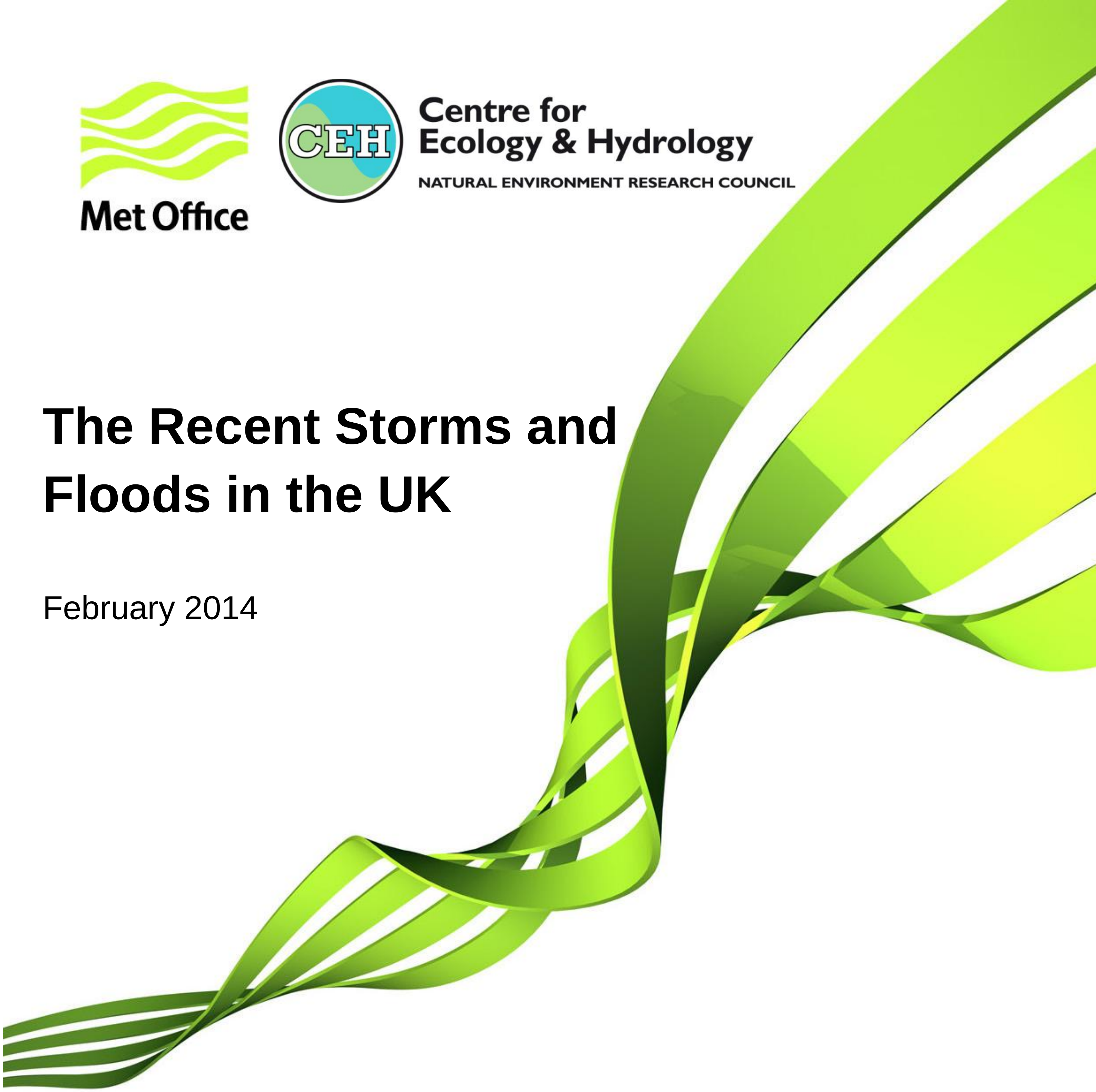
Met Office

Centre for Ecology & Hydrology
NATURAL ENVIRONMENT RESEARCH COUNCIL

The Recent Storms and Floods in the UK

February 2014



Summary

This winter the UK has been affected very severely by an exceptional run of winter storms, culminating in serious coastal damage and widespread, persistent flooding.

This period of weather has been part of major perturbations to the Pacific and North Atlantic jet streams driven, in part, by persistent rainfall over Indonesia and the tropical West Pacific.

The North Atlantic jet stream has also been unusually strong; this can be linked to exceptional wind patterns in the stratosphere with a very intense polar vortex.

This paper documents the record-breaking weather and flooding, considers the potential drivers and discusses whether climate change contributed to the severity of the weather and its impacts.

Although no individual storm can be regarded as exceptional, the clustering and persistence of the storms is highly unusual. December and January were exceptionally wet. For England and Wales this was one of, if not the most, exceptional periods of winter rainfall in at least 248 years. The two-month total (December + January) of 372.2mm for the southeast and central southern England region is the wettest any 2-month period in the series from 1910.

During January and into February the tracks of the storms fell at a relatively low latitude, giving severe gales along the south and west coasts and pushing the bulk of the ocean wave energy toward the southwest of Ireland and England. Peak wave periods were exceptionally long; each wave carried a lot of energy and was able to inflict significant damage on coastal infrastructure.

In a series from 1883, flow rates on the River Thames remained exceptionally high for longer than in any previous flood episode. Correspondingly, floodplain inundations were extensive and protracted.

The severe weather in the UK coincided with exceptionally cold weather in Canada and the USA. These extreme weather events on both sides of the Atlantic were linked to a persistent pattern of perturbations to the jet stream over the Pacific Ocean and North America. There is a strong association with the stormy weather experienced in the UK during December and January and the up-stream perturbations to the jet stream over North America and the North Pacific.

The major changes in the Pacific jet stream were driven by a persistent pattern of enhanced rainfall over Indonesia and the tropical West Pacific associated with higher than normal ocean temperatures in that region.

The North Atlantic jet stream has also been unusually strong; this can be linked to an unusually strong westerly phase of the stratospheric Quasi-Biennial Oscillation (QBO), which in turn has driven a very deep polar vortex and strong polar night jet.

As yet, there is no definitive answer on the possible contribution of climate change to the recent storminess, rainfall amounts and the consequent flooding. This is in part due to the highly variable nature of UK weather and climate.

Sea level along the English Channel has already risen during the 20th century due to ocean warming and melting of glaciers. With the warming we are already committed to over the next few decades, a further overall 11-16cm of sea level rise is likely by 2030, relative to 1990, of which at least two-thirds will be due to the effects of climate change.

Recent studies suggest an increase in the intensity of Atlantic storms that take a more southerly track, typical of this winter's extreme weather. Also the long-term warming of the

sub-tropical Atlantic will also act to enhance the amount of moisture being carried by storms that take this more southerly track.

There is an increasing body of evidence that extreme daily rainfall rates are becoming more intense, and that the rate of increase is consistent with what is expected from fundamental physics. There is no evidence to counter the basic premise that a warmer world will lead to more intense daily and hourly heavy rain events.

More research is urgently needed to deliver robust detection of changes in storminess and daily/hourly rain rates. The attribution of these changes to anthropogenic global warming requires climate models of sufficient resolution to capture storms and their associated rainfall. Such models are now becoming available and should be deployed as soon as possible to provide a solid evidence base for future investments in flood and coastal defences.

Record-breaking Weather

Throughout December, January and February 2013/14, the UK has been affected by an exceptional run of severe winter storms, culminating in the coastal damage and widespread flooding from January onwards. The impacts on individuals, businesses and infrastructure have been substantial. This paper documents the statistics of these storms, how unusual they were in the terms of past records, and considers the global context in which these storms formed. Finally the question of whether the intensity of these storms, and their impacts on flooding, has been influenced by climate change will be considered.

During December widespread high wind speeds were recorded across UK, as a sequence of deep lows tracked across or to the north of the country. The storm on 4th-5th December generated a major North Sea storm surge event, which coincided with one of the highest tides of the year and threatened much of the east coast in a similar manner to the 1953 event. With improved coastal defences built by the environment agency and accurate early warnings several days in advance major damage was avoided. The Environment Agency Thames Barrier was raised to protect London from the largest tide recorded at Southend since it became operational.

A measure of the extent and severity of the December storms can be seen in the number of stations from the observational network that recorded maximum gust speeds greater than 50, 60, or 70 Knots (excluding stations with an altitude >=250m and four exposed offshore sites). For each of the thresholds the number of high wind gusts in December 2013 is higher than for any other December back to 1969 (Figure 1), and is one of the windiest calendar months for the UK since January 1993.

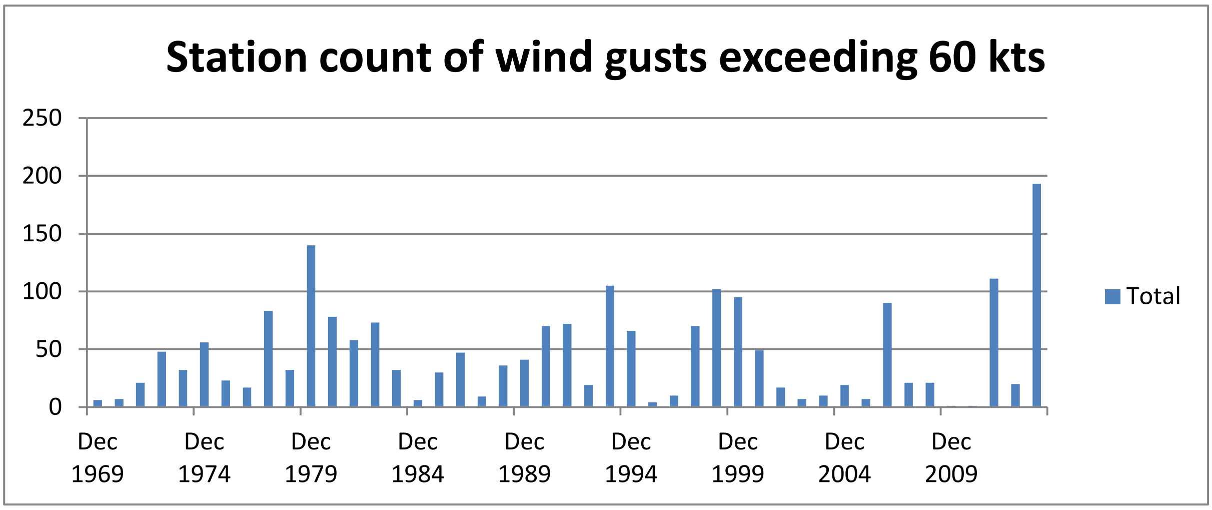


Figure 1: Record of the number of stations reporting wind gusts in excess of 60 kts during December.

The stormy weather continued into January with a major storm on 5th and 6th January, which caused widespread coastal damage and flooding in southern England. With a brief respite in January the stormy weather returned with the first week of February seeing a sequence of very deep depressions running into the UK with very high winds and storm surges that caused substantial damage along the south coast.

The exceptional duration of the stormy weather and the clustering of deep depressions has been a notable feature of this winter. Rainfall records were broken in both December and January (Figure 2). Scotland had its wettest December since records began in 1910. In southern England, January was the wettest recorded since 1910 (Figure 3), and the statistics suggest that this was one of, if not the most, exceptional periods for winter rainfall across

England and Wales in at least 248 years. The two-month total (December + January) of 372.2mm for the southeast and central southern England region is the wettest of any 2-month period in the series from 1910.

