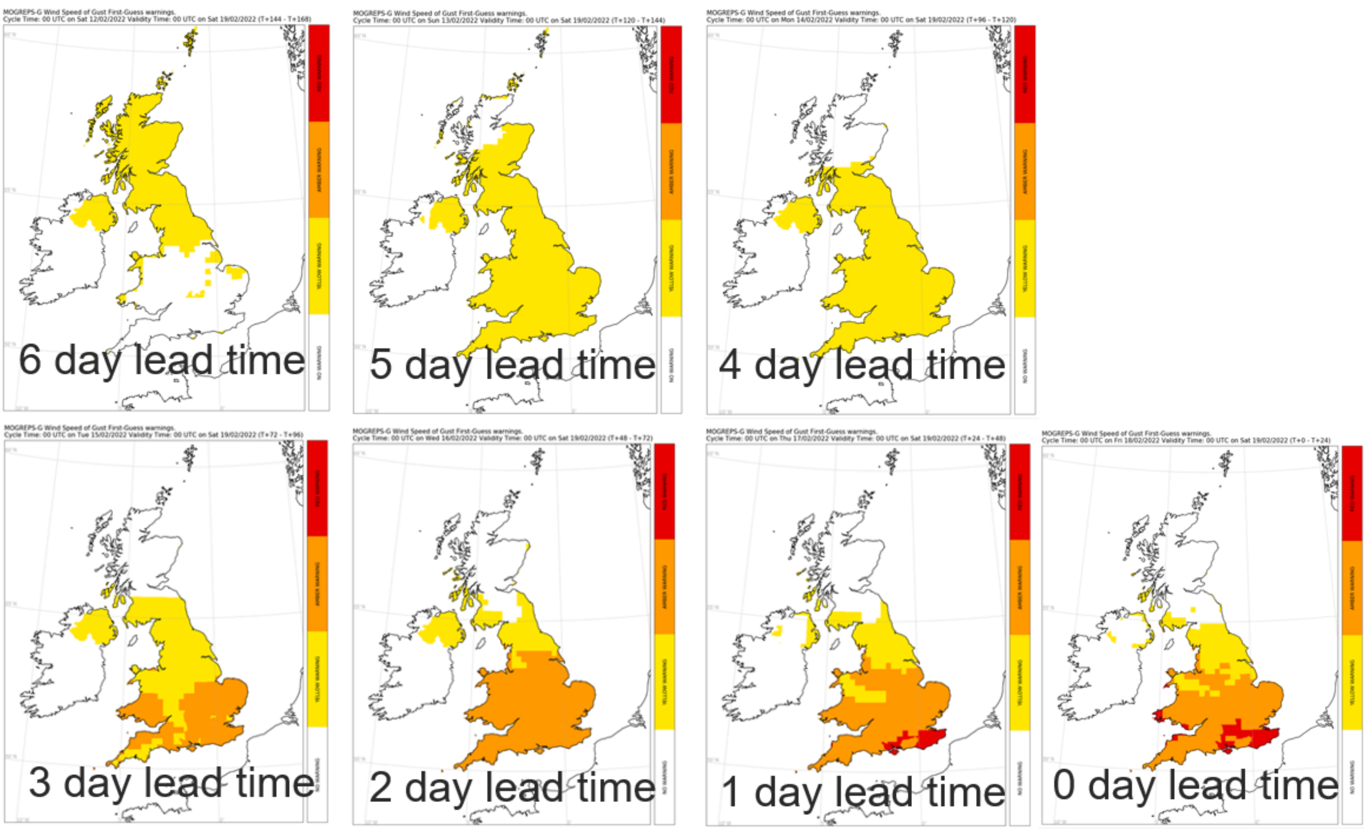


Figure 19. Evolution of MOGREPS-G first-guess warnings from a 6-day lead time all valid on 18th February 2022 (the day of Storm Eunice). Source: Met Office / Robert Neal.

A similar story can be seen from the MOGREPS-UK driven version of EPS-W (Figure 20), however here we have the advantage of additional spatial detail from the higher resolution model as well as benefits from hourly updates which enables a rapid assessment of forecast consistency. The MOGREPS-UK version also had amber areas from a three-day lead time and red areas from a one-day lead time. MOGREPS-UK also had red areas in parts of south-west England and south Wales bordering the Bristol channel at a 0-day lead time (still providing a few hours lead time), hence matching the location of the two forecaster-issued red warnings. However, as with MOGREPS-G, the extent of the red areas was less than what was issued by the forecasters.

Personal communication with the operational meteorologists on shift in the run up to Storm Eunice revealed that the EPS-W first guess warnings were more used to see how closely it aligns to the human take on the warnings and it is not really used as an initial go-to product as it is designed. There may be many reasons for this, one of which could be lack of trust in the gust diagnostic used (see earlier comment from Paul Gunderson) and the other may be 'information overload' with forecasting having to prioritise the key weather and hazard forecasting products in the limited time they have to get the warnings out.

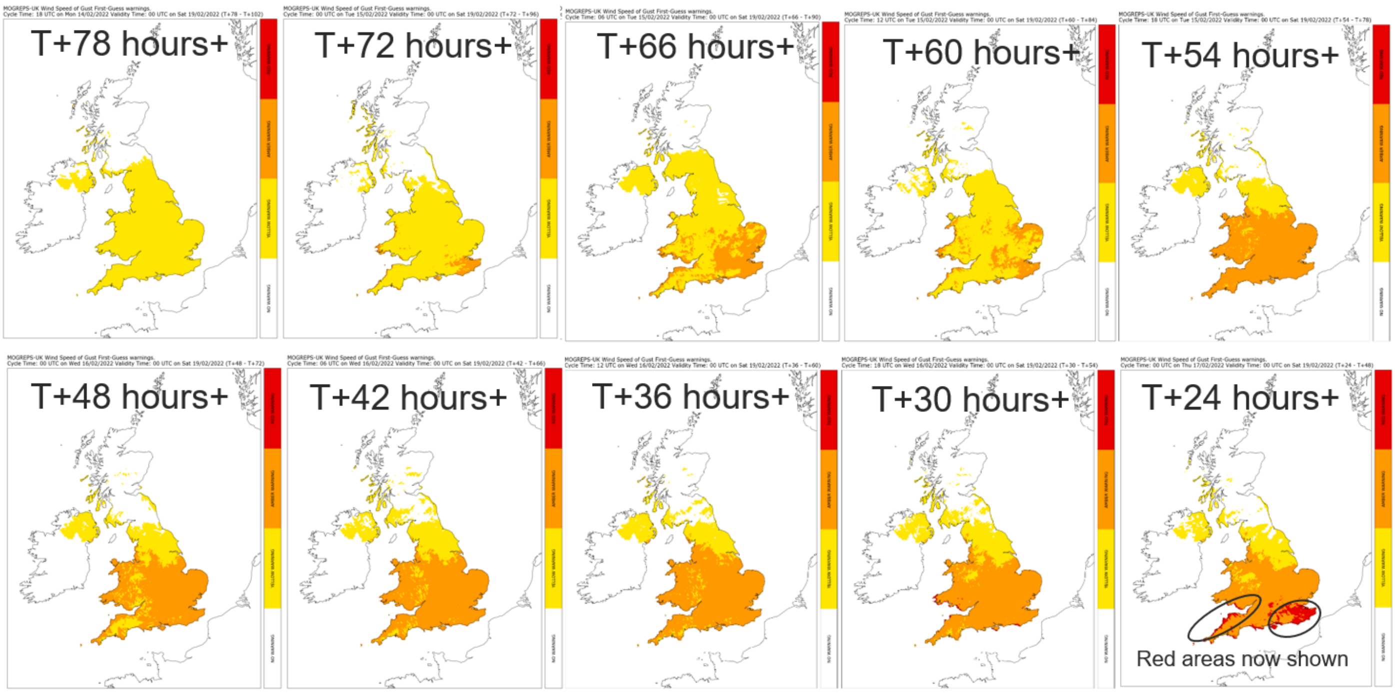


Figure 20. Evolution of MOGREPS-UK first-guess warnings (EPS-W) from a 78-hour lead time all valid on 18th February 2022 (the day of Storm Eunice). Source: Met Office / Robert Neal.

Global Hazard Map

The Met Office Global Hazard Map (Robbins and Titley, 2018) summarises the risk of high-impact weather across the globe over the coming week using global ensemble forecast data. In addition to Global Hazard Map gridded daily probability forecasts, a symbol and polygon-based summary layer gives an at-a-glance view of likely high-impact weather for the week ahead. Here we focus on the multi-model (MOGREPS-G/ECMWF) probability forecasts of exceeding the 99th centile ECMWF model climatology for wind gusts. Figure 21 shows such a forecast at a 3-day lead time, where large areas of England and Wales (as well as parts of Ireland and the Netherlands) have >80% probability of exceeding the 99th centile wind gust climatology. Using climatological percentiles has the advantage that the underlying thresholds vary by grid point making them more relevant to each locality. This means the exceedance of upper percentile thresholds (e.g., the 99th percentile as in the Global Hazard Map), is more likely to result in weather impacts.

Robbins, J., Titley, H. 2016. Evaluating high-impact precipitation forecasts from the Met Office Global Hazard Map (GHM) using a global impact database. Meteorological Applications, 25, 548-560, https://doi.org/10.1002/met.1720

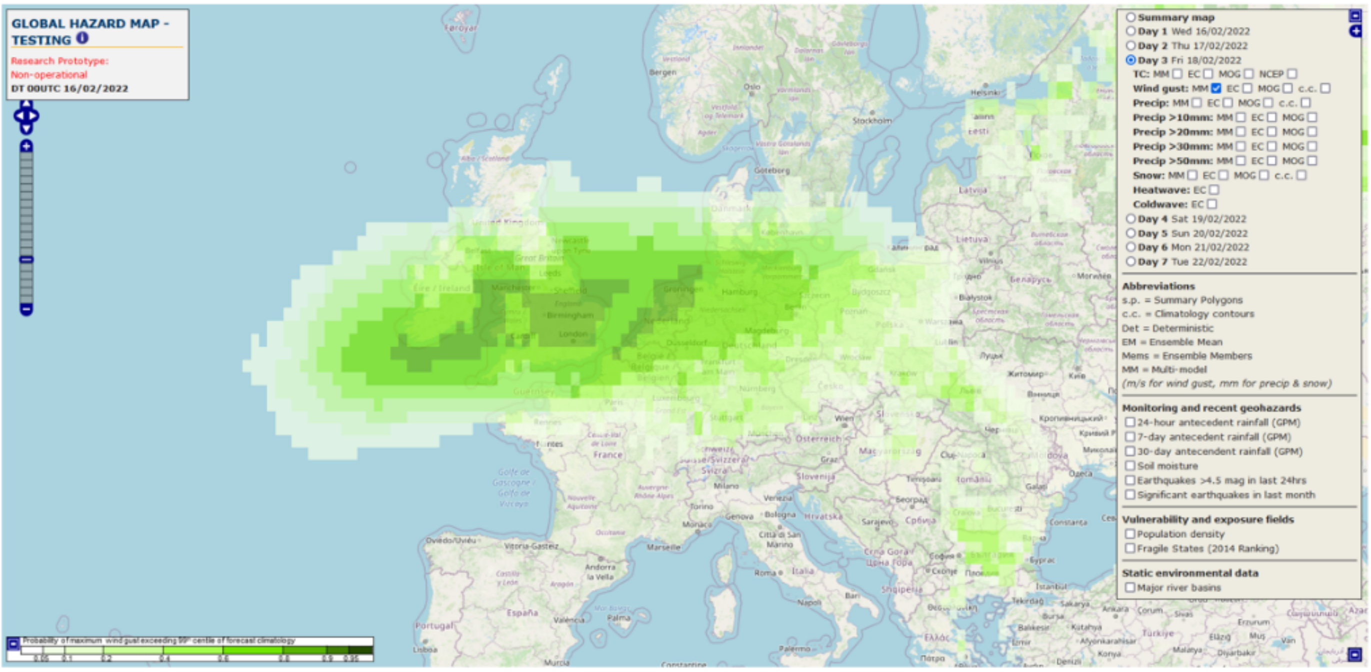


Figure 21. The Met Office Global Hazard Map showing the probability of wind gusts exceeding the 99th centile model climatology and provided by ECMWF. Here, the wind gust forecasts are taken as an average of probabilities between ECMWF and GEFS using the 00 UTC model updates on 16th February 2022. This forecast, valid on 18th February 2022 (the day of Storm Eunice) therefore provides a three-day lead time. Source: Met Office / Helen Titley / Joanne Robbins.

ECMWF Extreme Forecast Index (EFI)

The ECMWF Extreme Forecast Index (EFI; Petroliagis and Pinson, 2012) provides a measure of the difference between the ensemble forecast distribution and the model climate distribution, with grid point values ranging between -1 and 1. Positive values indicate a higher likelihood of extremes compared to the model climate (for the time of year and lead time) and negative values indicate a lower likelihood compared to normal of extremes compared to the model climate (for the time of year and lead time). However, negative values tend not to be shown for parameters bounded by zero (e.g., for wind gusts and precipitation).

Petroliagis, T., Pinson, P. 2012. Early warnings of extreme winds using the ECMWF Extreme Forecast Index. Meteorological Applications. 21, 171-185, https://doi.org/10.1002/met.1339

Forecaster experience suggests that EFI values between 0.5 and 0.8 generally signify that unusual weather is likely and values above 0.8 generally signify that *very* unusual weather is likely. The EFI is different to the Met Office Global Hazard map which only looks at the number of members exceeding a climatological model threshold (e.g., 99th centile), hence potentially missing important information from outlying (extreme) members. However, the EFI and Global Hazard Map both allow us to define the abnormality of the forecast weather situation without using specific (space- and time-dependent) thresholds.

The ECMWF's EFI output leading up to Storm Eunice is shown in Figure 22. Here, EFI values between 0.5 and 0.8 can be seen across parts of Europe including the UK at a 5-to-6-day lead time. EFI values increase to above 0.8 across large parts of England and Wales from around a 3-to-4-day lead time, indicating that very unusual weather is likely. This was around the time Storm Eunice was named and two days before the first amber NSWWS warning was issued.

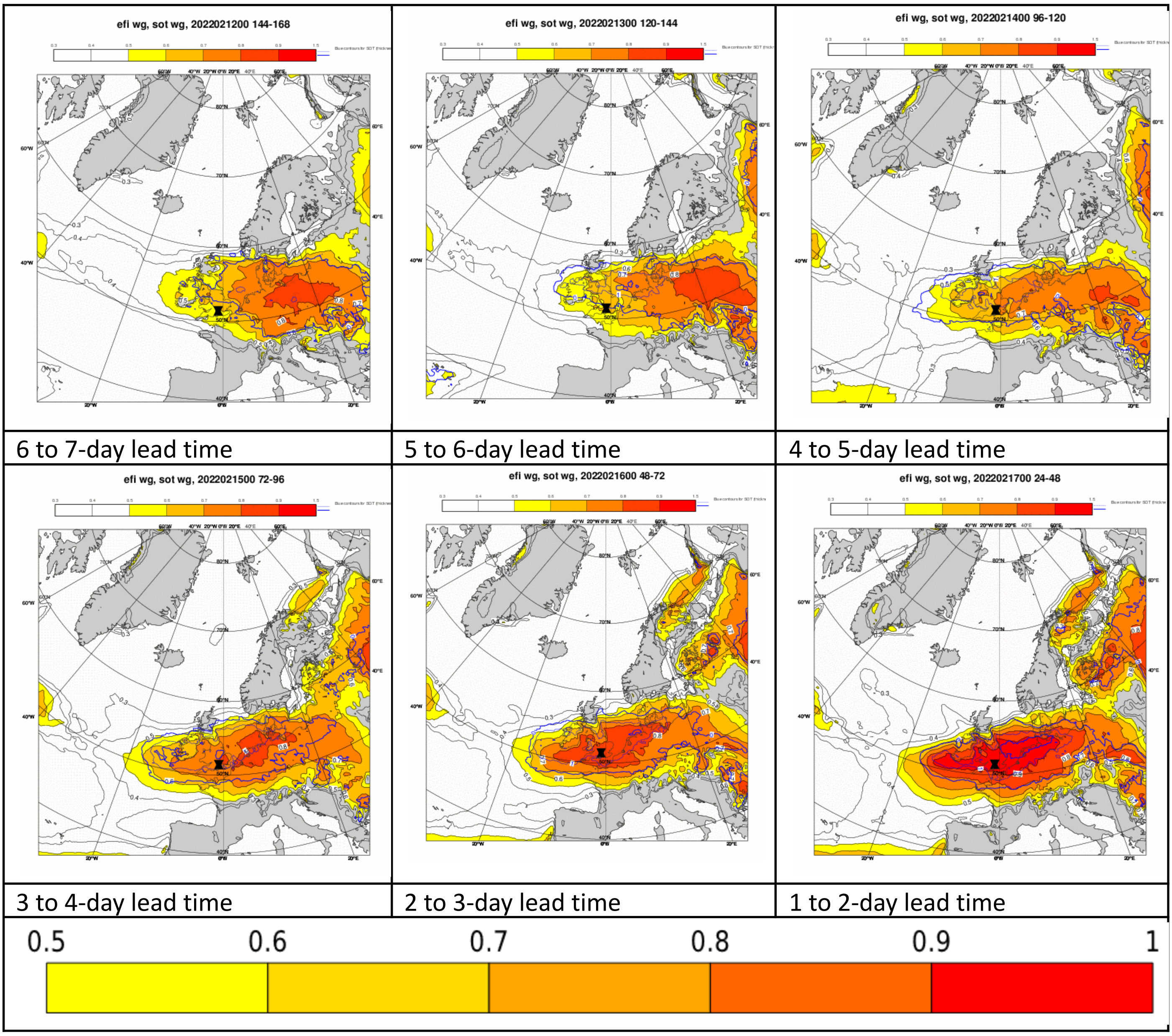


Figure 22. Evolution of ECMWF's EFI for wind gusts valid on 18th February 2022 (the day of Storm Eunice). Source: ECMWF Severe Event Catalogue at https://confluence.ecmwf.int/display/FCST/202202+-+Windstorm+-+Eunice / Linus Magnusson.

