North Atlantic Oscillation amplifies orographic precipitation and river flow in upland Britain

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[1] Large-scale climatic variability in the North Atlantic region modulates seasonal rainfall and river flow across the British Isles. We show how the North Atlantic Oscillation (NAO) dramatically increases orographic enhancement of upland precipitation. NAO variations cause large differences in seasonal precipitation totals compared to NAO-neutral conditions, an effect amplified with altitude—what we term "double orographic enhancement." For NAO conditions since 1825, this gives a maximum range of 150% in precipitation totals at the wettest (upland) location compared to NAO-neutral conditions. In autumn, winter, and spring, there is a strong positive relationship between upland precipitation and NAO; this is not seen at low altitude except on northwest coasts. In summer, significant negative relationships are evident in the English lowlands. These precipitation patterns directly translate to seasonal runoff. Our findings show that the hydroclimatology of rainfall and river flow in upland areas is closely coupled to the strength of atmospheric circulation, an effect which strengthens with increasing altitude. Identified effects are large enough to cause very high river flow during periods of highly positive NAO but may also lead to severe drought when NAO is highly negative.

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1. Introduction

[2] The North Atlantic Oscillation (NAO) is the most important mode of climatic variability in the northern hemisphere. It controls the strength of westerly winds between the "Azores high" and the "Icelandic low" that bring a succession of weather systems to Western Europe [*Rodwell et al*., 1999]. European climate exhibits a dipolar signal due to changes in the NAO: northern and southern Europe experience opposite effects [*Hurrell and Van Loon*, 1997; *Folland et al.*, 2012], with northern Europe having more frequent and intense winter rainfall from westerly circulation systems in comparison to southern Europe [*McGuffie et al*., 1999; *Meehl et al.*, 2007].

[3] The NAO is known to influence European precipitation and river flows in upland areas [*Mayes*, 1996; *Wedgbrow et al*., 2002; *Allan et al*., 2009]. However, there has been no quantitative analysis of the relationship between the NAO and orographic rainfall, despite the importance of upland catchment areas for flood generation and surface water supply in the surrounding lowlands. *Conway et al*. [1996] showed that all regions of the United Kingdom exhibit higher wet-day probability with increasing strength of flow over the British Isles. There was more regional variation in relation to precipitation amount, but the western (upland) regions tended to show an increase in precipitation amount, whereas the more easterly (lowland) series showed no change with flow strength. *Wilby et al*. [2002] also identified marked spatial gradients in the strength of NAO forcing of seasonal precipitation (including mean wet-day amount) across the British Isles. *Barker et al*. [2004] showed that winter precipitation totals for the upland English Lake District were strongly correlated with the NAO index (NAOI), but to a lesser extent in spring and autumn. *Fowler and Kilsby* [2002] linked variations in precipitation at seven locations in northern England to large-scale atmospheric circulation using the NAOI. They showed that at upland sites, NAOI, the frequency of weather types and precipitation totals were strongly correlated at annual, seasonal, and monthly timescales; positive and negative winter-NAO indices produced anomalies from the long-term winter precipitation average of 112% and 77%, respectively. *Malby et al*. [2007] noted subtle responses to the precipitation distribution across the Lake District, including links between airflow and infilling of rain-shadow areas beyond orographically forced zones. However, none of these studies has quantified the relationship between rainfall total, altitude, and the NAOI.

[4] When air masses are forced over a topographic barrier, considerable precipitation may accumulate in a very restricted area [*Sumner*, 1988]; this is the so-called "orographic enhancement effect." It is seen in mountainous regions throughout the world, at least up to a certain elevation, above which totals begin to decrease again [*Barry and Chorley*, 2010]. *Roe* [2005] makes the point that while many of the basic mechanisms responsible for orographic precipitation are understood, the mix of physical processes operating makes the quantitative prediction of precipitation over complex terrain a hard task. In the United Kingdom, the heaviest orographic precipitation has long been

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associated with strong southwest to westerly winds in the warm, moist sectors of frontal depressions [*Douglas and Glasspoole*, 1947; Browning et al., 1974]. One important mechanism involves the "seeder-feeder" process by which raindrops from upper-level (seeder) clouds wash out small droplets within low-level (feeder) clouds formed over the hills [*Bergeron*, 1965; *Herzegh and Hobbs*, 1980; *Hill et al.*, 1981]. This produces much higher rainfall intensities than either cloud layer would generate on its own.

