Title: The Meteorology of the Exceptional Winter of 2015/2016 across the UK and Ireland

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The meteorology of the exceptional winter of 2015/2016 across the UK and Ireland

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Introduction

The meteorological winter of 2015/2016 will be remembered as another exceptional winter across the UK and Ireland, with numerous climate records broken and high impact weather events causing considerable disruption from flooding and high winds. A succession of winter storms tracked across the region, bringing persistent and in places record-breaking rainfall, including the highest 24 and 48h rainfall accumulations on record, from storm *Desmond* on 4–6 December. Persistent rain, particularly through the first half of the winter, resulted in new records for both monthly and seasonal rainfall accumulations widely across Ireland, Scotland, Wales and northern England. Temperatures were also exceptionally high through much of December and in late January. In this paper we document the main meteorological and climate features that defined this exceptional winter season, and consider its wider historical context. The rain in early winter fell onto already saturated ground following a notably wet November, so we extend our analysis to include some consideration of November. Barker *et al*. (2016, this issue) discuss the hydrological situation.

In September 2015, the Met Office and Met Éireann announced a pilot project inviting the public to provide names for wind storms that were forecast to potentially cause substantial impacts to the UK or Ireland. The purpose of this was to communicate in unison the approach of severe weather through media partners and other government agencies to the public, and to help raise awareness of severe weather and improve public safety. It is reasonable to expect several named storms in a typical winter, and the naming of storms does not imply that any individual storm was climatologically exceptional. It should also be noted that the storm naming was based on the forecast of the likelihood of disruptive impact from high winds, for which the wind thresholds vary with place and time of day. For example, wind gusts occurring during the rush hour of major cities are more likely to cause significant impacts than the same strength winds across sparsely inhabited areas. It should be noted that storm naming during winter 2015/16 was not based on flood impacts, and some of the significant flood impacts discussed were caused by unnamed systems.

We begin with a summary of the winter overall, then consider the constituent months and briefly describe all named storms (*Abigail* to *Imogen*) that affected the UK and Ireland over the period November 2015 to February 2016. Of the final eleven named storms, six occurred during meteorological winter 2015/2016 (the months December to February), that is from Storm *Desmond* to Storm *Imogen*. We will conclude with brief consideration of the large-scale circulation and potential climatic drivers.

Winter summary

Figure 1(a) shows that the meteorological winter season spanning December to February was the wettest on record for the Island of Ireland in a rainfall series from 1850, at 189% of normal (602mm), followed by 2013/2014 at 173% (550mm). It was the second wettest for the UK at 159% of normal (519mm), behind 2013/2014, which saw 167% (545mm; Kendon and McCarthy, 2015), and for both Ireland and the UK the winters of 2013/2014 and 2015/2016 are the only winters in the series that have recorded winter rainfall totals in excess of 500mm. It was the eighth wettest in the England and Wales Precipitation Series that extends back to 1766 (Figure 1 restricted to 1851 for clarity). It was also the wettest winter on record for each of Scotland, Wales, Northern Ireland and northern England in series from 1910 (not shown). Southern and central England were wetter than average, primarily due to rainfall during January and February, but at 127% of average it was not an extreme season here. Rainfall in excess of twice normal was observed across southern Ireland, north Wales, north England and southern and eastern Scotland (Figure 2).

Across Ireland, mean air temperatures were above their Long-Term Average (LTA), with half of Irish stations reporting anomalies over 1 degC from their seasonal means. A time series of five long-term stations in Ireland, shown at the top of Figure 1(b), recorded an average winter temperature of 7.0°C, a value which has been exceeded only five times since 1901. It was the third mildest winter overall for the UK at 5.5°C, behind only 2007 (5.6°C) and 1989 (5.8°C). Temperatures were widely in excess of 2 degC above the 1981–2010 climatology across central and southern England and Wales, shown in Figure 2. In the long running Central England Temperature (CET) series from 1659, it was nominally the second warmest winter at 6.7°C, behind 1868/1869 (6.8°C); however, it should be noted that the uncertainty on monthly mean CET is estimated at ±0.2 degC (Parker and Horton, 2005), making these 2 years comparably warm given the uncertainty. For clarity the middle panel of Figure 1 only presents the CET from 1851 onwards. There are only 13 winters in the 357-year CET series that have mean winter temperatures that exceed 6.0°C; seven of these winters have occurred since 1975 and five have occurred since 1990.

As mentioned above the storm naming initiative provides a focus on wind storms over the winter, but we do not have climate records equivalent to named storms. Therefore, in order to evaluate the historical context for the storminess of the winter season, we have used the gale index of the Jenkinson–Collison indices derived from mean sea level pressure patterns from reanalyses centred over the UK and Ireland (Jones *et al.*, 2013). From these data a gale index has been derived based on the flow and shear vorticity, as described in Jones *et al.* (1993). Jenkinson and Collison (1977) defined a gale day over the UK as one where this gale index exceeded 30, and this has been extended by the Climatic Research Unit (CRU, 2016), with thresholds of 40 and 50 defined as days of severe gale and very severe gale respectively.

