should also be acknowledged: at the start of 2015 these still comprise over one-third of the UK’s official climatological station network. The UK is a small and geographically complex country, and often a high density of weather stations is needed to capture localised features of our climate. As demonstrated during winter 2013/2014, even a small range of hills such as the North York Moors – rising to a modest 454m above sea level at the highest point – can have a profound effect on the weather. It is the interaction between the highly variable climate and complex geography across the UK that makes monitoring its weather so interesting. We thank all writers for their contributions to this issue.

The UK’s wet and stormy winter of 2013/2014

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Introduction

Winter 2013/2014 was exceptionally wet and stormy as a succession of deep Atlantic low pressure systems, associated with a powerful jet stream, affected the UK. A major storm-surge down North Sea coasts on 5/6 December 2013 was followed by a quieter week before a sequence of major storms from mid-December to early January brought strong winds and heavy rain. The weather then remained very unsettled before a further rapid sequence of storms from late-January to mid-February.

This was the wettest winter in the UK’s observational records, and the stormiest period of weather experienced for at least 20 years. There were widespread impacts, many associated with the cumulative effect of so many storms arriving in rapid succession. Strong winds felled trees and caused some structural damage; persistent rain resulted in prolonged flooding of the Somerset Levels and the Thames Valley; huge waves made conditions around the coastline of the south and west extremely dangerous and caused significant damage. The winter storms caused widespread disruption to transport networks and disrupted power supplies; there were several fatalities and over 7000 homes and businesses were flooded (Gov.uk., 2014).

This article provides an outline of the weather events of winter 2013/2014, and compares some characteristics of this winter with other winters in the UK’s historical records. A second article (Muchan et al., 2015) describes the hydrological and hydrogeological responses and impacts, while a third (Sibley et al., 2015) covers coastal flooding. Further papers review the operational performance of Met Office weather forecast models through the storms (Lewis et al., 2015) and links to larger-scale global drivers (Huntingford et al., 2014).

Storm surge of 5/6 December

The first major event was on 5/6 December, as an area of low pressure tracked to the north of Scotland, rapidly deepening as it approached southern Norway (Figure 1(a)). The low pressure and strong northwest winds to the rear of the storm resulted in a storm-surge down North Sea coasts, with parts of northwest England and North Wales also affected. Across Scotland, winds gusted at 60–70kn, with Altnaharra (Sutherland) recording 81kn, Edinburgh, Blackford Hill 71kn and the mountain station at Aonach Mòr (1130m amsl) 123kn.

The strong winds were accompanied by around 50mm of rain across Highland Scotland, with blizzards across high ground, but of most significance was the storm-surge, which coincided with high spring tides. This was the largest storm-surge for 20 years, with total water levels comparable to – and in places in excess of – those of January 1953 (Sibley et al., 2015). Prichard (2013) gives more details of the 1953 event.

Over 70 severe flood warnings were issued and several hundred properties on the coasts of eastern England and North Wales were inundated. However, hundreds of thousands of others were protected by flood defences including the Thames Barrier – which saw multiple closures through the winter (Environment Agency, 2014). Over 2000km² of agricultural land was protected, and there were no flood-related fatalities. In contrast, the North Sea floods of 31 January 1953 caused 300 deaths in England and 1800 on the near-continent.

Storm sequence from mid-December to early January

After a quieter period, a stormy spell from mid-December to early January saw major winter storms affect the UK on 18/19 December, 23–25 December, 26/27 December, 30/31 December, 3 January and 5 January. These storms were driven rapidly across the Atlantic by a powerful jet stream, with the central track generally across Scotland. The areas of low pressure were both very deep and unusually large. Figure 1(b) shows the storm of 23–25 December, with the area of low pressure dominating most of the North Atlantic. The central pressure, 927hPa, was exceptionally low, with 936.4hPa recorded at Stornoway (Western Isles), the lowest mean-sea-level pressure (MSLP) since 1886 (Burt, 2007; 2014). Figure 2 shows MSLP time series through the winter at Stornoway and Valley (Anglesey). The initial downward spike is the storm-surge of 5/6 December, with the next set of spikes corresponding to the sequence of storms from mid-December to early January. During each of these events the pressure approached or fell below 950hPa; readings as low as this are relatively rare for UK land stations.