[5] This research quantifies the influence of NAO on orographic precipitation and river flow in upland Britain. There is then some discussion of the relationship between the NAO and other measures of atmospheric circulation as a basis for hypothesizing about the processes responsible for the observed effects.

2. Methods

[6] We used precipitation data from the British Atmospheric Data Centre Met Office Integrated Data Archive Service (MIDAS) database (http://badc.nerc.ac.uk/) and the UK Meteorological Office (UKMO) historic station database (http://www.metoffice.gov.uk/climate/uk/stationdata/), together with other available long records such as Durham [*Burt and Horton*, 2007] and Oxford [*Burt and Howden*, 2011]. By using all the gauges included in the UKMO historic series, we ensured a relatively even distribution of sites across the country. To this we added other gauges with very long records, including those studied by *Burt and Ferranti* [2012], since this was deemed beneficial to the subsequent analysis by providing a context for the shorter records included [*Burt*, 1994], particularly since the river flow time series tend to be shorter.

[7] We calculated seasonal precipitation totals for 90 station records of lengths between 24 and 181 years (mean: 74 years). Seasons were defined as: winter (December-February), spring (March-May), summer (June-August), and autumn (September-November). Based on previous work in northern England [*Shaw*, 1962; Burt, 1980], the maximum altitude within 2 km of each rain gauge (max2k) was used to indicate the effective height of local topography in order to link rainfall totals with altitude; using gauge altitude in an upland area may give a false impression of the general form of the topography since many gauges are located in valleys [*Salter*, 1918; *Chuan and Lockwood*, 1974; *Burt and Ferranti*, 2012].

[8] We used daily flow records and associated metadata (catchment elevation data) from the UK's National River Flow Archive (http://www.ceh.ac.uk/data/nrfa/) and calculated seasonal flow totals at 86 river gauging stations for records between 23 and 125 years' long (mean: 45 years), including those used by *Lavers et al*. [2010]. The 90th percentile height of the hypsometric curve was used to indicate the effective height of topography for each basin (90%DTM); these data were obtained from the National Rivers Flow Archive (NRFA).

[9] The NAOI is traditionally defined as the normalized pressure difference between a station on the Azores and one on Iceland; NAOI data were obtained from the Climatic Research Unit (http://www.cru.uea.ac.uk/). We derived relationships between seasonal totals of both precipitation and river flow and seasonal averages of the NAOI using ordinary least squares regression. Note that different record lengths were used (on a site-by-site basis), and so for a given significance level, a different value of the correlation coefficient will apply depending on series length. For each regression we confirmed that our assumption of linearity was valid through an analysis of residuals.

[10] Rainfall data from Sri Lanka (discussed briefly in section 3.1) were obtained from the Faculty of Agriculture, University of Ruhuna (Mapalana), and from the Meteorological Department of Sri Lanka (Ratnapura). Data for the Pacific North West (PNW) of the USA were downloaded from the NOAA National Climatic Data Center (http://www.ncdc.noaa.gov/oa/ncdc.html).

3. Results

3.1. Mapping of Results

[11] Figures 1 and 2 show both the strength of linear correlation (denoted by color) and its statistical significance (denoted by size and shape of symbol) between NAOI, precipitation and river flow at each site. It is immediately clear that there are strong and highly significant correlations between the NAOI, precipitation and river flow across the United Kingdom during winter, spring, and autumn; these are all concentrated in the uplands or on northwest coasts. In summer, precipitation shows few strong or significant correlations, but there are strong and significant negative correlations for river flow.

[12] There are relationships, both strong ($r > 0.6$) and significant ($p < 0.05$), between NAOI and total winter precipitation in the northern and western uplands, but these are almost completely absent in the lowlands further south and east (Figure 1a). There are two exceptions: first, some gauges on northwestern coasts have a strong and highly significant correlation with NAOI, which reflects their proximity to the main depression track in the North Atlantic. Second, two long lowland records also yield weak positive but significant correlations (Southampton: $n = 145$, $r = +0.195$, $p = 0.019$; Marlborough: $n = 127$, $r = +0.205$, $p = 0.021$), which suggests NAO may also influence lowland winter precipitation, but this can only be detected in long records [*Burt*, 1994]. Significant *negative* relationships between NAOI and winter rainfall are only found at Durham ($n = 160$, $r = -0.261$, $p = 0.0008$) and Cockle Park ($n = 109$, $r = -0.242$, $p = 0.012$), both near the east coast and in the rain shadow of the Pennine Hills immediately to their west (blue squares on Figure 1a). Note also that two other east-coast gauges (Swinton Park and Whitby) have negative correlations ($r < -0.2$) but neither are statistically significant (blue triangles).