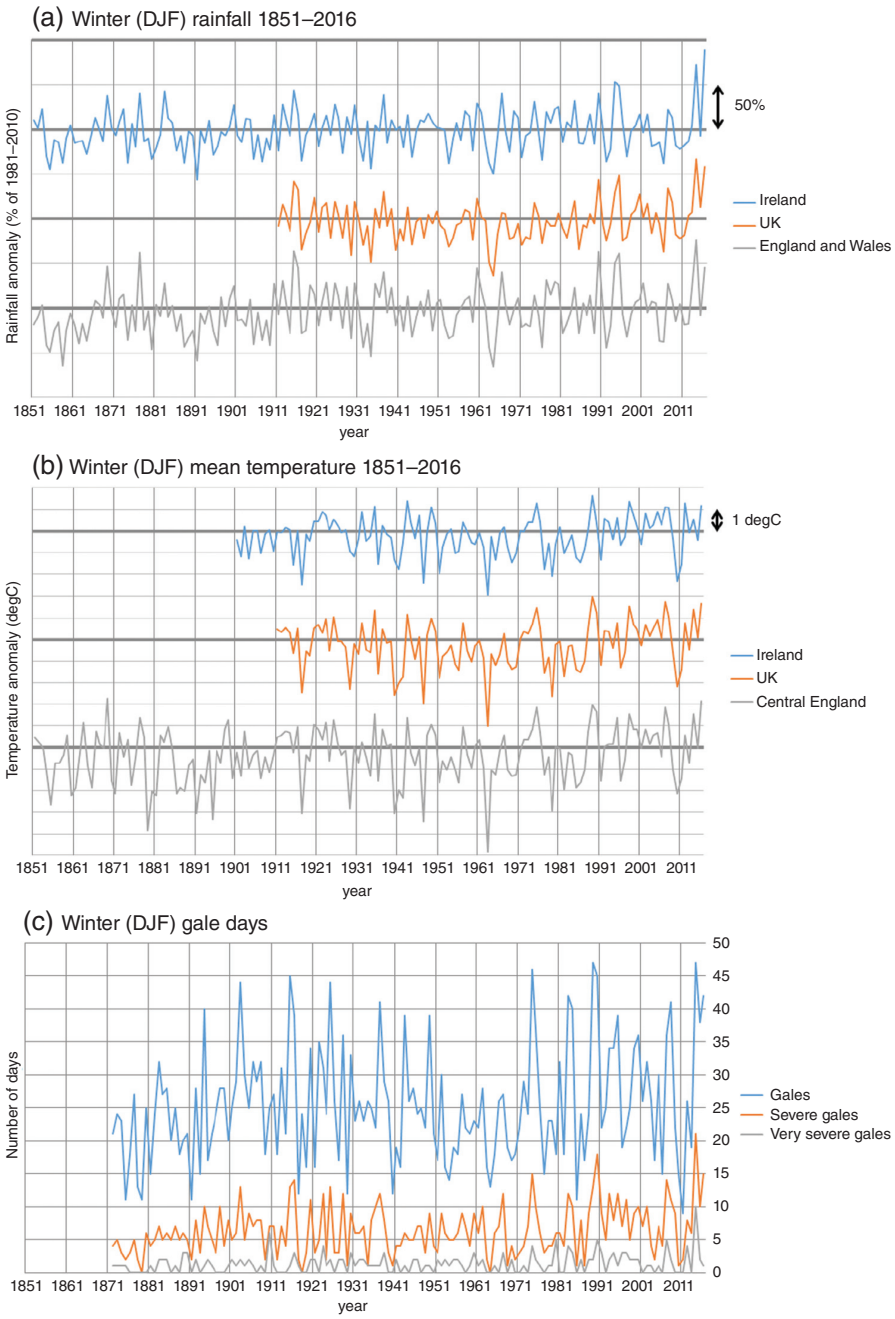

Figure 1. Time series spanning winter 1850/1851 to 2015/2016 of: (a) Winter rainfall anomaly as a percentage of the 1981–2010 climatology, from the Island of Ireland series (Noone et al., 2015), the UK national series (Perry and Hollis, 2005), and the England and Wales Precipitation Series (Alexander and Jones, 2000). Thick horizontal bars correspond to the 1981–2010 climatology and minor bars are 50%. Each series has been offset for clarity. (b) Winter mean temperature anomaly (degC) relative to 1981–2010 climatology for Ireland, UK (Perry and Hollis, 2005), and Central England Temperature (CET; Parker et al., 1992). Thick horizontal bars correspond to the 1981–2010 climatology and minor bars are 1 degC. (c) Jenkinson Gale Index derived from reanalysis mean sea level pressure fields over the British Isles region (Jones et al., 1993; 2013) – number of days classified as gale, severe gale or very severe gale.

Figure 1(c) shows the count of gale days for each standard winter season (DJF) since 1871/1872. With 42 gale days and 15 severe gale days, 2015/2016 ranks as the eighth highest for gale days and joint third for severe gales. Ten of the severe gale days, and the only very severe gale day (1 February 2016) were associated with named storms. 1989/1990 and 2013/2014 stand out as the stormiest winters. We can say that overall the winter 2015/2016 was notably stormy, but otherwise the comparison of years is very sensitive to the wind or storminess metric that is used, as well as the region of interest.

The context for the extremes of the winter season can be further drawn out from consideration of the monthly data. Figures 3 and 4 show maps of monthly rainfall and temperature anomalies; the month of November is included to provide the antecedent situation. Both November and December were exceptionally wet and mild months across the region as a consequence of a persistent moist southwesterly flow.

During November, England and Wales saw monthly mean temperatures widely 2–3 degC above the 1981–2010 average, and much of Ireland and Scotland were 1–2 degC above. Trawsgoed (Ceredigion) recorded 22.4°C on 1 November, with Dooks (County Kerry) reaching 20.1°C on the same day, which are the highest November daily maximum temperatures on record for UK and Ireland respectively.

For the UK (series from 1910), Central England Temperature (series from 1659), and Ireland (series from 1900), it was the third mildest November on record. It was also very wet for some, with much of southwest Scotland, northwest England and parts of central Ireland recording over twice the average November rainfall. For northwest England, north Wales and west Scotland, it was the second wettest November in a series from 1910, behind only 2009. In Ireland it was the tenth wettest November in the series since 1850.

December was the wettest calendar month on record for the UK in a series from 1910, with Wales, Scotland and northern England widely recording 2–4 times the 1981–2010 average. Fourteen sites across Cumbria and Snowdonia recorded monthly accumulations in excess of 1m, with 1396mm at Crib Goch (Snowdonia) and 1361mm at Birkside (Cumbria) both exceeding the previous monthly record of 1349mm at Styhead (Cumbria) from November 2009. These remarkable records are discussed in more detail by Burt (2016) in this issue. It was the wettest December over Ireland in a time series from 1850, with the greatest anomalies in the south and southwest. Five stations in counties Cork and Kerry broke the previous Irish record monthly accumulation of 790mm, with a new record of 943.5mm occurring at Gernapeka, County Cork. Impacts, especially from severe flooding, were of national significance following a number of the weather events that contributed to these remarkable rainfall accumulations. The impact of this rainfall was exacerbated by the already saturated ground in many areas following the high rainfall during November.

December was exceptionally mild in most parts of the region, with mean temperatures 5–6 degC above the 1981–2010 climatology across southern England (Figure 4). At Exeter airport the mean temperature for December was 11.2°C, 5.5 degC above average and higher than the months of January to April, October and November of that year. At 3.6 degC above average, Dublin (Phoenix Park) recorded its mildest December in a series back to 1855. It was the mildest

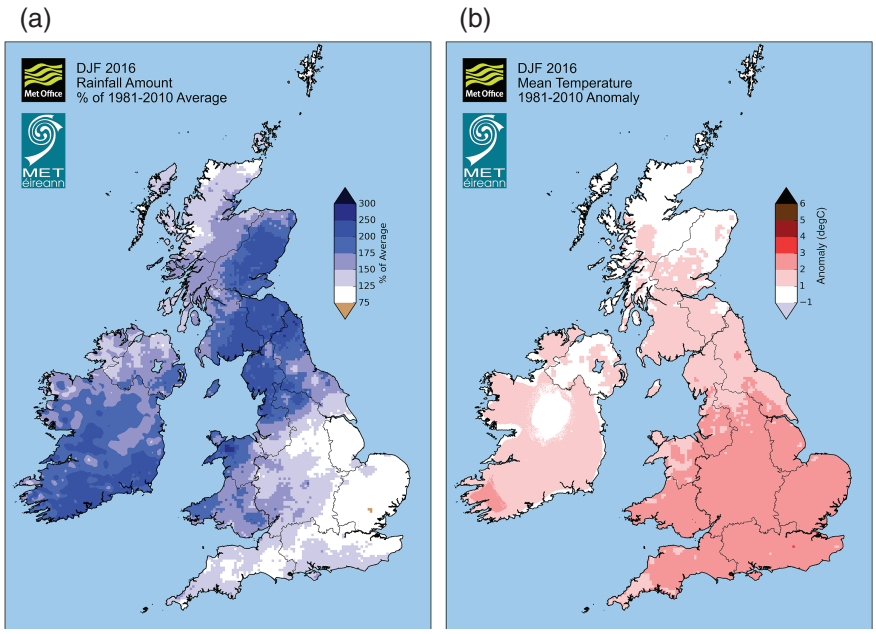

Figure 2. Winter (DJF) anomalies of (a) rainfall as a percentage of the 1981–2010 mean and (b) temperature anomaly relative to 1981 to 2010 climatology.