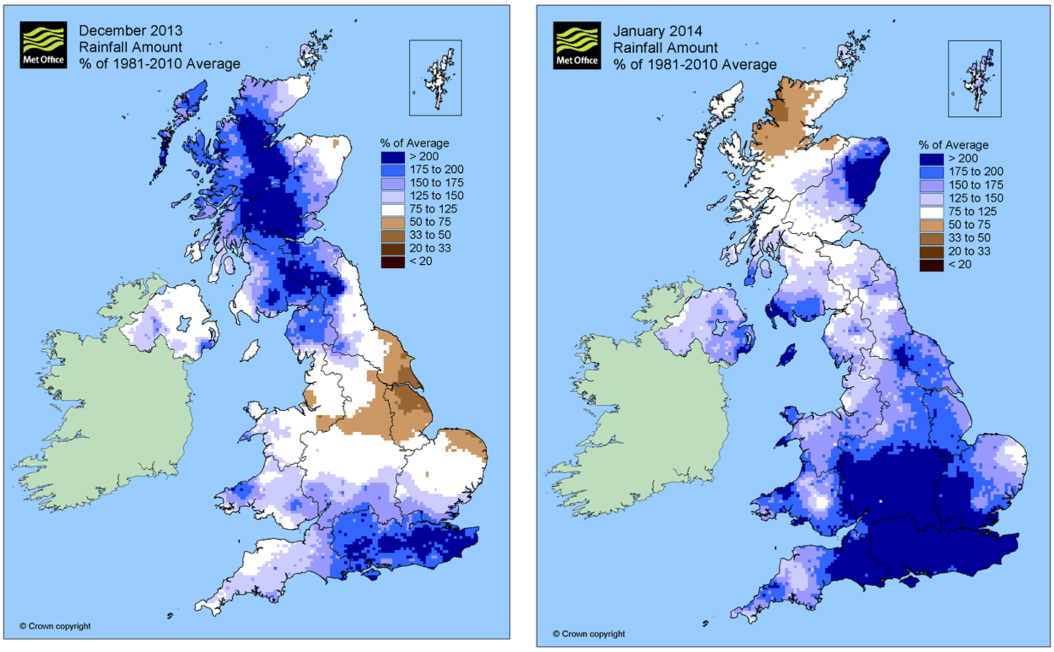


Figure 2: Rainfall for December 2013 and January 2014 from the observational network, showing the distribution of rainfall anomalies as a % of the long-term average from 1981-2010.

A particularly exceptional aspect of January 2014 has been the number of days with rain across southern England (Figure 3, lower panel), which far exceeded anything previously recorded for January. Overall there have been very few dry days since 12th December. This continuous sequence of rain events led to increasing saturation of the ground so that widespread flooding became inevitable when the major storm of 5th and 6th January arrived over the UK. The Thames, in particular, recorded some of the highest flow rates ever measured at this time of year. In January 2014, the Environment Agency Thames Barrier was raised on 13 consecutive times to protect people and property as high fluvial flows and high spring tides coincided. Rainfall continued to be well above average through January, giving little respite for areas already affected by flooding especially in southern England, and notably Somerset.

As already noted this winter has been exceptionally stormy. A particularly intense depression passed to the north of UK on 24th December with Stornaway recording a mean sea level pressure of 936mb (Figure 4). Pressures below 950mb for UK land stations are relatively rare, and this is the lowest such value at a UK land station for many years. Based on an analysis by Burt (2007)[1] it is potentially the lowest land station pressure record since 1886. This storm led to widespread disruption to travel and the loss of power to hundreds of thousands of homes over the Christmas period.

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[1] *Burt, 2007*: The Lowest of the Lows … extremes of barometric pressure in the British Isles, part 1 – the deepest depressions. *Weather,* 62, 4-14 http://onlinelibrary.wiley.com/doi/10.1002/wea.20/abstract

[2] The jet stream describes ribbons of strong westerly winds high in the atmosphere, typically between 200 and 300mb that circumnavigate the northern and southern mid-latitudes. In the northern

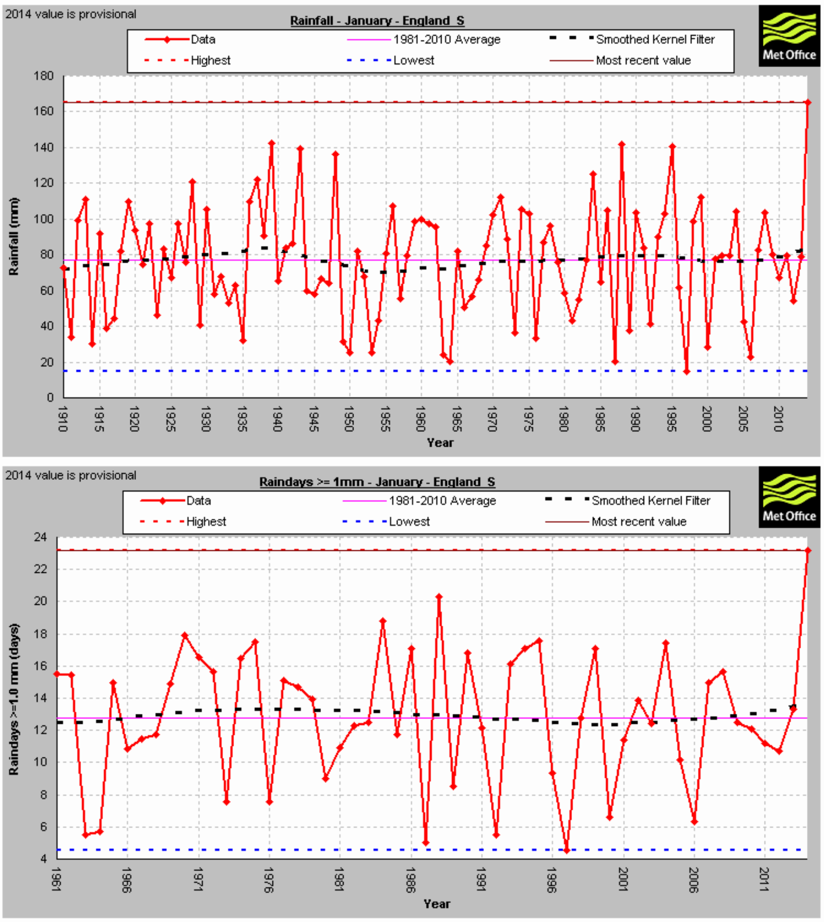


Figure 3: Time series of total rainfall (mm) for January in southern England from records going back to 1910 (top panel), and the number of days with rain (>1mm) in southern England from records going back to 1961 (bottom panel).

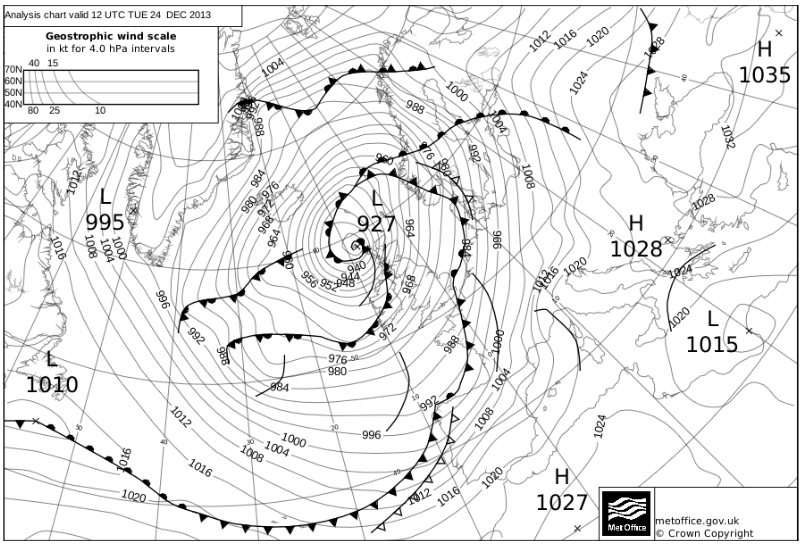


Figure 4: Surface pressure chart for 12z, 24th December showing the formation of an intense depression to the north of Scotland.

This sequence of storms continued into January 2014, with a deep depression forming over the North Atlantic on 5th January. A notable feature of this storm was the size of the depression (Figure 5), which affected the whole North Atlantic. Storms of such size and intensity are rare. This meant that the fetch and strength of the winds built up a huge swell with some of highest recorded wave heights reaching the shores of Western Europe. The west coasts of the UK were severely affected by the storm surge and the exceptionally high waves resulting in extensive damage to sea defences. Rainfall associated with this system also caused extensive flooding in areas already saturated by the wet weather in the preceding months.

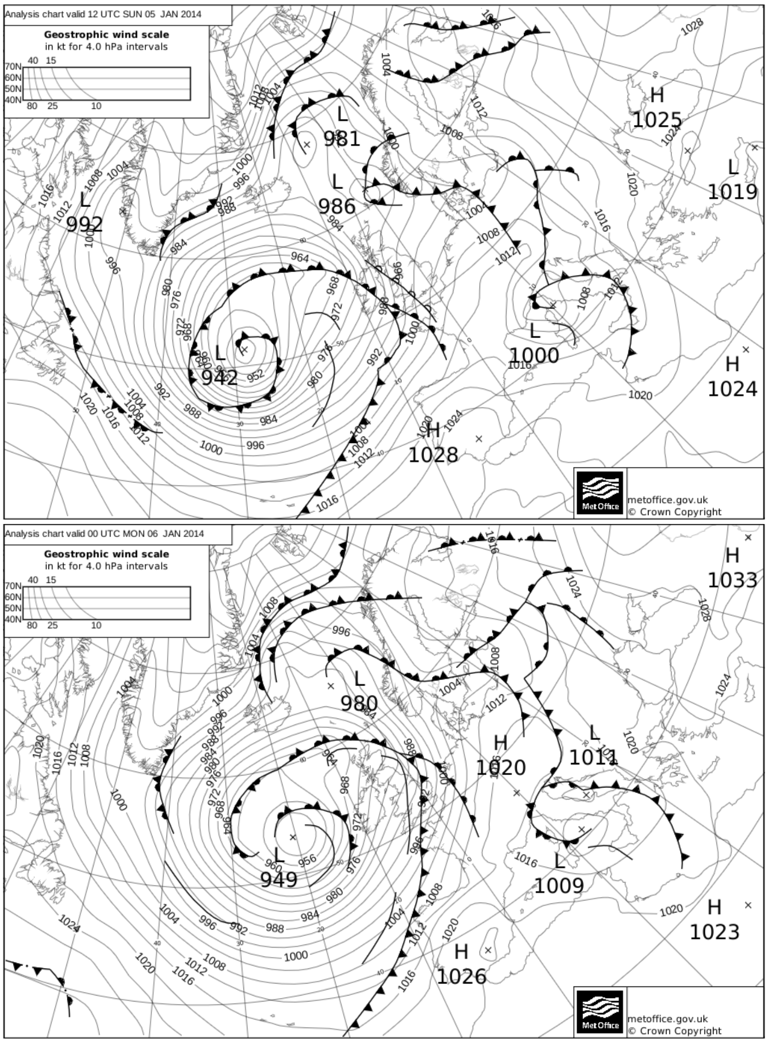
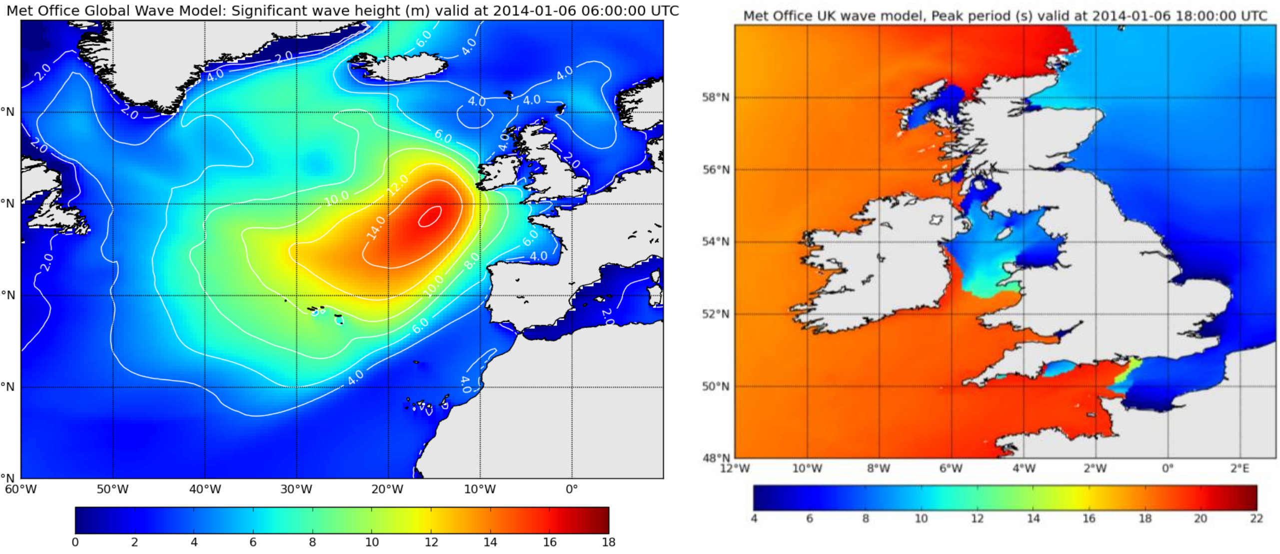


Figure 5: Surface pressure charts for 12z, 5th January and 00z, 6th January showing the strength and size of the depression and its associated frontal systems.