[13] NAO impact on winter precipitation totals translates directly to river flow (Figure 2), with large ($r > 0.6$) and highly significant correlations ($p < 0.001$) in both large and small basins. The only significant ($p = 0.019$) but moderate ($r = -0.349$) negative relationship between winter flow and NAOI is again in northeast England (River Coquet, NRFA 22001: small blue square); there is a negative correlation ($r = -0.295$) for the Derwent at Buttercrambe (NRFA 27041), but this is not significant ($p = 0.08$: blue triangle). There are fewer significant positive relationships in spring and autumn, but these are again all in the uplands or on northwest coasts.

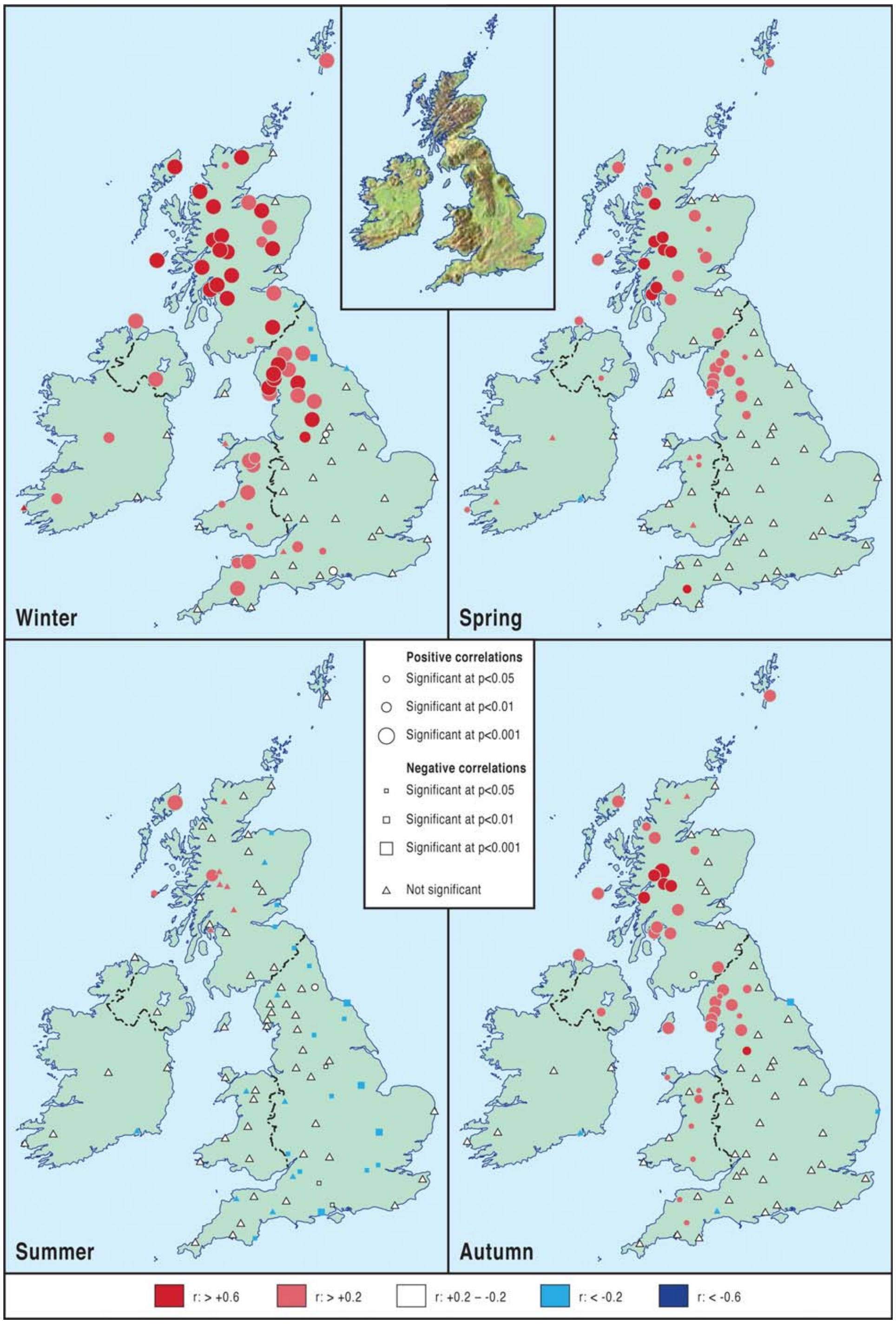

Figure 1. Derived relationships between NAOI and seasonal precipitation totals. Note that lengths of record differ between sites.

[14] There is an inverse relationship between summer rainfall and the NAOI for many sites in lowland, southern and eastern England (Figure 1). Significant negative correlations between NAOI and summer rainfall are fewer and weaker, compared to those for river flow (Figure 2), where seven rivers (including the Coquet) have correlations below -0.6 and are highly significant ($p < 0.001$: large dark blue squares). This opposite effect in summer, in terms of both sign and location, is not unexpected: summer brings a weaker NAO, and the Azores anticyclone tends to cover much of the North Atlantic.

[15] The linear relationships between NAOI, precipitation, and river flow allow us to distinguish the seasonal precipitation and flow totals where the NAOI is neutral (NAOI $= 0$: i.e., the intercept) and the increase (or decrease) in seasonal totals per unit change in NAOI