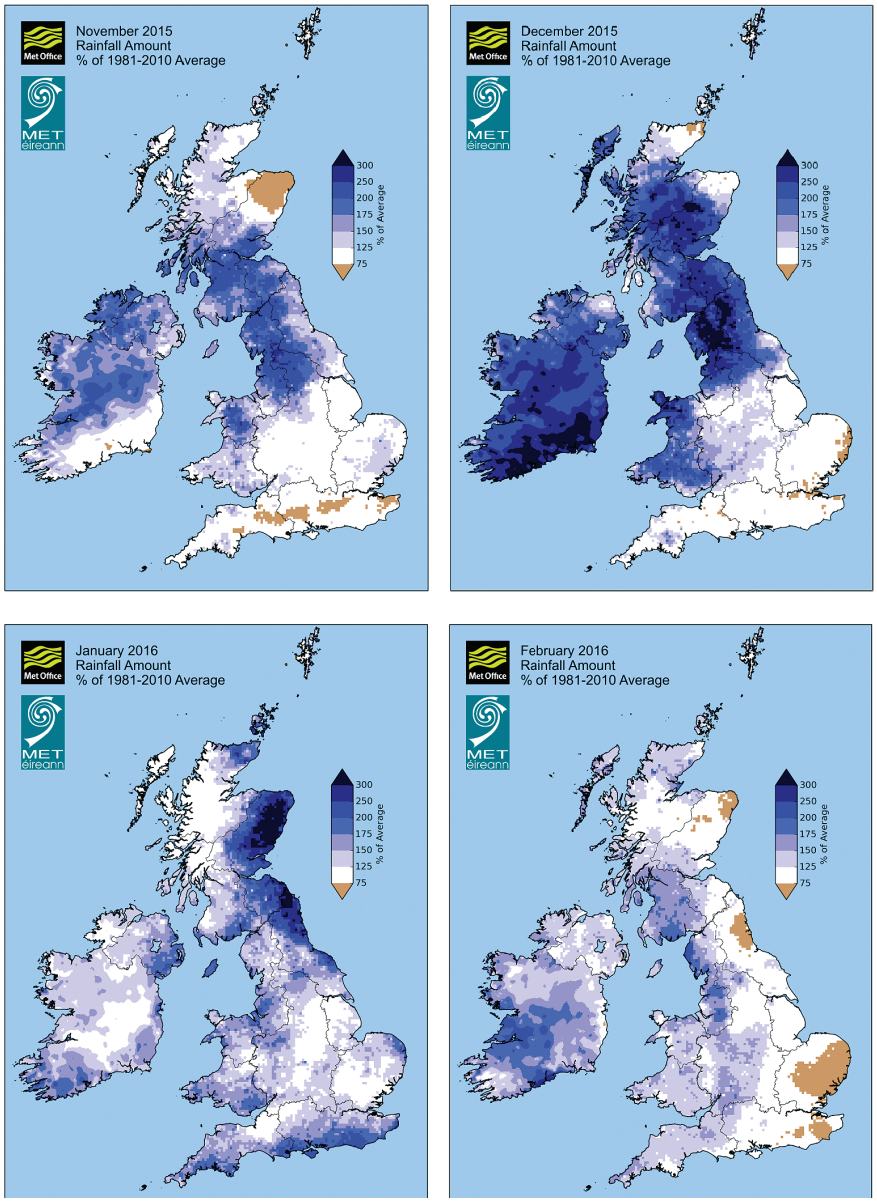

Figure 3. As Figure 2 for monthly rainfall anomalies for the period November 2015 to February 2016.

December on record for England and Wales by a considerable margin, the fifth mildest for Scotland and the mildest for Ireland. In the long running Central England Temperature series, December 2015 is the highest monthly anomaly for any calendar month on record. More detail on the remarkable temperatures in December is provided by Burt and Kendon (2016) elsewhere in this issue.

The first week of January saw continued persistent rain affecting most of the British Isles, but particularly eastern Scotland and northeast England. Parts of Aberdeenshire exceeded their monthly average January rainfall within the first 3 days of the month, and had received 2–3 times the normal monthly January rainfall by the 7th. Widespread flooding and associated disruption consequently affected parts of eastern Scotland, especially from rivers draining the eastern Grampians. A number of sites across Ireland, including Cork and Dublin, also reported their wettest January in 20–40 years, with nearly half the total for the month falling in just 2 days on the 5th and 9th. A spell of colder and generally drier weather did manage to take hold as the flow became northerly for a time in the middle of the month. Milder conditions returned towards the end of the month when there was a further flow of exceptionally mild tropical maritime air reminiscent of December. Once again there was heavy rain across the north and west, while on 24 January temperatures reached 15°C in the London area and around Chester, Carlisle, Edinburgh and Inverness, and 16°C in the northwest Highlands. Oxford recorded 15.9°C, the highest January temperature there in a 163-year record. Overall January temperatures were closer to average than the preceding months, but they remained widely 1–2 degC above average.

The first half of February remained unsettled and in a west to southwesterly flow. Mid-month it turned generally colder, drier and sunnier. Southwest Ireland recorded some of the highest rainfall anomalies of the month, with some locations receiving twice their long-term average: Carron (Clare) recorded 265mm (223% of average), and Ballymacoda (Cork) recorded 187mm (253% of average). Rainfall was also above average across western areas of the UK, with Capel Curig (Gwynedd) recording a further 345mm (154% of average), and Keswick (Cumbria), 192mm (160% of average). Rainfall was, however, below normal in eastern areas. Temperatures remained above average across England and Wales, but were up to 1 degC below average across Scotland and Ireland. The season therefore concluded somewhat closer to seasonal normals, but still wet.

