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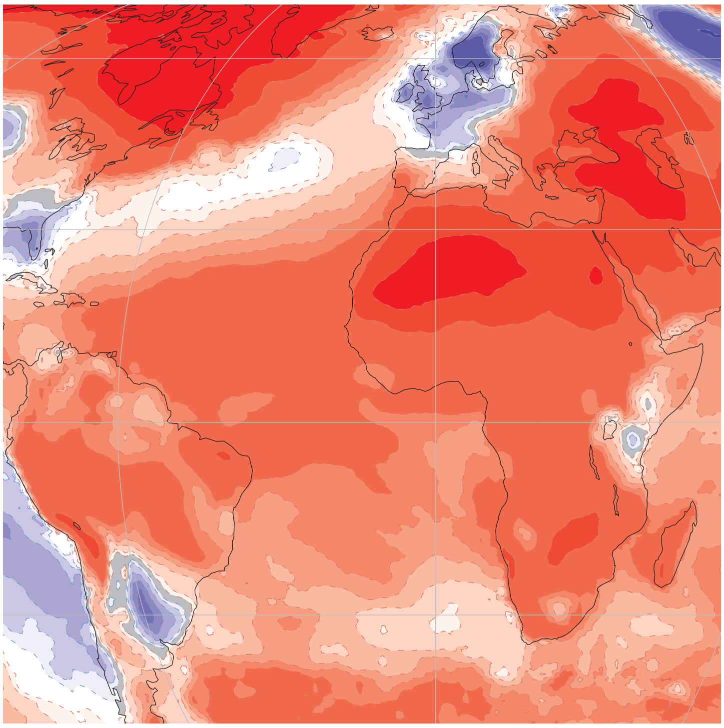
METEOROLOGY

Windstorms in northwest Europe in late 2013



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Windstorms in northwest Europe in late 2013

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The winter period of 2013/14 has been very active in terms of windstorms affecting northwest Europe. This article provides a short summary of two such storms, from 28 October (Christian) and 5 December (Xaver), and the handling thereof by the ECMWF IFS (Integrated Forecasting System). It is shown that for both storms IFS output provided an indication of high winds 5 to 6 days in advance. This is important because a key component of ECMWF's strategy is to provide Member States' National Meteorological Services with reliable forecasts of severe weather across the medium range.

Figure 1 shows a model-based estimate of areas where the 5-year return period of 24-hour maximum wind gust was exceeded for Christian and for Xaver. Here we have used ERA-Interim forecasts as a proxy for observations, with red squares denoting those grid points where maximum wind gust in the short-range (0–24 hour) forecast from ERA-Interim exceeded the 5-year return period value. Return period values were first estimated by fitting the generalised extreme value distribution to a 20-year block of annual maximum wind gust (again using 0–24 hour ERA-Interim forecasts). The results in Figure 1 suggest that in some locations these were indeed very rare events.

Whilst the representation of extreme gusts in windstorms in ERA-Interim suffers from resolution limitations, this issue can to some extent be circumvented by comparing model climate with model forecast, as we have done here. Indeed similar results are seen in real observations exceeding the 5-year event for Christian over Germany and the Netherlands, as computed by the 'European Climate Assessment and Dataset' (ECA&D).

28 October (Christian)

On 28 October a small but vicious windstorm hit northwest Europe, killing 19 people (8 in Germany, 5 in UK, 3 in the Netherlands, 2 in Denmark and 1 in France) and causing extensive disruption. The highest ever wind gust for Denmark was measured at Kegnäs on Als (53 ms^{-1}). The storm was named Christian by the Institute of Meteorology at Berlin's Free University, though other institutions have used alternative names including St Jude and Simone.

The cyclone first appeared, as a cold front wave, south of Nova Scotia late on 25 October. It then transferred rapidly east-northeast and deepened, with the centre moving into southern Sweden late on the afternoon of the 28th. According to the Met Office surface synoptic charts the 6-hour period of most rapid deepening was 06 to 12 UTC on the 28th (fall of 9 hPa), between eastern England and the eastern North Sea. It was during this period, and the subsequent few hours, that the strongest surface gusts were recorded, south of the track.

Figure 2e shows observed maximum wind gusts during the 28th (24-hour period). The band of very strong gusts started in Brittany in France and followed the English Channel and southern England, up through the southern North Sea and on towards Denmark, but with exceptional values reserved for northern parts of The Netherlands, northernmost Germany and southern Denmark. Strong wind gusts were also experienced along the Baltic Sea coasts. The surface pressure field around the storm at 12 UTC on 28th can be seen on Figure 2d (this is actually a 12-hour forecast, but is quite accurate).