How reliable and accurate were the hazard forecasts? i

The hazard forecasts were driven by the underlying NWP and so most of the uncertainties shown here are also apparent in the weather forecasts. The hazard forecasts flagged the possibility of a severe wind event from as early as a 6 to 7-day lead time. However, probabilities were low and the spatial footprint of the event was not correct. It was not until the 5-to-6-day lead time that the location of the hazard became more accurate with probabilities increasing from there on in.

What process or trigger(s) identified the event as hazardous and started the warning process? i

The storm naming four-days in advance (on 14th February 2022) started the warning process and coincided with the issuance of the large yellow weather warning for wind covering all of England, Wales, and Northern Ireland, as well as southern parts of Scotland. This followed high confidence in the most likely track of the storm (e.g., as shown by the Cyclone Database) as well as high confidence in the storm's hazard footprint (e.g., as shown by EPS-W, the EFI and Global Hazard Map). It is possible with hindsight that a low likelihood yellow warning could have been issued at a 5-day lead time. For example, EPS-W was suggesting a large low likelihood yellow warning at a 5-day lead time, backed up by other products such as the ECMWF EFI. However, the spatial extent of this warning was very large and refinement including an escalation to amber and red would have still been needed as the forecast confidence increased. Following the advice of the hazard forecasting products at a longer lead time than 5-days may have resulted in the focus of any warnings being too far north.

============================== Hazard Observations ================================

Hazard observations and analyses i

Official Met Office wind gust observations from 18th February 2022 (Figure 14) show that the strongest winds were around the west coast of Wales and south and south-west coast of England. In this region, several stations recorded gusts of over 70 kts (81 mph) including 106 kts (122 mph) at Needles Old Battery (Isle of Wight), which set a new record for England. In addition, most stations in England south of London recorded gusts of over 60 kts (69 mph). Wind speeds as high as this are extreme for southern England and might be regarded as approximately 10 kts higher than those experienced during a more typical winter storm. Therefore, the wind hazard footprint can be considered to be very larger, covering much of Wales and Central/Southern England. For more information, please see the equivalent section under 'weather observations'.

What crowdsourcing/citizen science was used for hazard observations? i

The Met Office Weather Observations Website (WOW; https://wow.metoffice.gov.uk/) which shows both official Met Office observations as well as observations submitted by members of the public.

How did the hazard(s) relate to climatology? i

As previously mentioned, official Met Office observations and archives (compiled by the National Climate Information Centre) show that the 122 mph gust at Needles Old Battery set a new England gust speed record, exceeding the previous record of 103 kts (118 mph) at Gwennap Head (Cornwall) on 15th December 1979. Many stations recorded their highest February gust since 26th February 1990, and some recorded their highest February gust on record, such as Chivenor (37 years) and Thorney Island, West Sussex (33 years). Most stations in England south of London also recorded gusts of over 60 kts (69 mph) – such as 68 kn (78 mph) at Charlwood (Surrey) and 67 kn (77 mph) at Boscombe Down (Wiltshire), which might be regarded as approximately 10 kts higher than those experienced during a more typical winter storm. For more information, please see the equivalent section under 'weather observations'.

How was the hazard(s) made worse by pre-existing conditions? i

Storm Eunice was the middle of three named storms which affected the UK within the space of a week and brought with it the greatest impacts. However, the main hazard of wind would have been unaffected by pre-existing conditions. Impacts on the other hand were affected by pre-existing conditions. Storm Eunice followed Storm Dudley which occurred only four days earlier (on 14th February 2022) and brought with it strong winds and heavy rain to much of the country. This may have weakened some building structures and caused preliminary damage to trees making them more susceptible to damage in following storms. In addition, heavy rain falling in the proceeding days would have saturated the ground in places making trees more susceptible to being blown over.

Additional analysis i

Nothing to add.

Successes/issues/challenges experienced i

These hazard forecasts were available to operational meteorologists in real time in the lead up to Storm Eunice and they provided a useful forecast signal up to 24-hours ahead of the storm naming and first warning issuance.

Part 2c. Supplementary information about impacts i

Editors (Robert Neal and Helen Titley, Met Office, Exeter, UK):

Brief overview of the impact(s) i

Impacts from Storm Eunice were widely observed across England and Wales. Based on the 2-day lead time amber warning (of a 'medium likelihood of high impacts'), lots of pre-emptive action was taken. This included advanced cancellations of most rail and bus services in south Wales and parts of southern England, advanced cancellations of refuse collections, school closures, cancellations of many non-urgent health care appointments, as well as short lead time closures to some main road transport links (including closures of several bridges). During the event there was disruption at ferry terminals and the Port of Dover was forced to close for several hours. There were also impacts on the roads (primarily overturned vehicles), at airports (hundreds of flights were cancelled), as well as structural damage, thousands of felled trees and widespread power outages to homes and businesses. In total, three fatalities were recorded. Following the event, disruption continued on some minor road networks as it took several days to clear all felled trees and many thousands of homes remained without power. There was also disruption caused by the rearrangement of health care appointments and refuse collections. In addition, public transport was affected in the following days as trains, buses and planes (as well as drivers) were not always in the right place. A detailed list of impacts and the sources of information are provided later on in this section of the questionnaire.

=================================== Impact forecast ==================================

Data used in the impact forecast or model i

The Met Office has been issuing impact-based weather warnings as part of the National Severe Weather Warning Service (NSWWS) since April 2011. Warnings are colour-coded yellow, amber or red, which relate to a position within the warning impact matrix (Figure 23) hence providing an indication of likelihood and impact. For example, a yellow warning could be a 'high likelihood of low impacts' or a 'low likelihood of high impacts'. There is an argument for putting more than one tick in the matrix and this is something that is under review, but it is common to have a case such as Storm Eunice whereby there is high confidence the storm will track across England and Wales, but there is uncertainty in the severity due to interactions with the jet stream and the resulting rapid cyclogenesis. This alludes to the potential for high impacts but with low likelihood (at least at earlier lead times). In addition, it may be prudent to emphasise the potential for high impacts even if likelihoods are low, as end users then have the option to take mitigating action depending on their risk appetite. More information on the Met Office warnings can be found at https://www.metoffice.gov.uk/weather/guides/warnings.

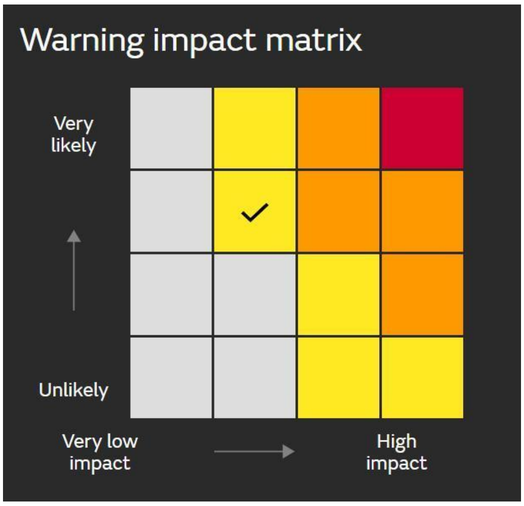


Figure 23. The Met Office weather warning impact matrix. Source: Met Office.

The Chief forecaster on shift at the time is responsible for the final likelihood and impact level of warnings, but this decision is made after analysing output from several forecasting tools (many of which are shown in this questionnaire) as well as consulting colleagues including Met Office regional civil contingency advisors who are responsible for Government Office regions in England and Wales, Scotland and Northern Ireland. These advisors regularly engage with representatives from responder organisations such as the emergency services, local authorities, the health sector and utilities and have built up a good understanding of how weather impacts on these organisations at the regional level. This information is then fed back up to the chief forecaster who has to make a partly subjective interpretation of the expected impacts based on the weather and hazard forecasts. More information on the Met Office regional civil contingency advisors can be found at https://www.metoffice.gov.uk/services/government/environmental-hazard-resilience/civil-contingencies-advisors.

The forecasters also have access to a non-operational wind hazard impact model (HIM) developed as part of the UK Natural Hazards Partnership. HIM has three wind modules, all of which are relevant to Storm Eunice:

1. A vehicle overturning (VOT) module presents the risk of disruption from vehicles overturning on the main road network of the UK which includes all motorways and some A-roads.
2. A bridge module presents the risk of vehicle overturning on around 20 key transport bridges around the UK which have different vulnerabilities compared to the main road network.
3. An airport landing module provides the risk of disruption caused to airplane landings at several UK airports.

The first two of these modules were available in real time to operational meteorologists in the lead up to Storm Eunice. The airport HIM module was running in research mode at the time of Storm Eunice but was not accessible to operational meteorologists. HIM forecast output typically gives a 'risk of disruption' (as a value between 0 and 1) and this is calculated using a ‘hazard × vulnerability × exposure’ calculation (e.g., as in Figure 24 for the wind road HIM).

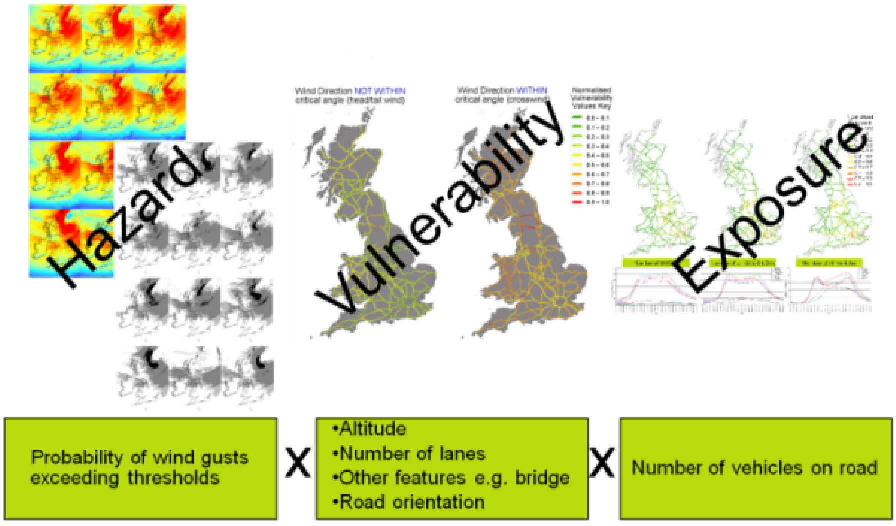


Figure 24. Data used in the 'risk of disruption' calculation within the road wind HIM. The hazard component comes from MOGREPS-UK. The vulnerability component comes from a range of static data layers. The exposure component is based on an historical record of traffic flow and varies over time. Source: Met Office / Joanne Robbins.

Impact prediction models/tools (if used) i

Name	**Method**
Road wind HIM	Hazard (driven by MOGREPS-UK) × vulnerability × exposure calculation.
Bridge wind HIM	Hazard (driven by MOGREPS-UK) × vulnerability × exposure calculation.
Airport landing HIM	Hazard (driven by MOGREPS-UK) × vulnerability × exposure calculation.

Informal rules/tools used to identify impacts i

As well as the objective hazard impact modelling explained above, operational meteorologists utilise a number of more subjective approaches to forecasting the likelihood of impacts, which are well established though the impact-based National Severe Weather Warning Service (NSWWS) introduced earlier. This includes consultation with Met Office regional civil contingency officers who have close contact with emergency responders, to discuss the likelihood of impacts in specific areas. These discussions will include assessing non-weather-related factors which may affect the impact level for the warning, such as time of day and/or time of year, antecedent conditions and whether there are any major outdoor events in the area most at risk.

Impact forecast outputs and examples i

Road wind HIM

The Road HIM forecasts (Hemingway and Robbins, 2020; Figure 25) highlight a yellow, amber and red risk of disruption throughout the period Storm Eunice affected England and Wales. The areas at risk can be seen to transition from west to east as the storm moved through with roads at greatest risk experiencing a cross wind, such as the M1 motorway north of London (red shading) and stretches of the M5 motorway north of Bristol (amber shading).

> *Hemingway, R., Robbins, J. 2020. Developing a hazard-impact model to support impact-based forecasts and warnings: The Vehicle OverTurning (VOT) Model. Meteorological Applications, 27, e1819, https://doi.org/10.1002/met.1819.*

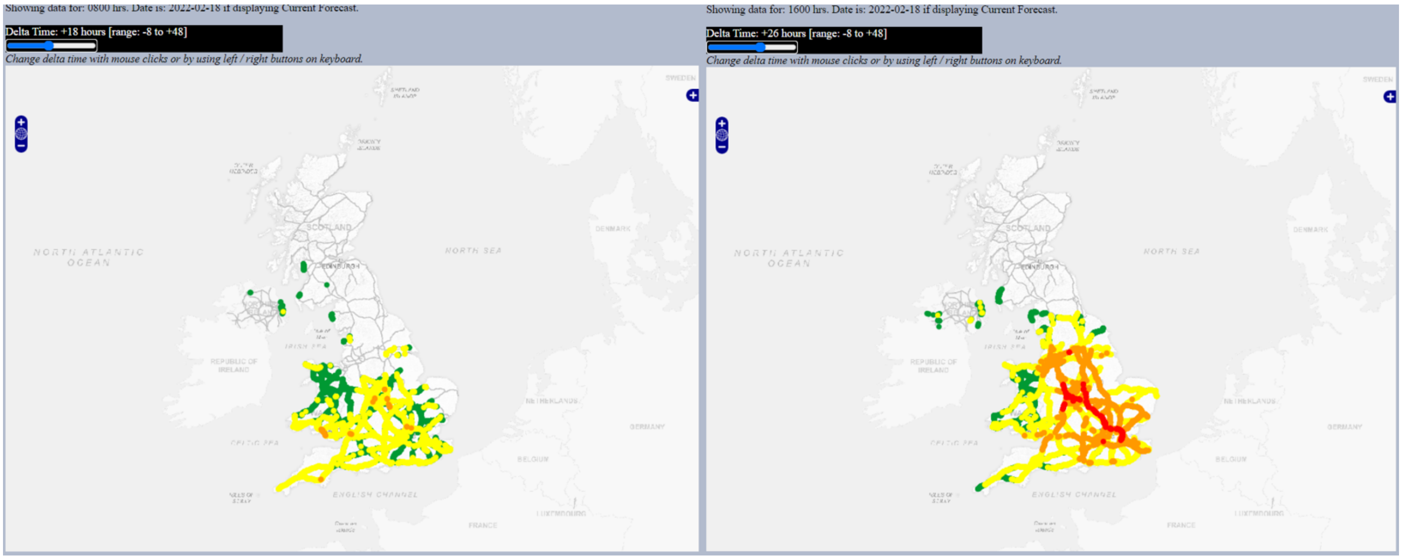


Figure 25. Forecast output from the road wind HIM showing the forecast of risk of disruption from vehicles overturning on UK motorways and some A-roads. Left image shows an 18-hour forecast valid at 0800 UTC on 18th February 2022 and the right image shows a 26-hour forecast valid at 1600 UTC on 18th February 2022. Source: Met Office / Faye Wyatt / John Mooney.