The accumulation of rainfall through the whole period is shown in Figure 5 for

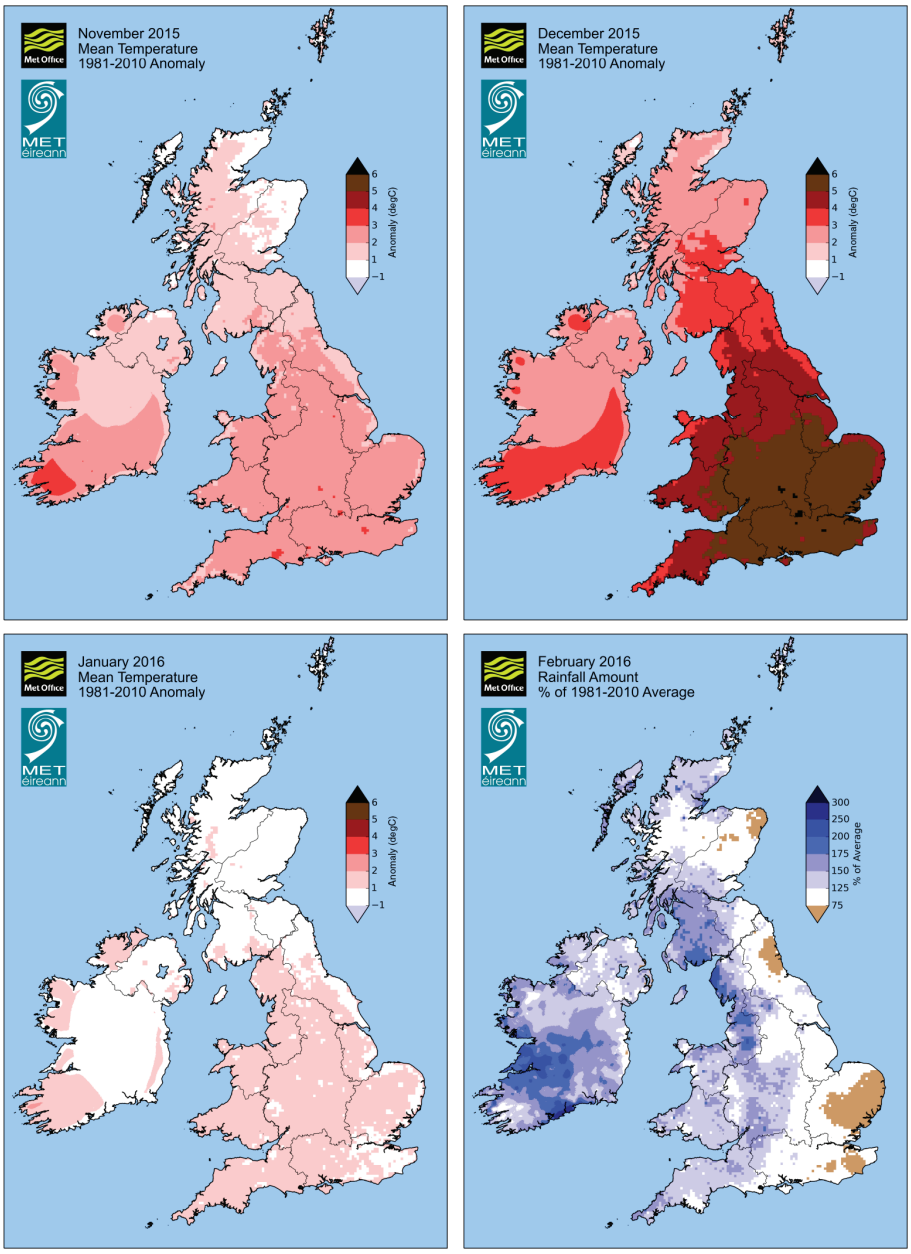

Figure 4. As Figure 3 for monthly mean temperature anomalies.

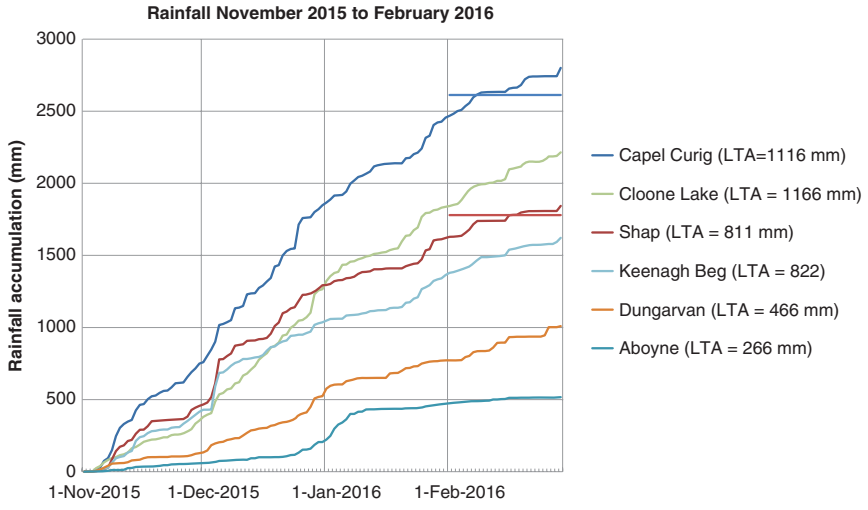

Figure 5. Rainfall accumulation from 1 November 2015 to 29 February 2016 at selected rain gauges in the UK (Capel Curig (Gwynedd), Shap (Cumbria), Aboyne (Aberdeenshire)) and Ireland (Cloone Lake (Kerry), Keenagh Beg (Mayo) and Dungarvan (Waterford)). 1981–2010 long-term averages (LTA) for the November–February period are provided in the legend. Horizontal lines depict the annual average rainfall accumulation at Capel Curig (blue, 2612mm) and Shap (red, 1780mm).

a selection of rain gauges representing some of the worst affected areas. The significant rainfall events such as *Desmond* in early December and the rain in early January across Aberdeenshire, and late January across northern England and north Wales are particularly notable. At Aboyne (Aberdeenshire) 314mm fell in the period spanning the last 10 days of December and first 10 days of January, amounting to 60% of the 517mm that fell through the whole period. At Capel Curig 2801mm was recorded in these 4 months, exceeding the average annual accumulation at this location of 2612mm. At Shap in Cumbria, 1843mm fell, also exceeding its annual average rainfall. Typically the November to February period accounts for around 40–45% of annual rainfall, but both the sites had exceeded their long-term November to February average by 9 December.

Significant weather

Daily minimum sea level pressures at Belmullet (County Mayo), Malin Head (County Donegal), Stornoway (Western Isles) and Lerwick (Shetland) are shown in Figure 6. The passages of the significant storm events are marked, and Table 1 provides the maximum wind gusts associated with each storm. The season was stormy, but in comparison the 2013/2014 winter season saw the storms track slightly further south, and sea level pressure dipped close to or below 950hPa at Stornoway on several days that winter (Kendon and McCarthy, 2015) leading to considerable issues along exposed coastlines from storm surges (Sibley *et al.*, 2015).

November

The first of the named storms, *Abigail*, passed to the north of Ireland and Scotland through the 12th and 13th with a maximum wind gust of 73kn (38ms^{-1}) at South Uist. Fronts associated with the low pressure system following directly behind *Abigail* through the 14th and 15th resulted in rainfall accumulations of 50–100mm or more on the 14th leading to flooding incidents across north Wales and northwest England as well as parts of Northern Ireland and southwest Scotland. Seathwaite in Cumbria recorded 207.8mm between 0900 UTC on the 14th and 0900 UTC on the 15th, which accounted for nearly a quarter of the rainfall for the month and over half of the monthly long-term average. Storm *Barney* brought high winds, continued rainfall and further disruption through 16–18 November. Storm *Clodagh* at the end of the month saw further heavy rain and wind, gusting to 91kn (47ms^{-1}) at High Bradfield (south Yorkshire). A wind gust of 69kn (35ms^{-1}) at Shannon Airport (County Clare) on the 17th, associated with Storm *Barney*, was the highest