Throughout the development of the storm that affected the UK on 5th, 6th and 7th January, the Met Office ocean and wave forecast models were giving very useful guidance. On the global scale, significant wave heights in excess of 16m were predicted to the south west of the UK, consistent with other estimates of wave heights exceeding 15m (50ft) (Figure 6, left panel). Higher resolution forecasts using the UK 4km model showed that these waves would reach UK shores as a strong, very long period swell (Figure 6, right panel). Consequently, each wave carried a lot of energy and was able to inflict significant damage on coastal infrastructure.

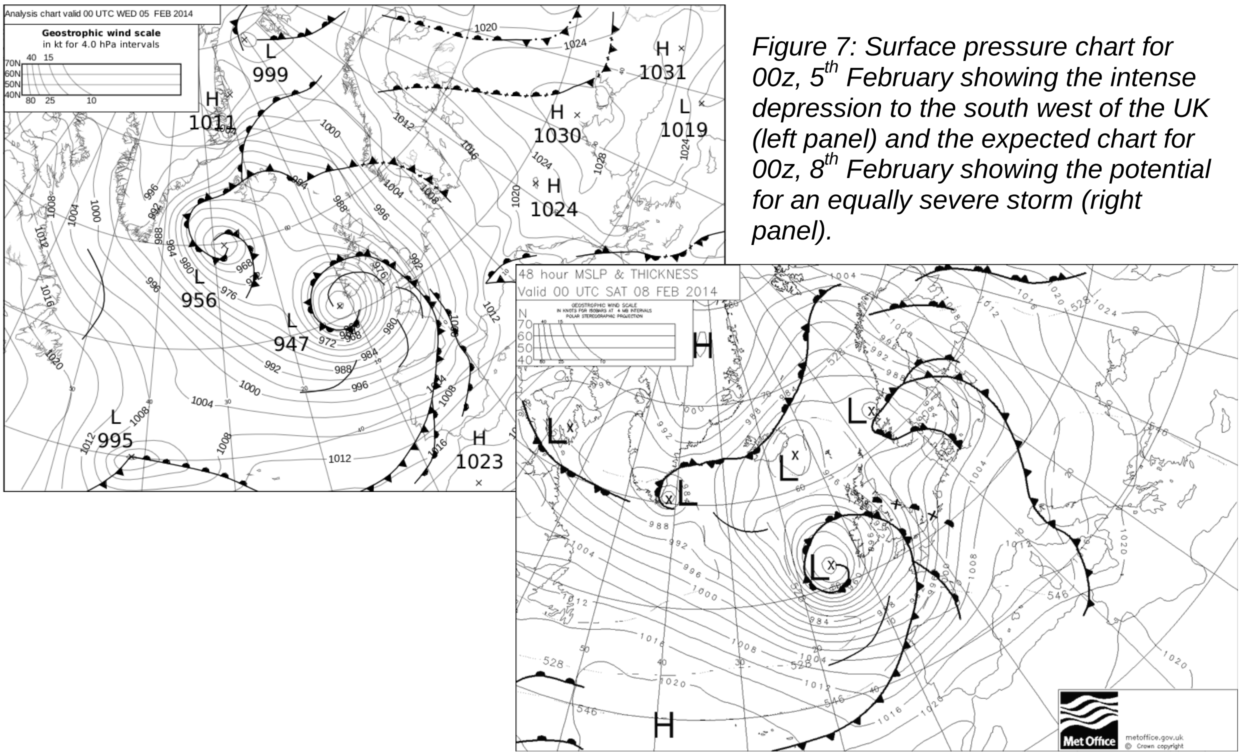
Storms generating waves of this height are not particularly unusual for the northeast Atlantic, but several factors mark out the event on 6th and 7th January. The track of the storm fell at a relatively low latitude for an event of this type, pushing the bulk of the wave energy towards the southwest of Ireland and England. Peak wave periods were exceptionally long (even compared with storms of similar wave height occurring in December), and enhanced the impact of the waves at the coastline. The combination of significant wave height and peak period is likely to mark out the storm as a one in 5-10 year event in the southwest of the UK, based on experience of waves over the last 30 years. In terms of the coastal system as a whole, pre-existing river and groundwater levels plus impact on coastal sediment levels of a sequence of highly energetic wave events during December may make this is a far rarer event.


Met Office Global Wave Model: Significant wave height (m) valid at 2014-01-06 06:00:00 UTC

Met Office UK wave model, Peak period (s) valid at 2014-01-06 18:00:00 UTC

Figure 6: Significant wave heights (m) from the Met Office global wave model valid for 06z on 6th January (left panel) and peak period (seconds) between waves from the UK 4km model for 18z on 6th January.

With sea defences already weakened the storms that affected southern England on 4th and 5th February, and expected for 7th and 8th February, (Figure 7) have caused serious localised damage to infrastructure. The strength the waves, driven onshore by the very strong winds, and the consequent height of the storm surge produced very dangerous conditions along southern coasts. The heavy rainfall that accompanied these systems also led to worsening conditions in areas already affected by prolonged flooding.


Analysis chart valid 00 UTC WED 05 FEB 2014

48 hour MSLP & THICKNESS Valid 00 UTC SAT 08 FEB 2014

Figure 7: Surface pressure chart for 00z, 5th February showing the intense depression to the south west of the UK (left panel) and the expected chart for 00z, 8th February showing the potential for an equally severe storm (right panel).

Record -breaking Flooding

The exceptional run of severe winter storms which carried with them large amounts of rain led to very serious flooding across southern England. With catchments across most of the UK saturated by mid-December, the full gamut of flood manifestations – tidal, pluvial (flash), fluvial and groundwater – were experienced over the ensuing seven to eight weeks.

Initially, the focus was on tidal flooding. In the first week of December, eastern and southern England experienced their highest storm surge since the extensive tidal flooding in January 1953. The flooding, whilst extensive, was considerably less than the 1953 event (1953: 307 deaths, 24,000 properties and 65,000 hectares compared with 2013: 0 flood related deaths, 1,400 properties and 6,800 hectares) due to the warning, response and flood defences put in place by the Environment Agency and others since 1953.

The damage was moderate in comparison to that major disaster, but substantial evacuations were required (e.g. in Boston, Lincolnshire) and the ingress of seawater damaged a number of important wetlands (e.g. Blakeney, Norfolk). High tides, exacerbated by intense low pressure systems and frequent strong south-westerly winds, continued to contribute to coastal and estuarine flood risk well into 2014.

Thereafter, the second half of December and early January witnessed a succession of very deep cyclonic systems. Particularly influential in the hydrological context was the system which brought notable rainfall totals (>30 mm, with some exceptionally high totals in western uplands) to many areas on the 23rd/24th December. This triggered flash flooding, particularly in south-west England, and a steep increase in river flows across most of the UK. Estimated outflows from Great Britain remained close to the highest ever recorded during late December (Figure 8) and, subsequently, throughout most of January across large parts of England and Wales (Figure 9).

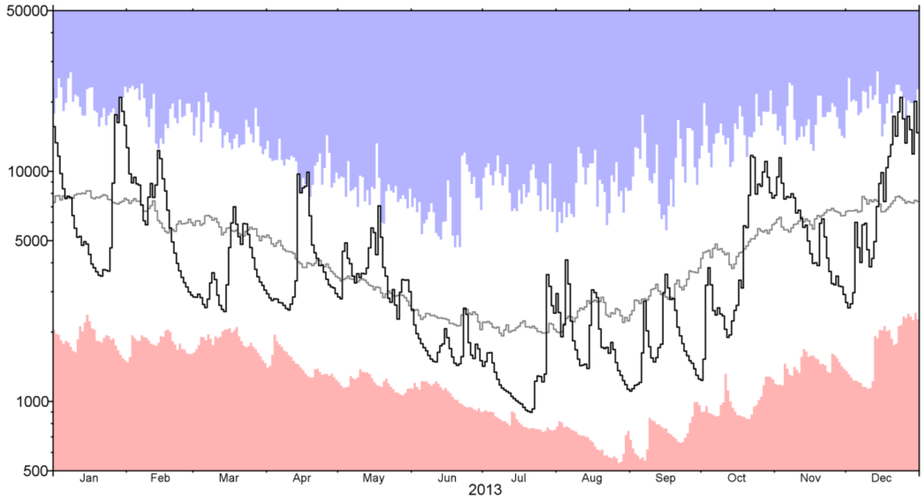


Figure 8: Outflows (m^3 s^{-1}; black) from Great Britain in 2013, plotted against period of record (1961-2013) daily maximum flows (blue), daily minimum flows (pink) and mean daily flows (grey)

Relative to the average, runoff rates were generally most outstanding across southern and central England and the singular nature of this episode is well illustrated by flow patterns on the Thames. In a series from 1883, flows at Kingston (close to the tidal limit) remained above 275 m^3 s^{-1} for longer than in any previous flood episode (Table 1), and continue to exceed this threshold into early February. Correspondingly, floodplain inundations were extensive and protracted, owing to the succession of low pressure systems producing rainfall over saturated ground. A preliminary analysis suggest that outflows aggregated over six weeks were the greatest since the 1947 floods – the most extensive in England and Wales during the 20th century.

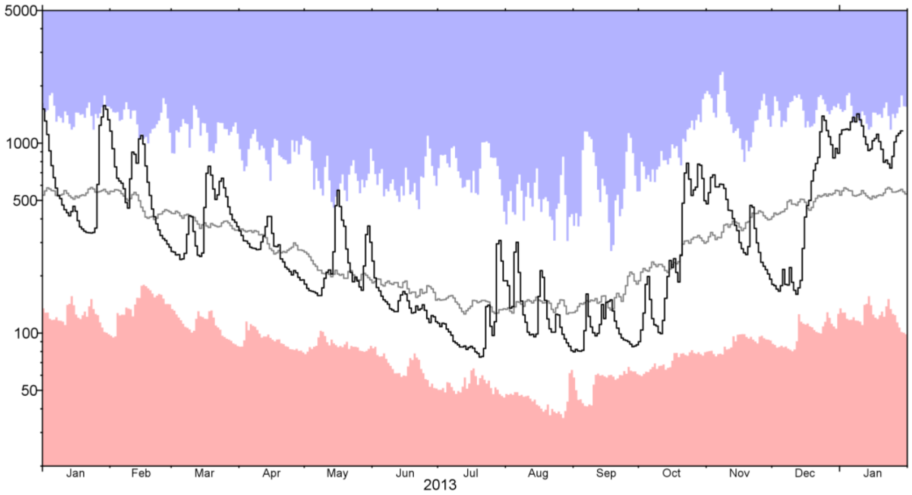


Figure 9: Combined flows ($m^3 s^{-1}$; black) for the Thames, Severn, Trent, Yorkshire Ouse and Usk in 2013 and January 2014, plotted against period of record (1969-2013) daily maximum flows (blue), daily minimum flows (pink) and daily mean flows (grey)

Start Date	***End Date***	***No. of consecutive days >275 $m^3 s^{-1}$***	***Highest flow ($m^3 s^{-1}$)***
24/12/2013	**31/01/2014**	**39***	**477**
12/03/1947	**08/04/1947**	**28**	**714**
01/02/1904	23/02/1904	23	517
18/03/1916	06/04/1916	20	373
04/12/2000	21/12/2000	18	450
20/01/1995	06/02/1995	18	385
31/01/1990	17/02/1990	18	427
17/01/1939	03/02/1939	18	369
01/12/1929	18/12/1929	18	552
30/12/1914	15/01/1915	17	585

** 2013/14 flows remain above 275 $m^3 s^{-1}$ at month-end*

Table 1: Long duration high flow events on the Thames at Kingston (1883-2014)

In December and January, a few rivers (including the Mole, Wey and Medway, which, on the basis of preliminary data, recorded their highest flows since the extreme floods of September 1968) registered outstanding maximum flows. However, generally, the peak flows registered during the recent flooding were not extreme. On the Thames the highest flow in 2014 has been exceeded during 14 earlier floods (most prior to 1950; Figure 10).