Each of these storms was associated with very strong winds, gusting at 60–70kn or higher across Scotland and exposed coastlines elsewhere across the British Isles; Edinburgh, Blackford Hill recorded gusts of 66kn on 14 December, 60kn on 18 December, 64kn on 20 December and 65kn on 24 December. Gusts of over 100kn were...
recorded across Scotland’s mountains, with Cairngorm summit (1237m amsl) recording 108kn on 19 December and 119kn on 27 December. Initially, the strongest winds were across Scotland, but the focus then shifted further south, with Aberdaron (Gwynedd) recording 95kn on 26 December and Needles Old Battery (Isle of Wight) 92kn on 3 January. These two stations are in particularly exposed locations; elsewhere winds gusted at 50–60kn or higher along the west and south coasts. Inland locations also saw gusts of 40–50kn or higher, for example Odham, Hampshire recorded 62kn on 23 December and Wisley, Surrey 51kn on 3 January.

At first, most of the weather impacts were associated with strong winds to the north of the UK, causing widespread disruption to transport networks and loss of power supplies. However, the storm of 23/24 December brought 50–70mm of rainfall in 24h across a swathe from Dorset to Kent – around two-thirds of the whole-month average rain for December falling on already saturated ground, shifting the emphasis to both pluvial and fluvial flooding. Leatherhead, Surrey, was badly affected as the River Mole burst its banks and flights at Gatwick Airport were severely disrupted in the busy run-up to and over the Christmas period (BBC News, 2013). Towards Christmas, the persistence of the late-December storms, each bringing around 20–30mm of rain, led to growing concerns over larger-scale fluvial flooding (Muchan et al., 2015). Flows
Storm sequence from late January to mid-February

After the first sequence of storms, the weather remained persistently unsettled and very wet across most of the UK through January, as low pressure dominated, although it was less stormy. Individual daily rainfall totals were unexceptional, but there were only a handful of dry days in the month and rainfall accumulations continued to mount, particularly across southern England. Towards the end of the month and well into February a second sequence of major winter storms again affected the UK, with events on 25/26 January, 31 January/1 February, 4/5 February, 8/9 February, 12 February and 14/15 February. These storms were again associated with unusually large and deep areas of low pressure – the central pressure typically dropping to around 950hPa. Figure 1(d–f) shows the storms of 4 February, 12 February and 14 February respectively, each with remarkably similar pressure patterns. The drop of MSLP for each of these storms can be seen in the downward spikes in Figure 2. This second sequence of storms tracked typically across Wales and central England, so impacts extended to the south coast. In Figure 2 the MSLP at Stornoway was lower than Valley for the first sequence of storms, but this is reversed for several storms in the second sequence, indicating the lower-latitude storm-tracks. The ongoing wet and stormy weather prolonged and exacerbated existing flooding problems. Flows in the Thames and Severn, which had increased rapidly in late December, were sustained at very high levels until mid-March (Muchan et al., 2015). There was extensive and prolonged flooding in the Thames catchment, while large areas of the Somerset Levels also remained inundated until early March (see aerial photograph of Somerset Levels flooding, Figure S1). The strongest winds were from the storm of 12 February, when the Met Office issued a red warning for wind – the first issued for wind by the Met Office National Severe Weather Warning Service since 3 January 2012.\(^1\) Maximum recorded gust speeds included 94kn at Aberdaron (Gwynedd), 83kn at Lake Vyrnwy (Powys) and 81kn at Capel Curig (Gwynedd). These are close to record values for these stations; Aberdaron recorded an hourly mean wind speed to 1700 UTC of 68kn. Around 100 000 homes and businesses were without power, and there was some structural damage reported. This was one of the most significant storms to affect Wales and northwest England in recent decades. The other storms in the sequence also resulted in some very strong winds, with gusts of 80kn at St Mary’s Airport, Isles of Scilly on 4 February, 80kn at Needles Old Battery on 8 February, and 95kn again at Needles on 14 February. Inland locations again repeatedly saw gusts of 40–50kn or higher; Heathrow recorded 52kn on 25 January and South Farnborough, Hampshire 64kn on 14 February. As well as inland flooding, there were numerous impacts from the storms around the coastlines of west Wales and southern England. Strong winds, high tides and tidal surges acting in combination led to huge waves battering the coastline. The wavelength of the swell was particularly long, with individual waves building up large amounts of speed and energy, and reaching record heights; for example, on 12 February, Kinsale Energy Gas Platform off southern Ireland recorded a maximum wave height of 25m (Met Eireann, 2014). Huge waves overtopped coastal flood defences, and many coastal communities in Cornwall, Devon and Dorset experienced flooding and damage to infrastructure, buildings and sea defences. The South West Mainline railway was severely damaged at Dawlish, Devon during the storm of 4/5 February, severing a key transport link for many weeks (see photographs of waves at Porthleven, Cornwall, and the Dawlish railway line on the inside front cover of this issue).