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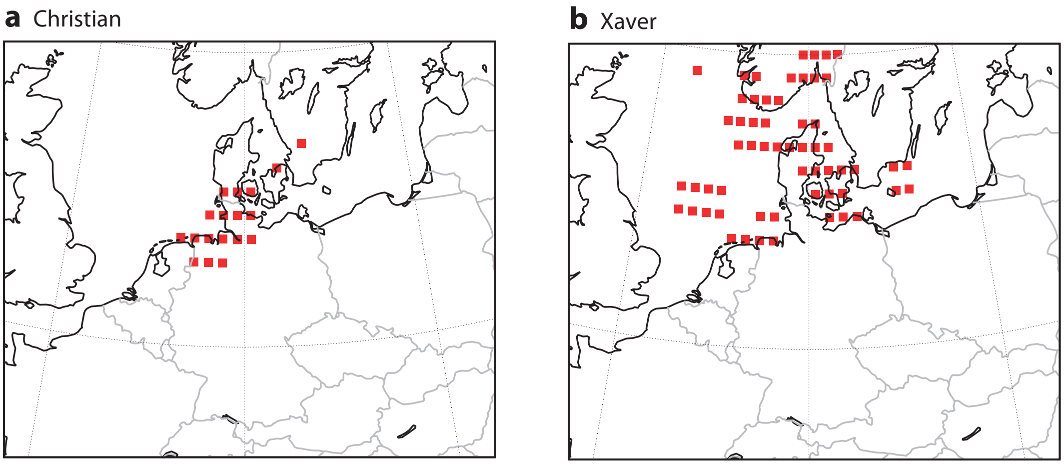

Figure 1 Areas exceeding the 5-year return period of 24-hour maximum wind gust for windstorms (a) Christian and (b) Xaver as diagnosed using the ERA-Interim reanalysis as a proxy for observations.

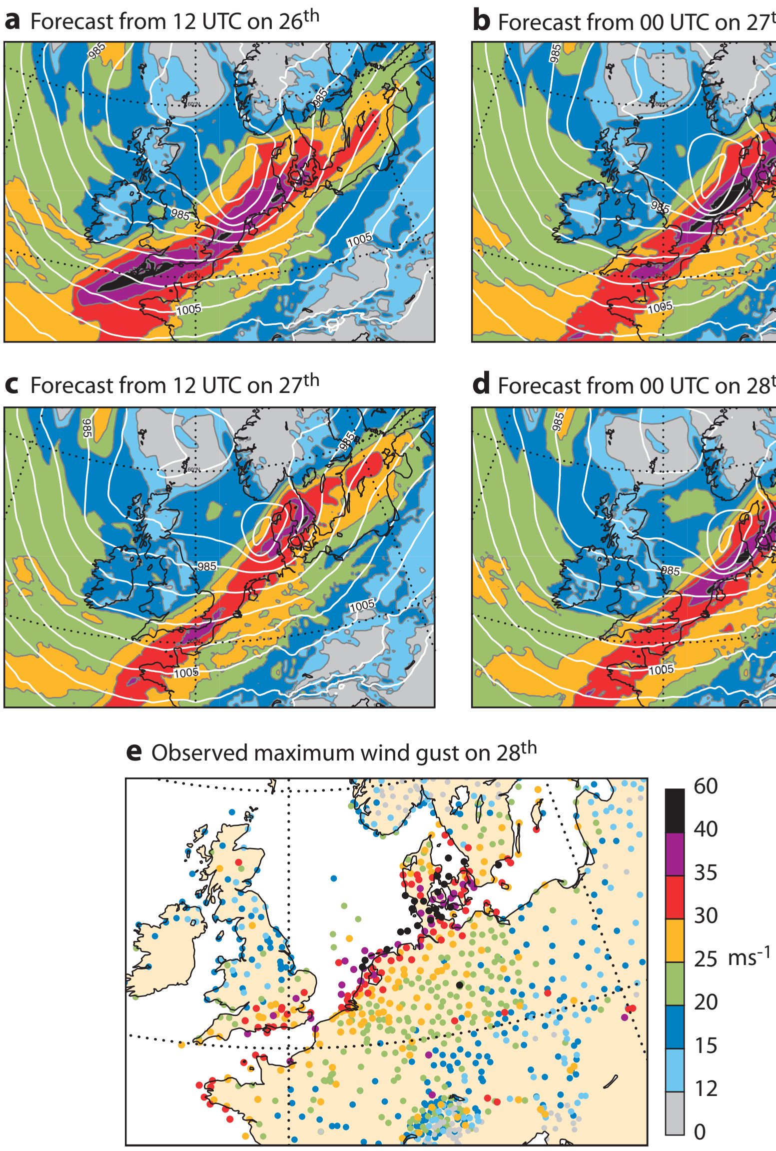

Figure 2 Forecasts of 24-hour maximum wind gust between 00 and 24 UTC on 28 October (shading) with the mean-sea-level pressure for 12 UTC on the 28th (contours) from HRES from data times (a) 12 UTC on 26 October, (b) 00 UTC on 27 October, (c) 12 UTC on 27 October and (d) 00 UTC on 28 October 2013. Panel (e) shows verifying data from observations.