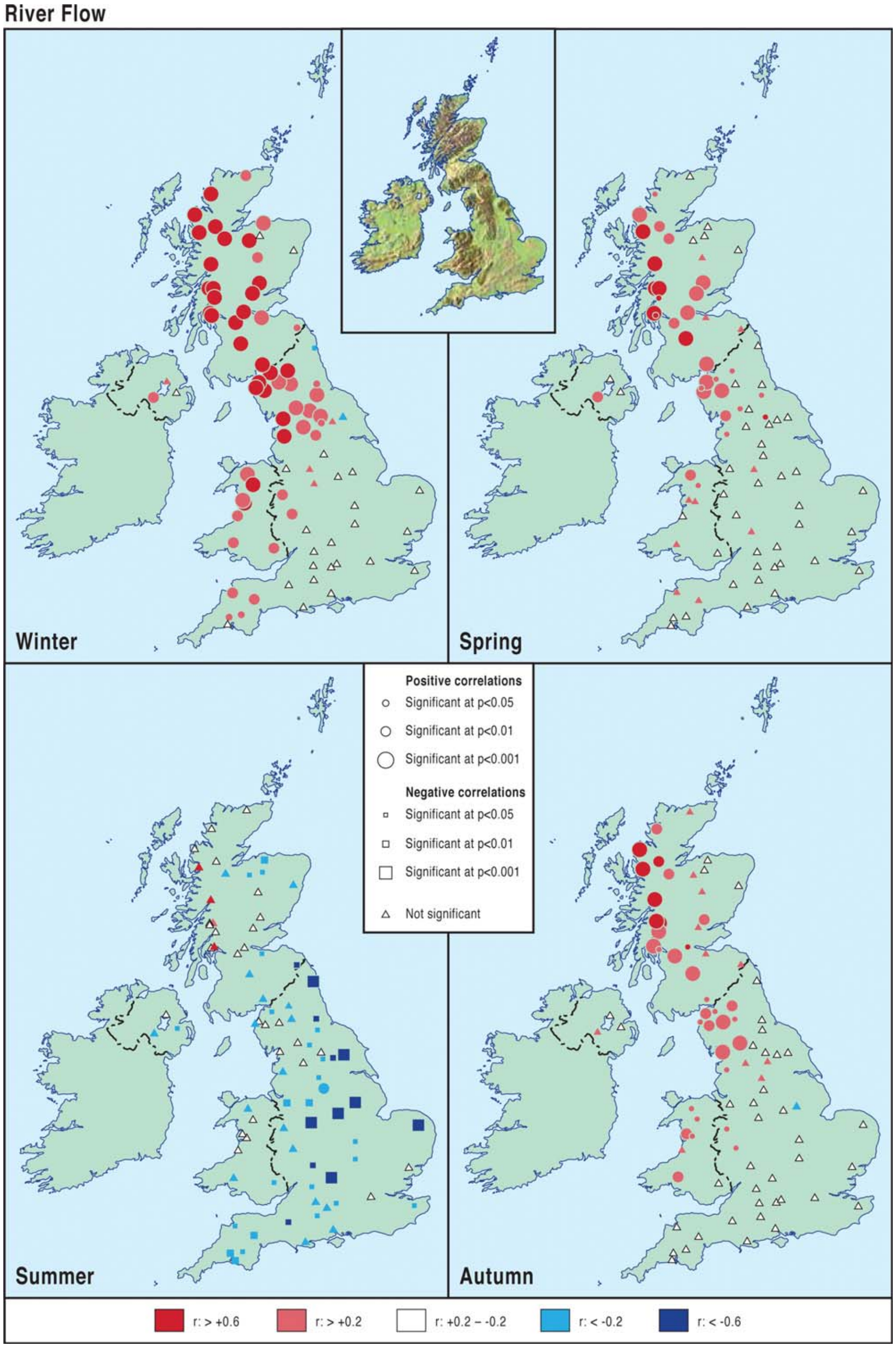

Figure 2. Derived relationships between NAOI and seasonal river flow totals. Note that lengths of record differ between sites.

(ΔNAOI: i.e., the slope). What we term "the double orographic enhancement effect" (DOE) was identified as follows: first, we identified how seasonal precipitation and river flow totals change with altitude for neutral NAOI (Figure 3); we then identified the relationship between slope and intercept terms (Figure 4). The former identifies the change in seasonal totals with altitude, without the effect of NAOI; the latter shows how NAOI modulates this effect.

3.2. Effects With Altitude for NAOI = 0

[16] Figure 3 shows the relationship between generalized altitude (max2k, 90%DTM) and seasonal precipitation and river flow totals for neutral NAOI ($P_{\mathrm{NAOI}=0}$, $Q_{\mathrm{NAOI}=0}$). In