The second half of February remained very unsettled, with further periods of rain, but fortunately by mid-February the worst of the storms were over.

Temperature, snow and sunshine

With westerly Atlantic weather dominating almost throughout, winter 2013/2014 was mild; the UK winter mean temperature was the fifth highest in a series from 1910, with a marked absence of cold spells (Kendall et al., 2015). There were few air frosts, especially in February with none at all at many inland parts of southeast England. There was also little or no snow during the winter, especially at lower elevations and for the southern half of the UK. By contrast, the Scottish mountains saw exceptionally deep and prolonged cover at higher elevations, with persistent snowfalls at higher levels through the storms from mid-December to mid-February lying unmelted until late February or March. At Cairnsgorm Summit (1237m amsl), the temperature hovered around −3°C, rarely falling below −5°C or above 0°C from 18 December until 8 March, whereas nearby Aviemore (228m amsl) was consistently around 6°C warmer through this period. This consistent temperature difference was linked to the persistent Atlantic weather type and

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\(^1\)The Met Office National Severe Weather Warning Service typically issues only one or two red warnings per year (for wind, rain or snow).
absence of temperature inversions. During settled spells of weather in winter it is not uncommon for inversions to develop, leaving cold air trapped at lower levels, with mountain tops above the inversion in warmer air. However, during unsettled spells of weather lapse rates are steeper and, at lower levels, less likely to be complicated by inversions, leaving Cairngorm Summit consistently several degrees colder than Aviemore. Snow cover built up to very great depths, with cornices and avalanches being significant hazards for hill-walkers and climbers; several very large avalanches occurred during rapid thaws in late February (SAIS, 2014 provides many images of Scottish snow cover – see photograph of snow cover on Carn Liath, on page 47 of this issue).

Sunshine totals were well below average across the north and west of the UK, with less than 50% of average sunshine hours in some areas. Eskdalemuir (Dumfriesshire) recorded only 45h of sunshine for the winter, on average 0.5h per day. However, it was a sunny winter across southern and eastern England with sunshine hours exceeding the average by more than 20% quite widely (NCIC, 2014). There was an absence of gloomy days with anticyclonic stratus cloud, and frequent periods of sunshine between the mobile weather systems.

**Storminess**

The storm of 12 February was unusually severe but, though very significant, the other storms were individually not exceptional for a typical UK winter; more severe storms have occurred relatively recently – for example two severe storms affected Scotland on 8 December 2011 and 3 January 2012. The winter was unusual for the relatively low-latitude track of the storm systems, but especially for the number of major storms to affect the UK.

One measure of duration, extent and severity of storms is the number of UK stations each day recording maximum gust speeds greater than 60kn. This analysis suggests that winter 2013/2014 was the stormiest winter for around 20 years, with December 2013 probably within the top 10 stormiest months in the last 50 years. February 2014 was also very stormy, but January 2014 was more exceptional for rainfall totals rather than wind.

An alternative measure of the frequency of severe storms to affect the UK is the Jenkinson Gale Index (G > 50) based on reanalysis-derived surface pressure fields (Jones et al., 1993). This provides a more homogeneous time series of storminess from 1871 to date, although observations are not directly of gust speeds. An analysis by Comer (2014) indicates that the number

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2See http://www.metoffice.gov.uk/climate/uk/interesting for further details of these storms.

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| Table 1 |
| --- | --- | --- | --- |
| **Period** | **Area** | **Rank (1 = wettest)** | **Comment** |
| December | UK | 4 | Wettest since 1999 |
| | Scotland | 1 | Wettest calendar month |
| | England SE and Central S | 7 | Wettest since 1959 |
| | EWP | ~30 out of 248 | December 2012 was wetter |
| | England SW and S Wales | 2 | Wettest since 1923 |
| | England SE and Central S | 2 | Wettest since 1951 |
| | EWP | 7 out of 249 | Wettest since 1990 |
| January | UK | 3 | Wettest since 2008 |
| | England SW and S Wales | 1 | Wettest calendar month |
| | England SE and Central S | 1 | Wettest calendar month |
| | EWP | 1 out of 249 | |
| February | UK | 3 | Wettest since 2002 |
| | England SW and S Wales | 2 | Wettest since 1923 |
| | England SE and Central S | 2 | Wettest since 1951 |
| | EWP | 7 out of 249 | Wettest since 1990 |
| Winter (DJF) | UK | 1 | for N Ireland, shared with 1994 |
| | England, Wales, Scotland, N Ireland | 1 | Wettest by a wide margin |
| | England SE and Central S | 1 | Wettest since 2014 |
| | EWP | 1 out of 248 | Wettest since 1990 |

New records are in **bold**. The boundaries of the climate regions are shown in Figure 3. Further climate statistics for the UK and regions are available at http://www.metoffice.gov.uk/climate
of severe storms to affect the UK during the winter, based on this index, was 10, with the next highest in this series being 6 in winter 1909/1910, and only 1–2 such storms in an average winter. In a separate study, Matthews et al. (2014) found that this was the stormiest winter for the UK and Ireland in a 143-year series.