Bridge wind HIM

The Bridge HIM example in this questionnaire (Figure 26) shows forecasts which are valid at the same times as in the Road HIM (Figure 25). Here, it is also evident that the risk of disruption to bridges transitions from west to east with the passage of the storm. The two River Severn Bridges near Bristol show a risk of disruption under all three impact types, which are implementation of a speed restriction (yellow), closure of the bridge to high sided vehicles (orange) and closure of the bridge to all traffic (brown). These two bridges were both eventually closed as a precautionary measure. The Humber bridge in northeast England was also closed as a precautionary measure, with the Bridge HIM showing the risk of disruption under two impact types, which were implementation of a speed restriction (yellow) and closure of the bridge to high sided vehicles (orange). Bridge HIM visualisation such as in Figure 27 can then be used to identify the precise level of risk under each of the forecast impact categories.

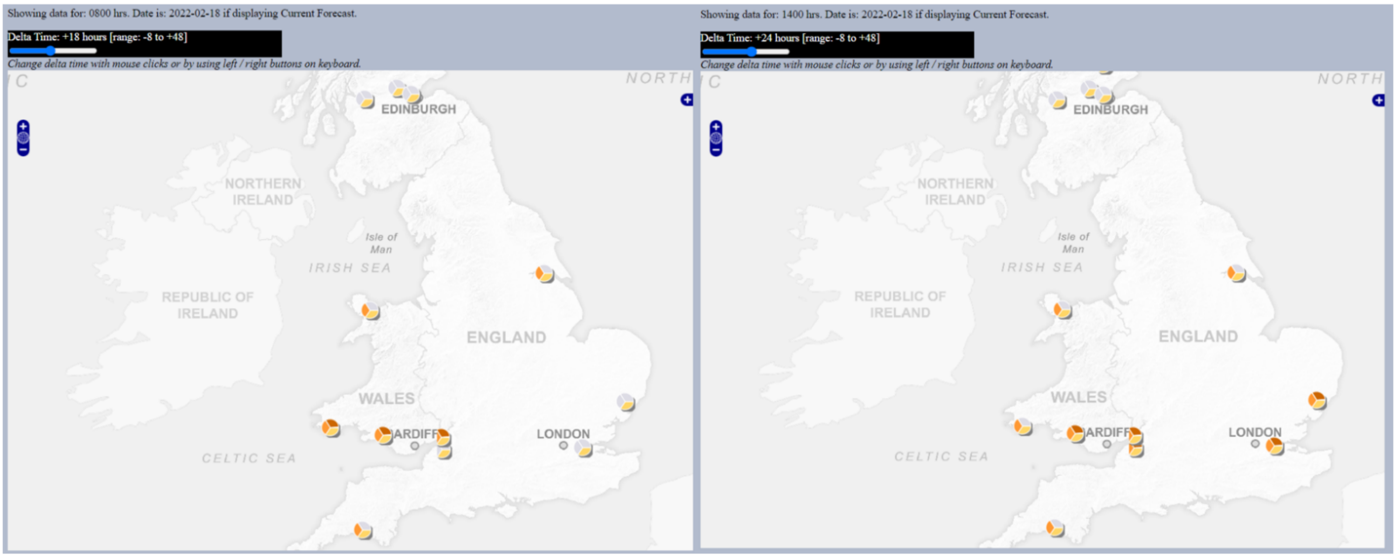


Figure 26. Top-level forecast output from the bridge wind HIM, visualising the forecast likelihood of the following types of impact, each of which could affect bridge use: (1) Implementation of a speed restriction (yellow), (2) closure of the bridge to high sided vehicles (orange) and (3) closure of the bridge to all traffic (brown). Grey shading indicates that the corresponding impact is not forecast. Left image shows an 18-hour forecast valid at 0800 UTC on 18th February 2022 and the right image shows a 24-hour forecast valid at 1400 UTC on 18th February 2022. Source: Met Office / Faye Wyatt / John Mooney.

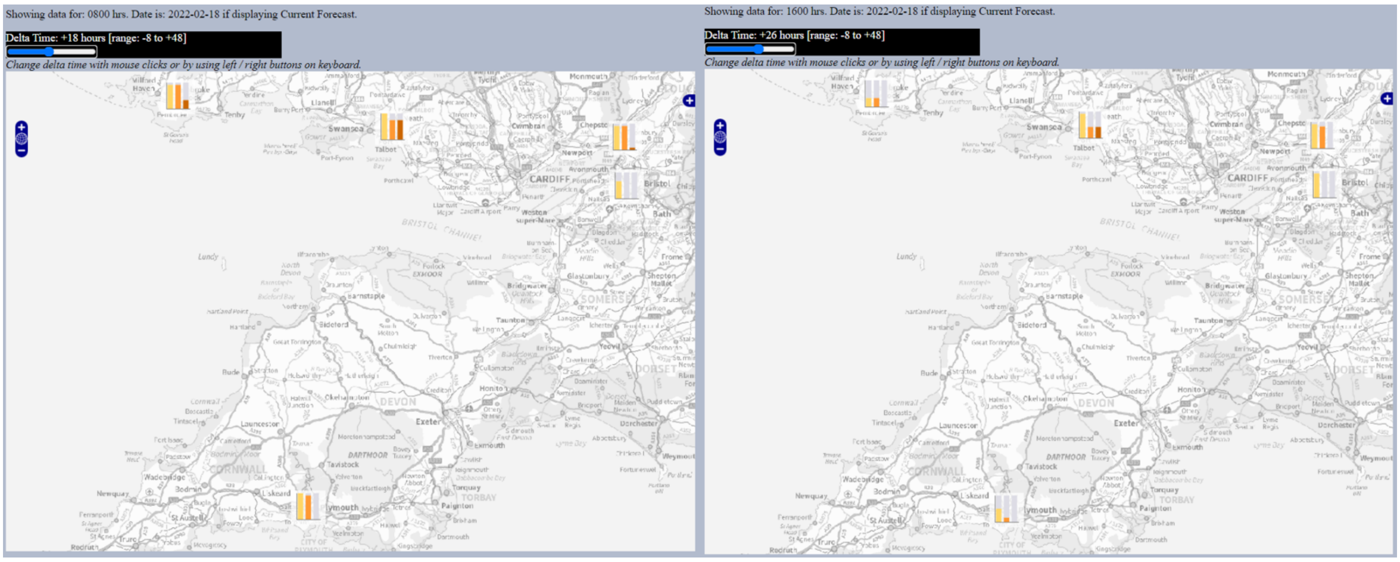


Figure 27. A zoomed in version of the bridge wind HIM showing the risk of disruption from each of the three impacts being forecast, colour coded in the same way as Figure 26. A fully coloured bar indicates a risk of 1.0, with the risk declining as the proportion of the bar that is grey increases. In the bar charts grey is used to make the full height of all three bars equal to the maximum likelihood of 1.0. Left image shows an 18-hour forecast valid at 0800 UTC on 18th February 2022 and the right image shows a 26-hour forecast valid at 1600 UTC on 18th February 2022.When zoomed into a location, a simple gar graph is used to indicate the risk of each impact type. Source: Met Office / Faye Wyatt / John Mooney.

Prototype airport landing HIM

A prototype airport landing HIM (Figures 28 and 29) was also running in real time during Storm Eunice, however it was not available to forecasters due to its development still being in the early research stages. However, it is included here as an example of an impact forecasting tool which could be available in the future and to see if it may have added any value to the warnings. The disruption to aviation from Storm Eunice was significant with 436 flight cancellations (Reuters, https://www.reuters.com/world/uk/uk-sees-436-flights-cancelled-amid-storm-eunice-cirium-data-2022-02-18/) and so forecasting tools like this could be very useful in the future.

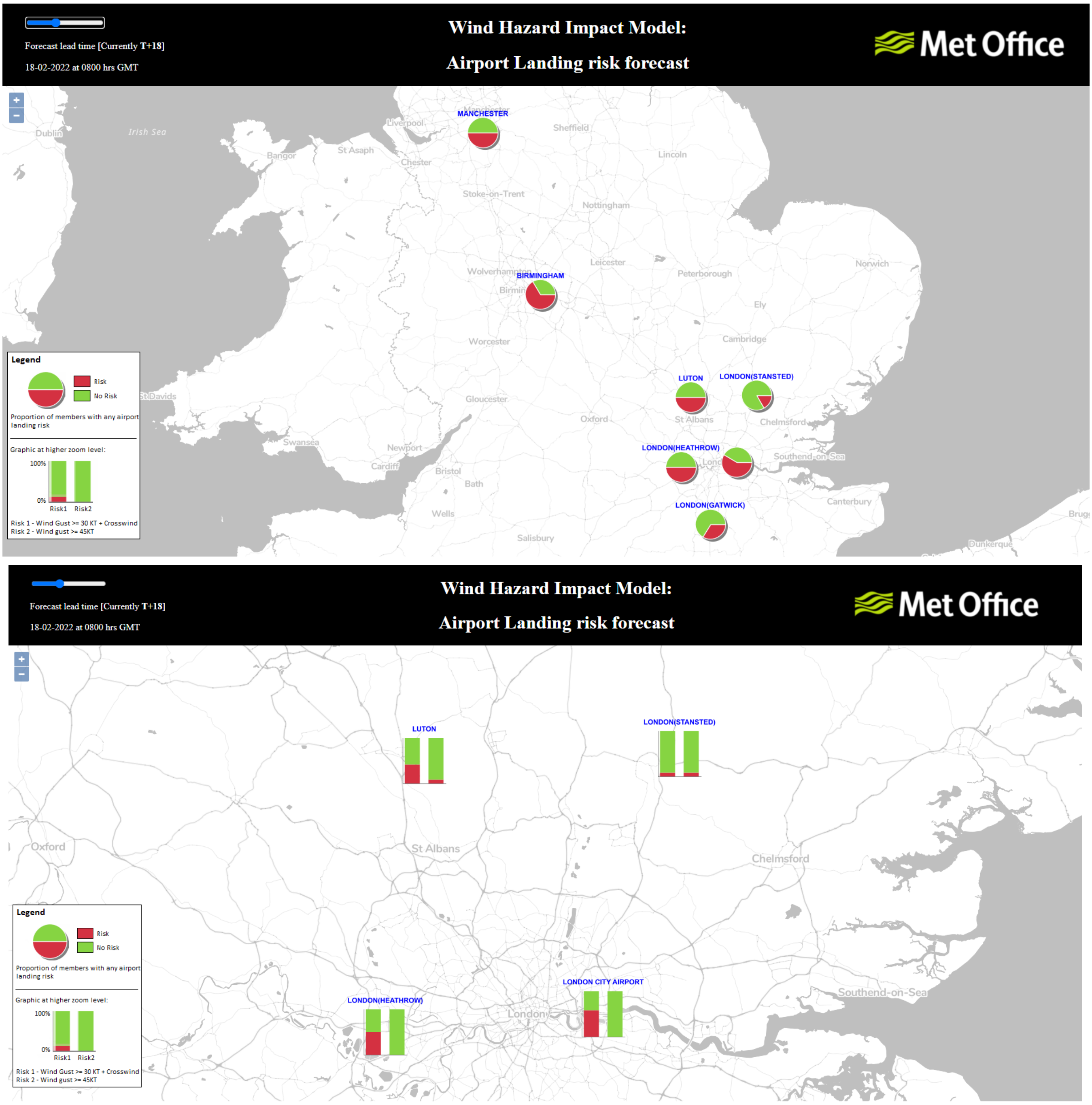


Figure 28. An 18-hour forecast from the prototype airport landing HIM valid at 0800 UTC on 18th February 2022. Top: The top-level view showing the proportion of members with any airport landing risk. Bottom: Zoomed in view showing the proportion of members which have a wind gust ≥ 30 knots + crosswind (risk level 1; left bar) and the proportion of members which have a wind gust ≥ 45 knots (risk level 2; right bar). Source: Met Office / Faye Wyatt / John Mooney.

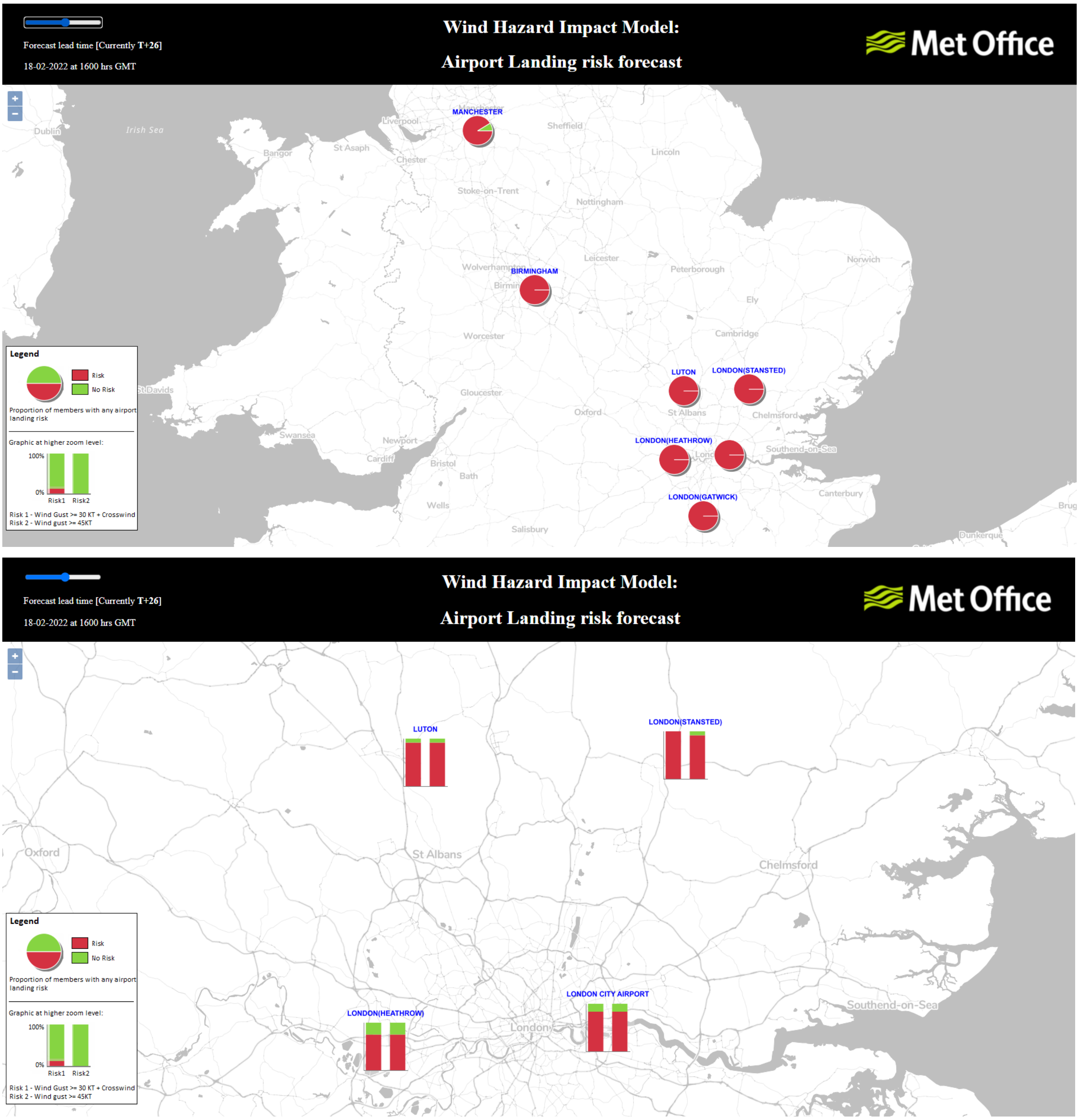


Figure 29. A 26-hour forecast from the prototype airport landing HIM valid at 1600 UTC on 18th February 2022. Top: The top-level view showing the proportion of members with any airport landing risk. Bottom: Zoomed in view showing the proportion of members which have a wind gust ≥ 30 knots + crosswind (risk level 1; left bar) and the proportion of members which have a wind gust ≥ 45 knots (risk level 2; right bar). Source: Met Office / Faye Wyatt / John Mooney.

Comparison of predicted/expected and actual impacts i

The wind HIM modules shown above (Figures 25 to 29) predicted impacts on the roads, bridges and at airports with high confidence over a day in advance. These predicted impacts compare well to those observed (see next section), which saw several instances of overturned vehicles and precautionary closures of bridges and airports during the windiest parts of the day.