High-resolution forecast

Figures 2a to 2d show the 24-hour maximum wind gust for the 28th from the high-resolution forecasts (HRESs) starting at 48, 36, 24 and 12 hours before 12 UTC on the 28th. HRES from 00 UTC on the 28th (Figure 2d) and 00 UTC on the 27th (Figure 2b) both agree well with observations. However, the forecast from in-between, from 12 UTC on the 27th (Figure 2c), is less good, showing less strong gusts in general, notably over the far north of the Netherlands. Meanwhile, forecasts from data times before 00 UTC on the 27th, whilst capturing peak intensity quite well, tended to develop the storm too soon, and as a result placed the strongest winds too far to the southwest, and often over the sea. The forecast from 12 UTC on the 26th (Figure 2a) is one such example – note the peak over and southwest of southwest England.

Preliminary investigations of observational data suggest that the most extreme winds associated with this windstorm were probably attributable to a 'sting jet' (after *Browning*, 2004). This is a very rare phenomenon comprising a pulsing stream of strong winds that can descend rapidly from within the cyclone's cloud head region. When this stream of strong winds hits the surface, very strong gusts can arise for short periods, with inland locations being especially vulnerable to major impacts. In numerical experiments it has been shown that high spatial resolution is necessary to predict this phenomenon. Thus this case provided a stern test for the ECMWF IFS.

Only a small subset of rapidly-deepening extratropical cyclones exhibits the sting jet phenomenon. This is an ongoing area of research but evidence to date suggests that in order for a cyclone to possess a sting jet, the cyclone's cloud head region must, as a minimum, be unstable to slantwise convection, and should contain warm air from a relatively low-latitude source. Conventional observations have also been shown to exhibit hallmarks of the sting jet in past cases; these include evaporating cloud filaments emanating from the tip of the cloud head (in imagery), and surface observations that show gusts that peak downwind of the gaps between these filaments. It is on the basis of observational evidence of this type that we think Christian was probably a sting jet storm.

The sting jet phase likely terminated over eastern Denmark. Note how wind gust strength in Figure 2e is generally maintained across the landmasses of Denmark, but dies away much more rapidly inland over southern Sweden. This behaviour over Sweden is more typical of strong winds in the 'cold conveyor belt' (CCB) zone of a cyclone, which tend to follow and overlap any sting jet phase. In this CCB phase the forced descent of high momentum air is lacking, so unless there is an alternative mechanism for bringing the high momentum air downwards, such as convective overturning, gusts tend to not be as strong.

Ensemble forecast

At lead times of 7–10 days, the ensemble forecasts (ENSs) generally provided cyclonic solutions for northwest Europe, but with the more extreme cyclones mostly located west of the UK. Figure 3 encapsulates the ENS handling at shorter leads, showing the Extreme Forecast Index (EFI) and shift of tails (SOT) for 24-hour maximum wind gusts for (a) 5–6, (b) 3–4 and (c) 1–2 day forecasts, all valid on 28 October, as well as 24-hour maximum wind gust CDFs (cumulative distribution functions) for Leeuwarden in the north of the Netherlands. By 5–6 days before the event, the EFI (indicating, broadly, the likelihood of high gusts) and SOT (signifying how extreme the gusts might be) were pointing to the potential for a major windstorm (Figure 3a). Closer to the event the signal increased (Figures 3b and 3c). The most noteworthy feature of these plots is perhaps the fact that the SOT reaches a value of 5 over Denmark in the 1–2 day forecast. For *very extreme* events the EFI saturates, as it is unaffected by changes in forecasts beyond the maximum of the model climate. The SOT on the other hand can be more useful here, as it is designed to focus on the domain beyond the model climate maximum, telling the forecaster how extreme an extreme event might really be (*Zsótér,* 2006).

The wind gust CDFs for Leeuwarden (Figure 3d) confirm that many forecast outcomes, at different lead times, lay above the maximum of the model climate (shown here for lead time 24–48 hours). Also one can see 'jumpiness' in the ENS probabilities at short leads, that roughly mirrors HRES behaviour discussed above (for the Leeuwarden grid point, the corresponding HRES values are shown with spots on Figure 3d). Following the last four forecast sets, highlighted with arrows, one sees a steady reduction in maximum gusts (a movement of the CDFs to the left, dashed blue to solid blue to purple) until the very last forecast (red) which jumps back to stronger values.