Rainfall

We have compared monthly and seasonal areal rainfall totals to other winters in the last 100 years, based on 5km gridded data sets from 1910 (Perry and Hollis, 2005), while the historic England and Wales precipitation (EWP) series from 1766 (Alexander and Jones, 2001) provides a longer-term perspective. Figure 3 shows monthly and seasonal rainfall anomalies, while Table 1 provides a selection of areal statistics.

In December, the wettest areas were across Scotland and southeast England, reflecting the track of the low pressure systems, initially across Scotland and then across more southern parts. Some sheltered parts of eastern England, such as Lincolnshire, received below average rainfall. Most of Highland Scotland received twice the average rainfall, and this was the wettest calendar month for Scotland on record. However, in contrast to southeast England, there were few reports impacts (apart from landslides), and flooding was limited due to this being a climatologically wet area of mountainous topography, sparsely populated with few developments in the floodplain.

In January, the wettest weather was across southern England and eastern Scotland, with two to three times the long-term average rainfall – this was the wettest calendar month on record for the region of England SE and Central S. February again saw two to three times the average rainfall across many parts of the UK, including Northern Ireland, and for the regions of England SE and Central S, and England SW and S Wales, this was the second-wettest February in the series (Table 1).

Rainfall statistics through the winter were record-breaking due to the persistence of the wet weather, rather than any individual event. This is illustrated by Figure 4, which shows daily rainfall totals for Charlwood (Surrey). The only exceptionally wet day was 23 December, with 58.8mm, but there were 22 days in a 62-day period from 15 December to 14 February with 10mm or more, almost three times the winter 1981–2010 average of 7.5 days. The 62-day accumulation was 596.2mm, 259% of the winter 1981–2010 average rainfall and, remarkably, 73% of the annual average for this station. More widely, much of central southern England, parts of south Wales and eastern Scotland received half a year’s worth of rainfall or more in just over two months. Northwestern areas were similarly wet from mid-December to early January with Cluanie Inn, Highland and sea than 300m amsl in the Lake District recorded over 2000mm of rain for the winter.

Figure 3(d) shows UK rainfall totals for winter 2013/2014. Most of southern England, parts of northwest England, and southern and eastern Scotland received over twice the winter average rainfall, with over 250% in a swath from Hampshire to East Sussex, but almost all parts of the UK were wetter than average. This was the wettest winter in the UK series from 1910 with 545mm, 165% of average, and also the wettest winter in the EWP series from 1766 with 456mm, 175% of average. The exceptional nature of winter 2013/2014 is illustrated in the 100-year UK time series (Figure 5). Winter 19151 was the wettest winter in the first half of this series, with 1990 and 1995 both comparable, but 2013/2014 is easily the wettest by a margin of 60mm – 5% of the annual average. For England SE and Central S, the winter rainfall total was the wettest in the series from 1910 by a huge margin (2013/2014 – 514mm, 1915 – 437mm).

Circulation types and historical analogues

We have investigated the characteristics of the seasonal mean circulation to identify a set of analogous seasons within historical records. This uses the Twentieth Century Reanalysis (20CR) (Compo et al., 2011), NCEP/NCAR reanalysis for winter 20142

1All other winters are referred to by the year in which January and February fall.
220CR being unavailable for the most recent winter.
mid-latitude jet stream for (a) wet winters dominated by westerly weather types (b) those dominated by cyclonic weather types (c) winter 2013/2014 and (d) the long-term average (1981–2010). The westerly winters have a strengthened North Atlantic jet stream sitting over the UK and slightly south of its climatological position (Figure 7(a)). These winters tend to exhibit a more west–east contrast in rainfall anomalies, particularly in the northern half of the UK, as shown in Figure 8(a) for 1990. By contrast, the cyclonic winters see the jet stream sitting further south again, and the storms typically crossing the south of the UK (Figure 7(b)). In this situation, there is often also a southeasterly flow in the North Sea, leading to heavy rain to the east coast of the UK as shown in the example of 1915 in Figure 8(b).