================================ Impact Observations ==================================

Observed impacts:

The following impacts are based on a Google news search for terms such as "Storm Eunice power cuts" and "Storm Eunice flight cancellations" etc. Relevant news articles have been referenced where relevant. In addition, some impacts have been included as provided directly by Met Office regional civil contingency advisors and the responder community / partners.

Health and social impacts i:

- Three fatalities in the UK (BBC News; https://www.bbc.co.uk/news/uk-60439651).
- All non-urgent (out-patient) medical appointments were cancelled in advance across southern Wales (Wales Online, https://www.walesonline.co.uk/news/wales-news/storm-eunice-everything-closed-wales-23133095) as well as across many districts in England, such as Treliske hospital in Cornwall (Cornwall Live, https://www.cornwalllive.com/news/cornwall-news/treliske-hospital-cancels-outpatient-appointments-6679477) and Alexandra Hospital in Portsmouth (The Portsmouth News, https://www.portsmouth.co.uk/news/people/storm-eunice-cancels-appointments-at-queen-alexandra-hospital-3574251).
- According to the Met Office regional civil contingency advisor for Wales, there was an enormous amount of pre-emptive mitigating action by the Wales Government and Local Authorities that meant that effectively much of southern parts of Wales was in a state of informal lockdown on Friday morning (18th February) – with many businesses/facilities/schools/offices closed and all trains and virtually all bus services withdrawn and a shutdown of both Severn bridges. This meant very few people were travelling and therefore exposed to danger.

Property and business impacts i:

- There were widespread reports of structural damage across England and Wales. For example:
    - In Wales there were numerous examples of buildings damaged/roofs damaged or removed, especially in the Newport area where six houses were affected in one incident (according to the Met Office regional civil contingency advisor for Wales)
    - The top of a church spire in Wells, Somerset, England, was blown down (The Independent, https://www.independent.co.uk/climate-change/news/storm-eunice-winds-church-b2018306.html).
    - The O2 arena (previously known as the Millennium Dome) in London had part of its roof damaged ((BBC News, https://www.bbc.co.uk/news/uk-england-london-60434549).
- Many schools and businesses closed in advance although homeworking helped mitigate some of the impacts of this (The Sun, https://www.thesun.co.uk/news/17686070/storm-eunice-school-closures-full-list-south-west/). It is difficult to put a figure on the number of school closures, but it is thought to be in the hundreds.

Critical infrastructure damage and service disruption i:

- Hundreds of thousands of homes across England and Wales were left without power as strong winds brought down trees, with ongoing power cuts lasting several days. It is thought that over 1 million homes were affected although it is difficult to find a reliable source on the internet. However, the southwest, one of the worst affected regions, experienced the most power outages ever reported in one day (according to Western Power Distribution).
- There was major transport disruption:
    - o Trains were cancelled (The Gaudian, https://www.theguardian.com/uk-news/2022/feb/18/storm-eunice-wreaks-uk-travel-chaos-as-roads-closed-and-trains-curtailed), roads were blocked by fallen trees and there were several overturned lorries e.g., on the M4 in south Wales (Figures 30 and 31).
    - o A total of 436 flights were cancelled in the UK (Reuters, https://www.reuters.com/world/uk/uk-sees-436-flights-cancelled-amid-storm-eunice-cirium-data-2022-02-18/) and many aircraft struggled to land in the strong winds. London Luton Airport was temporarily closed in advance of the storm due to the risk posed from strong cross winds.
    - o There was ferry port disruption, including full closure of the Port of Dover (City AM, https://www.cityam.com/storm-eunice-hits-shipping-port-closure-bottlenecks/).
    - o There were bridge closures including the Humber bridge for only the fourth time in its 40 year history (BBC News, https://www.bbc.co.uk/news/uk-england-humber-60431423) and both River Severn bridges for the first time in their history (South Wales Argus, https://www.southwalesargus.co.uk/news/19934708.storm-eunice-prince-wales-bridge-m48-severn-crossing-closed/)
    - o Further north, there was also significant transport disruption in parts of Scotland and northern England from snow (The Scotsman, https://www.scotsman.com/news/weather/storm-eunice-snow-brings-disruption-to-travel-and-schools-3574340).
- Refuse collections were cancelled across most of south Wales and many regions of England, including Cornwall, Devon, Somerset, Dorset, Hampshire and Kent to name a few. A Google search for ‘refuse collections cancelled storm Eunice’ raises multiple returns.

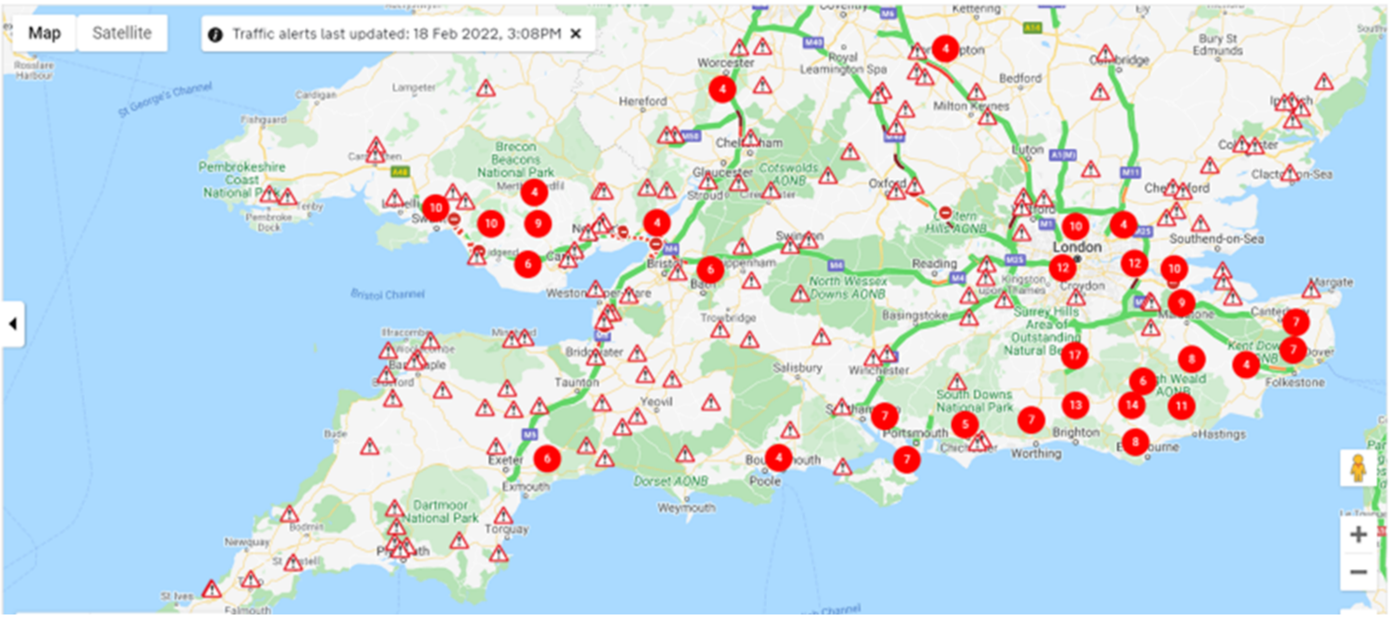


Figure 30. A snapshot of weather-related traffic incidents at 15:08 UTC on 18th February 2022, from the AA-traffic monitoring website (https://www.theaa.com/route-planner/traffic-news). With thanks to Faye Wyatt for extracting this data.

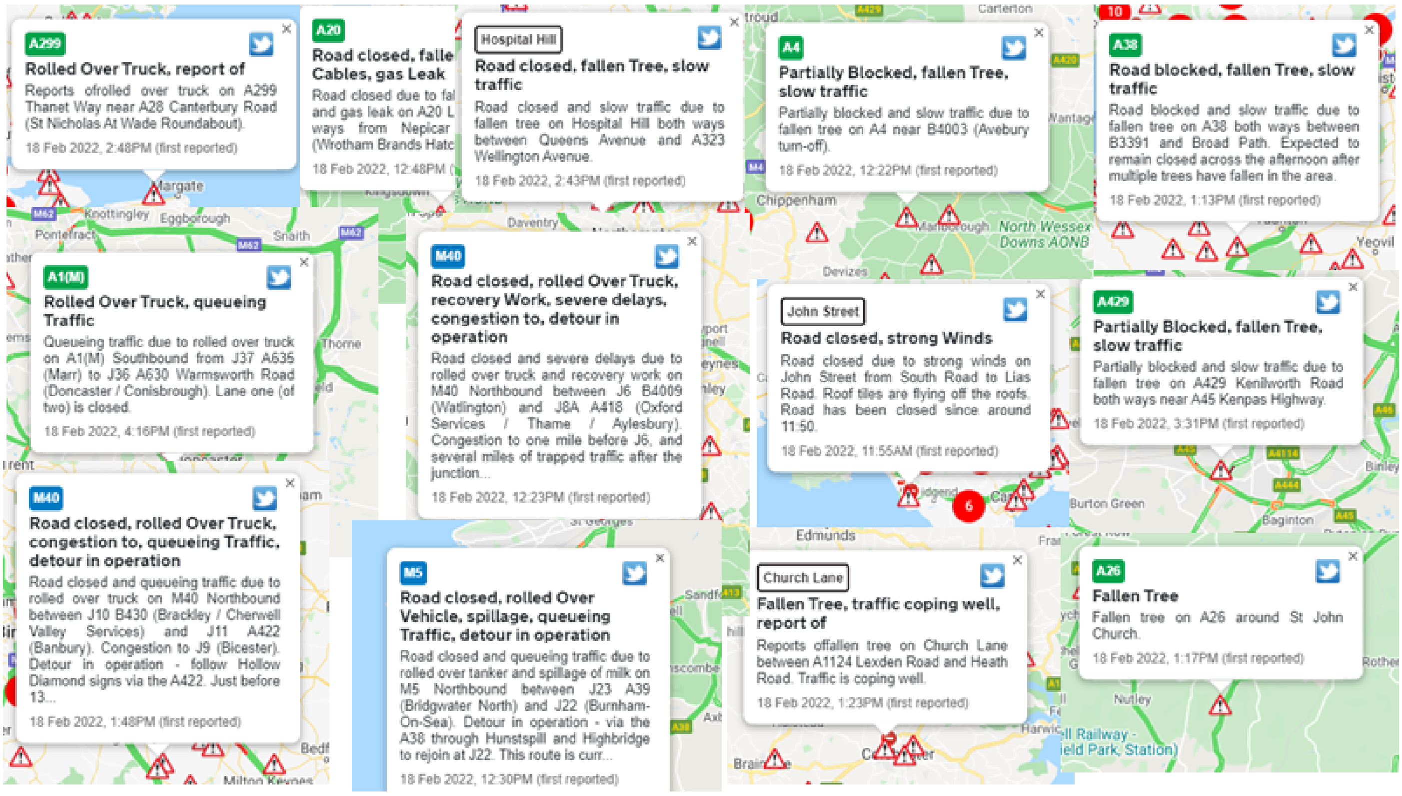


Figure 31. A selection of weather-related traffic disruption tweets from 18th February 2022, from the AA-traffic monitoring website (https://www.theaa.com/route-planner/traffic-news). With thanks to Faye Wyatt for extracting this data.

Environmental damage i:

- Thousands of trees fell over (BBC News, https://www.bbc.co.uk/news/uk-england-london-60431369) – including large mature trees such as a local landmark tree in Bude, Cornwall (Cornwall Live, https://www.cornwalllive.com/news/cornwall-news/iconic-bude-triangle-tree-felled-7554250), and at National Trust properties around the southwest (BBC, https://www.bbc.co.uk/news/uk-england-devon-60495295).

- Large waves, together with a storm surge on top of high spring tides battered western and southern coastlines and the Severn Estuary. For the first time, the whole of the Welsh Coastline was highlighted as being at severe risk of flooding by the Flood Forecasting Centre (Source: Met Office). However, thankfully flooding impacts ended up being less severe than first thought as Storm Eunice arrived a few hours later than first forecasts hence missing the peak of the spring tide (Metro, https://metro.co.uk/2022/02/17/storm-eunice-warnings-of-tidal-surges-and-severe-flooding-in-wales-16123415/)

What crowdsourcing/citizen science was used for impact observations? i

- Social media – Twitter
- The Met Office Weather Observations Website (https://wow.metoffice.gov.uk/)

Who and what were exposed to the hazards, when, for how long? i

Storm Eunice had a large hazard footprint with large areas seeing wind gusts in excess of 60 mph, which from past events is typically a threshold where medium to high impacts can start to be seen over parts of the UK subject to many other non-weather-related factors such as the time of day and antecedent conditions. Using this criterion, the hazard footprint covered much of Wales as well as parts of England south of Birmingham (including SW England, central and southern England, SE England, and East Anglia). This includes some of the most populated parts of the UK including the large towns or cities of London, Bristol, Cardiff, Reading, Oxford, Cambridge, and Exeter, to name a few. The strongest winds arrived into western parts during the early hours of 18th February and peaked here during the morning rush hour during what was a normal working day outside of the school holidays. This meant lots of commuters and school children would have been exposed to the hazard had mitigating action not been taken. The strongest of the winds moved east during the day affected most areas during daylight hours when many people would be out and about, including lorries transporting goods. The strongest winds arrived in the populated SE England (including London) during the afternoon coinciding with some of the evening rush hour. Even once the strongest winds had past (within 2 or 3 hours), the wind was still very gusty and even weaker gusts had the potential following the storm to cause impacts where structures and trees had been weakened.

Of those exposed, who and what were vulnerable to the hazards and why? i

The storm occurred on a normal working day and affected most areas exposed to the wind hazard during daylight hours when many members of the public would have been out on their normal activities and businesses and public transport would have been operating. Those most vulnerable therefore included a wide spectrum of society, including:

- children making their way to and from school,
- commuters getting to and from work,
- lorries transporting goods across the county,
- construction work,
- poorly maintained buildings,
- and old or diseased trees exposed to the wind.

Additional analysis i

Nothing to add.

Successes/issues/challenges experienced i

The weather impact matrix (Figure 23) provided a well-established framework for issuing the impact-based probabilistic warnings, which were issued as early as a 4-day lead time. This involved Met Office chief meteorologists regularly liaising with Met Office regional civil contingency officers when drafting out warnings, which allowed for lots of discussion around the expected impacts in different areas of the country. The Met Office chief meteorologists have a large range of forecasting products available to them for use in supporting the warning process. This included a wide range of weather and hazard forecasting tools – most of which are operationally supported and easily accessible on the forecasting bench, but a smaller pool of impact-based forecasting tools as shown in this section. This results in two key challenges:

(1) Information overload on the operational forecasting bench meaning that not all forecasting tools get looked at. This can often mean that weather and hazard forecasting tools are prioritised over impact-based tools.
(2) Possible lack of trust or understanding in some of the less established and non-operationally supported forecasting support tools, which includes some of the hazard and particularly impact-based forecasting tools.

Part 2d. Supplementary information about warning communication

Editors (Robert Neal and Helen Titley, Met Office, Exeter, UK):

Brief overview of the communication "story" i

Storm Eunice was named 4-days before the main impacts were experienced in western areas, which coincided with a large yellow warning being issued (Figure 32). This warning was escalated to amber two days later (Figure 33). A smaller red warning was then issued for parts of the south-west one day before (Figure 34) with an additional red warning being issued for parts of south-east England in the early hours of the day of the storm (Figure 35). This information was communicated through the Met Office website and social media (including Twitter, Facebook and TikTok), through the Met Office and BBC weather mobile phone apps, as well as through national and regional TV and radio weather forecasts on the mainstream channels (including BBC, ITV, Channel 4 and Channel 5) and 24-hour news channels. The information was also cascaded to the emergency responder community directly from the Met Office. A more detailed timeline of events is given below.

Monday 14th February 2022; four days before Storm Eunice

- Storm Eunice was officially named by the Met Office during the morning of Monday 14th February 2022, providing a 4-day lead time of the first impacts being experienced in western parts of England and Wales.
- This coincided with the issuance of a large yellow weather warning (at 10:19 UTC; Figure 32), which covered all of England and Wales, Northern Ireland and southern parts of Scotland. The weather warning was issued within the 'high impacts' column of the weather impact matrix, suggesting a low likelihood of high impacts. The location of the warning within the matrix showed scope for further escalation to amber or red if forecast confidence increases sufficiently.

Tuesday 15th February 2022; three days before Storm Eunice

- Warnings were reviewed but forecast confidence had not changed enough to warrant any updates.