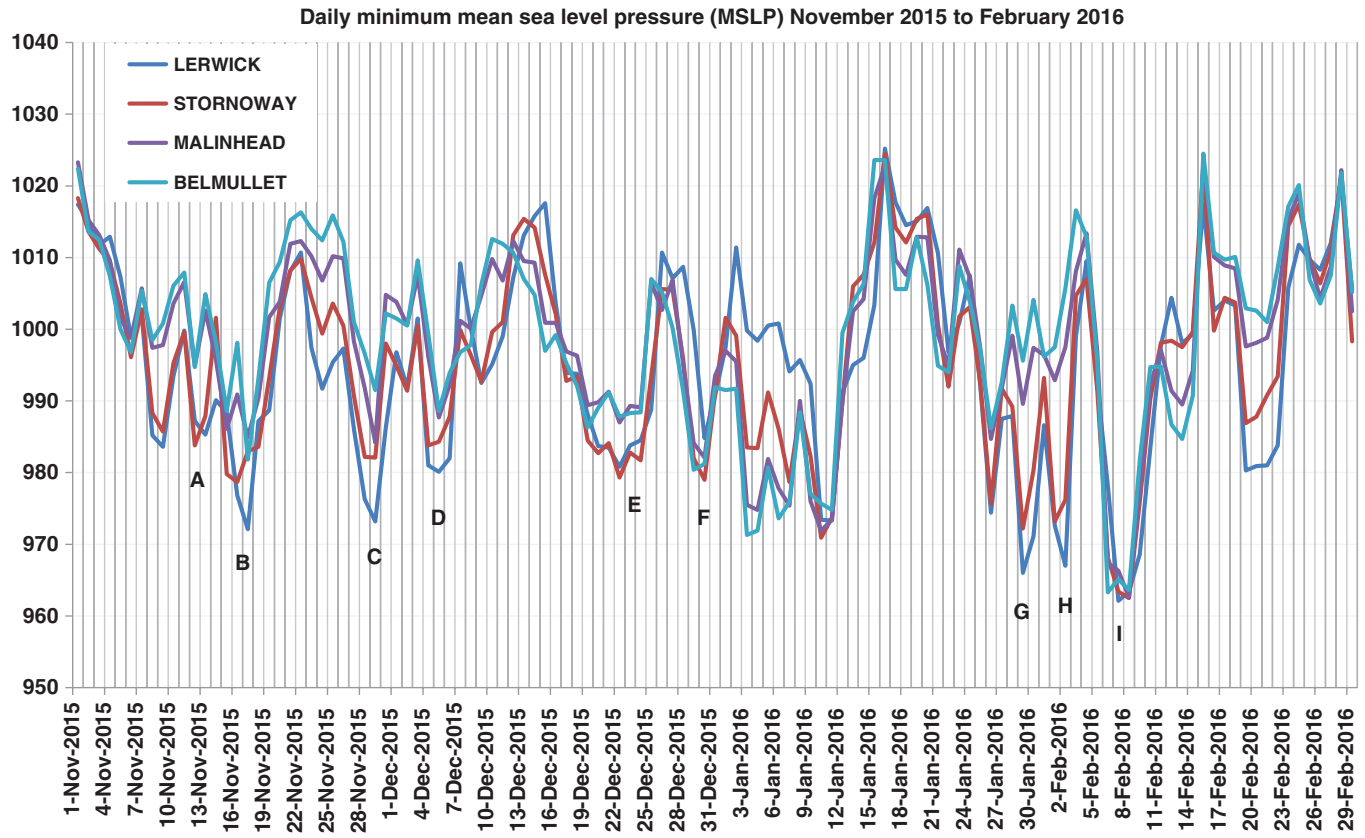

Figure 6. Daily minimum mean sea level pressure (hPa) at Belmullet (Mayo), Malin Head (Donegal), Stornoway (Western Isles) and Lerwick (Shetland) from 1 November 2015 to 29 February 2016. The named storms are annotated A (Abigail) to I (Imogen).

Table 1

Recorded maximum wind gusts (kn (ms^{-1})) for Ireland and UK for each of the named storms.

	Ireland			*UK*		
Name	*Max gust (kn (ms^{-1}))*	*Location*	*Date*	*Max gust (kn (ms^{-1}))*	*Location*	*Date*
Abigail	65 (33)	Belmullet (Mayo)	12 November	73 (38)	South Uist (Western Isles)	12 November
Barney	69 (35)	Shannon Airport (Clare)	17 November	74 (38)	Aberdaron (Gwynedd)	17 November
Clodagh	65 (33)	Finner (Donegal)	29 November	84 (43)	High Bradfield (South Yorkshire)	29 November
Desmond	64 (33)	Mace Head (Galway)	4 December	78 (40)	Capel Curig (Gwynedd)	5 December
Eva	73 (38)	Belmullet (Mayo)	23 December	72 (37)	Capel Curig (Gwynedd)	24 December
Frank	72 (37)	Sherkin Island (Cork)	30 December	74 (38)	South Uist (Western Isles)	29 December
Gertrude	70 (36)	Malin Head (Donegal)	29 January	91 (47)	Baltasound (Shetland)	29 January
Henry	70 (36)	Malin Head (Donegal)	1 February	78 (40)	South Uist (Western Isles)	1 February
Imogen	73 (38)	Sherkin Island (Cork)	8 February	81 (42)	Needles (Isle of Wight)	8 February

November gust recorded in the station's 70-year history.

December

Storm *Desmond* was a highly significant storm system that affected Ireland and the UK from 4–6 December. The storm tracked to the north of Scotland, but an exceptionally mild and moist air mass was associated with a very slow-moving trailing front. This front brought persistent rainfall across southern Scotland, northwest England and parts of Ireland. While the Cumbrian coast received less than 25mm of rain, orographic enhancement resulted in 200–300mm across the Cumbrian fells. In the 24h to 1800 UTC on the 5th, 341.4mm fell at Honister Pass (Cumbria), setting a new UK record for any 24h period. The nearby gauge at Thirlmere recorded 405.0mm in the 48h ending at 0900 UTC on 6 December, which is also a new UK record. The previous records for both 24 and 48h accumulations were set in Cumbria during November 2009. Some further discussion on the remarkable rainfall over Cumbria during December 2015 is also provided by Burt *et al.* (2016). The highest daily (0900–0900 UTC) rainfall accumulation in Ireland was 165mm at Keenagh Beg in County Mayo; the gauge at Leenane (Galway) recorded the highest 48h total of 259.7mm, which is the highest on record in the Irish digital database, which dates from 1941.

The synoptic features associated with *Desmond* bear similarities with the extreme event of November 2009, an event which also saw record-breaking rainfall accumulations and led to significant flooding in the south of Ireland and Cumbria. Figure 7 compares the surface analysis charts for 1200 UTC on 5 December 2016 with that of 19 November 2009. Both these events were associated with near stationary trailing fronts with a very warm and humid sector to the

