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# Winter 2009/2010 temperatures and a record-breaking North Atlantic Oscillation index

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The 2009/2010 winter was notable for a number of reasons. While the global average temperature was close to a record high according to the analysis of Hansen *et al.* (2006; Figure 1(a)) and was the fifth highest (Figure 1(b)) in the 160-year record of Brohan *et al.* (2006), the UK had extensive snow cover and lower-than-average temperatures (National Climate Information Centre, 2010). The Central England Temperature (CET; Parker *et al.*, 1992) for winter 2009/2010 was 2.43 °C, an anomaly of –1.65 degC compared with the 1961–1990 mean. Although there have been 56 colder winters in the CET record since 1659, none occurred during the last three decades and 2009/2010 was the coldest since 1978/1979.

These low temperatures over the UK were part of a much more extensive pattern (Figure 2(a)) with negative temperature anomalies extending over many mid-latitude landmasses of the Northern Hemisphere (NH). The temperature anomalies for the UK grid boxes shown in Figure 2(a) are slightly smaller than the CET anomaly (in the range –1 to –1.5 degC) because this figure combines CRUTEM3 land air temperature observations with HadSST2 sea-surface temperatures (SST), and the latter did not have such strong negative anomalies around the UK in 2009/2010. Note that the HadCRUT3 blend of these data (Brohan *et al.*, 2006) uses a weighted mean of the land and sea data for grid boxes that are part land and part ocean, where the weights are dependent on the estimated error for each observation. This typically gives considerably greater

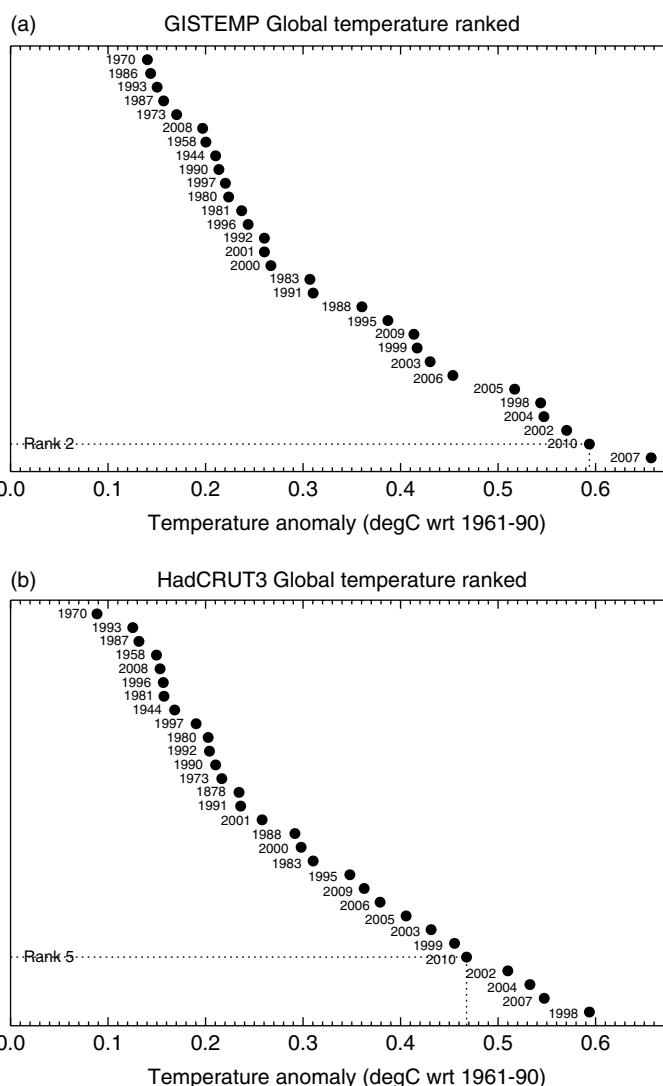


Figure 1. Global-mean temperature anomalies (degC from the 1961–1990 mean) averaged over each winter (December–February, DJF) and ranked into ascending order from (a) the NASA Goddard Institute for Space Studies (GISS) dataset (Hansen *et al.*, 2006); and (b) the Hadley Centre–Climatic Research Unit (HadCRUT3) dataset (Brohan *et al.*, 2006). Only the warmest 30 winters in each record are shown; winter 2009/2010 (marked as 2010) and its rank are indicated by the dotted lines.

