Coastal flooding in England and Wales from Atlantic and North Sea storms during the 2013/2014 winter

Andrew Sibley,1 Dave Cox2 and Helen Titley3
1Met Office Hazard Centre, Exeter
2Flood Forecasting Centre, Exeter
3Met Office, Weather Science, Weather Impacts Team, Exeter

Introduction
This paper will look at a selection of storms from the winter of 2013/2014 that led to coastal flooding in parts of England and Wales. The first part will examine events in early December that caused the most significant North Sea storm surge for over 60 years, as well as coastal flooding in northwest England and North Wales. The second part will discuss several Atlantic storms that produced coastal flooding along west and south coasts of England and Wales. Brief discussions about modelling capability and performance will be included. However, pluvial and fluvial flooding during this period will not be considered; this is discussed elsewhere (Kendon and McCarthy, 2015; Lewis et al., 2015; Muchan et al., 2015). This study will be of general interest to meteorologists and climatologists. It will also show how effective modelling, forecasting and warnings, together with emergency planning and work to strengthen coastal defences, has helped to protect lives and property.

Part I – North Sea storm surge 5/6 December 2013

Synoptic situation
On 5 December 2013 a rapidly deepening Atlantic depression tracked eastwards to the north of Scotland, bringing very strong northwesterly winds to northern Britain. Widespread gusts of 50–70kn were recorded, with some mountain sites registering much stronger gusts: 123kn at Aonach Mòr (1130m amsl), near Fort William, at 0600 UTC, and 119kn at Cairnwell (933m amsl), Cairngorms, at 0700 UTC. Edinburgh reported gusts of 71kn at 0900 UTC, with 66kn at Boulmer, Northumberland at 1100 UTC, and 60kn gusts at Weybourne, Norfolk at 1500 UTC. Mean speeds of around 50kn were reported at some North Sea buoys and platforms, for instance at 56.3°N 02.4°E at 1200 UTC with combined wave heights typically 8–10m. The strongest winds were reported near to the cold front and associated troughs. The synoptic situation shows the low deepening rapidly and tracking to the north of Scotland and into southern Norway, dropping 40hPa in 24h, from around 1007hPa at 1200 UTC 4 December, to 967hPa 24h later (Figure 1).

Figure 1.Comparison between the synoptic pattern and development of the February 1953 east coast flood event, versus the December 2013 event. Note the difference in time steps – 12h versus 24h.

The northwesterly winds and lowering pressure produced an extreme storm surge down the west and east coasts of Britain. Combined with spring tides, the total water levels along the North Sea coast were comparable or higher than those observed during the catastrophic flood of 1953, particularly in more northern locations (Table 1). Total water level is determined by the combination of the astronomical tide plus a surge component forced by...
Coastal flooding in England and Wales

Thousands of people were evacuated from homes in East Anglia as sea levels rose. Flooding was reported in Great Yarmouth, Lowestoft, Wells-next-the-sea, Blakeney and Cley. With erosion to coastal cliffs a number of dwellings were undermined as cliffs collapsed, for instance near Hemsby, Norfolk where a lifeboat station was destroyed. Several hundred homes were evacuated in Kent, with risk of flooding in Sandwich and Seasalter.

Coastal flooding was also experienced in northwest England, for instance in New Brighton on Merseyside and Blackpool, with the highest water levels since 1987. Significant coastal flood impacts were also reported in North Wales at Conwy,