The floodplain inundations caused major disruption to transport, agriculture and restricted sporting and recreational activities, and resulted in severe difficulties for some low-lying hamlets (most notably in the Somerset Levels). However, given the overall volume of runoff, the amount of property flooding at the national scale was relatively modest.

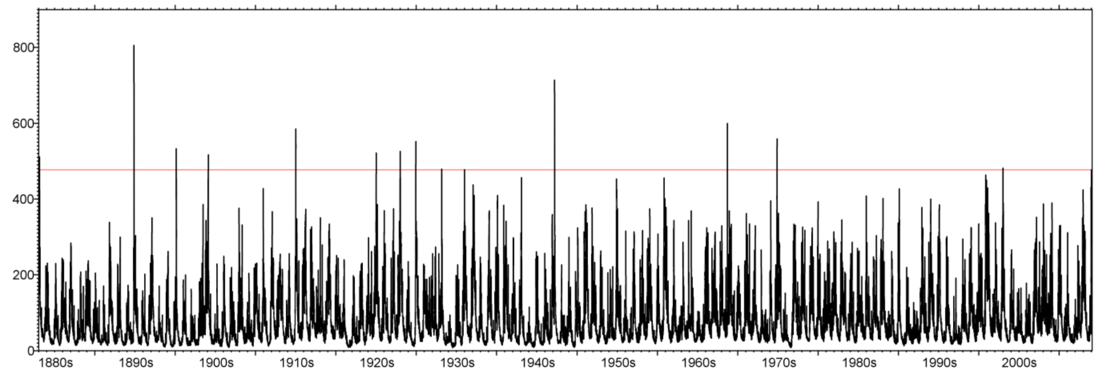


Figure 10: Naturalised daily flows (m^3 s^{-1}; black) for the Thames at Kingston (1883-2014), compared against peak flow in December 2013 / January 2014 (red line)

Groundwater levels were generally below the seasonal average at the end of the autumn in 2013, but as infiltration rates increased markedly through December, the recovery in groundwater levels was dramatic in many aquifer outcrop areas – the southern Chalk in particular. At Tilshead, on Salisbury Plain, levels rose by 20 metres in around a fortnight and the well was artesian by late January (Figure 11). In Sussex the Chilgrove House well was also overflowing – there have been around six similar artesian episodes in a record extending back to 1836. As a consequence, examples of groundwater flooding, first noted in mid-December (e.g. in Dorset and Hampshire), became increasingly common in vulnerable areas (e.g. South Downs and Berkshire Downs) with an expectation that more widespread flooding will occur as groundwater levels rise in the slower-responding aquifers (e.g. the Chilterns).

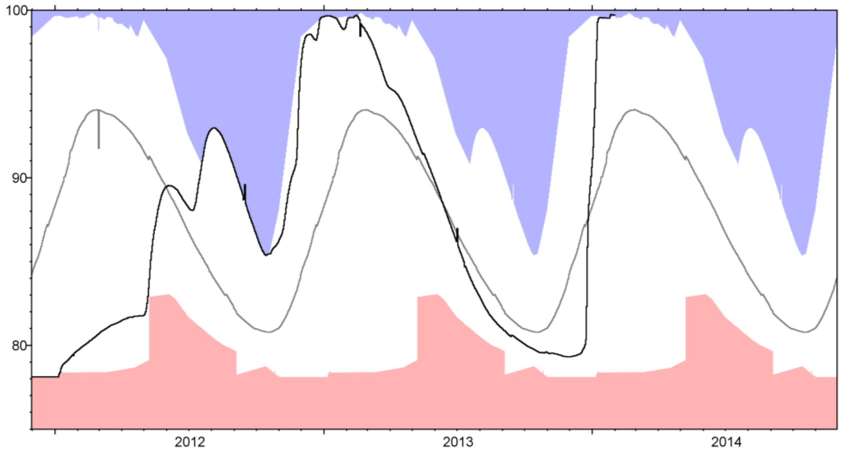


Figure 11: Groundwater levels (m aOD; black) at Tilshead, plotted against period of record (1966-2013) maximum (blue), minimum (pink) and mean (grey) levels

Soils are likely to remain close to saturation into the early spring, continuing the risk of floodplain inundations in response to even moderate amounts of rainfall. The lagged response of groundwater levels to the persistent rainfall is likely to contribute to further flooding in vulnerable aquifer areas of southern England.

Global Context of recent UK Weather

The exceptional weather experienced over the UK in December and January was part of a hemispheric pattern of severe weather. This included exceptionally low temperatures across Canada and the US from the mid-west to the eastern seaboard and reaching as far south as Texas (Figure 12). The peak of this cold event occurred on the 5th and 6th January, coinciding with the storminess over the UK. Early estimates suggest that in the US alone over 200 million people were affected with costs in excess of $5bn.

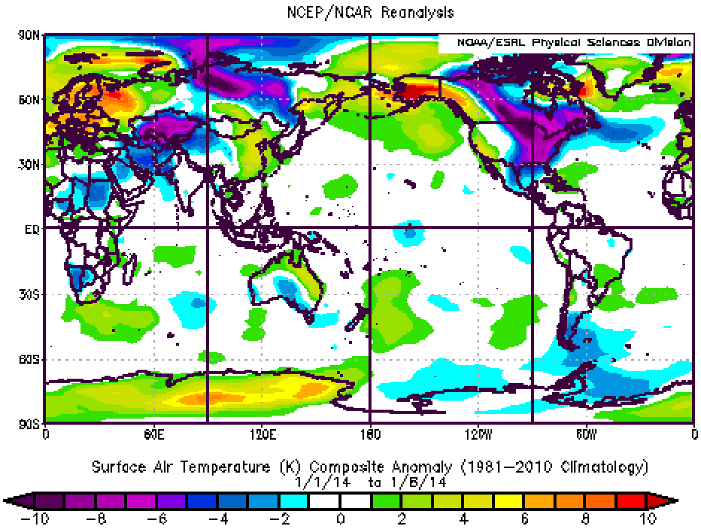


Figure 12: Surface air temperature anomalies (^{0}C) for the first week of January 2014 compared to the long-term climatology for 1981-2010.

These extreme weather events on both sides of the Atlantic were embedded in a persistent pattern of perturbations to the upper tropospheric jet stream[2] (Figure 13). The climatological distribution of the winter jet streams (Figure 13, left panels) shows the well-known Asian-Pacific jet stream, which extends across North Africa and out into the North West Pacific, close to Japan. A second jet stream forms over the US, extending in a north-easterly direction across the North Atlantic towards the UK. The North Atlantic jet stream acts to steer weather systems towards the UK, but there also exists a symbiotic relationship between the jet stream and the depressions that form on its flanks. The jet stream provides the atmospheric conditions that are favourable for cyclogenesis (the formation of depressions), but it also depends on the momentum from the depressions to maintain its own strength. So it is possible on occasions to observe a strengthening of the jet stream when there is a particularly active sequence of depressions, as was the case in December 2013 and January 2014 (Figure 13, right panels).

During December and January 2013/14 the pattern of winds over the North East Pacific and North America was very disturbed (Figure 13, right panels). The North Pacific jet was deflected a long way north, with a secondary branch extending southwards into the tropical Pacific accentuating the separation of the Pacific and Atlantic jet streams. The effects of this over North America and into the North Atlantic were profound. The deflection of the jet to the north led to colder air being carried south over Canada and the northern US (as seen in Figure 13) to enter the North Atlantic jet and establish a stronger than normal temperature

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[2] The jet stream describes ribbons of strong westerly winds high in the atmosphere, typically between 200 and 300mb that circumnavigate the northern and southern mid-latitudes. In the northern hemisphere, in particular, the jet stream is broken up into segments by the effects of mountains, land masses and planetary scale waves that are generated by large scale changes in tropical weather associated, for example, with El Nino.

gradient at the entrance of the North Atlantic Jet. This acted to strengthen the jet and provide the conditions for active cyclogenesis, which in turn led to a sequence of strong storms across the UK throughout December and January. As Figure 13 indicates, the North Atlantic jet was, on average, as much as 30% stronger than normal. Similar, but weaker, conditions can be seen in the southern hemisphere, mirroring those to the north and supporting the view that the tropics were driving at least some of what has been experienced this winter.

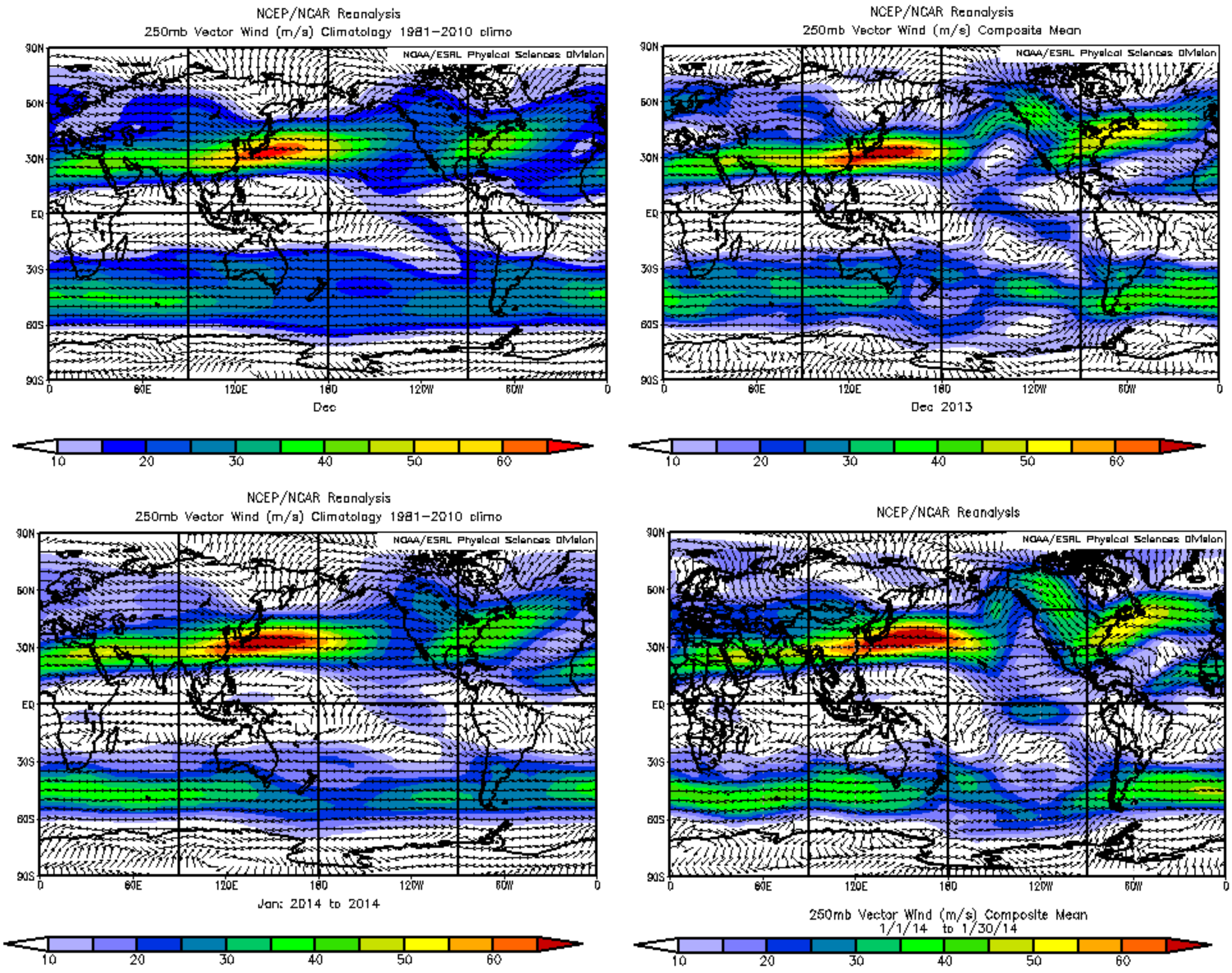

Figure 13: Climatological distribution of the winds in the upper troposphere at 250mb during December and January (left panels) and the actual distribution during December 2013 and January 2014 (right panels). Vectors show the direction of the winds and the colours indicate the strength of the winds (m/s).