Wednesday 16th February 2022; two days before Storm Eunice

- The yellow weather warning was escalated to amber at 10:40 UTC (Figure 33) and a Met Office Press Released was published at 11:44 UTC (https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2022/amber-warnings-in-force-for-storms-dudley-and-eunice). This was a large amber warning covering much of England and Wales. The tick in the weather impact matrix was placed in the 'high impacts' column just one box below red, indicating further potential for warning escalation.

Thursday 17th February 2022; one day before Storm Eunice

- A very rare red weather warning was issued covering parts of south-west England and south Wales (Figure 34) – encompassing the area bordering the River Severn estuary. This was issued at 10:50 UTC and coincided with another Met Office News Release which was published at 11:16 UTC (https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2022/red-weather-warning-issued-for-storm-eunice).

Friday 18th February 2022; the day of Storm Eunice

- A second very rare red weather warning was issued at 03:44 UTC (Figure 35) covering parts of south-east England including London and coincided with a third Met Office New Release which was published at 04:27 UTC (https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2022/red-weather-warnings-in-force-for-storm-eunice).

What information was provided to emergency responders, government and other stakeholders about the hazard and its possible impact(s), and by whom? i

Public warnings i

Warning name	Icon / colour	Lead time	Frequency	Issued by i	Warning area i	Type of warning i	Did it include safety advice?	Scaled i	Channels i
Wind warning	Yellow	4-days (Issued at 10:19 UTC on 14th February 2022)	NA	Met Office	All of England, Wales, Northern Ireland, and southern parts of Scotland.	Impact warning	No	Low likelihood of high impacts.	Met Office website and app, social media, TV, Radio.
Wind warning	Amber (superseding the yellow warning issued on 14th February)	2-days (Issued at 10:40 UTC on 16th February 2022)	NA	Met Office	Central and southern parts of England as well as all parts of Wales.	Impact warning	No	Medium likelihood of high impacts	Met Office website and app, social media, TV, Radio.
Wind warning	Red	1-day (Issued at 10:50 UTC on 17th February 2022)	NA	Met Office	Parts of south-west England and south Wales.	Impact warning	No	High likelihood of high impacts	Met Office website and app, social media, TV, Radio.

Wind warning	Red	0-day lead time (Issued at 03:44 UTC on 18th February)	NA	Met Office	Parts of south-east England including London.	Impact warning	No	High likelihood of high impacts	Met Office website and app, social media, TV, Radio.

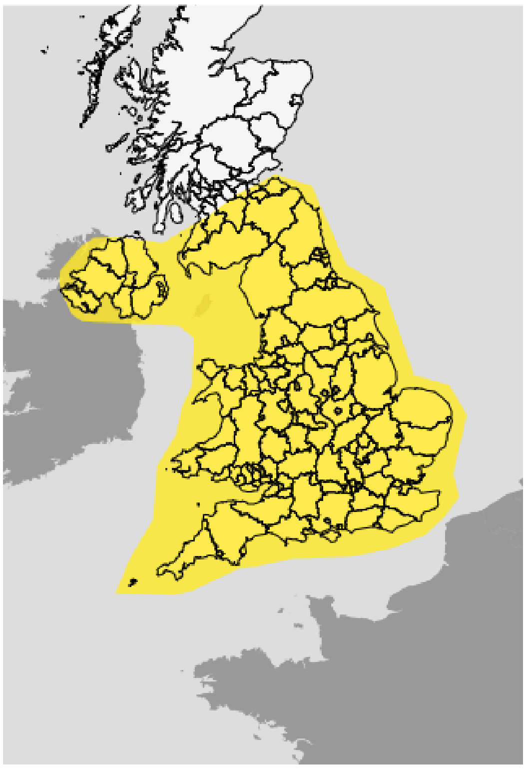
How was warning information communicated by other organizations including media? i

As soon as warnings were issued, the cascade of information took place. For example, warnings immediately appeared on the Met Office website and app. This included thousands of email alerts being sent out to people who have registered as well as alerts being sent out to the Met Office app users. The Met Office warnings were also automatically displayed on the BBC weather website and app. Media outlets published Met Office weather warnings on their web pages as part of wider news stories on Storm Eunice. This was done through embedding Met Office tweets of warning areas and presenting screenshots of the warnings from the Met Office website. Issuance of the red warnings led to breaking news stories on the 24-hour news channels including breaking news alerts being sent out to those people with news apps on their phones. The BBC One national TV news also ran with the red weather warning as its headline on 17th February (Figure 36), which would have reached millions of people.

Warning outputs and examples i

Yellow warning
Wind

Between
00:00 Fri 18 Feb 2022 and
21:00 Fri 18 Feb 2022



Storm Eunice is likely to affect the UK on Friday bringing a period of very strong winds that could cause significant disruption.

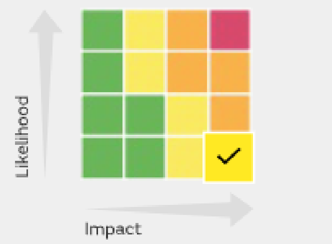
What to expect

- There is a small chance that flying debris will result in a danger to life, with fallen trees, damage to buildings and homes, roofs blown off and power lines brought down
- There is a small chance that injuries and danger to life could occur from large waves and beach material being thrown onto sea fronts, coastal roads and properties
- Where damaging winds occur, there is a chance that long interruptions to power supplies and other services may occur
- There is a small chance that roads, bridges and railway lines could close, with long delays and cancellations to bus, train, ferry services and flights

Further details

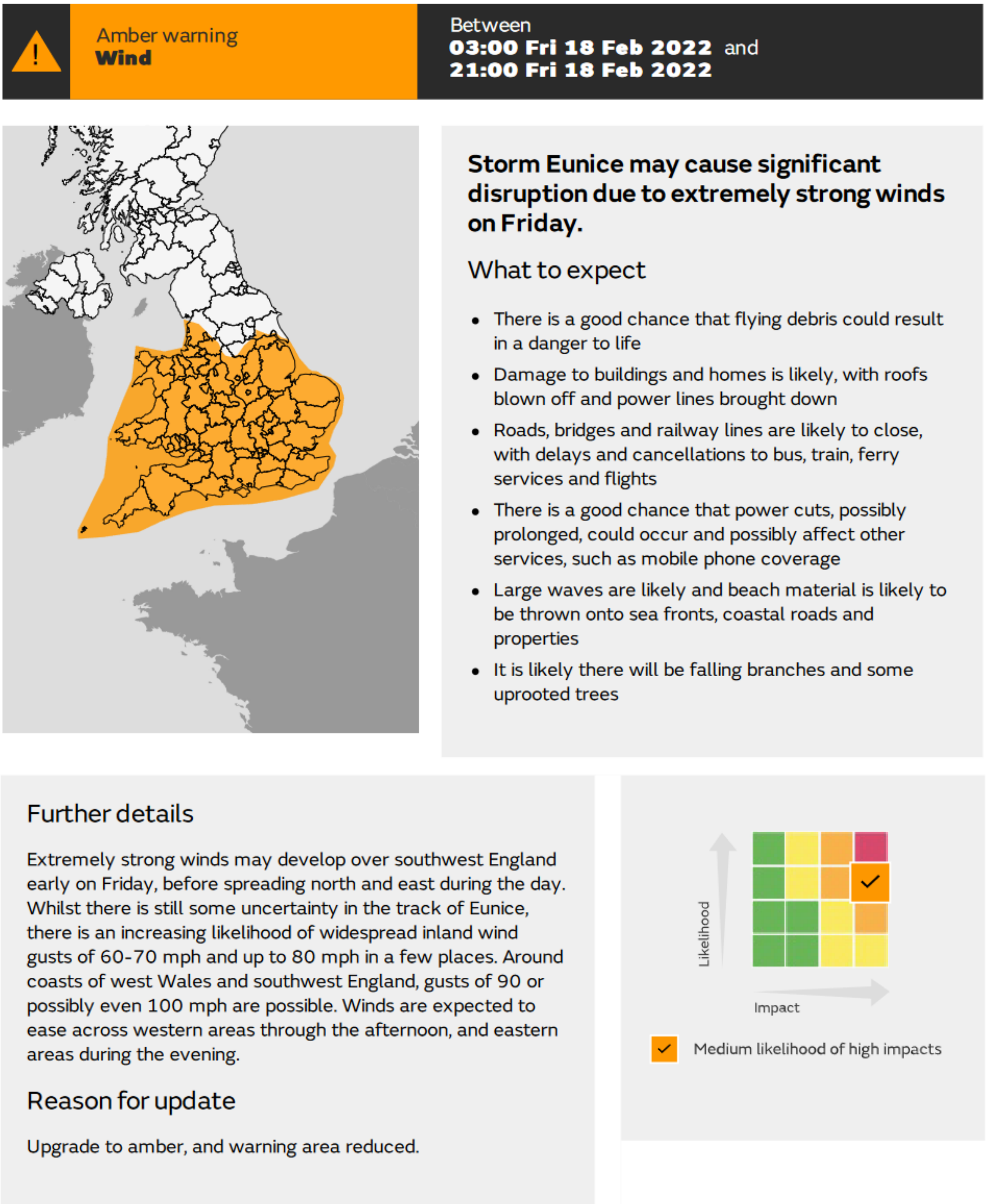
Extremely strong winds may develop over southwest England early on Friday, before spreading north and east during the morning. It is not yet clear where within the warning area the strongest winds will be but gusts of 60-70 mph are possible over a reasonably large area with a small chance of a brief period of gusts reaching 80 mph even inland. Coastal winds are likely to be the strongest.

In addition to the wind, there is the potential for a period of snow and perhaps blizzard conditions, most likely over northern England, parts of Scotland, Northern Ireland and north Wales. However, this is very dependant on the track of the weather system and most places will see heavy rain instead.



Very low likelihood of high impacts

Figure 32. First yellow weather warning (Issued at 10:19 UTC on 14th February 2022). Source: Met Office.



Amber warning
Wind

Between
03:00 Fri 18 Feb 2022 and
21:00 Fri 18 Feb 2022

Storm Eunice may cause significant disruption due to extremely strong winds on Friday.

What to expect

- There is a good chance that flying debris could result in a danger to life
- Damage to buildings and homes is likely, with roofs blown off and power lines brought down
- Roads, bridges and railway lines are likely to close, with delays and cancellations to bus, train, ferry services and flights
- There is a good chance that power cuts, possibly prolonged, could occur and possibly affect other services, such as mobile phone coverage
- Large waves are likely and beach material is likely to be thrown onto sea fronts, coastal roads and properties
- It is likely there will be falling branches and some uprooted trees

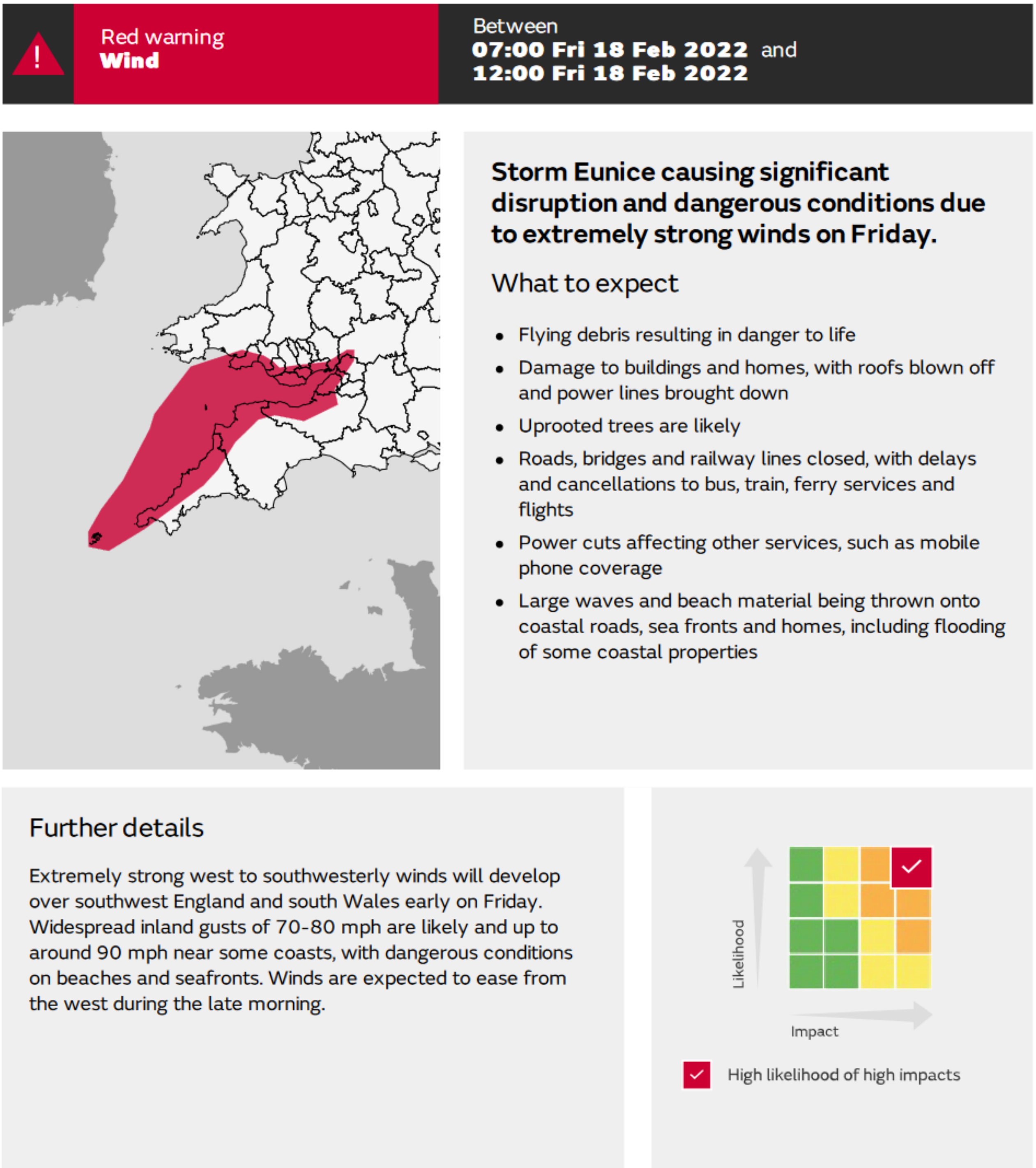
Further details

Extremely strong winds may develop over southwest England early on Friday, before spreading north and east during the day. Whilst there is still some uncertainty in the track of Eunice, there is an increasing likelihood of widespread inland wind gusts of 60-70 mph and up to 80 mph in a few places. Around coasts of west Wales and southwest England, gusts of 90 or possibly even 100 mph are possible. Winds are expected to ease across western areas through the afternoon, and eastern areas during the evening.

Reason for update

Upgrade to amber, and warning area reduced.

Figure 33. First amber weather warning (Issued at 10:40 UTC on 16th February 2022). Source: Met Office.



Red warning
Wind

Between
07:00 Fri 18 Feb 2022 and
12:00 Fri 18 Feb 2022

Storm Eunice causing significant disruption and dangerous conditions due to extremely strong winds on Friday.

What to expect

- Flying debris resulting in danger to life
- Damage to buildings and homes, with roofs blown off and power lines brought down
- Uprooted trees are likely
- Roads, bridges and railway lines closed, with delays and cancellations to bus, train, ferry services and flights
- Power cuts affecting other services, such as mobile phone coverage
- Large waves and beach material being thrown onto coastal roads, sea fronts and homes, including flooding of some coastal properties

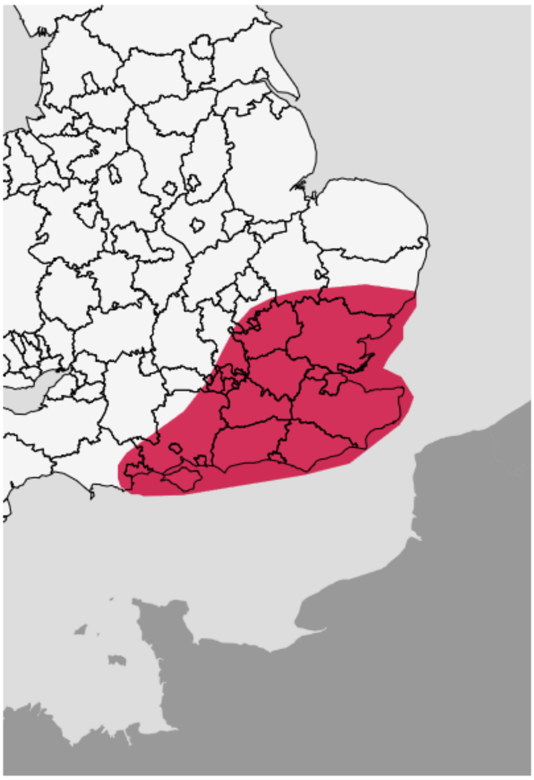
Further details

Extremely strong west to southwesterly winds will develop over southwest England and south Wales early on Friday. Widespread inland gusts of 70-80 mph are likely and up to around 90 mph near some coasts, with dangerous conditions on beaches and seafronts. Winds are expected to ease from the west during the late morning.