To explain the changes depicted in Figure 3d in spatial, synoptic terms, one can reference ECMWF extratropical cyclone products (see *Hewson*, 2009), as illustrated in 'dalmatian chart' format in Figure 4. These charts show the positions of all synoptic-scale cyclonic features from all IFS runs. Forecasts from 12 UTC on the 26th (a, b) commonly showed intense solutions, as denoted by bright colours, but also highlighted uncertainty. In the runs from 00 UTC on the 27th (c, d) uncertainty seems to have increased,

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at least for 12 UTC on the 28th (d), when the storm turned out to be near to its peak. The 'maximum 1 km wind' represented ranges from 55–60 knots (dark green, equivalent to an ordinary winter cyclone) to 80–85 knots (light magenta, equivalent to a once in a lifetime event!). The positions of these cyclones also varied, the weaker cyclones having progressed further east, commensurate with less interaction with upper levels; this is a common feature of dalmatian charts in potentially cyclogenetic situations.

For the forecasts from 12 UTC on the 27th (e, f) the spatial range of the outcomes had narrowed, and intensities had weakened, to lie generally between 60 and 70 knots. The short-range forecast then jumped back, to show outcomes of mostly 70–75 knots (h). This final change seems to relate, in turn, to the analysis at 00 UTC on 28th (g) being on the edge of the range of the previous 12-hour forecast (e) – i.e. the surface cyclone being a little slower and therefore perhaps interacting a little more favourably with upper-level forcing.

One can thus see how finely balanced the situation was and, if this is added to the related difficulties of modelling mesoscale structures (e.g. the sting jet), it starts to become apparent why we may occasionally see unwanted jumps in ECMWF forecasts in such situations. Intertwined with all this is the issue of initial condition uncertainty, which other studies have shown is the major factor leading to jumpy forecasts.