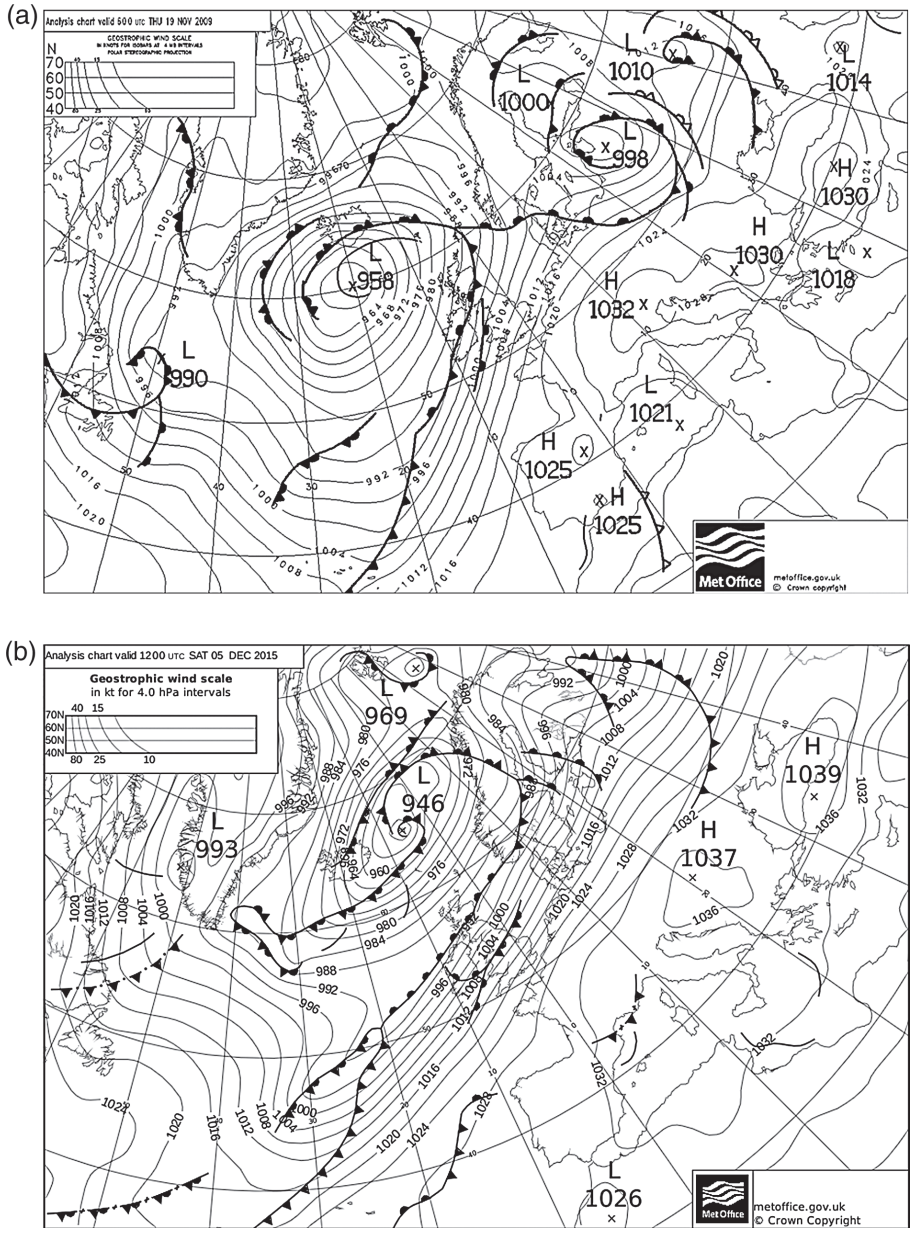

Figure 7. T+00 Surface analysis charts for (a) 0600 UTC on 19 November 2009 and (b) 1200 UTC on 5 December 2015 (lower).

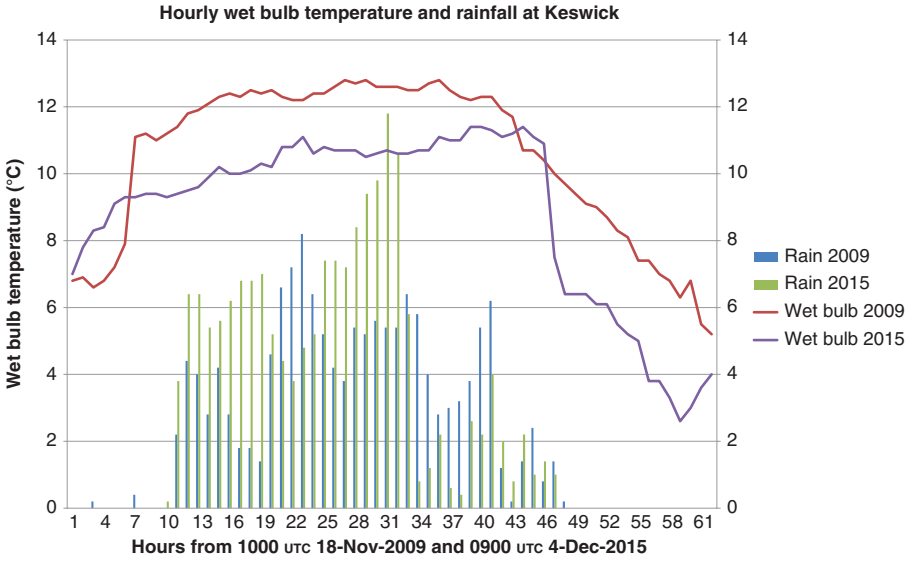

Figure 8. Hourly wet-bulb temperature (°C) at Keswick (Cumbria) for 62h periods from 1100 UTC on 18 November 2009 and 0900 UTC on 4 December 2015, to compare the evolution of these two extreme events.

south. Wet-bulb temperatures recorded at Keswick (Cumbria) exceeded 11°C for both events, and rain lasted for 38h as shown in Figure 8. For the period from 2000 UTC on 4 December to 1800 UTC on 5 December, hourly rain rates at Honister Pass in Cumbria were in excess of 10mmh^{-1} with peak hourly rate 25.6mm. The passage of the frontal system southward on the morning of 6 December is then clearly marked with a sharp transition to cooler air at Keswick and is coincident with the termination of the rain. The rainfall was exceptional as a result of its sustained nature, rather than intensity during any individual hour. Another example of a similar synoptic set-up also occurred on 7 January 2005 (not shown), which also led to severe flooding in western Ireland, north Wales and parts of northern England.

Although the exceptional rainfall from *Desmond* dominated much of the coverage of the event, there were also impacts from the high winds, with reports of overturned lorries, fallen trees and power cuts across northern England. Costs of the overall damage from storm *Desmond* were estimated at £400m to £500m (PwC, 2015). The Irish Defence Forces were deployed to assist the local authorities with flood defence operations in the counties of Cork and Kerry on Saturday 5 December 2015, with further personnel sent to Galway, Clare, Limerick and Westmeath between Monday 7 December and Wednesday 9 December (e.g. Defence Forces Ireland, 2015). In the Yorkshire Dales, Malham Cove waterfall flowed again for the first time in living memory, making this (briefly) England's highest single drop waterfall above ground (BBC, 2015).

On 23 and 24 December storm *Eva* brought further disruption from high winds, but more notable was the continued and persistent rain through the 25th and 26th, resulting in flooding across parts of Lancashire, north Manchester and west Yorkshire, with thousands of properties flooded and 20 000 homes without power. 100–120mm of rain fell across the high ground of the south Pennines across north Manchester, Lancashire and West Yorkshire, typically between half and three-quarters of the December whole-month average rainfall – with this falling on saturated ground and with rivers already in spate, extensive severe flooding followed. Storm *Frank* on the 29th/30th then brought further serious flooding to Scotland, resulting in evacuations from thousands of homes, with border towns – including Dumfries – being particularly badly affected. Serious flooding also occurred in the south and southeast of Ireland.

The strongest winds of the named storms affecting Ireland occurred during *Frank* on 30 December with 10min mean (sustained) winds of 55kn (28ms^{-1}) and during *Eva* with a gust of 73kn (38ms^{-1}) at Belmullet (County Mayo). The Office of Public Works (OPW,

Ireland) remained in a 'severe flooding' situation in the Shannon rainfall catchment for much of December. It was also a notably dull month in the south and southwest of Ireland, with the climate station at Sherkin Island (Cork) recording a total of just 2.8h sunshine, a record low value.

In total, early estimates suggest 16 000 properties were flooded during December 2015 in England alone. The Association of British Insurers estimated the claims associated with flooding and damage from the winter 2015/2016 storms would be around £1.3bn, exceeding those for winter 2013/2014 (ABI, 2015).