While the winter of 2013/2014 exhibited distinct periods of storminess of somewhat different character, overall the mean winter circulation (Figure 7(c)) is arguably closer to the exceptionally wet situation of 1915 and 1877 than more recent extremes in 1990 and 1995 — although for 2013/2014 the jet stream is also much strengthened across most of the Atlantic. We therefore recommend that analysis of 2013/2014 winter should consider these important historical analogies. Matthews et al. (2014), who also base their analysis on the NCEP/NCAR reanalysis and 20CR, similarly note the comparison with winter 1915. However, it is worth mentioning that not all historical winters with a prevalence of cyclonic or westerly types were necessarily wet for the UK. This is because the UK’s rainfall pattern is very sensitive to the precise location of the jet stream and storm-track position; slight north- or southward shifts may result in much more moderate rainfall for the UK.

Possible global drivers

The UK’s exceptional wet and stormy winter was linked to low temperatures on the North American continent — for example temperatures for January 2014 were much below normal, although not record-breaking, for the eastern USA (NCDC, 2014). The contrast between cold air advecting south across the USA, and the warm tropical Atlantic are likely to have been partly responsible for the persistence and unusual strength of the North Atlantic jet stream (apparent in Figure 7(c)), and created ideal conditions for generation of storm systems. This in turn may have been related to the filling of the Aleutian Low in the northeast Pacific, which itself may relate to high sea surface temperatures and a westward displacement of precipitation in the tropical Pacific (Huntingford et al., 2014).

However, the filling of the Aleutian low, for example, is not apparent for the other wet winters over the last century that are discussed above. There may be other global mechanisms that yield comparably wet and stormy weather for the UK, and in terms of the global circulation there will always be limitations in discussing possible historical analogues for such events. Huntingford et al. (2014) also acknowledge the possible influence of the tropical stratosphere and the potential for Arctic sea ice extent and solar activity to affect the UK’s climate. Further research is required to better understand drivers of extreme UK winters and, due to their rare nature and high impact, understand the consequences of climate change on the risk of such seasonal extremes.

Summary

The UK’s wet and stormy winter of 2013/2014 will be remembered for its persistent storminess and record-breaking rainfall, with the influence of the jet stream of fundamental importance to the character of the winter. It will also be remembered for the multiple nature of the impacts – particularly the fluvial and coastal flooding – which led to repercussions not just, of course, to those affected, but also for important questions relating to management of extreme weather impacts – for example emergency response, long-term flood defences and insurance. The widespread impacts resulted in sustained media interest, and these impacts were also felt across NW France, Ireland and northern Iberia.

The winter once again led to questions of whether the UK is experiencing more record-breaking weather than in the past (Kendon, 2014) but it is also important to acknowledge the highly variable nature of the UK’s climate. While there have

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For more details on these historical winters, scanned copies of the first page of Met Office Monthly Weather Reports from 1884 to 1993 are available at http://www.metoffice.gov.uk/archive/monthly-weather-report and scanned copies of British Rainfall from 1860 to 1968 are available at http://www.metoffice.gov.uk/archive/british-rainfall.
been other very stormy periods in the recent past (for example late-November to mid-December 2011), there have also been other recent winters of completely opposite character – as demonstrated by the cold, snowy winter of 2009/2010 which saw prolonged blocked, anticyclonic weather patterns.

Of fundamental importance is the need for long-running (centennial-scale) records, so that close analogues to such winters can be investigated. Observational networks are needed, not only for weather forecasting but for monitoring extreme weather events in the context of these long-term records, and clearly these networks need to be robust to impacts from the severe weather they are recording. Centennial reanalyses such as the 20CR are also proving to be an invaluable resource with which to place contemporary climate events into context that could not be achieved with in-situ climate statistics alone. These reanalyses depend crucially on

Figure 7. 250hPa vector wind. Colours represent magnitude and arrows indicate direction. Images provided by the NOAA-ESRL Physical Sciences Division, Boulder, Colorado from their website at http://www.esrl.noaa.gov/psd/ (a) 1990, 1995, 1937 westerly, (b) 1915, 1877, 1960 cyclonic, (c) 2014, (d) 1981–2010 average.

Figure 8. UK seasonal rainfall anomalies as percentage of 1981–2010 long-term average – for comparison see also Figure 3(d). (a) Winter 1990, (b) winter 1915.
availability of digitised data and, in many cases, active programs of recovery of historical global climate data records.

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Supporting information
The following material is available as part of the online article.
Figure S1. An aerial view of flooding of the Somerset Levels, 2 February 2014.

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