Figure 34. First red weather warning (Issued at 10:50 UTC on 17th February 2022). Source: Met Office.

Red warning
Wind

Between
10:00 Fri 18 Feb 2022 and
15:00 Fri 18 Feb 2022



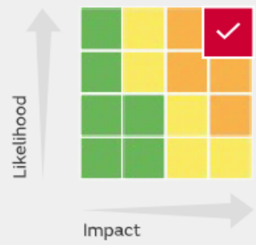
Storm Eunice causing significant disruption and dangerous conditions due to extremely strong winds on Friday

What to expect

- Flying debris resulting in danger to life
- Damage to buildings and homes, with roofs blown off and power lines brought down
- Roads, bridges and railway lines closed, with delays and cancellations to bus, train, ferry services and flights
- Power cuts affecting other services, such as mobile phone coverage
- Large waves and beach material being thrown onto coastal roads, sea fronts and homes

Further details

Extremely strong west to southwesterly winds will develop mid morning on Friday, transferring eastwards across southern and southeast England through the middle of the day then slowly easing from the west during the afternoon. Gusts of 60-70 mph are likely widely, perhaps briefly 80 mph in a few places, mainly on English Channel coasts.



High likelihood of high impacts

Figure 35. Second red weather warning (Issued at 03:44 UTC on 18th February). Source: Met Office.

Figure 36. A screen shot from the BBC One 6 O'clock national news, which had the headline running with the story about the recent issuance of the first red weather warning. Here the new presenter is showing the weather warning map. Source: BBC/YouTube (https://www.youtube.com/watch?v=fwu8PmdGCS8).

Comment on the use of uncertainty information in the warning i

Forecast uncertainty is given by the position of the weather warning within the weather impact matrix. The first warning (issued at a 4-day lead time) described the warning as a 'low likelihood of high impacts'. The likelihood level associated with subsequent warnings gradually increased, with the first amber warning issued at a 2-day lead time being described as having a 'medium likelihood of high impacts'. The final red warnings were then described as having a 'high likelihood of high impacts' and were positioned in the top-right hand corner of the matrix. The likelihood and impact levels are subjectively derived by the Met Office chief meteorologists on shift at the time following detailed analysis of the NWP output and specialised forecasting tools shown in this questionnaire. Chief meteorologists will also discuss optimal warning levels (with regards to likelihood and impacts) with Met Office regional civil contingency advisors as previously discussed in this questionnaire.

To what extent were communication systems in place and operating effectively? i

No issues were reported, and the cascade of information worked smoothly using well established channels. Various teams around the Met Office immediately swung into action to inform stakeholders and keep them updated with the latest information and data. The stakeholders are wide ranging and include UK Government, as well as the Governments in Scotland, Wales and Northern Ireland, the Environment Agency, Scottish Environment Protection Agency, local authorities and emergency services across the country, energy providers, road and rail operators, the Civil Aviation Authority, National Air Traffic Service, and airports including Heathrow. Not least of these were the Met Office civil contingency advisors whose efforts helped to mitigate the impacts of the storm in their various regions.

To what extent were warning messages received and understood by the public? i

Getting the message out accurately and clearly to as broad an audience as possible involved a multi-channel approach and support from Met Office staff in both the digital and communications and engagement teams. The resulting statistics were collated by the Met Office Digital team and provide some phenomenal figures as to the reach of the Met Office warnings:

- During Storms Dudley and Eunice, the Met Office website saw 4.55M unique visitors.
- The Met Office website had a peak of 687k visitors per hour during Storm Eunice.
- The Met Office app warning details pages were viewed 5.6 million times during Storm Eunice.
- On social media, over the week of the three named storms:
    - The Met Office main Twitter feed received 27 million impressions.
    - The Met Office Facebook site reached 7.5 million people.
    - The Met Office TikTok received over 5.4 million video views.
    - The Met Office YouTube channel reached 1.5 million views.

The Met Office also commissions post-event surveys for most amber and red weather warnings which assess the reach and response taken by members of the public. The statistics are analysed and used to improve warning in the future. According to post-event surveys for Storm Eunice (Figures 37 and 38), 99% of people within the red warning area in the southeast were aware of the warnings, while 98% of those within the red warning area in southwest England and south Wales knew about the warning. This also resulted in 89% and 91% of people respectively taking action as a result, which suggests that the warnings were well understood. These surveys typically survey around 500 people from the warning regions across a range of demographics and are conducted via telephone and internet. This sample size makes the results statistically significant at the 95% confidence level.

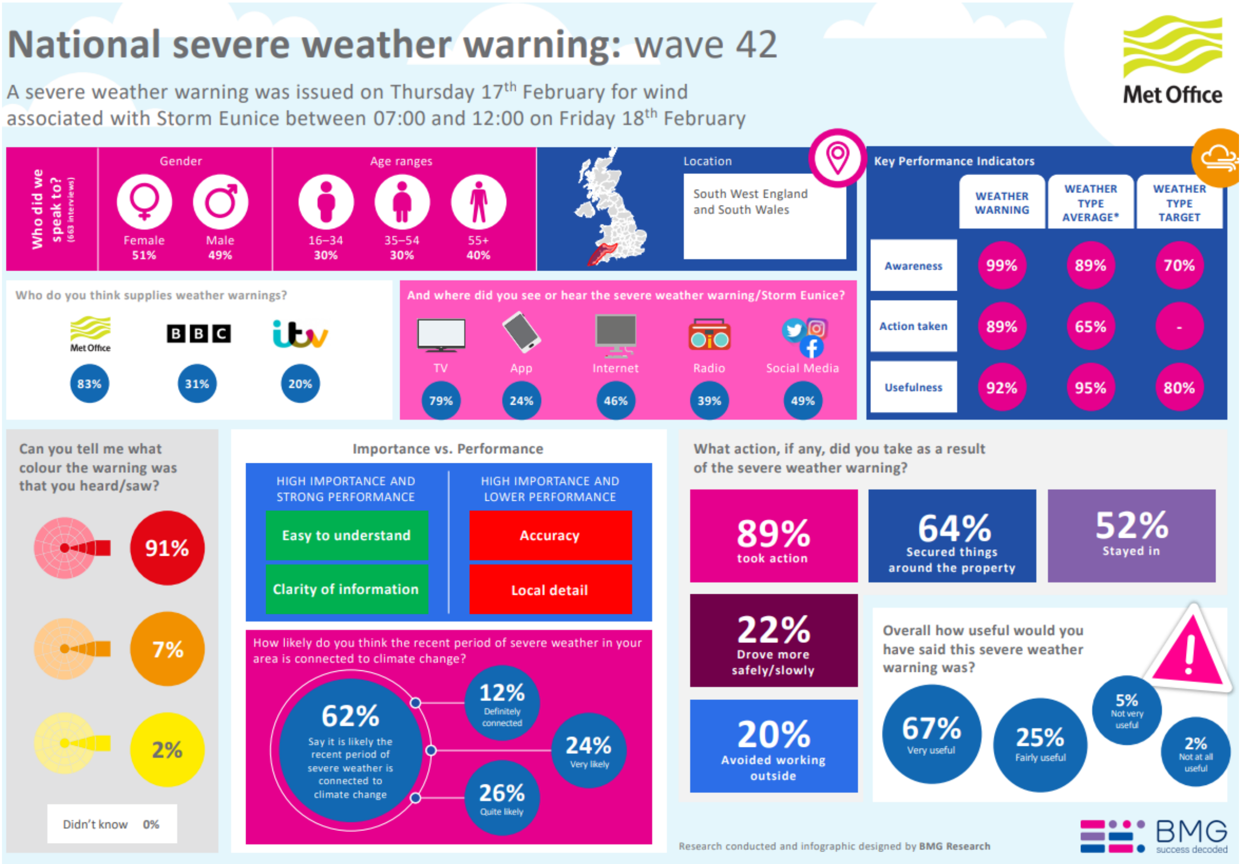


Figure 37. Results from the SW England / South Wales red wind warning post event survey carried out by BMG Research on behalf of the Met Office. Source: Met Office / Lesley Barratt.

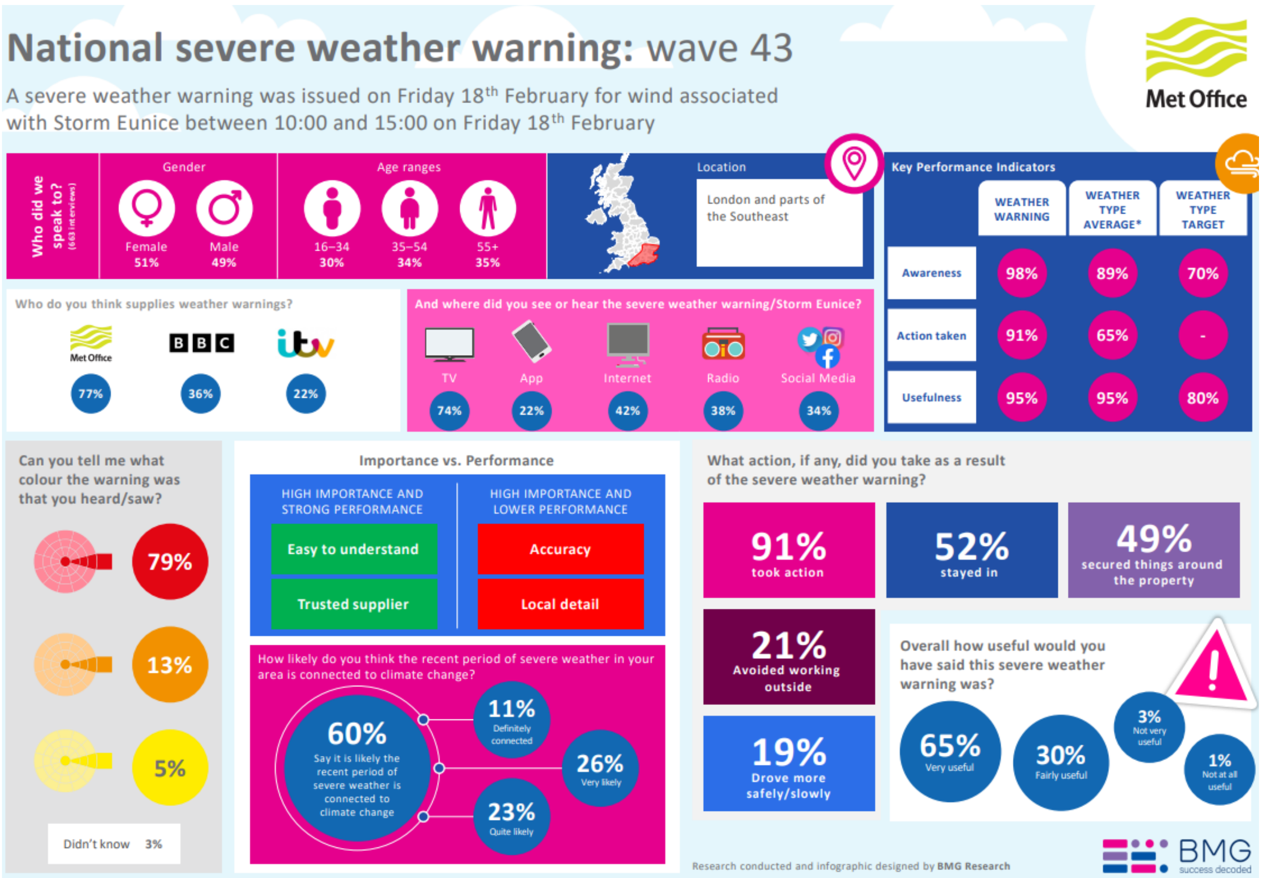


Figure 38. Results from the SE England / London red wind warning post event survey carried out by BMG Research on behalf of the Met Office. Source: Met Office / Lesley Barratt.

To what extent was crowdsourcing/citizen science used for warning dissemination? i

Not applicable.

Comment on how the needs of specific communities and populations were addressed i

New communication channels were employed for the first time, extending the reach of the warnings to new audiences, particularly those in the younger demographic. This involved utilising TikTok (see example in Figure 39), live Twitter Spaces and Instagram Live featuring our presenters and representatives alongside partners such as Energy Network Association (ENA) and RNLI. Meanwhile the Press Office received over 1000 emails, sent out 9 press releases and arranged over 30 national broadcast interviews (details from a Met Office internal communication to staff after the event).

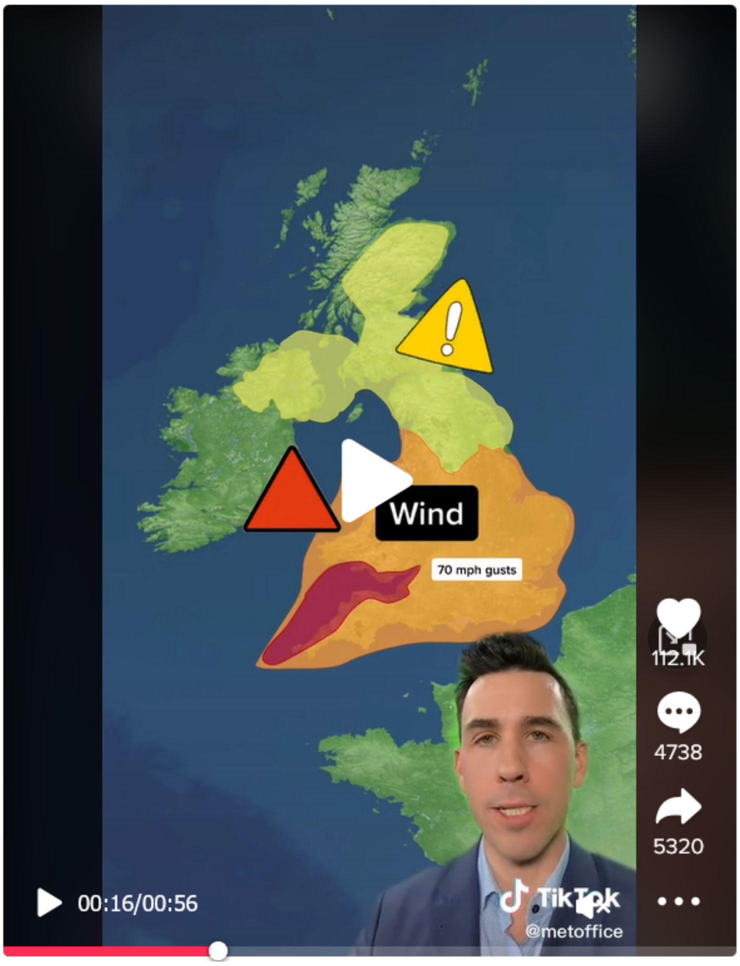


Figure 39. Example Met Office TikTok video with over 100,000 views. View the video at https://www.tiktok.com/@metoffice/video/7065774596615605510?is_from_webapp=v1&item_id=7065774596615605510 (Source: Met Office / TikTok).

Additional analysis i

Nothing to add.

Communication success/issues/challenges experienced i

The communication of the warnings was very successful as measured by the extensive reach across a wide range of channels. The Met Office post-event surveys for Storm Eunice (Figures 37 and 38) showed that 99% of people within the red warning area in the southeast were aware of the warnings, while 98% of those within the red warning area in southwest England and south Wales knew about the warning. This also resulted in 89% and 91% of people respectively taking action as a result.

One challenge came with communicating the likelihood and impact level of the warnings, as typically members of the public and the media focus on the warning colour only due to time constraints. However, the responder community and Met Office partners have more time to delve into the details of the warning and also have a better understanding of how Met Office warnings are derived. This communication issue may be partly down to the way warnings are presented and partly down to education. For example, the Met Office website and app present warning colours at the top level and drilling down reveals the warning map. There is then a further link which needs clicking (typically under 'further information') which reveals the warning impact matrix (as in Figure 23), hence making it easy to miss. In addition, the BBC weather website (which also gets many views) takes a direct feed of Met Office weather warnings, and although the warning colour and region is displayed prominently (excluding a map), the matrix is not shown at all.