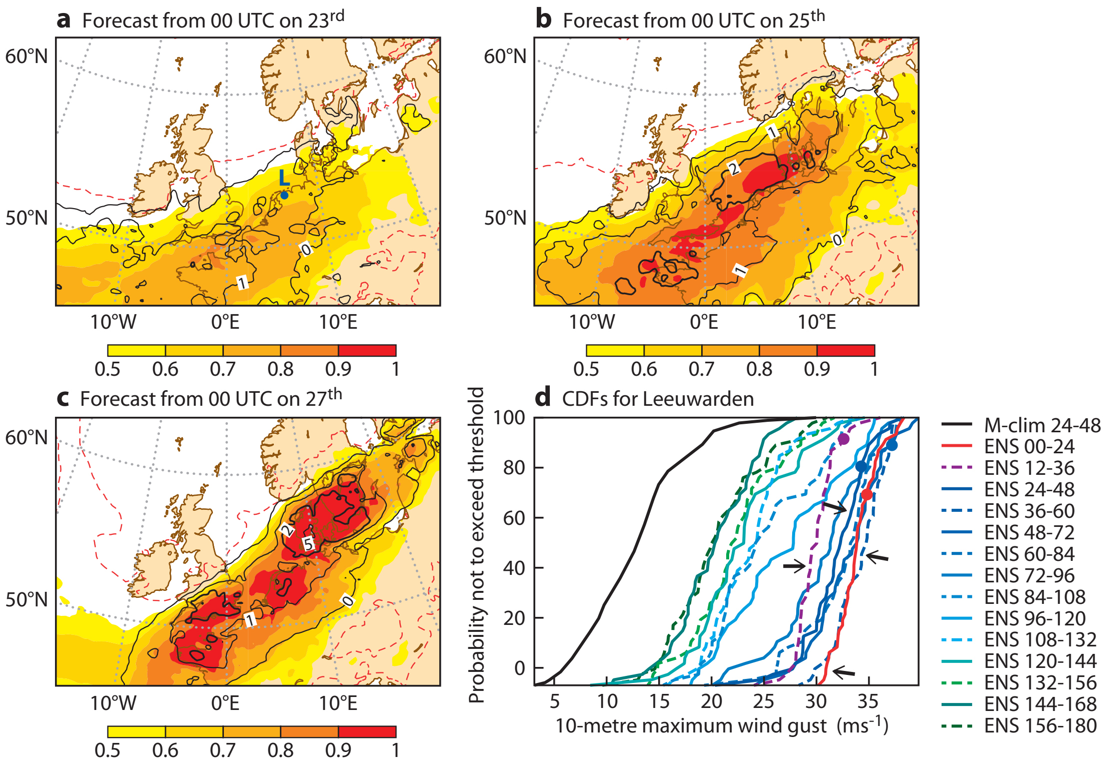

Figure 3 Maximum gust forecasts from ENS represented as the EFI (shading as on legend, and red contours = 0.3) and SOT (black contours = 0, 1, 2, 5) for 00 to 24 UTC on 28 October 2013 from data times (a) 00 UTC on the 23rd, (b) 00 UTC on the 25th and (c) 00 UTC on the 27th. Panel (d) shows, for the same 24-hour period, maximum wind gust CDFs for Leeuwarden in the Netherlands (location 'L' marked on panel (a)) from 14 ENS runs (see legend), with spots denoting the corresponding HRES from the last four runs (colours as on legend). Arrows highlight CDFs referred to in the text. M-clim (black line) is the 20-year model climate distribution based on 500 realisations.

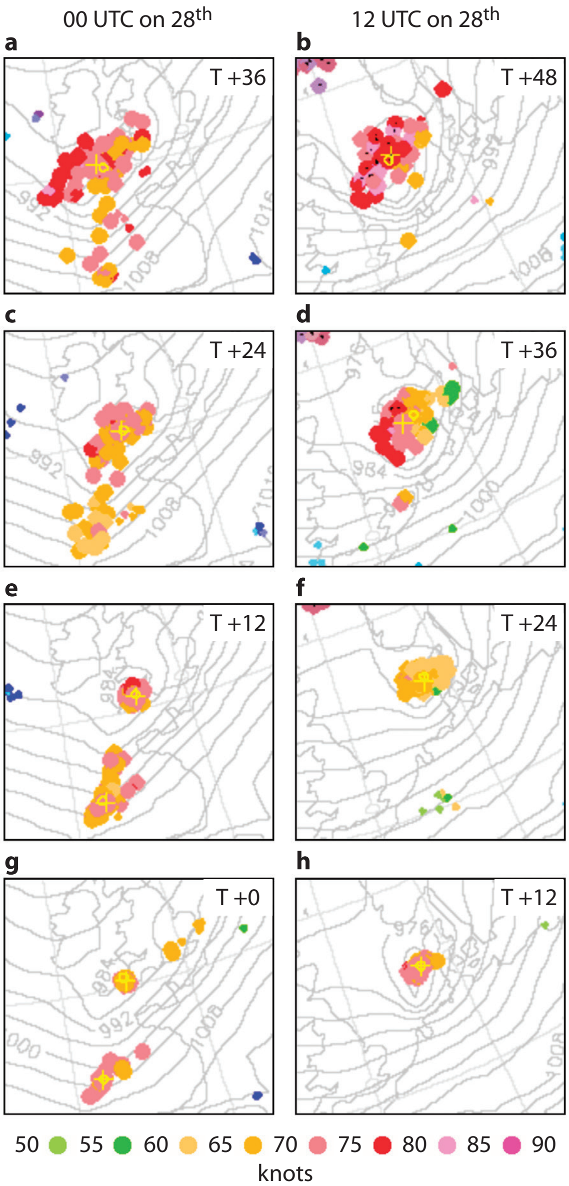

Figure 4 'Dalmatian max wind attribute' charts from the ECMWF extratropical cyclone tracking system, for two validity times: 00 UTC on 28 October (left side) and 12 UTC on 28 October 2013 (right side) from forecasts with data times of (a, b) 12 UTC on the 26th, (c, d) 00 UTC on the 27th, (e, f) 12 UTC on the 27th and (g, h) 00 UTC on the 28th. Each spot denotes a cyclonic feature (frontal wave, barotropic low or diminutive frontal wave) identified in one of 52 IFS runs. A small spot means that the feature lies on a front that is thermally weak. Black dots denote barotropic low centres. Colours signify a 'maximum 1 km wind' attribute: this is the maximum of all the grid point mean wind speed values lying within a 300 km radius of the feature point, on a level that is everywhere 1 km above the Earth's surface, in the relevant model run. Legend below is in knots (1 knot ≈ 0.5 ms^{-1}); the limits of a colour's range are the values either side. Contours show mean-sea-level pressure from the control run. Yellow circles/crosses denote respectively control/deterministic run features; these features are plotted last.

5 December (Xaver)

On 5 December a large and violent cyclonic storm hit the North Sea region and several adjacent countries. Problems were caused both by high wind speeds and a related storm surge. The surge reached 6 metres on the Elbe in Hamburg for example, and along the east coast of England and in the south of the Netherlands it was the highest for 60 years. In the cold air outbreak following the storm a blizzard hit Sweden. The storm system was name Xaver by Berlin's Free University; other names assigned elsewhere include Bodil, Sven and St. Nicholas.