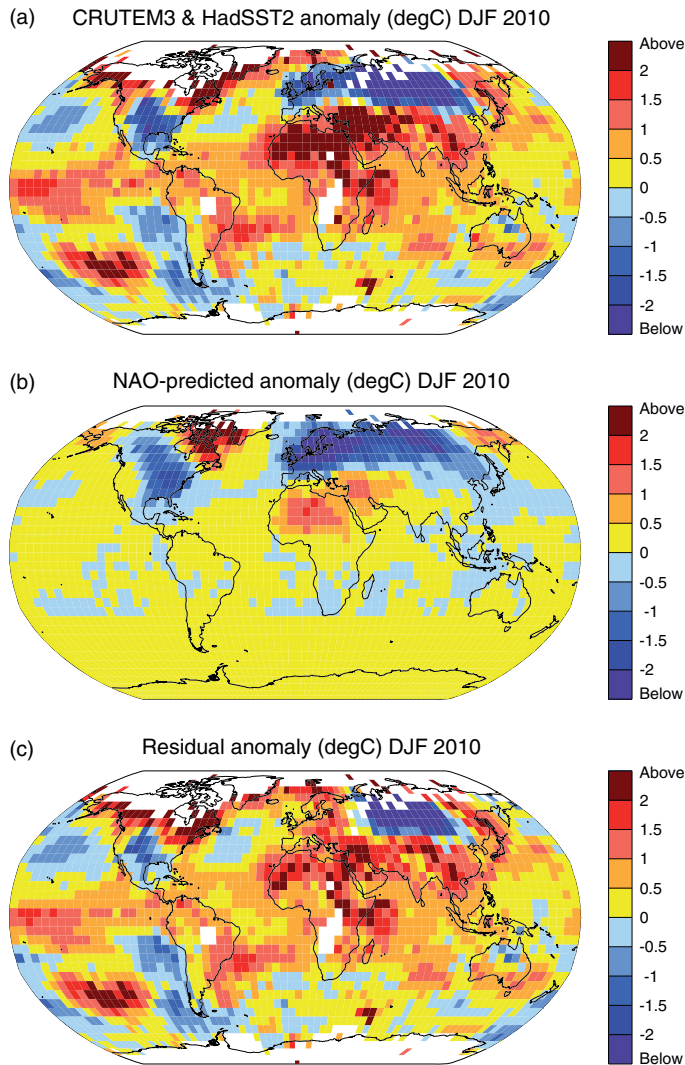


Figure 2. Temperature anomalies (degC from the 1961–1990 mean) for winter 2009/2010, (a) as observed in the CRUTEM3 land air temperature and HadSST2 SST dataset; (b) as predicted using linear regression with the NAO index; (c) the residual (observed minus predicted). To increase the completeness of the spatial fields, grid boxes with missing data are replaced by the average of their neighbouring values if there are at least four such non-missing values.

weight (e.g. >90%) to the SST observations than to the land temperature observations even in grid boxes that are almost entirely land (e.g. Figure 8 of Brohan *et al.*, 2006). This may be appropriate if the true temperature anomalies are expected to be the same over land and sea, but it is inappropriate where they are expected to differ (such as here, where we are considering a relatively short-term anomaly lasting three months, and the greater heat capacity of the ocean mixed layer would usually dampen the magnitude of any anomalies). In this analysis, therefore, the CRUTEM3 and HadSST2 temperature anomalies are blended in coastal boxes by a weighting that is based only on the area of land and ocean within each 5° by 5° grid box.

The pattern of temperature anomalies (Figure 2(a)) shows the quadrupole structure characteristic of the North Atlantic Oscillation (NAO): same-signed anomalies in eastern USA and northern

Eurasia, with opposite-signed anomalies in northern Africa and the Labrador Sea region. Hurrell and von Loon (1997) demonstrated that this pattern arises primarily from the advection of heat by the mean atmospheric flow anomalies associated with the NAO: with the NAO in its 'negative' phase, reduced advection of mild air from the subtropics into USA and from the Atlantic over northern Eurasia can lead to negative temperature anomalies in these regions. Conversely, reduced advection of cold air from the Arctic into the northwestern Atlantic and from northern Asia into northern Africa can lead to positive temperature anomalies in those regions. Trigo *et al.* (2002) reported that modulation of the radiation balance by NAO-related changes in cloud cover also contributed to the patterns of temperature anomalies associated with the NAO, though to a much lesser extent than the atmospheric advection of heat.

The NAO index, a measure of the mean atmospheric pressure gradient between the Azores High and the Iceland Low, had a record negative value in winter 2009/2010 (Figure 3). This particular NAO index (Jones *et al.*, 1997), based on pressure observations at Gibraltar and in southwest Iceland, extends back to the winter of 1823/1824. The winter 2009/2010 value of the NAO index (−2.4) is considerably more negative than the previous four most negative index winters (1995/1996, 1962/1963, 1968/1969 and 1916/1917) which all had NAO indices close to −1.7 (note that there are a number of scaling conventions that have been used for the NAO index; here the winter-mean index has been scaled to have zero mean and unit variance over the 1961–1990 period). These four winters, with the previous most negative NAO indices, were also cold over the UK; indeed the CET averaged across these four winters was only 1.84°C (compared with 2.43°C for winter 2009/2010).

The relationship between the NAO and surface temperatures can be estimated via the least-squares regression slope between monthly temperatures and monthly values of the NAO index. Here, the monthly NAO index is first scaled to have unit variance, so that the regression slope expresses the temperature anomaly associated with a one-standard-deviation increase in the NAO index. The patterns of regression slopes vary according to the month of the year. Figure 4 shows the average of the December, January and February patterns, and exhibits the quadrupole structure described earlier.