Part 2e. Supplementary information about responses

Editors (Robert Neal and Helen Titley, Met Office, Exeter, UK):

Brief overview of the response to the hazard by emergency services and other partners i

There are many examples of mitigating action emergency responders and other partners took in response to the issued warnings. As the warnings were issued with relatively long lead time (the first yellow warning had a 4-day lead time) there was no sense of panic with enough time to respond and take action where necessary. For example, the Environment Agency erected coastal flood defences along vulnerable coastal stretches of the Bristol Channel (Source: Flood Forecasting Centre), many local councils stopped refuse collections in the areas forecast to be worst affected, some schools closed in advance and some road closures were put in place. In addition, several hundred flights in the UK were cancelled in advance with London Luton Airport choosing to close completely for a limited period due to the risk posed from forecast strong cross winds. Also, authorities closed the Port of Dover temporarily to all shipping and the Humber bridge (north-east England) and both Severn bridges (linking England to Wales) were closed for the first time in their history. References for all these responses are provided in the 'observed impacts' section above.

Specific comments from one of the Met Office partners responsible for the national road network is given below. Here, Melanie Clarke, Customer Service Director (Operations) for National Highways, said:

> *"Storms Dudley, Eunice, and Franklin were some of the worst storms experienced in decades and certainly provided us with challenging conditions across our network of motorways and major A roads. Even though a lot of people heeded our advice not to travel, our army of traffic officers, control room operators and winter service teams were incredibly busy, keeping roads gritted, responding to incidents, and ensuring our network of motorways and major A roads remained safe."*

What were the main response actions by the public to the warnings? i

The public responded very well to the warnings with many changing their travel plans as a result. For example, the timing of the storm coincided with a typical working day in February, and as such, many office workers chose to work from home. This response and more resulted in over a fifth less traffic on the roads in England compared to normal as described by a Met Office blog published on 30th June 2022 (https://blog.metoffice.gov.uk/2022/06/30/over-a-fifth-less-traffic-on-the-roads-thanks-to-storm-eunice-warnings/). This reduction in traffic also helped to ease the burden on the Royal Automobile Club (RAC) breakdown crews, who experienced a 16% reduction in callouts across the UK than would typically be expected in a day. It was a 34% reduction in callouts for Wales alone.

Figure 40 illustrates the impacts of the huge response from the public with regards to the reduced travel described above, by comparing the number of road travel impacts between 17th February 2022 (a relatively calm day weather wise) and 18th February 2022 (the day of Storm Eunice). For example, there was a large reduction in vehicle recoveries, the number of broken-down vehicles was reduced, and the number of weather-related accidents increased by only a very small margin. The amount of road or carriageway management increased over four-fold, showing the massive authority response to the warnings. Even with this large reduction in travel, vehicle overturning increased six-fold even though the number of journeys was less, but it would have been much worse without the response to the warnings.

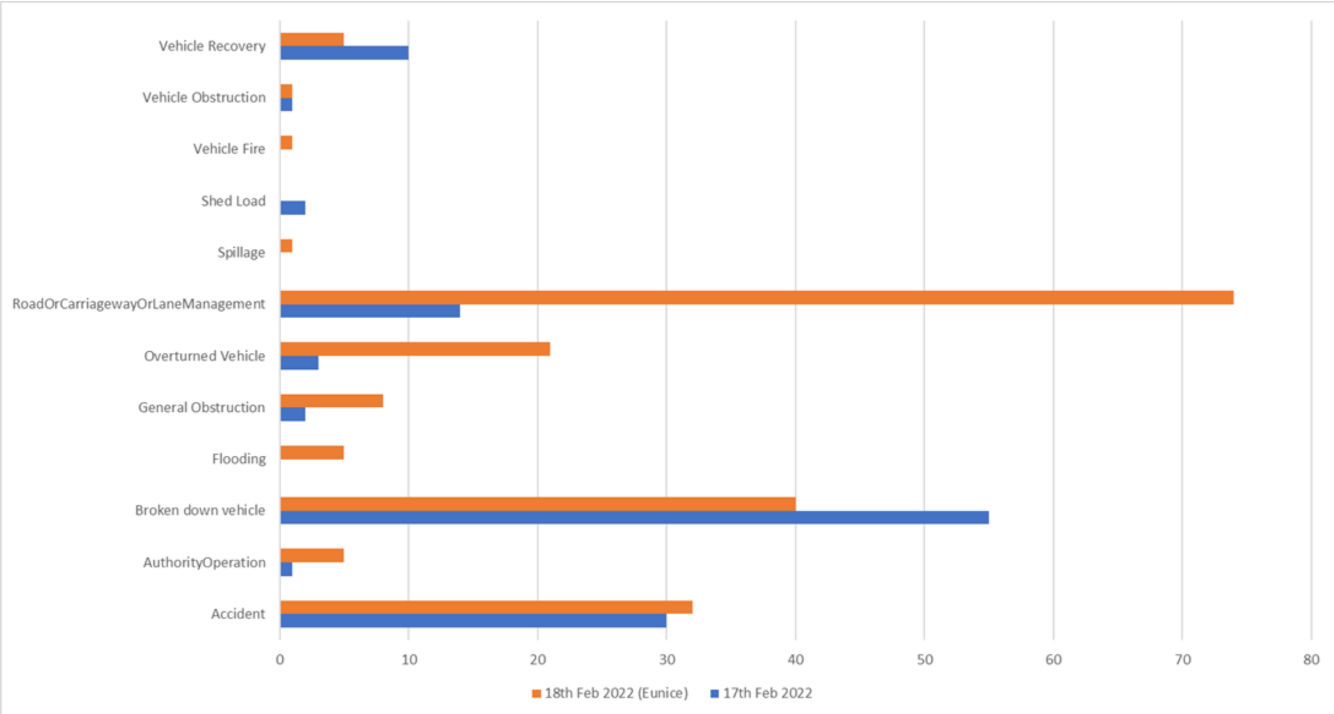


Figure 40. Count of road incidents over 24 hours for 17th February 2022 vs. 18th February 2022. Scraped from the Highways England RSS Feed (https://nationalhighways.co.uk/travel-updates/traffic-information-rss-feeds/) for all current incidents. Source: Met Office / Faye Wyatt.

Institutional responses to the warnings i

Response actions	Taken by whom	When taken	On the basis of what information?	Benefit (if any)	Cost
Closure of airports	National Air Traffic Services (NATS)	A day before and on the day of the event	Increasing confidence in strong winds and in particular strong cross winds on runways.	Avoids too many people arriving at the airport only to have their flights cancelled. It avoids the disruption of last-minute cancellations and allows customers to rebook their flights from home. It also reduces the likelihood of having planes in the wrong place at the wrong time and allowing for alternative plans to be put in place.	Knock-on disruption to customers and the cost they entail. Costs to airports and airlines of not always having the planes in the right places at the right times.
Closure of some roads and bridges	The highways authorities, e.g., Highways England	On the day of the event.	Increasing confidence in strong winds and in particular strong cross winds on roads. Closures were enforced as late as possible to reduce the amount of disruption following the close monitoring of weather observations.	A reduction in the amount of traffic on the roads in general as people are less likely to travel knowing that some routes are already closed. A reduction in the number of overblown vehicles and the knock-on disruption that would cause.	Costs to members of the public and businesses who need to use the roads and bridges for important journeys.
Temporary closure of the Port of Dover to all shipping	Port of Dover authorities.	On the day of the event.	Increasing confidence in strong winds and in particular strong cross winds on roads. Closures were enforced as late as possible to reduce the amount of disruption following the close monitoring of weather observations.	The general safety of passengers who may be more likely to fall over and suffer injuries on choppy crossings over the English Channel. In addition, there is a safety consideration when large ships and ferries are docking in port during exceptionally strong winds.	Costs to businesses who are unable to deliver their goods on time. Costs to the public who may have to stay over in hotels or rebook their travel.

School closures	Local school leaders	One day before and on the morning of the storm.	Issuance of the red weather warnings.	This allowed for a reduction in the number of high-side school buses on the roads during the peak of the storm as well as a general reduction in school children out and about during the peak of the winds.	Few costs as such other than impacts on parents who then need to stay at home to look after their children and support them in remote learning.
Refuse collection cancellations	Local councils	One day before the storm.	Issuance of the red weather warnings.	Less debris outside peoples' homes which may otherwise be blown about in the wind causing a hazard. In addition, it reduced the number of refuse collections needed during the peak of the storm meaning less refuse workers needed to work in potentially unsafe conditions.	Overtime costs for local councils as they have to play catch-up on refuse collections – e.g., by working over the weekend.

How did the overall response to this event compare to similar previous events? i

According to the Met Office post-event survey of over 600 members of the public, 89% of people surveyed took some sort of action in the southwest region warning area (Figure 37) and 91% of people surveyed took some sort of action in the southeast (London) region warning area (Figure 38). This compares to between 41 and 87% of people for all other surveyed red warnings since 2011 (Table 1), which totals three other warnings. This makes this the most successful pair or red weather warnings in terms of response since records began in April 2011 when the impact-based warning service was first introduced.

Table 1. The Met Office commissioned post-event survey results for all other red weather warnings since April 2011, excluding Storm Eunice. Source: Met Office, Lesley Barratt.

Area Surveyed	Agency	Level	Sample Size	Methodology	Old Wav	Wav	Survey	Awareness	Usefulness	Action Take	Target Awareness	Target Usefulness
S Wales, Herefordshire & Worcest	GfK NOP	Red	503	Telephone	37	6	Feb '14 Wind	90%	94%	41%	70%	85%
South West England and Wales	DJS	Red	500	Telephone	54	23	March '18 Snow and Winc	100%	98%	87%	80%	85%
E Scotland and NE England	BMG	Red	520	O/D/T	70	40	Nov '21 Wind #Arwen	97%	97%	87%	70%	85%
SW England and S Wales	BMG	Red	518	O/D/T	72	42	Feb '22 Wind #Eunice1	99%	92%	89%	70%	85%
London, SE and East England	BMG	Red	663	O/D/T	73	43	Feb '22 Wind #Eunice2	98%	95%	91%	70%	85%

Comment on the existence and use of disaster preparedness and response plans i

The UK is very used to experiencing strong winds with its locality in northwest Europe, making it very exposed to North Atlantic cyclones. However, the intensity is rarely high enough to implement pre-prepared disaster and response plans as seen in other countries such as the US where destructive hurricanes can be an annual feature. Therefore, wind events over the UK tend to be dealt with at the local level.

How did the key decision makers and institutions interact before, during and after the event?

The editors of this section don't have enough information at the time of writing to answer this question.

How knowledgeable was the community about the hazard and its associated risks? i

The UK public are used to experiencing storms, particularly during the winter months, and so they have a good understanding as to the actions required in the run up to a storm. This includes tying down loose objects outside including trampolines and avoiding walking in wooded areas or near large trees during high winds, as well as taking extra care when at the coast due to dangers posed by large waves and storm surges.

What capacity did the community have to respond to warnings? i

Emergency responders and government agencies are well used to taking action as a result of Met Office warnings and will mostly have pre-arranged plans and resources in place (e.g., for the closure of roads or bridges and the erection of flood defences). The public also has a good level of capacity to take mitigation action, particularly where the cost is very minimal, e.g., through working from home (where this is possible) and tying down loose objects in the garden or avoiding putting out rubbish/recycling for collection. The statistics from the Met Office post-event survey back this up, where around 90% of people interviewed said they took some sort of action as a result of the warnings (Figures 37 and 38 and Table 1).

Additional analysis i

Nothing to add.

Success/issues/challenges experienced i

The response by the public, as well as local and national resilience groups, was very good and this was aided by early, accurate forecasts and warnings, with Storm Eunice being named four days before it struck. Will Lang looks after managing severe weather events within the Met Office. He said:

> *"While no one wants severe weather to impact their plans, it was vital for everyone's safety that the public listened to the warnings and understood the risks during this week of impactful weather for the UK. We're very pleased that our early warnings helped people make arrangements to avoid taking to the roads during Storm Eunice. Without the reduction in traffic, the impacts on the roads could have been much worse."*

However, some responders in the southeast region provided feedback to the Met Office regional civil contingency advisor for that area that the late issuance of the red warning there at 03:44 in the morning (Figure 35), made it more difficult for them to change their response. This meant the response remained at the 'amber level' however they had factored in the potential for high impacts the previous day given the proximity of the warning within the weather impact matrix. In the Met Office's defence, forecast confidence was not high enough to issue a red warning any earlier as there was a lot of uncertainty in how the storm would continue to develop once it moved into the southwest and tracked east.

Part 2f. Analysis of the warning chain

Editors (Robert Neal and Helen Titley, Met Office, UK):

Information flow through the warning chain i

Warning chain	Was all necessary input information available? (yes/partially/no)	If not or partially available, what input information was missing?	Who should have provided the missing information?
Weather forecast	Yes		
Hazard forecast	Yes		
Impacts forecast	Partially	We were missing forecasts for wind impacts on trees, trains, power lines and buildings.	Further research and development are needed to develop these models, which could be carried out by Met Office scientists and their academic partners.
Warning communication	Yes / Partially	Warning communication was very good, with the initial yellow warning being issued as a low likelihood warning within the high impact column of the weather impact matrix. This allowed for further escalation of the warning within the same impact column. However, the impact level of the warning was not communicated to the same level as the warning colour, therefore increasing the chances of someone dismissing the warning as being insignificant.	The information on the matric location was provided to responders and the public. However, on the Met Office website the matrix is hidden away behind a link meaning that many people can miss this additional valuable information.
Warning response	Partially	Impact and response information was collected by Met Office regional contingency advisors and discussed at a post-event wash-up meeting. However, the archiving of this impact information is fairly ad-hoc and within PowerPoint slides making it difficult to access and interrogate. The impact information is also missing references in places.	The Met Office regional contingency advisors and Met Office teams involved in the post-event analysis.

Tools and operational workflows for sharing information between partners i

NA

How useful were social media/crowdsourcing/citizen science in the warning chain? i

Social media was extensively used to help increase the reach of the Met Office warnings. For example, the Met Office Twitter channel had over 27 million impressions during the week of the three named storms (including Eunice). See the Warnings section for more information.

Crowdsourcing had a small amount of use during the storm itself, in terms of viewing unofficial weather observations on platforms such as the Met Office Weather Observations Website (WOW). Impact observations were also crowdsourced after the event as part of the post-event analysis. For example, see the section on Impact observations for an example of this on UK roads.

Evidence that warning chain was effective in reducing fatalities, injuries, damage, and/or disruption i

There is a lot of evidence of pre-emptive action based on the warnings as shown in other sections of this questionnaire, both by local authorities (e.g., closure of schools and cancellation of public transport) and the general public (e.g., ~90% of those aware of the warnings took some sort of action; Figures 37 and 38). However, it is less easy to quantify to what extent this reduced the number of fatalities, injuries, damage etc. without a detailed comparison to past wind hazards of similar magnitude.

However, one area where a comparison can be made is on the roads, where it can be sensibly inferred that the level of disruption there was less than would have otherwise been experienced had people not heard the warnings and avoided unnecessary travel as advised by the authorities. For example, the public's response resulted in a fifth less traffic on England's roads (https://blog.metoffice.gov.uk/2022/06/30/over-a-fifth-less-traffic-on-the-roads-thanks-to-storm-eunice-warnings/), with a 16% reduction in breakdown callouts across the UK and a 34% reduction in breakdown callouts in Wales alone. Figure 40 also illustrates some interesting road traffic statistics for the UK as a whole by comparing traffic volumes and disruption between the day of Storm Eunice and the previous day which was relatively calm weather wise. Here, it can be seen that there were only relatively small increases in weather related incidents which would have been much higher had many people not stayed at home.

Another area where a comparison can be made is through the number of fatalities, although reliably information is difficult to come by. Storm Eunice, which had early warnings and a large response, was linked to three fatalities across the UK (BBC News; https://www.bbc.co.uk/news/uk-60439651). Whereas the 'Burns Day' storm of 25th January 1990 which occurred at a similar time of day was linked to 47 fatalities, however this storm generally experienced wind gusts 10 to 15 kts higher than Eunice (Source: Met Office case study sheet athttps://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/weather/learn-about/uk-past-events/interesting/1990/burns-day-storm---25-january-1990---met-office.pdf).

What were the strongest links (information flow) in the warning chain? i

The weather to hazard forecast links were very strong, with a range of probabilistic information available to forecasters at the time. The rapid development of the storm meant that weather and hazard forecasts were particularly uncertain; however, the warning impact matrix helped here by allowing for the issuance of a four-day lead time warning in the high impact column, but which was attributed to low likelihoods.