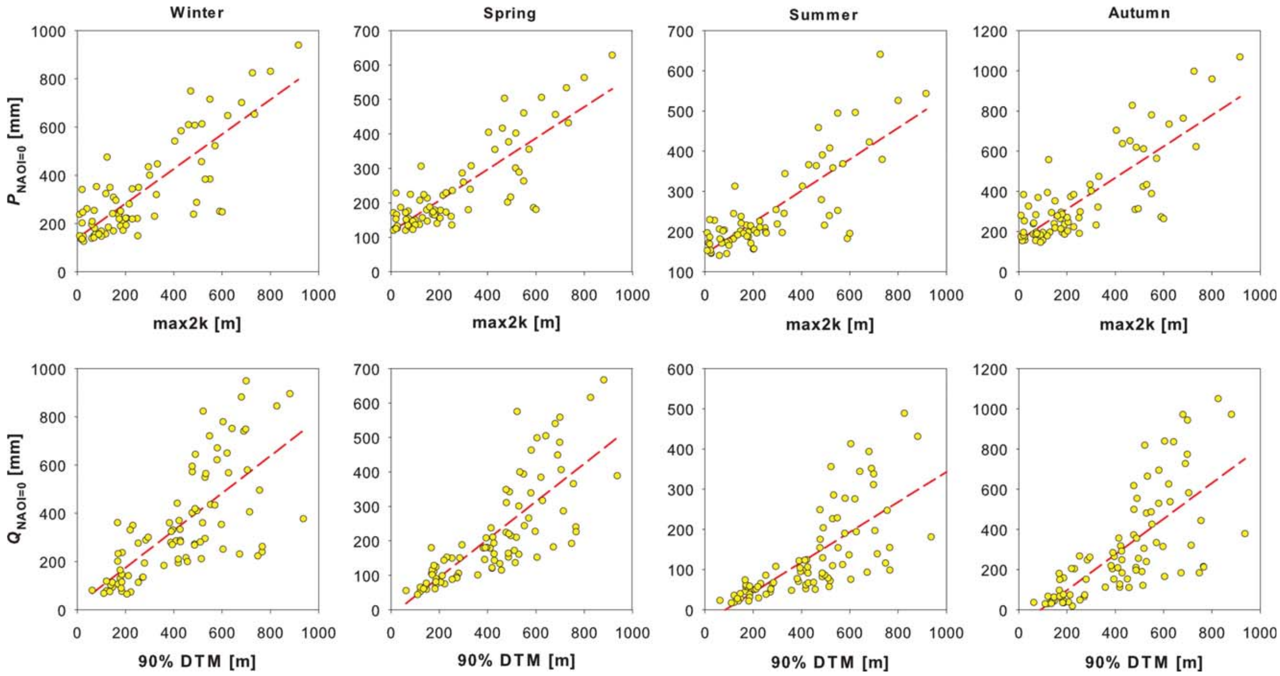

Figure 3. Relationship between generalized altitude (max2k and 90%DTM) and seasonal precipitation (P) and river flow (Q) totals for neutral NAOI ($P_{\mathrm{NAOI}=0}$). Regression details are as follows: all are significant at $p < 0.0001$. For precipitation: winter: $R^2 = 0.664$, intercept 139, gradient 0.718; spring: $R^2 = 0.692$, intercept 116, gradient 0.453; summer: $R^2 = 0.650$, intercept 145, gradient 0.392; autumn: $R^2 = 0.636$, intercept 156, gradient 0.779. For river flow: winter: $R^2 = 0.504$, intercept 19.2, gradient 0.772; spring: $R^2 = 0.607$, intercept -15.7, gradient 0.549; summer: $R^2 = 0.524$, intercept -31.8, gradient 0.374; autumn: $R^2 = 0.511$, intercept -80.5, gradient 0.887.

all seasons both $P_{\mathrm{NAOI}=0}$ and $Q_{\mathrm{NAOI}=0}$ increase significantly with altitude; this shows the orographic enhancement for neutral NAOI. All the regressions are highly significant: generalized altitude explains over 60% of the variance in precipitation and over 50% of the variance in river flow in all seasons.

3.3. Double Orographic Enhancement

[17] The double enhancement of orographic precipitation and its effect on river flows is defined in Figure 4 which includes every station where a significant relationship exists between seasonal NAOI and precipitation or river flow. The Walker test was used to verify field significance for the eight datasets in Figure 4, and to ensure our simultaneous evaluation of multiple hypothesis tests was valid [*Wilks*, 2006]. Figure 4 shows that even after accounting for altitude, precipitation also varies with changing NAOI. This constitutes double orographic enhancement: rainfall is expected to increase at altitude, but the effect is amplified when NAOI is positive (and vice versa).