The cyclone first developed around 00 UTC on the 4th as a warm front wave/diminutive wave, northeast of Newfoundland. In common with many formative North Atlantic windstorms, the cyclone was then situated between converging northerly and southerly airstreams, convergence which in turn gave rise to substantial increases in the strength of both the low-level thermal gradient and the upper-level westerly jet. Subsequently, under the influence of the accelerated jet stream, the cyclone sped northeast, then east along latitude 60°N, deepening explosively and attaining its minimum central pressure of 961 hPa near Oslo around 18 UTC on the 5th. The maximum 6-hour deepening (from Met Office surface charts and ECMWF analyses) was about 13 hPa, north of Scotland, between 00 and 06 UTC on the 5th, whilst the maximum 24-hour deepening was about 44 hPa, which is extreme.

The cyclone had a more complex structure than storm Christian, with an intense meso-vortex hanging back to the west of the main low for a time, and this enhanced the strong wind swathe running into western Scotland (see observations and model forecasts of 24-hour maximum gust in Figure 5). The barely discernible remnants of this meso-vortex (at 12 UTC on the 5th) are marked with white crosses in Figures 5a and 5b.

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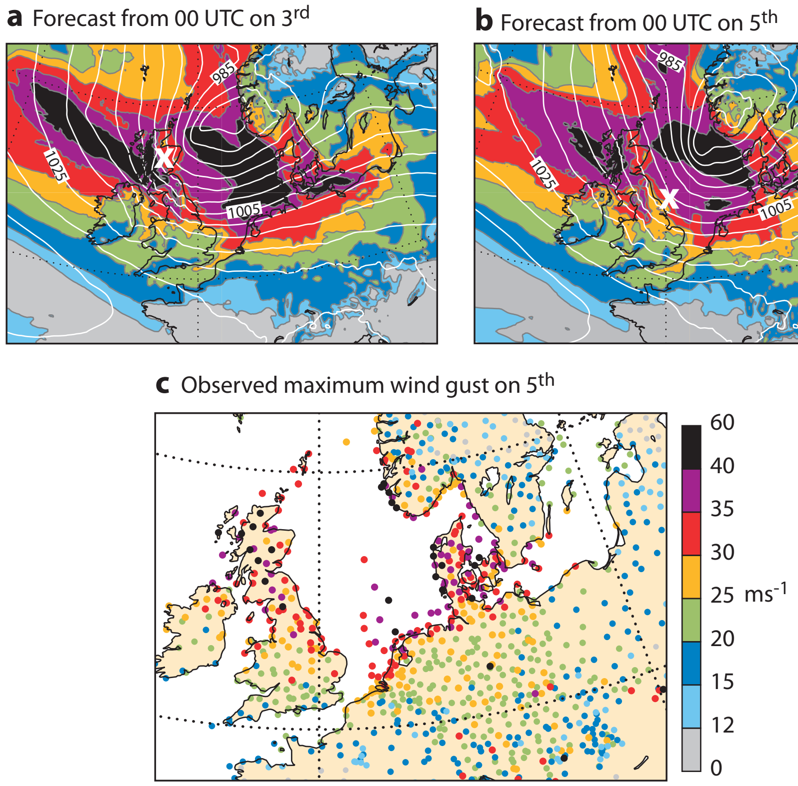

Figure 5 Forecasts, of 24-hour maximum wind gust between 00 and 24 UTC on the 5th (shading) with mean-sea-level pressure for 12 UTC on the 5th (contours) from data times of (a) 00 UTC on 3 December and (b) 00 UTC on 5 December 2013. White crosses denote the remnants of a meso-vortex discussed in the text. Panel (c) shows verifying data from observations.

High-resolution and ensemble forecasts

The main band of very strong gusts extended from the northern North Sea, around the coasts of southwest Norway and on into Denmark and the coastal fringes of the Netherlands, Germany and Sweden (Figure 5c). HRES in the lead up to this event generally captured the maximum wind gusts well (two examples are shown on Figure 5), albeit with an over-estimation inland over northern Germany, and with some timing errors (cyclone progress is too slow in the 60-hour forecast of surface pressure in Figure 5a).

The cause of the very strong winds appears to have been CCB flow around the southern flank of the cyclone. On imagery sequences, unlike for Christian, there was no signature of a sting jet. Indeed the cloud head, which should be the source region for any sting jet, was barely present, being very ragged and ill-defined. Note also how wind gust strength dies away downstream of coastlines for the Xaver case, both in observations and model output (e.g. compare the west coast of Jutland with other parts of Denmark in Figure 5). This relates to the CCB being the synoptic scale cause of the gusts, and not the sting jet, as discussed above for storm Christian. Meanwhile the wind gust CDFs for Torsminde (Figure 6d) show a signal for extreme winds that grows and then stabilises. This all contrasts with the more jumpy forecasts for storm Christian. CCB windstorms tend to cover larger areas and be more predictable than sting jet windstorms.