Table 1

| Observed Level OD(N) Source (BODC/EA) | First record / (years in record) | Continuous record since |
|--------------------------------------|----------------------------------|-------------------------|
| North Shields (Tynemouth)            | 5/6 December 2013                | 1947 (60 years)         |
| Whitby (North Yorks)                 | 4.32m (1)                        | 1980 (35 years)         |
| Immingham (Humberside)               | 5.22m (1)                        | 1953 (56 years)         |
| Lowestoft (Suffolk)                  | 3.26m (1) (1953 ≈ 3.35m visual estimate) Rossiter (1954) has 3.44m (11.3ft) in 1953 | 1964 (51 years)         |
| Dover                                | 4.76m (1)                        | 1924 (65 years)         |
| Sheerness (North Kent)               | 4.10m (1)                        | 1952 (48 years)         |
| Liverpool, Gladstone Dock            | 6.22m (1)                        | 1991 (24 years)         |
| Portsmouth                            | 2.83m (1)                        | 1991 (24 years)         |
| Newhaven                              | 4.27m (1)                        | 1982 (30 years)         |
| Ilfracombe                            | 5.70m (1)                        | 1968 (41 years)         |
| Hinkley Point                         | 7.45m (1)                        | 1981 (27 years)         |
| Newport                               | 8.03m (1)                        | 1993 (22 years)         |
| Mumbles                               | 5.73m (1)                        | 1988 (24 years)         |
| Milford Haven                         | 4.50m (1)                        | 1953 (54 years)         |
| Fishguard                             | 3.37m (1)                        | 1963 (50 years)         |
| Barmouth                              | 3.92m (1)                        | 1991 (23 years)         |
| Newlyn                                | 3.27m (6)                        | 1915 (100 years)        |
| Plymouth                              | 3.11m (5)                        | 1987 (25 years)         |
| Weymouth                              | 2.01m (3)                        | 1991 (24 years)         |
| Portsmouth                            | 2.76m (5)                        | 1991 (24 years)         |
| Plymouth                              | 2.93m (<10) (3.15m (rank = 1) was recorded 08:15 3 February 2014) | 1987 (25 years)         |
| Weymouth                              | 1.91m (<10)                      | 1991 (24 years)         |
| Plymouth                              | 3.12m (= 3)                      | 1987 (25 years)         |
| Weymouth                              | 2.00m (= 4)                      | 1991 (24 years)         |
| Portsmouth                            | 2.80m (2)                        | 1991 (24 years)         |

**Flooding reported**

On the North Sea coast parts of Newcastle's quayside were underwater at high tide as the Tyne estuary overflowed. Problems were also reported in Sunderland, other parts of Northumberland, and Teesside. Further south, Scarborough and Whitby seafront properties were flooded, with 200 properties affected in Whitby and power outages to the town making recovery difficult. Towns around the Humber estuary and river were also affected by flooding, for instance in Reedness and Goole. The River Haven at Boston, south Lincolnshire, also experienced breaches of sea defences with around 200 people evacuated.