January

A succession of fronts resulted in persistent rain causing localised flooding for parts of the UK at the start of January, and further flooding occurred in several counties in Ireland. On the 4th, widespread flooding affected eastern Scotland, especially Aboyne (Aberdeenshire), causing road and rail closures, and there was heavy erosion on the banks of the river Dee. Northern Ireland was also affected, and on the 6th/7th, homes and businesses on the shores of Lough Neagh were flooded as water levels reached a 30-year high.

The strongest storm of the month was Storm *Gertrude* on 29 January, with 10min mean (sustained) winds of 53kn (27ms^{-1}) and maximum gust of 70kn (36ms^{-1}, Table 1) at Malin Head (County Donegal). In Scotland storm *Gertrude* caused localised landslides, fallen trees, isolated cases of structural damage and left around 8500 properties without power. Shetland saw the strongest winds of the winter during *Gertrude*, with a maximum gust of 91kn (47ms^{-1}), but thankfully the impacts here were relatively minor considering the strength of the winds.

February

Shortly after *Gertrude* the centre of storm *Henry* clipped the north of Scotland overnight of 1/2 February, with strong winds affecting most areas. 1 February is also the only day to have passed the very severe gale threshold for the Jenkinson-Collison gale index presented in Figure 1(c). However, it was *Imogen* on the 7th that was the most significant storm of the month, with 10min mean (sustained) winds of 54kn (28ms^{-1}) and maximum gust of 73kn (38ms^{-1}) at Sherkin Island (County Cork). *Imogen* took a more southerly track compared to some other storms of the season, and consequently the stations in Figure 6 saw their lowest pressures recorded in the season, dipping to 962hPa at Lerwick. Heavy rain and high winds affected southwest England and Wales in particular, with the strongest wind gust recorded on the Isle of Wight. The coastline of southwest England was affected by huge swell waves – reminiscent of the winter 2013/2014 storms. Fortunately, the weather was generally much quieter during the remainder of the winter.

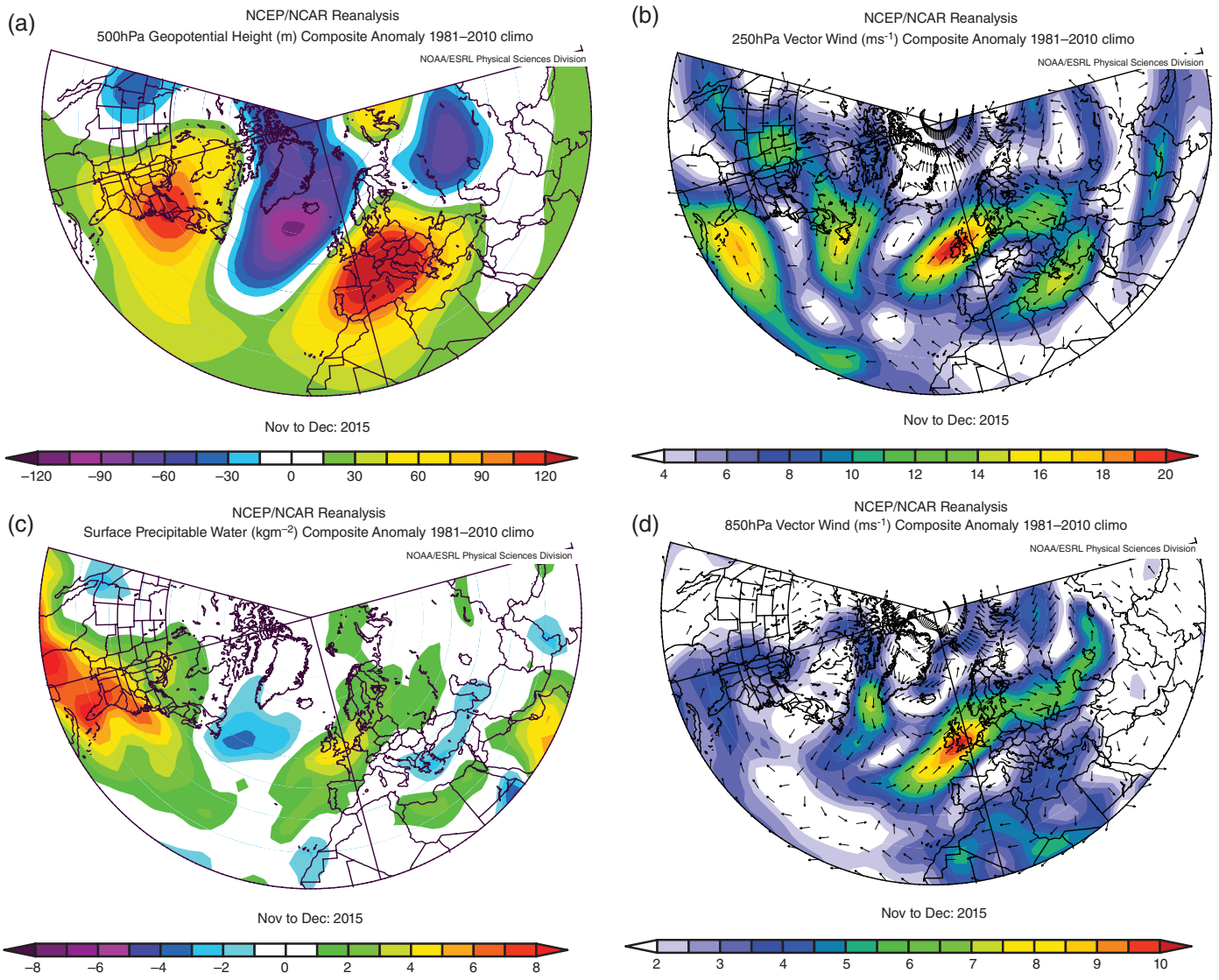

Figure 9. Anomaly maps of (a) 500hPa geopotential height, (b) 250hPa vector wind, (c) precipitable water and (d) 850hPa vector wind. From the NCEP reanalysis data (Kalnay et al., 1996). (Source: Images provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado from their website at http://www.esrl.noaa.gov/psd/)