In the lower troposphere, at 850mb (Figure 14), the winds over the North Atlantic were much stronger than normal during December and January 2013/14. Likewise the perturbed flow over the North Pacific is also very clear with an anomalous anticyclonic system off the west coast of North America, which has been a persistent feature of this winter's weather. At these lower levels in the atmosphere, the clash between the cold northerly airstream from North America with the warm, moist airstream from the tropical Atlantic is notable (see circled areas on Figure 14). Not only would this act to invigorate storms forming on the jet stream, but the inflow of warm, moist air from the tropics would enhance the moisture being carried by the storm systems and potentially lead to higher rainfall downstream over the UK.

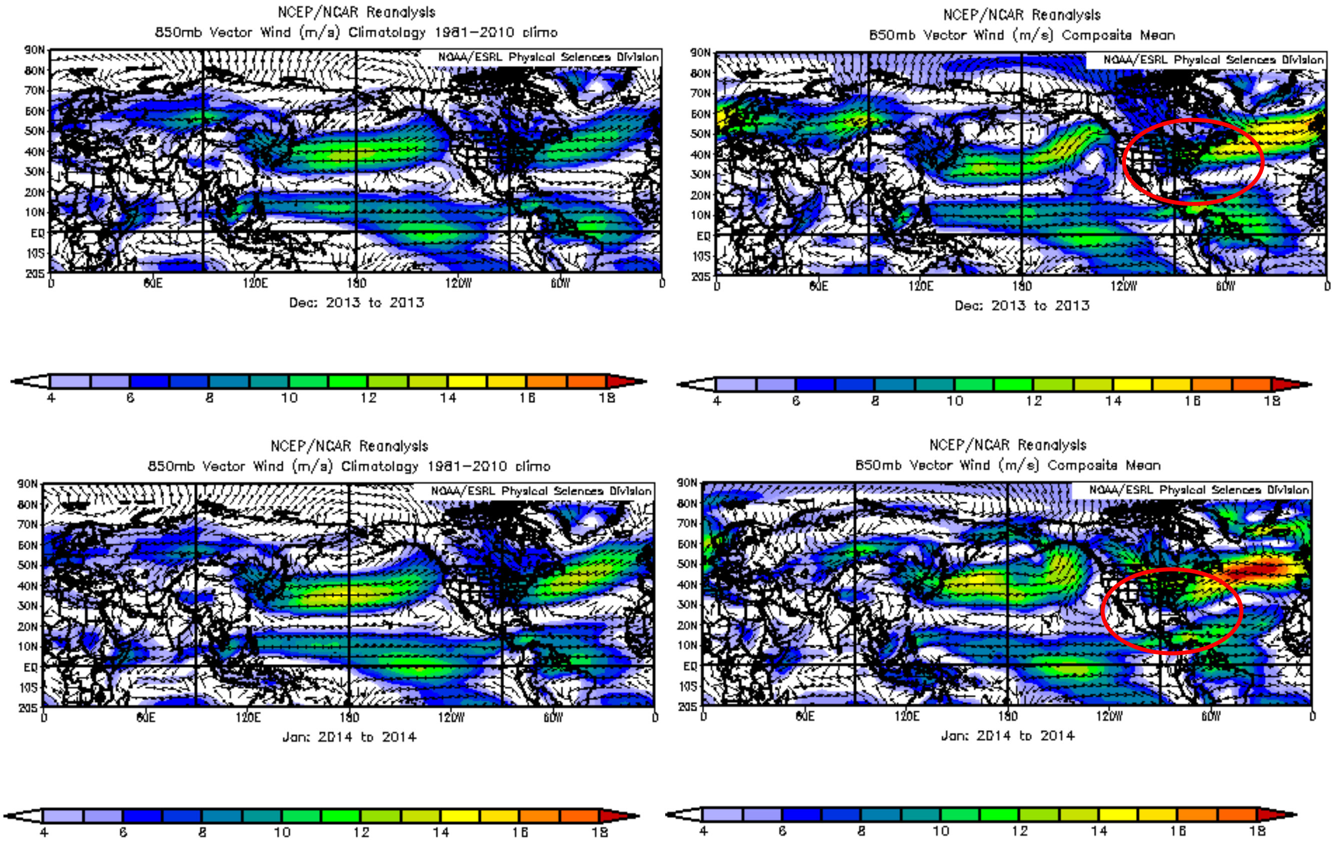

Figure 14: Climatological distribution of the winds in the lower troposphere at 850mb during December and January (left panels) and the actual distribution during December 2013 and January 2014 (right panels). Vectors show the direction of the winds and the colours indicate the strength of the winds (m/s). Red oval highlights the convergence of cold air from the north and warm air from the tropical Atlantic at the beginning of the storm track over the North Atlantic.

It is clear from Figures 13 and 14 that there is a strong association between the stormy weather experienced in the UK during December and January 2013/14 and the up-stream perturbations to the jet stream over North America and the North Pacific. So what might be the drivers of the changes over the Pacific?

It is well understood that El Nino and its cold counterpart La Nina have major effects on weather patterns around the globe[3]. Indeed the changes in the jet stream over the North Pacific, described above, are typical of what is observed during La Nina events (Figure 15), with the jet being deflected to the north by anomalously high pressure off the western seaboard of the US, and with a variable jet to the south along which disturbed weather forms. The polar jet stream is then deflected a long way south over the US bringing cold air with it

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[3] La Nina corresponds to the cold phase of El Nino Southern Oscillation (ENSO) cycle in which sea surface temperatures along the Peruvian coast and across the equatorial East Pacific are colder than normal; concurrently sea surface temperatures in the West Pacific tend to be warmer than normal. This change in the pattern of sea surface temperatures drives more rainfall and active weather systems over the warm waters of the West Pacific and Indonesian seas, and the global effects are felt as far as the UK through teleconnections involving changes in planetary waves and hence the position of the jet stream.

before re-joining the southern branch of the Pacific jet stream at the start of the North Atlantic jet stream, essentially as described in Figure 13 for December and January 2013/14.

It is reasonable therefore to argue that the weather that the UK has experienced has its roots in the tropics. However, the current sea surface temperature anomalies (Figure 16, left panel) suggest that neither El Nino nor La Nina were active, with temperatures in the equatorial East Pacific Ocean being close to normal. The West Pacific remains anomalously warm, as it has done for much of the past decade. Elsewhere in the Pacific the patterns of sea surface temperature anomalies still display elements of the negative phase of the Pacific Decadal Oscillation (PDO) that has contributed to the recent pause in global surface warming[4]. Likewise the very warm waters in the North Pacific (Figure 16) are a result of the systematic weakening of the Aleutian Low during the last decade, driven by the negative phase of the PDO.

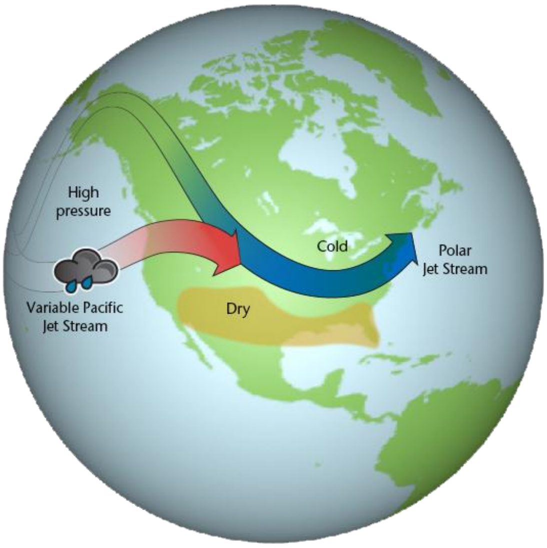

Figure 15: Schematic of the effects of La Nina on the Pacific jet stream and on the position of the polar jet stream over North America.

In the North Atlantic, ocean temperatures continue to be above normal near 30^{0}N which would also contribute to a strengthened north-south temperature gradient across the storm track, aiding the development of storms. As Figure 16 shows, the sub-tropical Atlantic is currently warmer than the average for the last 30 years (1981-2010), but substantially warmer than it was 30 years prior to that (1951-1980). This in itself will potentially increase the moisture being held in the atmosphere, above the ocean, and entering the storm systems as they moved towards the UK.

In terms of the global influences of El Nino/La Nina, it is the changes in tropical rainfall patterns that ultimately drive the perturbations to the atmospheric circulation described by Figure 15. So whilst the sea surface temperatures suggest neutral conditions in the tropical East Pacific, it seems that tropical rainfall patterns in December and January are consistent with a La Nina signal, with higher than normal rainfall over the West Pacific, Indonesia and the eastern Indian Ocean throughout December and January (Figure 17). Bearing in mind that the average rainfall in this region is between 8 and 12 mm/day, these anomalies in rainfall are substantial. This distribution of rainfall across the tropical Pacific is consistent with the warmer than normal sea surface temperatures in the tropical West Pacific (Figure 16, left panel).

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[4] See: http://www.metoffice.gov.uk/media/pdf/q/0/Paper2_recent_pause_in_global_warming.PDF and http://www.metoffice.gov.uk/media/pdf/1/8/decadal_forecast_2014-2018_jan2014.pdf

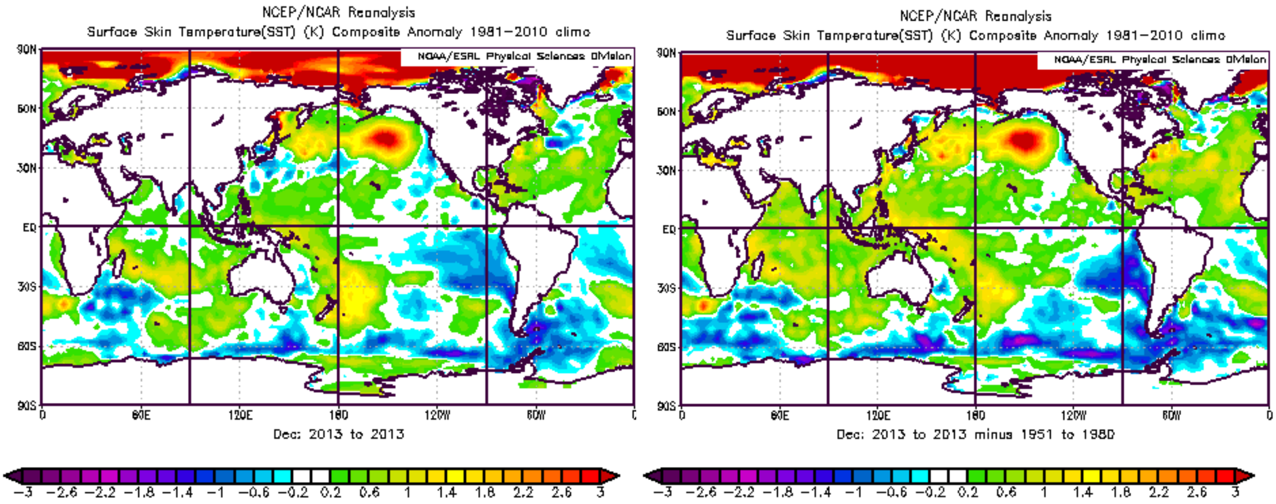

Figure 16: Global sea surface temperature anomalies for December 2013 against the most recent climatology for 1981-2010 (left panel) and against the past climatology for 1951-1980.

As well as the above normal rainfall over Indonesia, Figure 17 also highlights the sequence of disturbances entering the tropical East Pacific as part of the southern branch of the Pacific jet stream described by Figure 15 and evident in Figure 13. Even in these monthly mean fields it is possible to see the continuity between the disturbed weather over the tropical East Pacific and the run of depressions that brought heavy rain to the UK throughout the winter.