Table 1

| Port                  | Observed Level OD(N) Source (BODC/EA) | First record / (years in record) | Continuous record since |
|-----------------------|--------------------------------------|----------------------------------|-------------------------|
| North Shields (Tynemouth) | 5/6 December 2013                      | 1947 (60 years)                  | 1978                    |
| Whitby (North Yorks)  | 4.32m (1)                             | 1980 (35 years)                  | 1980                    |
| Immingham (Humberside) | 5.22m (1)                             | 1953 (56 years)                  | 1963                    |
| Lowestoft (Suffolk)   | 3.26m (1) (1953 ≈ 3.35m visual estimate) Rossiter (1954) has 3.44m (11.3ft) in 1953 | 1964 (51 years)                  | 1964                    |
| Dover                 | 4.76m (1)                             | 1924 (65 years)                  | 1958                    |
| Sheerness (North Kent)| 4.10m (1)                             | 1952 (48 years)                  | 1965                    |
| Liverpool, Gladstone Dock | 6.22m (1)                          | 1991 (24 years)                  | 1991                    |
| Portsmouth            | 2.83m (1)                             | 1991 (24 years)                  | 1991                    |
| Newhaven              | 4.27m (1)                             | 1982 (30 years)                  | 1991                    |
| Ilfracombe            | 5.70m (1)                             | 1968 (41 years)                  | 1977                    |
| Hinkley Point         | 7.45m (1)                             | 1981 (27 years)                  | 1990                    |
| Newport               | 8.03m (1)                             | 1993 (22 years)                  | 1993                    |
| Mumbles               | 5.73m (1)                             | 1988 (24 years)                  | 1997                    |
| Milford Haven         | 4.50m (1)                             | 1953 (54 years)                  | 1967                    |
| Fishguard             | 3.37m (1)                             | 1963 (50 years)                  | 1973                    |
| Barmouth              | 3.92m (1)                             | 1991 (23 years)                  | 1991                    |
| Newlyn                | 3.27m (6)                             | 1915 (100 years)                 | 1915                    |
| Plymouth              | 3.11m (5)                             | 1987 (25 years)                  | 1991                    |
| Weymouth              | 2.01m (3)                             | 1991 (24 years)                  | 1991                    |
| Portsmouth            | 2.76m (5)                             | 1991 (24 years)                  | 1991                    |
| Plymouth              | 2.93m (<10) (3.15m (rank = 1) was recorded 08:15 3 February 2014) | 1987 (25 years)                  | 1991                    |
| Weymouth              | 1.91m (<10)                           | 1991 (24 years)                  | 1991                    |
| Plymouth              | 3.12m (= 3)                           | 1987 (25 years)                  | 1991                    |
| Weymouth              | 2.00m (= 4)                           | 1991 (24 years)                  | 1991                    |
| Portsmouth            | 2.80m (2)                             | 1991 (24 years)                  | 1991                    |
Figure 2. Ensemble tidal surge graphs for Lowestoft (left) and North Shields (right). Top is the forecast from 0600 UTC 1 December 2013, bottom 0000 UTC 5 December 2013. On each port time series plot the MOGREPS-G driven short-range surge ensemble surge residual forecasts are in green (runs out to T + 66h), the MOGREPS-15 driven extended-range surge ensemble surge residual forecasts are in blue (runs out to T + 162h), and the deterministic surge model (driven by higher resolution data) is in orange (runs out to T + 48h). The surge residual driven by analysis data is coloured in cyan, while the raw observations residual from the tide gauge at that site are in black. The red lines in the top half of the plot show tide predictions subtracted from the port-specific alert level, indicating the surge elevation required for the total water level to exceed the alert threshold. Two versions of this alert threshold are shown: the solid line is calculated using the more reliable harmonic tide prediction, whilst the dotted line shows the tide lead predicted by the CS3X storm surge model.

Denbighshire and Flintshire. Four hundred people were evacuated as high tides and waves over-topped flood defences, with Rhyl and Conwy the worst affected towns (Moore, 2014).

Performance of storm surge ensemble forecasts

The Flood Forecasting Centre (FFC), the Environment Agency (EA) and Natural Resources Wales (NRW) utilise the storm surge ensemble forecast model run by the Met Office in collaboration with the EA (Flowerdew et al., 2010; 2013). This uses the National Oceanographic Centre (NOC) CS3X Storm Surge model, driven by wind and pressure forecasts from the Met Office MOGREPS-G (Bowler et al., 2008) and MOGREPS-15 ensemble weather forecast systems. The surge ensemble runs to T + 162h and provides an assessment of surge levels and overtopping risk at selected UK ports. Storm surge level, particularly for extreme surge events, can be very sensitive to small errors or uncertainties in the weather forecast, so it is particularly important to use an ensemble approach to understand the risks and the confidence in forecasts. The port time series plots for two time periods are shown for North Shields and Lowestoft in Figure 2. The details are discussed in the figure caption, but the important point of note is that when the black line crosses the red line, the observed total water level has exceeded the Tidal Alert Level at that location. As can be seen, the spread amongst ensemble members reduces markedly closer to the event, indicating increased confidence in the forecast.

Both the analysis and the observations are useful in evaluating the surge ensemble system performance. The analysis here is a simulation of the surge with the CS3X model forced with analysed weather and shows the best forecast that the model could have achieved. It is useful for evaluation of the meteorological uncertainties involved in the forecast and how well these are captured by the ensemble. The observations show the true observed surge (prior to quality control). Where the observed surge line differs substantially from the analysis it can highlight where the underlying surge model has had difficulties in representing the port-specific complexities in the tide and surge forecasts.

Overall the surge ensemble performance for this December 2013 event was very good. It indicated a low risk of a high-impact event 7 days in advance, and by 5–6 days ahead was showing significant risk of a very unusual and dangerous period of surge activity when combined with high tides, albeit c.12h later than observed. The FFC began passing briefings to the EA on Sunday 1 December, with the EA running ‘what-if’ scenarios for the most likely and worst case risks. The Flood Guidance Statement (FGS) from Monday 2 December warned of low likelihood of a significant event on the Thursday and Friday.