At longer lead times of 7 and 8 days (not shown) some ENS runs had produced vigorous cyclones in about the right location, though few if any of these were sufficiently extreme. As with Christian, the EFI and SOT products from the ENS provided an indication for the event from about 5–6 days in advance, and this signal strengthened in later forecasts (Figures 6a, 6b and 6c). The area with large values of EFI (>0.9 say) and SOT (>2 say) was greater than for Christian, though the maximum SOT was not as high (compare Figures 3c and 6c). These differences are consistent with the larger size of Xaver compared to Christian, and the different causes of the strong winds (CCB versus sting jet).

Ensemble storm surge forecast

The most significant impacts to have occurred in connection with Xaver were arguably related to the associated storm surge. Record surges were set up by the windstorm along the east coast of Britain, the coasts of the Netherlands and in the German Bight.

The atmosphere influences the sea surface elevation in two distinct, but related, ways:

- There is the inverse barometric effect where, as a rule-of-thumb, a 1 hPa reduction in surface pressure leads to a 1 cm increase in water level.
- Due to the Earth's rotation, winds will push water away at right angles, and to the right of the airflow direction, through what is known as Ekman transport.

In turn, a pulse of piled-up water will travel forwards as a Kelvin wave, with the coast to its right, as a consequence of the Coriolis effect. The North Sea is prone to such storm surges when the wind is blowing from the north or northwest. By piling up water along the east coast of Scotland, a pulse (the aforementioned Kelvin wave) is set off which travels southward before turning northward in the direction of Denmark.

Although storm surge forecasting is not performed by ECMWF, the 10-metre wind fields and surface pressure fields from our ensemble forecasts are put to use by KNMI and Rijkswaterstaat, who are jointly responsible for issuing ensemble storm surge forecasts for Dutch waters. The barotropic WAQUA/DCSM98 (Dutch Continental Shelf Model), which covers the northwest European Continental Shelf, including the North Sea, is run at 8 km resolution. A 51-member ensemble is integrated to 240 hours twice daily. The destructive potential of a storm surge depends on whether it coincides with the astronomical tide or not, and the Dutch system includes all the major tidal constituents (see *de Vries*, 2009).

Figure 7 shows the ensemble storm surge forecast for Vlissingen (location marked on Figure 6a), based on a data time of 00 UTC on 2 December. Box-and-whisker symbols denote water levels in the 51 ensemble members. Evidently the peak of the storm surge coincided quite closely with the fortnightly spring tide which will occur two or three days after the moon is new or full. There was a new moon on 3 December.

The Dutch forecasting system highlights the value of ensemble forecasts in planning and preparing for events with high destructive potential. The storm surge is but one of the hazards that storms bring to European coasts. Cyclones can also bring high waves (wind wave and swell) and large amounts of rain. The multi-hazard scenario of flooding, waves and surge can be a highly destructive mix for coastal Europe. Forecasting the joint probability of two or even all three of these events is within reach of the present suite of ensemble forecast products.