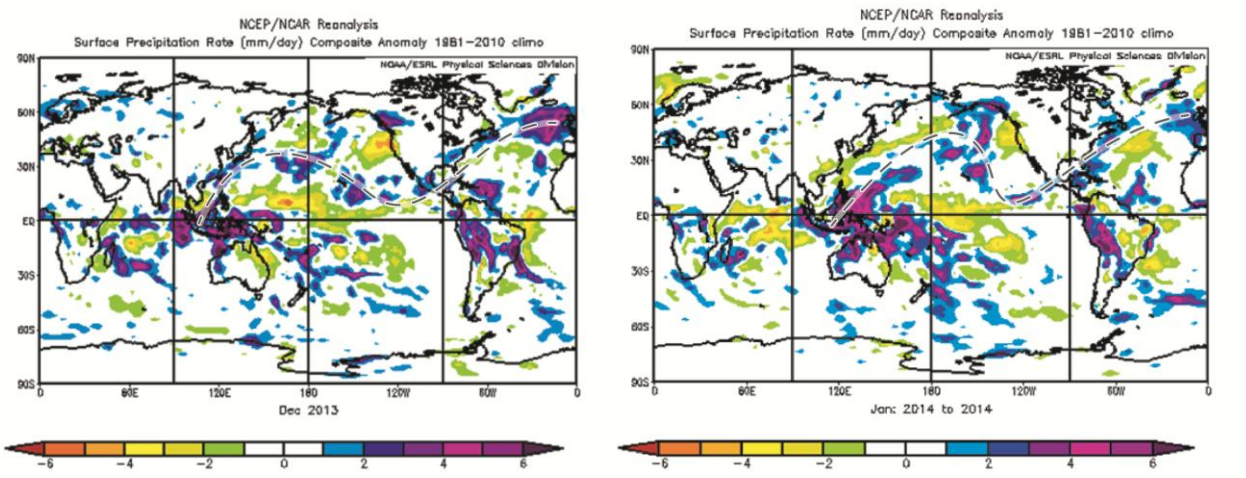

Figure 17: Monthly average precipitation anomalies (mm/day) for December 2013 (left panel) and January 2014 (right panel). The dashed line highlights the sequence of disturbances along the southern branch of the Pacific jet and into the North Atlantic jet stream.

Taking all the evidence from the winds and the rainfall, a notable feature of this winter's storms is the unusual reach of the North Atlantic jet stream back into the East Pacific and the continuous feed of disturbances from the tropical Pacific into the storm track. The disturbances in the tropical East Pacific come, themselves, from the North Pacific, and are able to propagate into the tropics because of the westerly winds in the upper troposphere over the East Pacific (Figure 13); they themselves are part of the response of the winds to the enhanced rainfall over Indonesia. Known as the westerly duct, this is an important conduit through which the tropics and extratropics are able to interact[5]; in La Nina-like conditions, as experienced this winter, the duct is stronger than normal and the propagation of disturbances from the North Pacific more significant.

As is evident in Figure 13, the ‘buckling’ of the jet stream over the Pacific and North America became much more pronounced during January 2014, as the precipitation anomaly over Indonesia and the West Pacific strengthened (Figure 17). A notable feature of this anomalous area of tropical precipitation is its northwards extent into the winter hemisphere where it is able to interact with the North Pacific jet and generate Rossby waves[6] that propagate along the jet and act to reinforce the huge meander of the jet stream off the west coast of North America. At the same time, Rossby waves propagate along the southern branch of the jet stream and enter the tropical East Pacific through the westerly duct, creating weather disturbances that can then get caught up in the entrance region of the Atlantic jet stream.

These Rossby wave interactions are very complex but appear to be fundamental to understanding this winter’s weather. The influence of the Pacific is very clear in the days preceding the major storm of 5/6th January. Figure 18 contains a sequence of maps from 31st December to 5th January showing satellite infrared observations of cloudiness on the left and 250mb winds on the right. The wave disturbances entering the tropical East Pacific westerly duct can be clearly seen in the wind fields throughout the period. These waves move into the entrance region of the North Atlantic jet which reaches unusually far west into the tropical Pacific. At the same time it is evident that waves are also entering the North Atlantic jet from the north via the polar jet. The sequence of satellite imagery of cloudiness shows how these waves translate into the development of the major cyclone over the North Atlantic by 5th January.

What Figure 18 also demonstrates very nicely is that the jet stream is highly variable day by day. It acts as a guide along which the Rossby waves propagate and is also strongly influenced by those waves. Early in the sequence shown in Figure 18 the jet stream over the North Atlantic is strong but as the major storm develops on 4th and 5th January the jet stream weakens as the storm takes momentum from it. Understanding these complex interactions between atmospheric waves and the jet stream is at the heart of understanding and forecasting our weather.

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[5] *Slingo, 1998*: Extratropical forcing of tropical convection in a northern winter simulation with the UGAMP GCM. *Quarterly Journal of the Royal Meteorological Society*, 124, 27–51, DOI: 10.1002/qj.49712454503

[6] Atmospheric Rossby waves describe the large scale meanders in the jet stream, of the type seen in Figure 7, and are due to the variation in the Coriolis force as air moves north and south. The waves were first identified 1939 by Carl-Gustaf Arvid Rossby and are fundamental to understanding the global circulation and its natural variability. It has been known for some time that variations in tropical heating associated with anomalous rainfall acts as a source of Rossby waves (e.g. Jin and Hoskins 1994). Furthermore, theory says that Rossby waves can only propagate where the ambient flow is westerly. This is why the westerly duct in the tropical East Pacific is critical in bringing wave energy into the deep tropics where it can activate weather systems and feed the Atlantic jet as described in this paper.

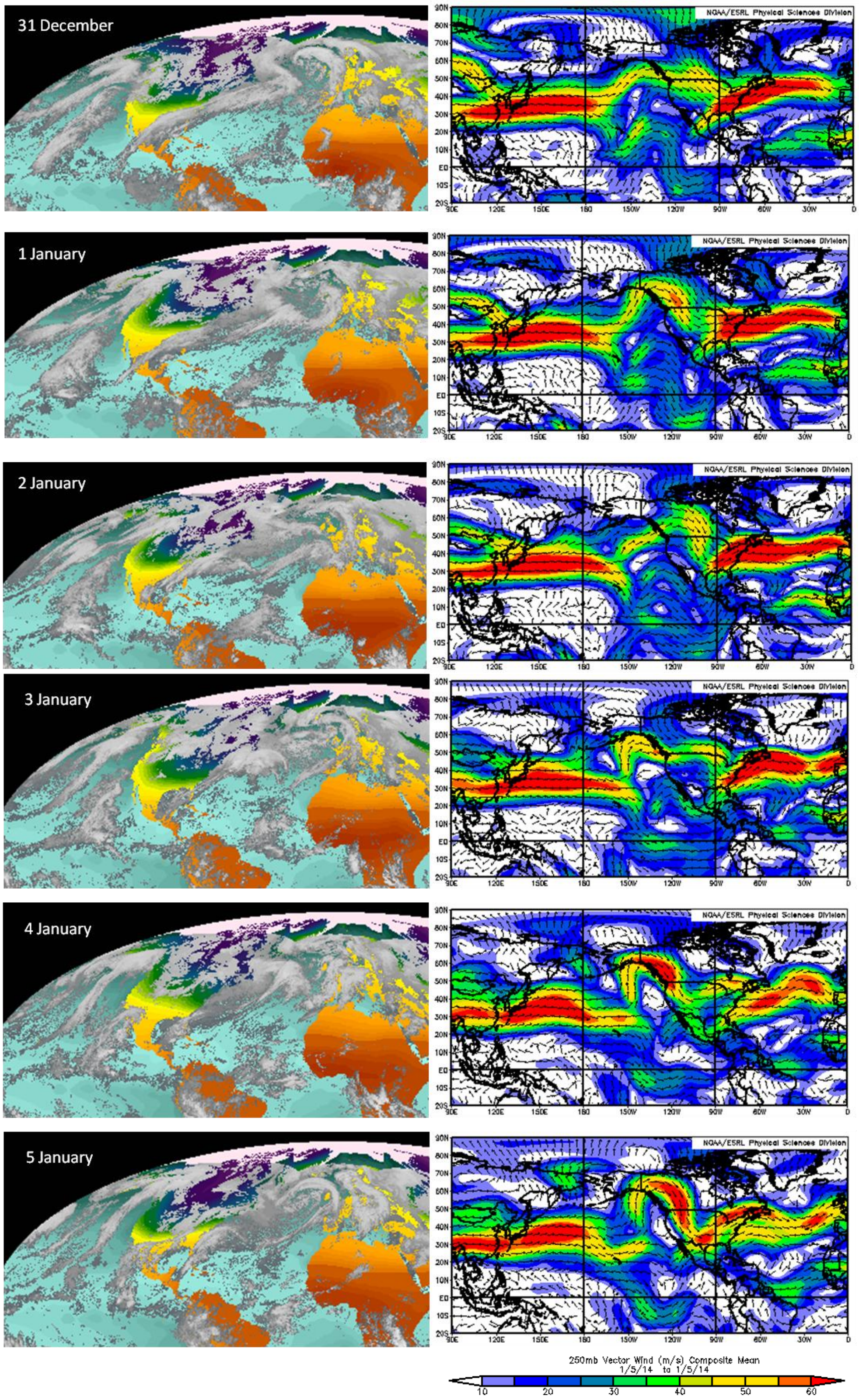

Figure 18: Sequence of infrared satellite images and upper tropospheric winds at 250mb from 31st December to 5th January.

Aside from the Pacific Ocean there are other facets of the global circulation which may have contributed to the stormy weather. Over recent years some major advances in understanding the influence of higher levels in the atmosphere – the stratosphere – on weather patterns in the troposphere have been achieved. Examples include last year's very cold spring[7], and the influence of the minimum of the 11-year solar cycle on the cold winter of 2009/10[8]. This winter's weather also appears to have been influenced by the stratosphere.

Above the troposphere, westerly winter winds in the polar night jet stream[9] were very strong during December and January. The polar night jet exceeded twice its normal strength at times during the winter, reaching speeds in excess of 100ms^{-1} in the upper stratosphere. A strengthening of the polar night jet often precedes periods of a strong Atlantic jet stream below and a positive North Atlantic Oscillation pattern, as was seen during the whole December to January period and consistent with the increased winter storminess this year.

Although internal fluctuations in the strength of the polar night jet cannot be excluded, there has also been an external factor in the current winter, again in the tropics, that has helped to precondition the system for a strong polar night jet. In the tropical stratosphere the winds circulate around the globe from west to east in some years and from east to west in others. This cycling of the tropical winds occurs roughly every two years - hence its name, the Quasi-Biennial Oscillation (QBO). Although it may seem remote from the North Atlantic, historical records show that when the QBO winds are westerly, this increases the chance of the positive phase of the North Atlantic Oscillation and a strong jet stream[10]. The QBO has been in an unusually strong westerly phase throughout this winter, and this factor was cited in the Met Office October long-range outlook for the November to January period, which pointed out the risk of increased storminess in early winter this year.

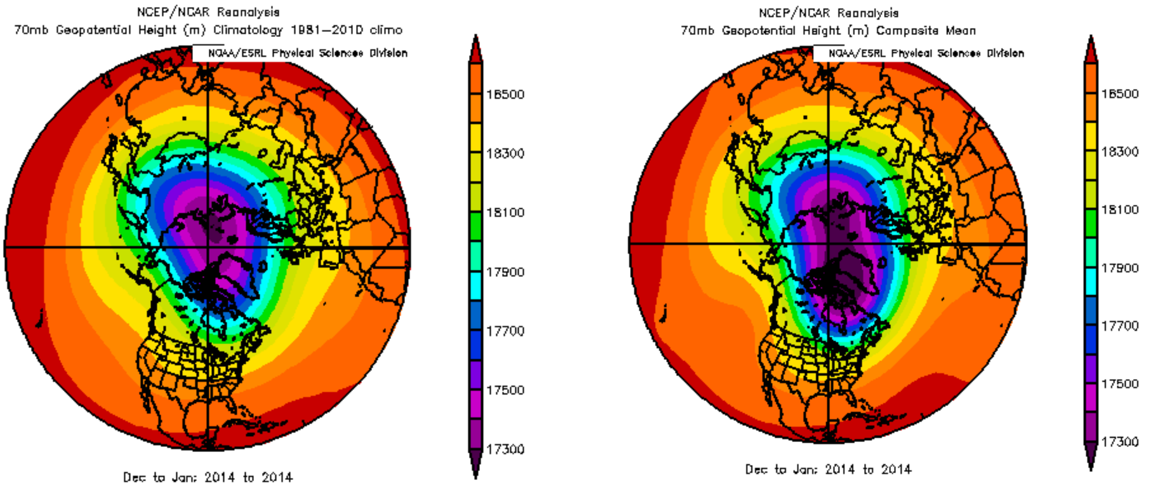

Figure 19: Climatological distribution of geopotential height (m) in the lower stratosphere at 70mb for December to January (left panel) and the actual distribution during December to January 2013/14.