The strength of the signal increased markedly for a high-impact event between runs at 1800 UTC 2 December and 0600 UTC 3 December. This coincided with the change from the MOGREPS-G to MOGREPS-15 forcing meteorology, when the meteorological confidence increased for an explosively deepening low with very strong north-northwest flow to its rear. The risk level on the FGS was elevated as confidence and foreseen impacts increased, becoming Red (high likelihood of severe impacts) for the East Anglia coast by 1030 UTC on 5 December.

The forecast increase in risk level led to regular FFC participation in National Flood Advisory Service briefings to Department for Food and Rural Affairs (Defra), Civil Contingencies Secretariat (CCS), and Department for Communities and Local Government (DCLG) several days ahead of the events, and even at Cabinet Office Briefing Room (COBR) level on 5/6 December. At short range the surge ensemble and deterministic surge models gave useful guidance for most ports, with the ensemble continuing to add value to the deterministic model by enhancing confidence and giving the range of surge levels still possible at this lead time.

The combination of early warning of a potentially significant event given by the surge ensemble and increased confidence by about T + 60 enabled FFC forecasters to notify customers of the forthcoming event via the FGS, and enabled the EA and NRW to issue Flood Warnings and Severe Flood Warnings well in advance of the event. Responders on the ground activated their emergency response plans, closed flood defences and evacuated vulnerable...
Coastal flooding in England and Wales

The December 2013 events correlate reasonably well with those of 1953. Both show a low pressure centre deepening to the south of Iceland and running to the north of Scotland at around 60°N. However, the low centre of the 1953 event turned south-eastward as it deepened in the North Sea (Prichard, 2013), while the 2013 low pressure continued eastwards into Scandinavia (Figure 1). However, with the 2013 system, subsequent troughs of low pressure can be seen running southwards down the North Sea as the gradient wind flow veered towards a more northerly direction, and severe gales and storms were reported at sea. The development of the 2013 event was also much quicker, with the low centre running from 34°W to 8°E in 24h. The 1953 event took 48h to cover a similar distance, but with a very strong northerly flow in the North Sea it is estimated that maximum wave heights correlated well with the time of high tide and surge (Wolf and Flather, 2005).

Maximum mean wind speeds and wave heights correlate reasonably well between the two events. Measured wave heights were 8–10m over the open sea in the December 2013 event, with wind speeds in excess of 50kn in places. Near to shore, the Tyne Tees WaveNet Buoy recorded a maximum significant wave height of 4.7m and period of 14s (Parsons and Frampton, 2014). Records of wave heights are not as easy to gather and assess with the 1953 event. Wolf and Flather (2005) report close-to-shore significant wave heights of 12ft (3.65m), and conservatively estimate significant wave heights of 7.8m and a 14s peak period over the open ocean, assuming 30ms⁻¹ wind speed (60kn) and a fully developed sea state.

The December 2013 surge water levels were higher than those of the 1953 storm surge in more northern locations, but possibly slightly less further south. However, due to damage to gauges in 1953 some of the data has been interpolated (Rossiter, 1954), North Shields gauge, operational since 1947, recorded 3.97m Ordnance Datum (Newlyn) at 1615 UTC on 5 December 2013, compared with 3.56m at 1700 UTC on 31 January 1953 (Parsons and Frampton, 2014). At Lowestoft in 1953 the OD(N) was 3.35m (astronomical tide level of 0.94m and surge 2.41m) although this was estimated visually (as reported by Wolf and Flather (2005), although Rossiter (1954) has it at 11.3ft (3.44m)), while in 2013 the overall water level was measured at 3.26m OD(N). Calculating return periods for total water level is problematic due to several variables, including time and height of the surge and variations in astronomical tides, but many ports recorded their highest water level for over 50 years in 2013 (Table 1). The return period for the 1953 surge component at Lowestoft is estimated to be around 50 years, although rising sea levels will likely reduce the return period in coming decades (Wolf and Flather, 2005). Sea levels around the coast of England and Wales are slowly rising from isostatic and eustatic adjustments (i.e. both geological movements and sea level changes). Between 1920 and 2012 the Newlyn annual mean sea level rose by 15.2cm, and by 20.6cm at North Shields (DECC, 2013).