The regression patterns can be used to 'predict' the temperature anomalies expected to result from particular values of the NAO index. Figure 2(b) shows the average of such predictions made using the NAO index values from December 2009, January 2010 and February 2010 and the corresponding regression patterns. As expected, it is opposite in sign to the NAO pattern itself (Figure 4) because the NAO index values were negative. I have assumed that the NAO has no relationship with temperatures south of 30°S, and have also made the pattern as complete as possible by estimating missing values from the average of neighbouring values (as noted in the caption of Figure 2).

Comparison of the temperature predicted purely on the basis of the record negative NAO index (Figure 2(b)) with the observed temperature anomalies (Figure 2(a)) indicates notable similarity over much of the extratropical NH. The residual difference between observation and prediction (Figure 2(c)) shows that temperatures across Europe were actually higher during winter 2009/2010 than would have been expected on the basis of the NAO index alone – by

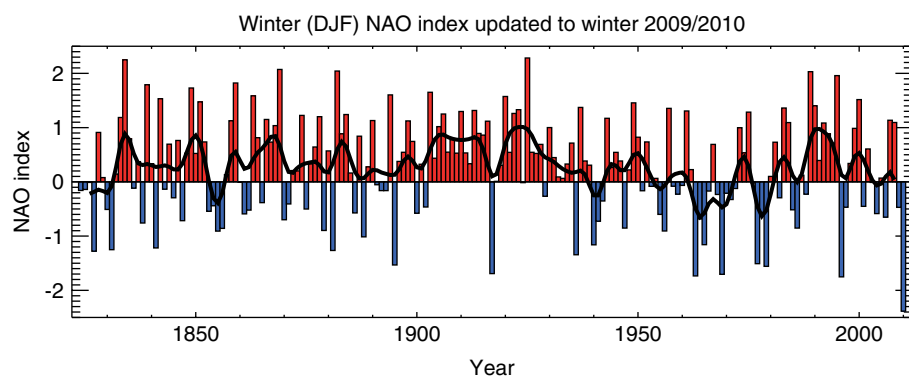


Figure 3. Winter NAO index based on the difference between normalised sea-level pressure observations at Gibraltar and southwest Iceland (Jones *et al.*, 1997; Osborn, 2006). The original series has been rescaled here so the DJF mean time series has zero mean and unit variance over the 1961–1990 period. The thick black line shows smoothed values from a 10-year Gaussian-weighted filter.

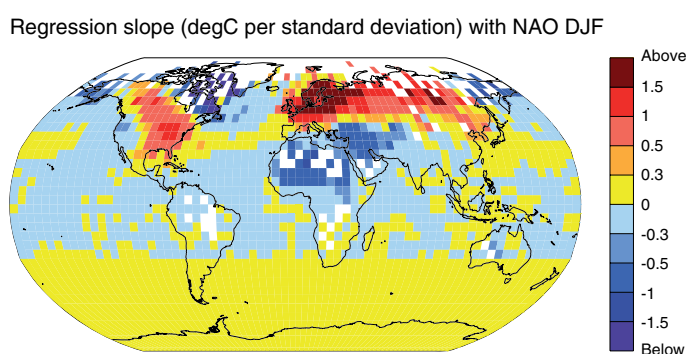


Figure 4. Slope of least-squares simple linear regression between monthly CRUTEM3 land/HadSST2 sea temperature anomalies and monthly NAO index values (normalised to have unit variance). Regression slopes were calculated separately for each month of the year, requiring at least 30 values; the map shows the average of the December, January and February regression slopes. Regression slopes are assumed to be zero south of 30°S.

more than 1.5 degC in parts of northern and eastern Europe. Elsewhere we see that the record negative NAO index – and the anomalous atmospheric circulation that it represents – can explain only part of the negative temperature anomalies observed over the USA and over Russia because the residual indicates that the temperatures in those regions were lower than the NAO-based prediction. The atmospheric pressure anomaly for winter 2009/2010 resembles the negative phase of the Northern Annular Mode, closely related to the NAO but with an influence on surface temperatures that extends further east (Thompson and Wallace, 2000), and this may explain a greater part of the cold residuals in east central Russia.

The positive temperature anomalies observed over northern Africa and the northwestern Atlantic can be partly explained by the negative NAO conditions,

but again there is residual warmth (Figure 2(c)). Elsewhere the NAO has little influence and the equatorial oceans, the southern subtropics and southern Asia are still warm in the residuals. Some of these are related to the El Niño event of 2009/2010, as are the cold residuals in southern USA and the warm residuals in western Canada (Ropelewski and Halpert, 1986).

In conclusion, the winter of 2009/2010 was notable for the record negative NAO index in the 187-year record of Jones *et al.* (1997), indicating the very unusual nature of atmospheric circulation over the Atlantic/European region. Despite 2009/2010 being a cold winter over the UK and Europe, it was actually around 0.5 to 1 degC warmer than might have been expected given this extreme pattern of atmospheric circulation. Considering observations averaged across the globe, winter 2009/2010 was one of the warmest on record.

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