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[7] See http://www.metoffice.gov.uk/research/news/cold-spring-2013

[8] *Ineson et al. 2011*: Solar forcing of winter climate variability in the Northern Hemisphere. *Nature Geoscience* **4**, 753–757 doi:10.1038/ngeo1282

[9] Polar night jet describes the strong winds that form around the polar vortex in the upper atmosphere, due to the strong thermal gradient created by the large cooling over the pole during the polar night.

[10] *Ebdon, 1975*: The quasi-biennial oscillation and its association with tropospheric circulation patterns. *Meteorological Magazine*, 104, 282 – 297.

Baldwin et al. 2001: The Quasi-Biennial Oscillation. *Reviews of Geophysics*, 39, 179-229.

With respect to the extreme cold temperatures over Canada and the US there has been a lot of additional debate about the influence of the polar vortex. The polar vortex refers to the persistent large-scale low pressure area situated above the North Pole in the stratosphere during winter. It is known that when the polar vortex breaks down, the eastern US, and indeed Western Europe, are often cold. This was the case in March 2013[11], when a substantial breakdown of the polar vortex occurred and the negative phase of the Arctic Oscillation was established, bringing exceptionally cold temperatures over the UK.

In terms of the recent extreme cold event over Canada and the US, the evidence suggests that the polar vortex has been stronger than normal, consistent with the increased winds in the polar night jet; the structure of the vortex has also been stretched with the core of the vortex extending southwards over Canada (Figure 19). The extent to which this temporary deformation of the polar vortex played a role in the recent extreme cold temperatures over North America is unclear at present. In terms of the UK weather, the stronger than normal polar vortex throughout the winter is an indication of a less variable and colder stratosphere than normal and a strong polar night jet. This predisposes the circulation towards the positive phase of the Arctic Oscillation with more stormy weather conditions over the North Atlantic (Figure 20).

In conclusion, the evidence suggests that the Pacific Ocean has been a major driver of this winter's severe weather, whilst the strong polar vortex and its influence on the Arctic Oscillation, potentially influenced by the unusually strong westerly phase of the QBO, has also been an important contributor to the very strong North Atlantic jet stream.

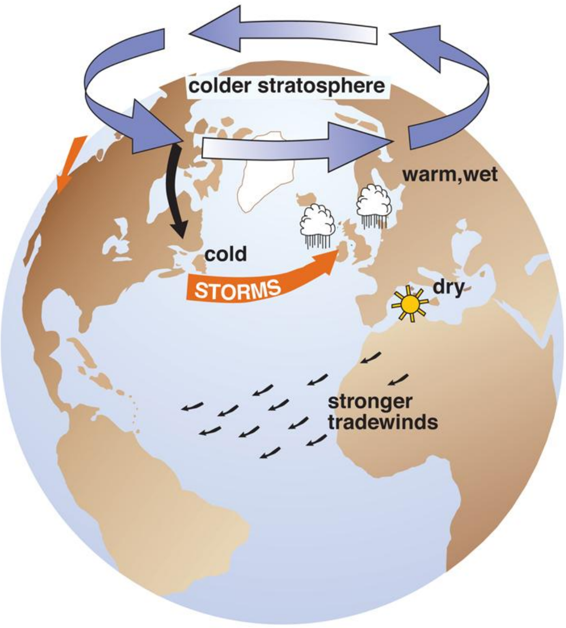

Figure 20: Schematic of the positive phase of the Arctic Oscillation, highlighting the links to the circulation of the stratosphere.

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[11] See http://www.metoffice.gov.uk/research/news/cold-spring-2013

Has climate change been a contributing factor?

It is natural, with the scale of the impacts of recent stormy weather that this question is asked, and there are three aspects that need to be considered. The first relates to the impact of sea level rise on coastal flooding; the second relates to storminess (i.e. the number and/or strength of the storms); and the third relates to rainfall. For rainfall this refers not only to seasonal or monthly means, but also to the intensity and frequency of daily, and even hourly, heavy rain events.

Sea level along the English Channel has already risen by about 12cm during the 20th century[12]; this is over and above the increases associated with sinking of the southern part of the UK due to isostatic adjustment[13] from the last Ice Age. With the warming we are already committed to over the next few decades, a further overall 11-16cm of sea level rise is likely by 2030, relative to 1990, of which at least two-thirds will be due to the effects of climate change[14]. We are very confident that sea level will continue to rise over coming decades as the planet continues to warm, and these numbers represent our current best estimate for the UK. Clearly sea level rise from whatever source has to be factored into discussions about resilience to coastal and river inundations.

In seeking to answer questions about the impact of climate change on severe weather, there are two distinct steps to be taken. The first is to detect a change in either the frequency or intensity of storminess or rainfall events that is more than just the natural variability in UK weather. UK weather is notoriously volatile and so detection is particularly challenging. Severe storms have always affected the UK and are documented in many historical records. The intensity of recent storms is unusual, as the climatological records discussed earlier indicate, but not necessarily unprecedented.

A comprehensive study of trends in storminess, for the period 1871-2010 from an ensemble of reanalyses by Wang et al. (2013)[15] provides some important insights. They show a robust signal of increasing numbers of strong winter cyclones and with increasing intensity for the high latitude North Atlantic (Figure 21), covering the region to the north of the UK and including Iceland. This is associated with a reduction in storminess further south and supports a wide body of evidence for a poleward shift of the Atlantic storm track.

However, their analysis of changes in storminess further south over the mid-latitude North Atlantic – the path of the recent storms – suggests a more complex signal. Although the number of strong winter cyclones has not increased since 1871, the mean intensity has. Notably, for very strong cyclones, the mean intensity has increased significantly. A more comprehensive study of storms affecting the UK is needed to explore these findings in more detail, but the current evidence does suggest an increase in storminess.

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[12] *Wahl et al. 2013*: Observed mean sea level changes around the North Sea coastline from 1800 to present. *Earth-Science Reviews*, 124, 51–67.

[13] Isostatic rebound refers to the rise of land masses that were depressed by the weight of ice during the last glacial maximum. For the UK this is seen in increasing land heights over Scotland and northern England and falling land heights (sinking) over southern regions. See *Bradley et al. 2008*: Glacial isostatic adjustment of the British Isles: New constraints from GPS measurements of crustal motion. *Geophysical Journal International*, doi:10.1111/j.1365-246x.2008.04033.x.

[14] *www.ukcip.org.uk/wordpress/wp-content/PDFs/UKCIP_sea-level.pdf*

[15] *Wang et al. 2012*: Trends and low frequency variability of extra-tropical cyclone activity in the ensemble of twentieth century reanalysis. *Climate Dynamics*, 40, 2775-2800.

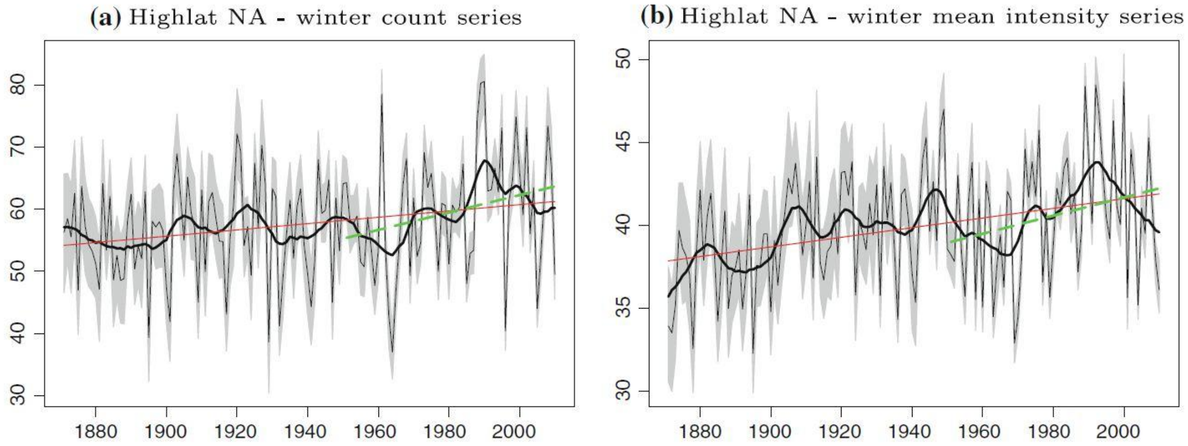

Figure 21: Ensemble average series of the winter cyclone count (per 1,000,000 km^2) and mean intensity (10-5 hPa/km^2) averaged over the high latitudes of the North Atlantic. Thick black curves are 11-year Gaussian filtered series. The grey shading indicates the 95% confidence interval of the ensemble spread. Red lines are the 1871-2010 linear trend and the dashed green lines are the 1951-2010 linear trend. From Wang et al. 2012.

The persistence of the recent storminess is unusual, and although clustering of storms is quite common, the continued run of deep depressions, through December, January and on into February, is not. It is this continued run of storms that has created the exceptional flooding conditions experienced in the Somerset Levels, for example.

The persistence of the weather patterns affecting both the UK and also the US, where abnormally cold conditions have continued to affect the eastern and southern states through January, has raised questions about whether the jet stream is making greater excursions, north and south, and whether these waves in the jet stream are becoming more locked in one position[16]. This is a critical question because it raises the possibility that disruption of our usual weather patterns may be how climate change may manifest itself. The Met Office is now actively researching the best way to detect changes in the dynamics of the jet stream.

Beyond the clustering of storms there is also the question of whether there is a detectable change in the amount of rain that the storms are carrying. Again this is a very difficult area because UK rainfall is highly variable in space and time. Changes in monthly, seasonal or annual mean amounts are difficult to detect so far, as the time series in Figure 3 demonstrates.

However, there is now some emerging evidence that, over the UK, daily heavy rain events may be more frequent (Figure 22). What in the 1960s and 1970s might have been a 1 in 125 day event is now more likely to be a 1 in 85 day event. This supports other evidence that UK rainfall is increasing in intensity[17]. This increase in the frequency/intensity of extreme daily

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[16] *Francis and Vavrus, 2012*: Evidence linking Arctic amplification to extreme weather in mid-latitudes. *Geophysical Research Letters*, DOI: 10.1029/2012GL051000;

Petoukhov et al. 2013: Quasiresonant amplification of planetary waves and recent Northern Hemisphere weather extremes. *Proceedings of the National Academy of Sciences (PNAS)*, doi: 10.1073/pnas.1222000110.

[17] *Jones et al., 2012:* An assessment of changes in seasonal and annual extreme rainfall in the UK between 1961 and 2009. *International Journal of Climatology*, 33, 1178-1194;

Maraun et al. 2008: United Kingdom daily precipitation intensity: improved early data, error estimates and an update from 2000 to 2006. *International Journal of Climatology*, 28, 833-842 rainfall events, as the planet warms and the atmosphere can hold more water, has been discussed in the literature for a number of years[18], and robust evidence for this is increasingly seen around the world[19].

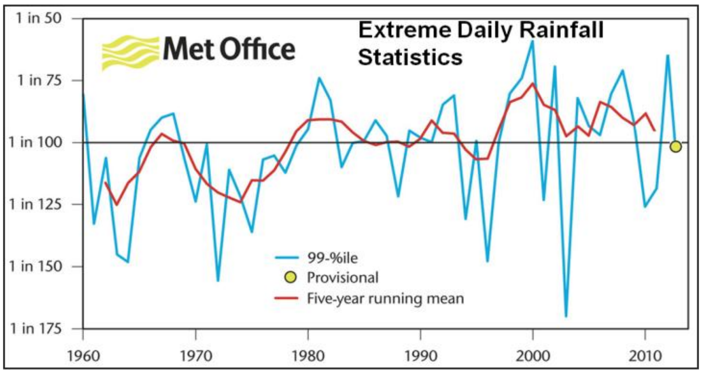

Figure 22: Time series of the annual frequency of what climate averages tell us should be roughly 1 in 100 day heavy rainfall events in each year. Over time, this gives a view of the frequency of 'extreme' rainfall.