Over 300 deaths occurred with the 1953 flood event in eastern England, and over 1800 deaths in the Netherlands (Wolf and Flather, 2005). Following the 1953 disaster, effective monitoring, forecasting and warning systems were put into place, together with significant investments in North Sea flood defences. Hundreds of thousands of properties and around 2000km² of agricultural land are now protected, including by the Hull and Thames Barriers. Early warnings of the 2013 event by the FFC, EA and NRW, and excellent planning by regional responders, meant that despite significant coastal flooding, no fatalities occurred as a direct result of flooding. There have also been a significant number of other severe North Sea tidal surges in recorded history, for instance on 13/14 January 1916, 3 February 1825 and 24 December 1717 (Lamb and Frydendahl, 2005).

Part II – West and south coast flooding events – January and February 2014

The coastal flooding experienced in parts of England and Wales in January and February 2014 was the result of a combination of factors, including significant storm surges, high-energy, long-period swell waves, and shorter period storm waves, these being coincident with normal high spring tides. Water levels in river estuaries, often swollen from excessive run-off during this period, experienced additional tidal blocking from the heightened tides.

The surge and swell waves were developed by rapidly deepening and fast moving Atlantic low pressure systems. These low pressure centres were unusually deep and maintained an unusually low latitudinal track. The following discussion will focus upon four Atlantic storm systems that led to the most significant storm surges and wave action, with damaging coastal flooding along the west and south coast of Britain. See Kendon and McCarthy (2015), this issue, for information about other events and impacts during the period.

3/4 January 2014

Coasts of northwest England (see front cover), west Wales, and southwest England were impacted by large waves and high tides on 3 January, with the Aberystwyth seafront badly damaged by wave action. Wave heights were reported in excess of 6m on the evening of 3 January at Aberporth Buoy, and nearly 6m at the Bristol Channel Buoy, with wave periods increasing to 15–20s the next morning (Figure 3). Record total water levels were seen at many ports in western Britain (Table 1), with the surge coinciding with a perigee new moon spring tide. A low pressure system, with central pressure 989mbar located at 43°N 44°W at 1200 UTC 1 January moved quickly across the Atlantic and deepened to 947hPa by 0000 UTC 3 January at 54°N 13°W (36h) (Figure 4). This deepening was linked with a
Coastal flooding in England and Wales

3–5 February 2014

This period was characterised by a rapidly deepening low pressure system moving quickly across the Atlantic with an unusually low latitudinal track. It is noteworthy that a gale-force southerly flow also affected the English Channel on 3 February, with coastal flooding reported in places along the coast of Devon and Cornwall, for instance at Salcombe (Figure 5). A new record maximum water level of 3.15m OD(N) was measured at 0815 at Plymouth on 3 February 2014. The secondary low pressure, 990mbar, was centred near 46°N 40°W at 1200 UTC on 3 February, then lying near the southwest tip of Ireland (approx. 51°N 12°W) with central pressure 947hPa 36h later (Figure 6). The occluded surface front at this time was lying near the Isle of Wight, with south-southeast severe gales or storms reported in the Channel ahead of the front around the time of high spring tides (evening of 4 February). Gusts of 80kn were reported at St Mary’s, Isles of Scilly at 1700 UTC.

Significant south coast storm surges were reported around 2100 UTC with the water level at Plymouth reaching 2.93m (OD(N)), although this level was not excessive. Similar water levels were reported the next morning at around 0900 UTC, with further coastal flooding experienced along the south coast. It was the south-southeast wind generated waves in the English Channel in addition to the surge that was the initial cause of damage, including to the railway line along the coast near Dawlish (see inside front cover). Damage occurs here periodically, but the length of track undermined and period of disruption was unusual; other recent occurrences of this nature include those of 11 February 1974, 26 February 1986, and 27 October 2004 (Network Rail, 2014). Dawlish wave buoy reported a maximum wave height of 5.6m on 4/5 February, with wave direction typically from a south-southeast direction. The swell waves arrived the next morning around the time of high tide (0900 UTC 5 February).
Coastal flooding in England and Wales