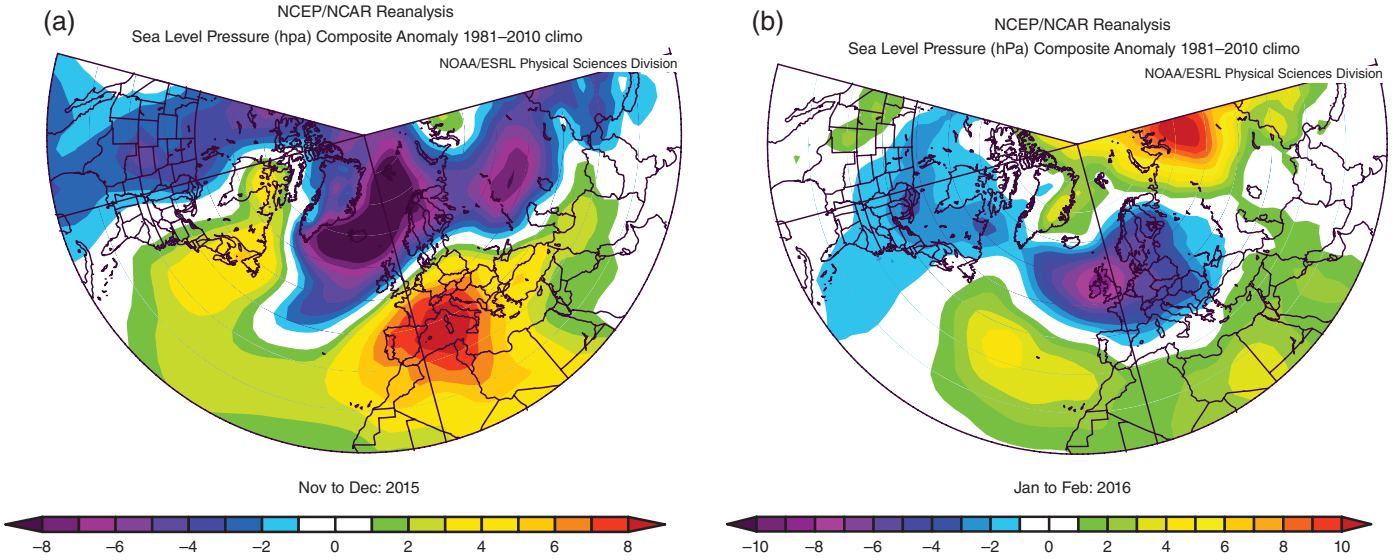

Figure 10. Mean sea level pressure anomalies for (a) November + December and (b) January + February. (Source: Images provided by the NOAA/ESRL Physical Sciences Division, Boulder, Colorado from their website at http://www.esrl.noaa.gov/psd/)

Hemispheric context

The exceptional weather across the UK and Ireland in winter 2015/2016 was, as would be expected, connected directly to wider hemispheric circulation patterns in early winter. These resulted in extremes and record breaking weather across parts of Europe, North America and the Arctic.

The northern hemisphere circulation anomaly during both November and December 2015 was characterised by a wave pattern of highs over the eastern USA, Europe, and east Asia, and lows between, with a particularly deep depression located over the north Atlantic as part of a wave train spanning the Atlantic basin as shown in Figure 9(a). The jet stream (Figure 9(b)) was perturbed north over the eastern USA, and the associated ridge drew warm, moist air with relatively high precipitable water content from the Gulf of Mexico, shown in Figure 9(c), resulting in unusually high temperatures and above-average precipitation. Twenty-nine US states experienced their warmest December on record, and it was overall the wettest December on record for the contiguous USA (NOAA, 2015). At the very end of December the presence of a low pressure over the Atlantic and a ridge of high pressure over eastern Europe resulted in warm, moist air penetrating far into the Arctic ocean; temperatures briefly spiked above the freezing level, with +0.7°C recorded by a buoy located near the North Pole on 30 December (NASA NSIDC, 2016).

The UK and Ireland sat immediately downstream of the Atlantic upper-level low anomaly, with the jet stream intensified and oriented southwest to northeast (Figure 9(b)), supporting cyclogenesis and the tracking of storm systems close to the British Isles and Ireland; Figure 9(d) shows the anomalously strong low level (850hPa) winds. The mean sea level pressure pattern in Figure 10(a) shows a deep low anomaly over the north Atlantic and high over the Mediterranean. The prevailing flow resulted in convergence of warm and moist air (Figure 9(c)) over the British Isles and Ireland as discussed previously.

Many countries across Europe experienced their mildest December on record, with the highest temperature anomalies above 4 degC in the north (Deutscher Wetterdienst, 2016). For precipitation it was a divided picture, with central and southern Europe having a significant rainfall deficit. Parts of the Mediterranean received less than 20% of average rainfall in December. Northern Europe, by contrast, was exceptionally wet, particularly in a band from southern Ireland to western Norway.

During January and February this regime broke down. The jet stream moved further south, and rainfall shifted to southern Europe. Much of northern Portugal, for example, received over 200% of average rainfall during January (IPMA, 2016). The low level circulation as represented by mean sea level pressure for November/December and January/February are shown in Figure 10(a) and (b). During January and February pressure increased over the Arctic relative to November/December, resulting in a low pressure anomaly now centred over the British Isles, consistent with the unsettled conditions experienced through the period, albeit not as exceptional as during November and December.

Drivers

Possible drivers of extreme seasons are particularly difficult to disentangle given the location and small geographic size of the UK and Ireland, along with sensitivity of rainfall patterns to even small shifts in the jet stream and storm track. The very large annual variability inherent in the climate of the UK and Ireland is demonstrated in Figure 1.

During 2015 one of the most significant El Niño events in the observational record developed in the Pacific. Fereday *et al.* (2008) have previously demonstrated a weak but significant correlation between El Niño-like patterns of sea surface temperatures in the tropical Pacific with the early winter (November/December) occurrence of circulation types that resemble the positive phase of the North Atlantic Oscillation (NAO) and strong zonal flow, as was observed in November and December of 2015. More recently Scaife *et al.* (2016) demonstrate that the predictable component of the 2015/2016 winter was picked up by the Met Office global seasonal forecast system, and in terms of the significant tropical drivers, it bears many similarities to the winter of 1982/1983.

2015 was also the warmest year on record globally, the northern hemisphere was 0.76 degC above the 1961–1990 average (WMO, 2016), and it is extremely likely that human influence has been the dominant cause of the observed warming since the mid-twentieth century (IPCC, 2013). The role of human forcing of climate on regional extreme weather events is a rapidly developing area of research (e.g. Stott *et al.*, 2016). Christidis and Stott (2015, hereafter CS15) provide evidence of increased risk of extreme winter (DJF) precipitation for the UK under circulation patterns similar to 2013/2014, and a weak shift to increased risk of 10-day rainfall extremes by a factor of about 7 as a consequence of anthropogenic climate change. This result is conditional on the correlation with the 500hPa geopotential height field over the British Isles and west Atlantic region from the 2013/2014 winter, for which there are qualitative similarities between 2013/2014 and 2015/2016, although the low anomaly

over the north Atlantic in 2015/2016 was not as deep as 2013/2014. An analysis of the R10x index used by CS15 (maximum 10-day precipitation, not shown) puts 2015/2016 as the sixth highest in a UK series from 1960, with the 10-day accumulation ending on 30 December 2015 representing the wettest 10-day period of the season. We would expect the quantitative results of CS15 to differ slightly if repeated with 2015/2016 circulation, and there are uncertainties inherent in such methods, but it is reasonable to consider the results of CS15 as indicative that we expect some contribution of anthropogenic climate change to an increased risk of 10-day rainfall extremes in winters like those of 2013/14 and 2015/16.

The winter 2015/2016 was certainly exceptional and has occurred during a cluster of stormy and wet winters since the 1990s (see Figure 1). Donat *et al.* (2011) used reanalysis data from 1871 and the Jenkinson–Collison indices discussed above to show a general upward trend in storminess over central, western and northern Europe. Kendon (2014) showed the 2010s contain more monthly to seasonal UK rainfall records than any other decade in the observational record, despite being only half a decade, and the period since 2000 accounts for 45% of all records. Rainfall records and severe impacts from events such as those in November 2009, winter 2013/2014 and now winter 2015/2016 are of particular note. Naturally these underlying trends raise questions about the clustering of extremes resulting from both natural variability and climate change that are subjects for ongoing UK climate research.

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