Furthermore, where there are sufficiently long records of hourly rainfall data, it has been shown that rain rates potentially increase with temperature at rates that exceed the simple thermodynamic Clausius-Clapeyron relationship (6-7% increase in humidity for 1^0C rise in temperature) between temperature and humidity[22] (Figure 23). This can be understood through the dynamic amplification of rain-bearing systems, where the induced circulation drives greater convergence of moisture into the system and hence heavier rainfall.

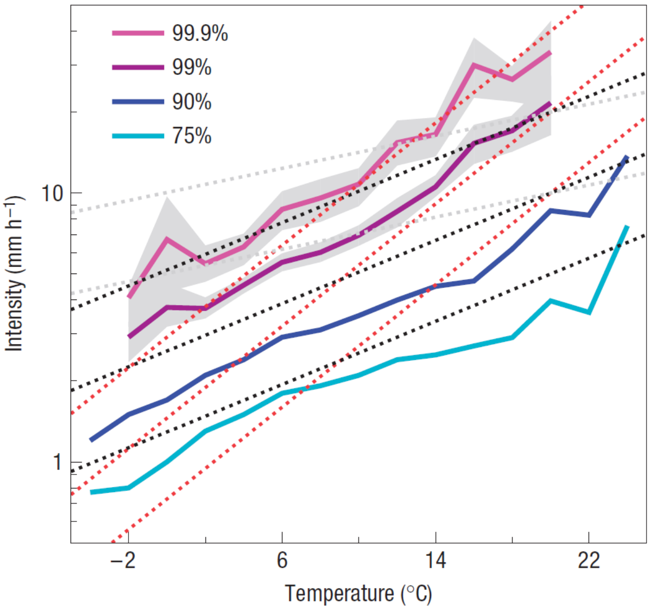

Figure 23: Percentiles of observed maximum 1 hour rainfall intensity (mm/hour) on a logarithmic scale as a function of temperature for a 99-year record from De Bilt, The Netherlands. Solid colour lines are the different percentiles. Grey bands, plotted only for the 99 and 99.9th percentile, are 90% confidence intervals. Dotted lines are the exponential relations given by 0.5 (light grey), 1 (black) and 2 (dark red) times the Clausius–Clapeyron relation. From Lenderink and Van Meigaard 2008.

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[18] *Allan and Soden, 2008*: Atmospheric Warming and the Amplification of Precipitation Extremes, *Science,* 321, 1481-1484, doi:10.1126/science.1160787.

[19] *Goswami et al., 2006*: Increasing Trend of Extreme Rain Events over India in a Warming *Environmental Science*, 314, 1442-1445, DOI: 10.1126/science.1132027;

Lei et al., 2011: Exploring the Interplay between Natural Decadal Variability and Anthropogenic Climate Change in Summer Rainfall over China. Part I: Observational Evidence. *J. Climate*, 24, 4584–4599, doi: http://dx.doi.org/10.1175/2010JCLI3794.1

[22] *Lenderink and Van Meijgaard 2008*: Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience,* 1, 511–514. doi:10.1038/ngeo262

The example shown in Figure 23 is from a 99-year record of quality controlled hourly precipitation observations at De Bilt in the Netherlands, and is therefore potentially representative of the UK. A detailed study of UK stations with long hourly rainfall records is urgently needed to corroborate this evidence.

Following on from the issues of *detecting* changes in storminess and rainfall discussed above, the process of then *attributing* even some aspects of those changes to anthropogenic climate change remains challenging. Attribution is fundamental to making the case for climate change. It is already able to provide robust and statistically significant statements about global and even continental temperature change[23]. The attribution of changes in mean rainfall, regional climate and weather extremes is much more challenging.

The attribution method depends fundamentally on climate models in order to separate out the effects of human-induced climate change from natural variability. Basically the models are used as a laboratory to perform the experiment of what the climate would have been like without anthropogenic greenhouse gases. By comparing model simulations with and without anthropogenic greenhouse gases it is possible to identify where changes in the climate can only be reproduced when the effects of anthropogenic greenhouse gas increases are invoked.

For this comparison to be reliable and to provide a robust evidence-base for decision-making, it is essential that the models are fit for the purpose. It is for this reason that model evaluation is a critical part of the IPCC process. In terms of the global temperature record, climate models are able to simulate the evolution of the observed record since 1860 with considerable skill and the difference between the simulations with and without anthropogenic greenhouse gases is statistically significant. It is this result that enabled the IPCC[18] to state that 'It is *extremely likely (95-100% certain)* that human activities caused more than half of the observed increase in global mean surface temperature from 1951 to 2010.'

It follows that to perform climate change attribution of the recent storminess and heavy rainfall requires a climate modeling system that is able to simulate these weather systems and their potential drivers. A limitation until recently has been model resolution (horizontal and vertical). It is only now that the climate models are reaching a level of detail and skill that is necessary to address the issues raised by recent events. This was demonstrated in a seminal paper on the attribution of extreme events by US and UK scientists in 2013[24].

Over the last 3 years there have been major advances in Met Office capabilities in simulating weather and climate variability[25]; for example, the climate model (HadGEM3) is now able to simulate the frequency of atmospheric blocking in the Atlantic that agrees with observations. These advances have come primarily through increased horizontal resolution (from typically 150km in the atmosphere and 1^0 in the ocean, to 60km and $1/4^0$ respectively) and increased vertical resolution (from 38 levels in the atmosphere and 40 levels in the ocean, to 85 levels and 75 levels respectively). This has facilitated substantial progress to be made in simulating

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[23] See http://www.climatechange2013.org/images/report/WG1AR5_Chapter10_FINAL.pdf

[24] *Peterson et al. 2013*: Explaining extreme events of 2013 from a climate perspective. *Bulletin of the American Met. Soc.*, 94, S1 – S74.

[25] *Scaife et al. 2011*: Improved Atlantic winter blocking in a climate model, *Geophysics Research Letters*, 38, DOI: 10.1029/2011GL049573;

Ineson and Scaife 2009: The role of the stratosphere in the European climate response to El Niño. *Nature Geoscience,* 2, 32 - 36

Ineson et al. 2011: Solar forcing of winter climate variability in the Northern Hemisphere. *Nature Geoscience,* 4, 753–757 and understanding the processes that determine the natural variability of the climate system (such as the North Atlantic Oscillation (NAO) and El Nino/La Nina and its global influences), and its response to factors such as solar variability and declining Arctic sea ice.

With a credible modeling system in place it should now be possible to perform scientifically robust assessments of changes in storminess, the degree to which they are related to natural variability and the degree to which there is a contribution from human-induced climate change. These studies are a high priority, although they are very computationally-intensive and require simulation of many decades of the climate to ensure a statistically significant result.

Extreme daily/hourly rainfall remains much more challenging because of the local nature of these events. However, recent advances in modeling at the kilometre scale for UK weather forecasting have opened up new opportunities. This model (UKV) with a grid scale of 1.5km has delivered a step change in simulating the morphology of rainfall events, with intensity and duration statistics that agree with radar observations (Figure 24). The utility of the UKV model to deliver climate change impacts, related to extreme rainfall at the local and regional scale, is already being explored and the results are very promising. This forms part of the Met Office long-term strategy to deliver an integrated approach to risk-based assessments of hazardous weather at the regional and local level, on all timescales, from hours to decades[26].

So what can be said about rainfall in the meantime? There is an increasing body of evidence that shows that extreme daily rainfall rates are becoming more intense, and that the rate of increase is consistent with what is expected from fundamental physics. Although formal attribution is still challenging, it is possible to identify a contribution from climate change for some major flooding events, as the recent paper by Peterson et al. (2013)[19] on the attribution of extremes showed. It is worth emphasizing that there is no evidence to counter the basic premise that a warmer world will lead to more intense daily and hourly heavy rain events.

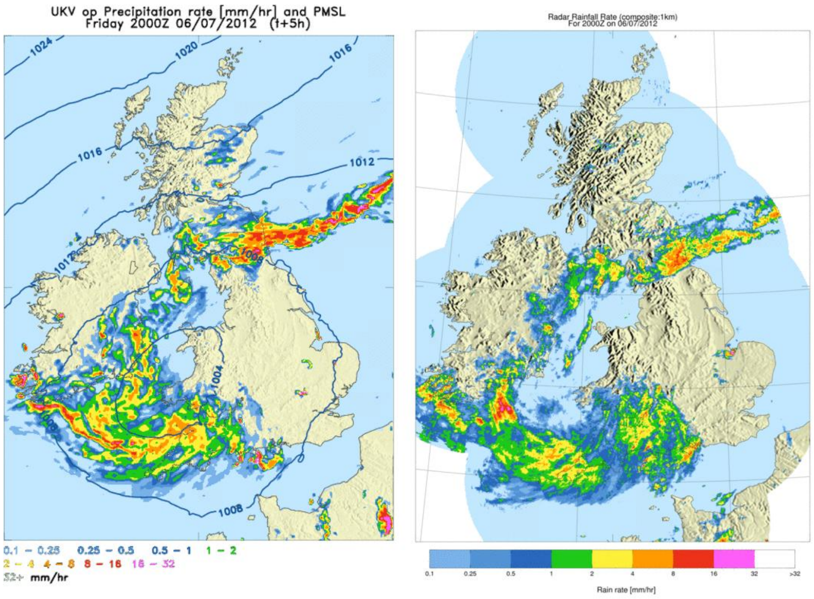

Figure 24: Example of a 5-hour forecast from the 1.5km UKV model versus the radar observations for the extreme flooding event of 6/7th July 2012. Colours show instantaneous rain rate in mm/hour.

In terms of the impacts of changing weather and climate patterns, the cluster of drought and flood events through the early years of the 21st century and the recent runoff and recharge patterns, are near to the extreme range of historical variability. They therefore also raise the

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[26] See http://www.metoffice.gov.uk/media/pdf/a/t/Science_strategy-1.pdf

question that they may reflect anthropogenic climate change. It is important to note, however, that differing flood types may be expected to respond differently to increasing temperatures. Tidal flood risk is increasing as sea levels rise but the outlook is more complex in relation to fluvial flooding.

Published studies have observed increased river flows in the winter half-year[27] and a tendency for higher flows to occur more frequently[28], and this has been reinforced in recent years. Importantly, however, such a trend may not be accompanied by any increase in magnitude of major flood events. In the UK, no positive trend in water-year maxima was found in the 130-year series for the Thames[29].

Enhanced groundwater flood risk may be expected if average winter rainfall in the UK increases. Flash flooding, which can be exacerbated by land management and land use practices (particularly the extension of impermeable areas), may also increase if the recent intensification in rainfall translates into an enduring trend.

In terms of the storms and floods of winter 2013/2014, it is not possible, yet, to give a definitive answer on whether climate change has been a contributor or not. The climatological context discussed earlier was unusual, with the Atlantic jet stream being more intense and reaching further back into the tropical East Pacific than normal. Those factors in themselves would allow warmer and moister air to enter the storm systems. It is also the case that the sub-tropical Atlantic is now warmer than it was several decades ago and that too would act to enhance the moisture content of the storms.

More research is urgently needed to deliver robust detection of changes in storminess and daily/hourly rain rates. The attribution of these changes to anthropogenic global warming requires climate models of sufficient resolution to capture storms and their associated rainfall. Such models are now becoming available and should be deployed as soon as possible to provide a solid evidence base for future investments in flood and coastal defences.

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[27] *Hannaford and Buys 2012:* Trends in seasonal river flow regimes in the UK. *Journal of Hydrology*, 475, 158-174

[28] *Hannaford and Marsh 2008:* High-flow and flood trends in a network of undisturbed catchments in the UK. *International Journal of Climatology*, 28, 1325-1338

[29] *Marsh and Harvey 2012*: The Thames flood series: a lack of trend in flood magnitude and a decline in maximum levels. *Hydrology Research*, 43, 203-214

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