From the Poole Bay Wavenet Buoy (Figure 7) a south-southeast wave direction was evident in the English Channel during the evening of the 4 February around the time of high tide. Significant wave heights increased to around 4m with a period of 8–10s. It was around 0800 UTC on the 5 February that wave direction veered to the southwest with period increasing to 15–20s and height peaking around 6m at 1000–1200 UTC, and significant wave heights increased above 8.5m at the Channel Light Vessel. In comparison, the Met Office wave model forecast a peak of around 9.5m here at 1200 UTC (Figure 8), although because this is a light vessel, and not a buoy, it may not fully respond to actual wave heights and therefore under-read. Wave models generally performed well during this period in open water, although with some differences nearer to shore.

During this period the harbour gate at Porthleven was breached, which led to several boats sinking. A number of coastal towns saw large waves break over sea defences (see inside front cover). The well-known clock tower at Kingsand was damaged, and Newlyn, St Mawes, Perranporth and Looe experienced flooding. Many coastal towns in Cornwall, Devon and Dorset experienced wave over-topping along the sea front, including at Chiswell on Portland. Waves were over-topping the sea defences at Seaton and Lyme Regis, with water coming onto the harbour roads on the morning of the 5 February. Storm surges were experienced in several river estuaries, for instance on the Exe and Axe rivers, with Exmouth and Topsham flooded. Eyewitness testimony from sources at Topsham Museum suggests the flooding in the town exceeded the 1974 levels and was the worst since at least 1964 (although prior to 1970 flooding also resulted from poor drainage). Severe flood warnings were issued for much of the south coast of Devon, Cornwall and Dorset. This event occurred several days after the second new moon high spring tide of the year.

Model runs on the 31 January and 1 February picked up a significant low pressure centre running towards the UK on the 4 and 5 February. This was consistently maintained through the forecast sequence with a significant risk of coastal flooding indicated 4–5 days ahead by the storm surge ensemble. The surge ensemble continued to provide useful guidance as the lead time narrowed, showing a reduction in spread (increased confidence) as the uncertainty reduced. The forecast from 0000 UTC 4 February shows that at Plymouth for the high tide around 0920 UTC 5 February there was a forecast ensemble spread of the order of 30cm, centred around the CS3X deterministic forecast surge of 80cm. This was very close to the later observation. However, the alert level was not breached at Plymouth, suggesting that the additional impact of wave action was a key factor in coastal flooding. The high tide at Weymouth at around 1015 UTC was at the bottom end of the ensemble spread with a surge of 70cm (not shown).

14 February 2014

The identifiable low centre was located at 40°N 46°W with central pressure 998mbar at 0000 UTC 13 February. The low deepened rapidly and moved quickly eastwards,
Near record tides were reported by eye witnesses in places due to the surge and wind and wave action.

Coastal flooding was reported along the English Channel. Further loss of the railway embankment at Dawlish was experienced, and there was severe damage to the tourist tramline along the Axe estuary on Tuesday evening, with water overtopping the embankment. This tramline lies upon a railway embankment built in 1868. Seawater also overtopped the estuary road at Axmouth, and an unusually high level is indicated by wrack marks (Figure 10), and initial eyewitness accounts suggest such water levels have not been seen at least since the 1970s, although further investigations are necessary to confirm this. Tide gauges at Plymouth and Weymouth do not seem to have captured the local surge in Lyme Bay on this occasion. Further swell waves affected coasts along Chesil Beach, although degradation of sea defences from previous storms and insufficient time for repair may have added to the level of impact.

The surge ensemble model had indicated the risk of a significant surge several days ahead of the event. Post-event analysis shows that the observation at Plymouth was close to or above the ensemble spread in many runs, including at the short range. For example, the run from 0600 UTC 13 February showed a surge ensemble spread of around 50cm (range 60–110cm) for the Plymouth high tide at around 1740 UTC, 14 February centred around the deterministic CS3X model forecast surge of around 80cm. However, the tide gauge at Plymouth reported a surge of around 115–120cm, just above the model spread. The high tide at Weymouth at around 1850 UTC was inside the ensemble spread, with a surge of around 100cm (Figure 11).