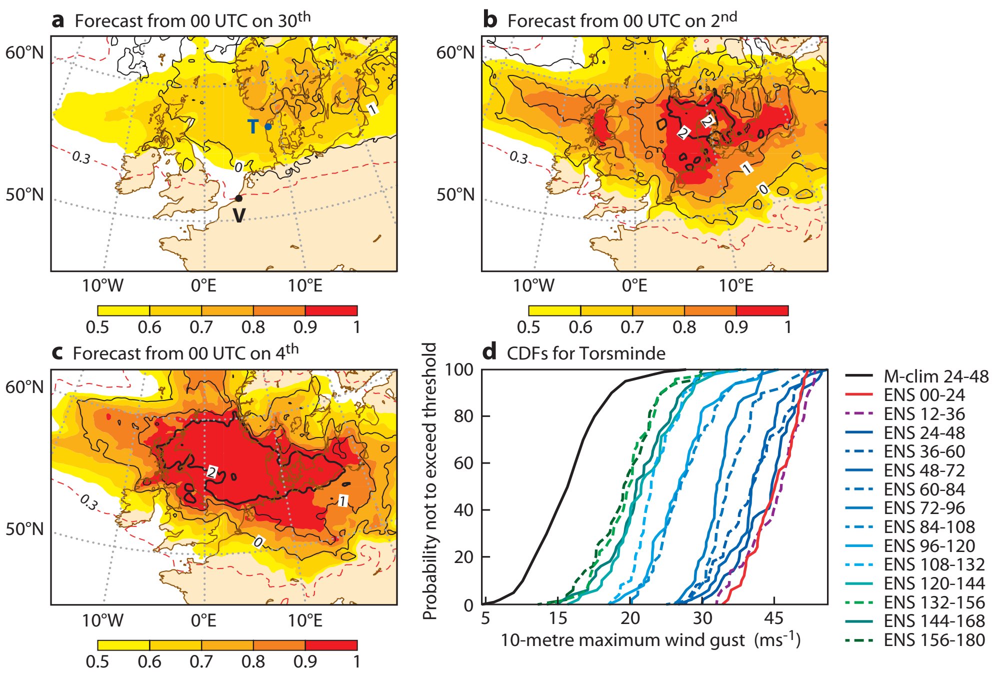

Figure 6 Maximum gust forecasts from ENS represented as the EFI (shading as on legend, and red contours = 0.3) and SOT (black contours = 0, 1, 2, 5) for 00 to 24 UTC on 5 December 2013 from data times (a) 00 UTC on 30 November, (b) 00 UTC on 2 December and (c) 00 UTC on 4 December 2013. Panel (d) shows, for the same 24-hour period, maximum wind gust CDFs for Torsminde in northwest Denmark (location 'T' marked on panel (a) from 14 ENS runs (see legend). M-clim (black line) is the model climate, as in Figure 3.

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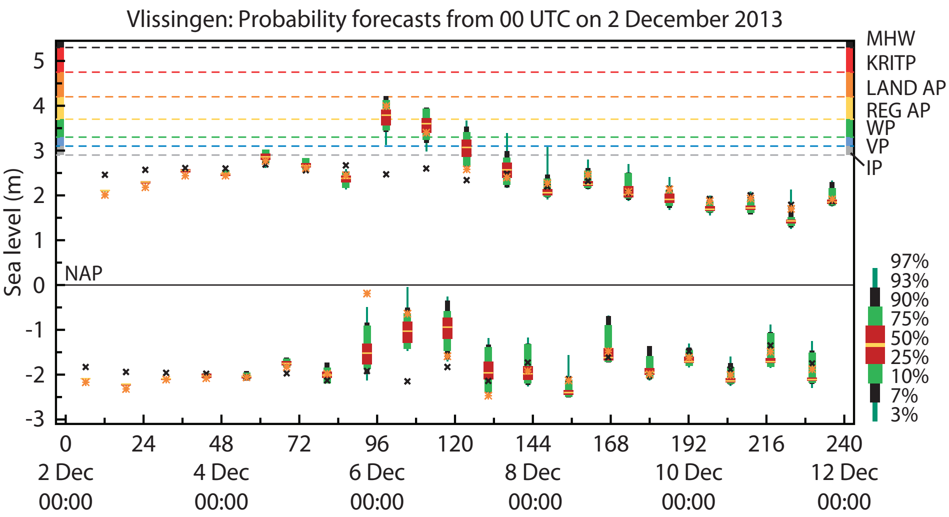

Figure 7 The ensemble storm surge forecast for Vlissingen (location marked on Figure 6a), from 00 UTC on 2 December 2013. Box-plots show water level probabilities for high and low waters as derived from the 51 ENS inputs. Marked with black through to grey dashed lines are various risk levels for the coastal district. The semi-diurnal tide is clearly visible as the box-plots jump between high and low water roughly every six hours. The fortnightly spring-neap tidal cycle is less visible, but reaches its peak on 4 December, 1.5 days before the peak of the storm surge. Orange asterisks are the observed water levels and grey crosses show, as a reference point, the pure astronomical tides.

Importance of case studies

In this study we have evaluated forecasts for the extreme windstorms Christian and Xaver, which both hit northwest Europe in late 2013. For both storms the EFI and SOT provided an indication of extreme wind gusts 5–6 days in advance. However, the finer details regarding timing and strength of Christian were not well forecast even one day before the event. These uncertainties probably relate to the sting jet, a small-scale phenomenon that presents resolution difficulties for models, and to a simultaneous and probably related high sensitivity to subtle differences in synoptic-scale forcing. For the larger storm Xaver, the strongest gusts were instead connected to the cold conveyor belt, and were more consistently and accurately predicted.

To make a robust evaluation of a forecasting system, verification should be aggregated over many cases, not just two. This type of multi-case evaluation has been undertaken in a companion article in this issue of the *ECMWF Newsletter* starting on page 29. However, for such an evaluation, one has to include less extreme cases in order to obtain reliable statistics. Therefore, we need always to complement statistical assessments with case studies, such as those presented here, to obtain a more complete picture of IFS performance for severe weather, and to get pointers to weaker aspects that should be further explored.

Further reading

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