The communication of the warning within the value chain is also deemed very strong as shown by the excellent reach and response to the warnings, both by the public and authorities. However, although the warning colour was communicated very well to the public (through multiple media channels), the position of the warning within the matrix tended to be missed. This is potentially very useful information to end users as it may enable them to respond better based on individual risk appetites and vulnerabilities. The matrix was however communicated well to the responder community who have a better understanding of how to act based on different forecast uncertainties and impacts.

What were the weakest links (information flow) in the warning chain? i

One of the weakest links may be between the weather/hazard forecast and the impact forecasts. This is partly due to the impact forecasting tools being non-operational and so data flows may not be supported. It is also likely the impact-based forecasting tools are not used regularly by meteorologists due to their general busyness when on shift and the need to focus their limited time on key elements of the weather and hazard. Many of the hazard forecasts are also unique in their presentation and so there is likely to be outstanding training needs for downstream users.

Another weak link may be through the process of collecting evidence of responses taken by authorities and the public. Data is collated post-event by Met Office regional contingency advisors, but this process is ad-hoc in its presentation with evidence tending to be presented in PowerPoint slides. This results in different ways of presenting the evidence making it harder to interrogate in the future and make comparisons to other warnings.

What procedures were used to identify lessons learned from the event? i

The Met Office commission post-event surveys for most amber and red weather warnings, which involve interviewing around 500 members of the public from a range of demographic to get an understanding of warning reach and response. For example, the statistics for Storm Eunice can be seen in Figures 37 and 38 showing a 98 to 99% reach and a 90% action rate, which is higher than previous events. These statistics along with evidence of responses collated by Met Office regional civil contingency advisors are discussed in 'wash-up' meetings following the event and any lessons learnt are discussed.

Comment on lessons learnt from previous events and their contributions to greater warning success for this event i

The Met Office changed the way they issue warnings in April 2011, moving away from threshold-based warnings which had no direct relationship to impacts and towards impact-based warnings which also include a likelihood component (as shown in the warning impact matrix; Figure 23). This has created much more flexibility in the way warnings are issued, for example by defining impacts at the local/regional level and by choosing whether to prioritise likelihood or impact. Where impact is prioritised (e.g., as in Storm Eunice), this allows warnings to be issued when the likelihood is still low, potentially increasing the lead time of warnings compared to the old approach.

Before Storm Eunice, the last red wind warning was valid on 12th February 2014 for parts of Wales and northwest England (Figure 41). This was the just before storm naming came in during the autumn of 2015. Storms are named when they have the potential to be associated with an amber or red warning (https://www.metoffice.gov.uk/weather/warnings-and-advice/uk-storm-centre/index), which means they are commonly named with the issuance of an early yellow warning as was the case with Storm Eunice. It is thought that storm naming has been one of the leading factors (alongside increased use of a range of communication channels) in improving the reach to members of the public of Met Office weather warnings. The Met Office post-event public surveys (introduced earlier) show that the 2014 red weather warning (before storm naming) reached 90% of people but only 41% of those aware took any action, possibly because they didn't understand the warnings enough. However, this compares to up to a 99% reach and ~80% action rate for Storm Eunice, highlighting the progress that has been made in the communication.

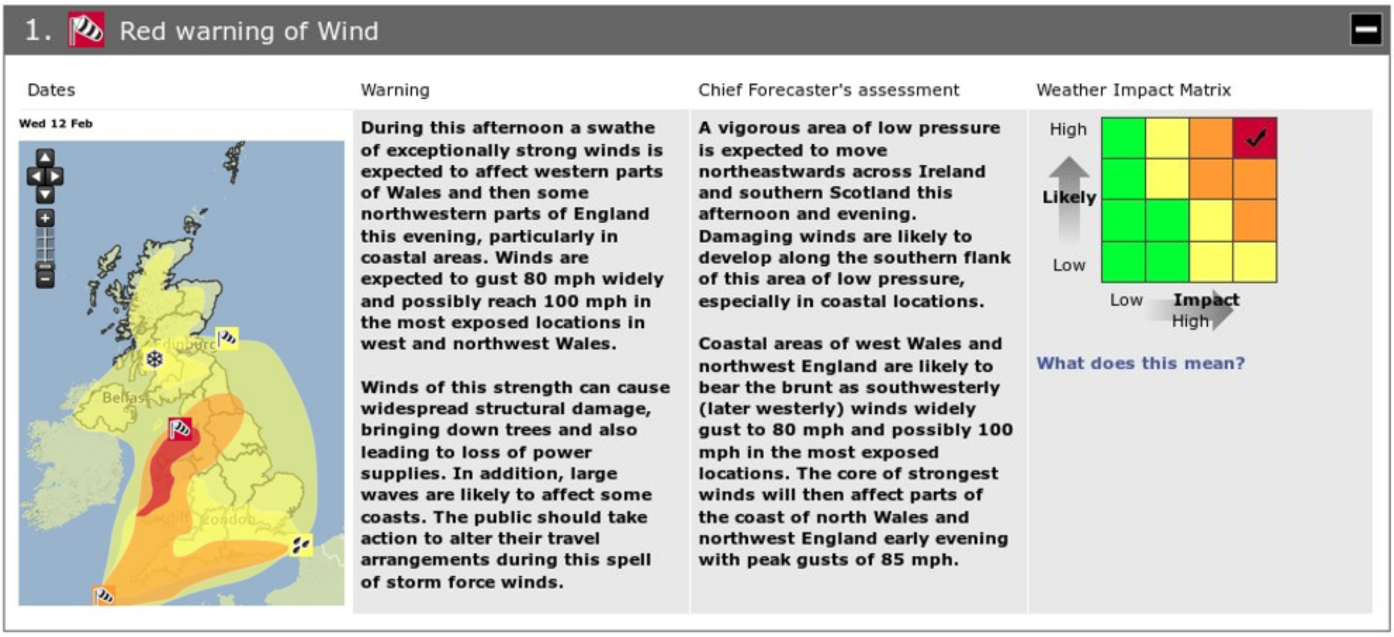


Figure 41. A red warning for wind valid on 12th February 2014, which is the most recent wind red weather warning before Storm Eunice.

Additional analysis i

Nothing to add.

Part 3. Assessment of the end-to-end warning chain

The assessment of the end-to-end warning chain was carried out by the Met Office Weather Impacts Science Team, whereby scores were averaged across members. Members of this team develop and maintain weather, hazard and impact forecasting tools for Met Office meteorologists and have expertise in a large number of the value chain components. Those members of the team who contributed towards the final scores given below were Robert Neal, Helen Titley, Brian Golding, Joanne Robbins, Caroline Jones, John Mooney, Seshu Kolusu and Faye Wyatt. The scoring was completed on 21st November 2022 after an extensive assessment of the evidence presented in this questionnaire.

Please rate your team's level of expertise on a scale of 1 (no expertise) to 5 (established expert) for:

Weather:	5
Hazard:	5
Impact:	5
Warning/communication:	5
Response:	4
High-impact weather event evaluation:	5

HOW SUCCESSFUL WERE THE FORECASTS, WARNINGS AND RESPONSES?

How well do you think the event was observed? *Scale of 1 (poor) to 5 (excellent)*
4.8 (Average of 5, 4, 5, 5, 4, 5, 5, 5)
Reason for this rating i

- This received the highest score of all value chain components due to the availability of a very comprehensive set of observations for use by the NWP models.

How well do you think the weather was forecast? *Scale of 1 (poor) to 5 (excellent)*
3.8 (Average of 4, 4, 3, 4, 4, 4, 3, 4)
Reason for this rating i

- This value chain component was given the lowest score of all components. However, it is still a good score, and it is worth noting that this was a very difficult event to forecast in general given the rapid cyclogenesis involved. The main reason for the lower score is due to the forecast uncertainties involved as explained below.
- The storm was not flagged until a 6-day lead time, and even then, the track was too far north. The track moved south at a 5-day lead time, however there was little confidence in the most likely track at this stage resulting in the storm naming and first warning only happening at a 4-day lead time.
- At a 2- to 3-day lead time the Met Office model was thought to have been over deepening the low and the ECMWF model was thought to have been producing a low that was too shallow. This also coincided with an under-dispersive MOGREPS-G ensemble, where all members had deep lows.
- Wind gust forecasts did not reflect the final observed magnitude until around a 2-day lead time.
- The deterministic models were the first to accurately forecast the observed wind gusts, but at these lead times there was still a majority of ensemble members forecasting lower wind speeds, which added to the overall forecast uncertainty and contributed towards the delayed issuance of the amber and red warnings.
- At shorter lead times it was difficult to get reliable wind gust forecasts, leaving some meteorologists to return to "first principles" analysing model profiles.

How well do you think the hazards were forecast? *Scale of 1 (poor) to 5 (excellent)*
3.9 (Average of 3.5, 4, 4, 4, 4, 4, 4, 4)
Reason for this rating i

- Hazard forecasting applications including EPS-W first-guess warnings, the ECMWF EFI and Cyclone tracking all identified the main hazard very well, but these systems rely heavily on input from the NWP, which had a number of limitations as discussed in the previous section. Although EPS-W represented the issued warning areas very well and ahead of the issued warnings, it was not used to draft the warnings as intended, but instead used to check the forecaster take on the warning areas.
- The IMPROVER (post-processed) probability maps for wind gusts in excess of 70 and 80 mph performed better than much of the raw model output in terms of representing both the event footprint and magnitude.

How well do you think the impacts were predicted? *Scale of 1 (poor) to 5 (excellent)*
4.1 (Average of 4, 4, 5, 4, 4, 4, 4, 4)
Reason for this rating i

- The impacts were very well predicted by meteorologists through good collaboration with the Met Office Regional Civil Contingency Advisors, who in turn had good contact with the responder community. This led to a good understanding of how the hazard may impact regions differently by considering factors such as the timing of the storm (which affected western parts in the morning rush-hour and eastern parts in the afternoon/evening rush-hour), population density and location of transport and energy networks. This forecasting practice is also well established at the Met Office, since the NSWWS became impact-based in April 2011.
- Automated hazard impact models (HIMs) such as the vehicle overturning model also provided good guidance. The main reason this section was not scored higher was because automated impact forecasts were missing on the risk of falling trees, which was a major impact of this storm.
- Finally, many of the impacts experienced were not a direct result of the hazard. For example, impacts were caused by pre-emptive mass closures of transport networks and the pre-emptive closures of schools, which are not accounted for in the impact-based forecasts.

How well do you think warnings were communicated? *Scale of 1 (poor) to 5 (excellent)*
3.9 (Average of 4.5, 3.5, 4, 4, 3, 3.5, 4, 5)
Reason for this rating i

- The warnings were communicated very well across a range of channels, which led to a very high reach of over 98% and over 89% of people took some sort of mitigating action as a result (according to Met Office post-event surveys).
- The use of the Storm naming helped differentiate the three high impact wind events with the general public, during what was several consecutive days of unsettled and stormy conditions.
- However, the maximum score of 5 was not reached because of the following reasons:
    1. More emphasis could have been placed on forecast uncertainties. For example, little time if any was given to communicating the information from the weather impact matrix. This information is available to the public, but it is hidden away below a number of clicks on the Met Office website. However, the matrix information was available more prominently to the responder community who have more training in its use.
    2. The second red warning was issued at 03:44 UTC (providing a 6 hour lead time for the arrival of the storm), resulting in limited communication channels at this time of day. The time of day and relatively late issuance also meant that changes in response from the responder community were limited.
    3. The initial yellow warning was issued within the high impact column of the matrix, but with low likelihoods. It is possible that more could have been made of this within the initial messaging of the warning.

How well do you think the warnings were used? *Scale of 1 (poor) to 5 (excellent)*

4.0 (Average of 4, 4, 5, 4, 3, 5, 4, 3)
Reason for this rating i

- The reach was excellent (at over 98%) and over 89% of people took some sort of mitigating action as a result of the warnings.
- There was an excellent response from the responder community including emergency services, transport companies (e.g., most rail services were cancelled during the peak of the storm) and highways authorities (with the closure of bridges).
- However, there was a lot of emphasis on warning colour at the expense of uncertainty and impact information. For example, the initial yellow warning may have been discounted by some as being insignificant until it was escalated to amber and red. However, the original yellow warning was still of note to vulnerable communities and infrastructure due to its positioning within the high-impact column of the weather impact matrix.
- In addition, some of the public and responders within the amber areas only changed their response once the warning went red, or once a red warning was issued nearby. For example, many schools in amber warning areas only chose to close once the first red warning was issued. This may be because the issuance of the first red warning generated additional publicity in the media and had the warning remained at amber then the overall response could have been less.

How well do you think the entire warning chain performed overall? *Scale of 1 (poor) to 5 (excellent)*
4.0 *(Average of 4, 4, 5, 4, 3, 5, 4, 3)*

This event scored very well overall, with all areas of the value chain scoring close to 4, with the exception of observations which scored close to 5. The warnings and response were very successful in reducing the number of direct impacts; however, the main reasons for not scoring 5 were due to (1) the forecast uncertainties from the NWP, (2) no availability of impact forecasts for falling trees, (3) relatively little mention of forecast uncertainties and impact levels within the warning communication (i.e., a focus on waring colour and area), and (4) the relatively late overnight issuance of the second red warning leaving very little time for any change in response.

General feedback on the value chain questionnaire and scoring process:

- The Met Office is a large organisation and so the questionnaire editors were fortunate in being able to draw on help from several colleagues when collating evidence. For example, information was readily available on the climatological context of the storm, written and video forecaster guidance was archived internally, and statistics were readily available on warning reach and response. This allowed sufficient evidence to be provided under all value chain components, which may be more difficult for smaller organisations, or for case studies which require coordinating evidence across several organisations.
- Although the quantity and quality of evidence was extremely good for this case study, the consequence of this was that it took several days to extract and interpret the most relevant examples. This level of time resource would not be sustainable if the process was to be repeated for several events, therefore a more slim-lined version of the questionnaire may be useful for more rapid assessments.
- Scoring was completed by eight members of the Met Office Weather Impacts Science Team who have good levels of understanding across most value chain components. However, the range of scores across team members still varied considerably (ranging from between 3 and 5 for many of the value chain components). This suggests that taking an average score across several people is a sensible approach due to the different ways evidence can be interpreted.
- We did not discus whether we should use whole of decimal numbers before completing the scoring as individuals. This resulted in some members scoring to the nearest whole number and others scoring to one decimal place. Had we agreed before then some members may have changed their score. We therefore recommend this is discussed before any future group scoring takes place.

- Finally, where possible, future group scoring exercises may benefit from using experts from across a range of specialist areas (e.g., at least one in each value chain component) to ensure the scoring is as fair as possible.

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Annex 1: *List of hazards adapted from the [UNDRR-ISC Hazard Information Profiles]()*

1. Convective-related
    - Downburst
    - Lightning (Electrical Storm) Thunderstorm

2. Flood
    - Coastal Flood
    - Estuarine (Coastal) Flood
    - Flash Flood
    - Fluvial (Riverine) Flood
    - Groundwater Flood
    - Ice-Jam Flood Including Debris Ponding (Drainage)
    - Snowmelt Flood
    - Surface Water Flooding
    - Glacial Lake Outburst Flood

3. Lithometeors
    - Black Carbon (Brown Clouds)
    - Dust storm or Sandstorm
    - Fog
    - Haze
    - Polluted Air
    - Sand haze
    - Smoke

4. Marine
    - Ocean Acidification
    - Rogue Wave
    - Sea Water Intrusion
    - Sea Ice (Ice Bergs)
    - Ice Flow
    - Seiche
    - Storm Surge
    - Storm Tides
    - Tsunami

5. Pressure-related
    - Depression or Cyclone (Low Pressure Area)
    - Extra-tropical Cyclone
    - Sub-Tropical Cyclone

6. Precipitation-related
    - Acid Rain
    - Rain
    - Blizzard
    - Drought
    - Hail
    - Ice Storm
    - Snow
    - Snow Storm

7. Temperature-related
    - Cold Wave
    - Dzud
    - Freeze
    - Frost (Hoar Frost)
    - Freezing Rain (Supercooled Rain)
    - Glaze
    - Ground Frost
    - Heatwave
    - Icing (Including Ice)
    - Thaw

8. Terrestrial
    - Avalanche
    - Mud Flow
    - Rockslide
    - Landslide

9. Wind-related
    - Derecho
    - Gale (Strong Gale)
    - Squall
    - Subtropical Storm
    - Tropical Cyclone (Cyclonic Wind, Rain [Storm] Surge)
    - Tropical Storm
    - Tornado
    - Wind

10. Environmental
    - Wildfires
    - Coastal Erosion