Discussion of south and west coast flooding events

South and west coast storm surges have common predictive characteristics. These were described by Lennon (1963) who identified a number of indicators that may be used to predict surges in southwest Britain. These include a secondary deep depression approaching the UK with a critical speed of around 40kn. However, Lennon’s strict criteria are not always necessary for significant surge events (Procter and Flather, 1989), and operationally use of the criteria has been superseded by more accurate numerical modelling of sea states and storm surges, for instance in the CS3X deterministic and surge ensemble models.

As shown above, for several significant storm surge events the model suite provided good early notification of significant surges at least three days in advance and
trapped-fetch scenarios (for instance Sibley and Cox, 2014). For ideal trapped-fetch conditions the velocity of the low pressure centre should be in phase with the group wave speed and persist for some 48h, and the group wave speed needs to be about half the surface wind speed. As an example, for ideal conditions a surface wind speed of 60kn would require the low centre to move at around 30kn in the same direction as the waves. The low pressure systems described above generally had speeds of movement across the Atlantic close to 40kn, but reduced in speed as they matured and approached the British Isles, becoming near stationary in some cases.

This then may appear to be out of phase with ideal conditions for the generation of significant trapped-fetch events. As shown above, some of the damage in southwest Britain, particularly with the February events, was caused by wave action from shorter period wind waves that were coincident with the storm surge and driven by south-southeast severe gales or storms. The longer period swell waves generally arrived later, although at times correlating with subsequent high tides, giving spectacular

Figure 10. Wrack marks at Axmouth, Devon, showing water level reached on 14 February 2014. © Jon Sibley.

Figure 11. Tidal surge graphs for Weymouth (top), and Plymouth (bottom). Period is 1200 UTC 13 February 2014, to 1200 UTC 15 February 2014. The model run was 1200 UTC 13 February 2014. The MOGREPS G ensemble is in green, the CS3X in pink and the observed tide level in dark red (see legend).
Coastal flooding in England and Wales

The synoptic situations described above were complex, with deep areas of low pressure following in quick succession and leading to a background high sea state, which was then re-energised by subsequent low pressure systems. An unusual feature of these storm systems was that the low pressure centres maintained a markedly low-latitudinal track through much of their development. The unusual frequency of these surge and storm events also meant there was limited time for repairs or mitigation work before the next storm arrived. In some locations, such as at Chesil Beach, the degraded defences led to potentially more significant impacts in subsequent events.

Such complexity calls for an integrated approach to modelling of tides, storm surges and waves. The Met Office is working within the Nucleus for European Modelling of the Ocean (NEMO) modelling framework, developed in collaboration with European partners, to better forecast storm surges. Waves will continue to be modelled with WAVEWATCH III in the near-term, but for the longer-term a coupled modelling framework is being pursued to represent tide-surge-wave interactions.

It is uncertain whether these coastal flood events can be attributed directly to climate change (Slingo et al., 2014), although historical records indicate rising sea levels over the past century. As sea levels continue to rise, the frequency of coastal flooding is likely to increase in future years from storm surges. Wave heights have also increased as a result of the North Atlantic Oscillation (NAO) in recent decades, although this is a multi-decadal fluctuation related to atmospheric pressure patterns, and changes may even lead to a decrease in wave heights in future years (Woolf et al., 2002; Tsimplis et al., 2005; Scaife et al., 2008). The formation of significant swell waves is also related to resonance in trapped-fetch conditions, and is not just a matter of forcing from the strength of the wind alone.

Acknowledgements

Thanks to Adrian Wynn (EA/FFC) and Steve Chapman (EA) for information relating to tidal levels at Dawlish and in the Exe and Axe estuaries, (also thanks to Catriona Batty from the Topsham Museum). Thanks to Ken Milne, Andrew Saulter, Nick Hopkins and Adam Scaife from the Met Office for offering comments. This study (especially Table 1) has used data from the National Tidal and Sea Level Facility, provided by the British Oceanographic Data Centre (BODC) and funded by the Environment Agency. Wave data was sourced through the Centre for Environment Fisheries and Aquaculture Science (CEFAS/Defra Agency) website. Thanks to the two reviewers for additional comments. Thanks to the RNL for permission to use the photo in Figure 5.

References

Bowler NE, Arribas A, Mylne KR et al. 2008. The MOCREPS short-range ensemble prediction system. Q. J. R. Meteorol. Soc. 134: 703–722.

Department of Energy and Climate Change (DECC). 2013. UK sea level. 26 June 2013.

Flowerdew J, Horsburgh K, Wilson C et al. 2010. Development and evaluation of an ensemble forecasting system for coastal storm surges. Q. J. R. Meteorol. Soc. 136: 1444–1456.

Flowerdew J, Mylne K, Jones C et al. 2013. Extending the forecast range of the UK storm surge ensemble. Q. J. R. Meteorol. Soc. 139: 184–197.

Kendon M, McCarthy M. 2015. The UK’s wet and stormy winter of 2013/2014. Weather 70: 40–47.

Lamb H, Frydendahl K. 2005. Historic Storms of the North Sea, British Isles and North-west Europe. Cambridge University Press: Cambridge, UK.

Lennon GW. 1963. The identification of weather conditions associated with the generation of major storm surges along the west coast of the British Isles. Q. J. R. Meteorol. Soc. 89: 381–394.

Lewis H, Mittermaier M, Mylne K et al. 2015. From months to minutes – exploring the value of high resolution rainfall observation and prediction during the UK winter storms of 2013/2014. Meteorol. Appl. 22: 90–104, doi:10.1002/met.1493 (in press).

Moore C. 2014. Forecasting floods during the wettest winter on record in the UK. Presentation at the Hazard Impact Model Conference, Natural Hazard Partnership, Exeter, UK, March 2014.

Muchan K, Lewis M, Hannaford J et al. 2015. The UK winter of 2013/2014: hydrological responses and impacts. Weather 70: 55–61. doi:10.1002/wea.2469.

Network Rail. 2014. West of Exeter Route Resilience Study, Network Rail, 15 July, London.

Parsons A, Frampton A. 2014. Cell 1. Regional Coastal Monitoring Programme Wave Data Analysis Report 2: 2013–2014. Halcrow Group Ltd/Scarborough Borough Council on behalf of North East Coastal Group, Scarborough, Ontario, Canada.

Prichard R. 2013. The North Sea surge and east coast floods of 1953. Weather 68: 31–36.

Proctor A, Flather RA. 1989. Storm surge prediction in the Bristol Channel—the floods of 13 December 1981. Cont. Shelf Res. 9: 889–918.

Rossiter JR. 1954. The North Sea Storm surge of 31 January and 1 February 1953. Philos. Trans. R. Soc. London, Ser. A 246: 371–400.

Scaife AA, Folland CK, Alexander L et al. 2008. European climate extremes and the North Atlantic Oscillation. J. Clim. 21: 72–83.

Sibley A, Cox D. 2014. Flooding along English Channel coast due to long-period swell waves. Weather 69: 59–66.

Slingo J, Belcher S, Scaife A et al. 2014. The Recent Storms and Floods in the UK. Met Office and Centre for Ecology and Hydrology, Exeter, February 2014.

Tsimplis MN, Woolf DK, Osborn TJ et al. 2005. Towards a vulnerability assessment of the UK and northern European coasts: the role of regional climate variability. Phil. Trans. R. Soc. A 363(1831): 1329–1358.

Wolf J, Flather RA. 2005. Modelling waves and surges during the 1953 storm. Philos. Trans. R. Soc. London Ser. A 363: 1359–1375.

Woolf DK, Challenger PG, Cotton PD. 2002. The variability and predictability of North Atlantic wave climate. J. Geophys. Res. 107(C10): 3145.

Correspondence to: Andrew Sibley andrew.sibley@metoffice.gov.uk

© 2015 Crown copyright. Weather published by John Wiley & Sons Ltd on behalf of Royal Meteorological Society.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited and is not used for commercial purposes.

This article is published with the permission of the Controller of HMSO and the Queen’s Printer for Scotland.

doi:10.1002/wea.2471