[18] Figure 5 plots results from all sites and shows that the correlations between NAOI and seasonal precipitation and flow totals become stronger with altitude; these results are summarized in Table 1. Of more interest are the subsets of significant results: for these sites too, higher-elevation sites are more strongly correlated with NAOI than the low-elevation sites in autumn, winter, and spring. This strengthens the argument for a DOE effect in that high-elevation sites do not simply experience a stronger absolute response to NAO variability (roughly proportional to mean rainfall); there is a stronger correlation at altitude, which implies that the underlying process mechanisms become more effective at higher altitudes.

[19] Figure 4 shows the average rate of enhancement per unit NAOI for winter rainfall is 22% of NAOI-neutral total; for a site with 500 mm winter precipitation at NAOI = 0, each unit change in NAOI would change rainfall by ± 78 mm. Given that winter NAOI has varied between -3.12 and $+3.35$ since 1825, this implies a maximum range of 157–869 mm (31% and 174% of 500 mm, respectively). Because NAOI-neutral precipitation totals increase with altitude and the enhancement also varies positively with NAO, this means that the greatest absolute effects will be seen at the highest altitudes. A similar pattern of enhancement is seen for rainfall in autumn and spring (Figure 4). In summer, excluding three northwest sites with positive correlations, there is no clear pattern other than to emphasize the negative sign for $\Delta P_{\Delta\mathrm{NAOI}}$. For river flow, the same seasonal patterns are seen as for rainfall except that in summer there is an inverse relationship between $Q_{\mathrm{NAOI}=0}$ and $\Delta Q_{\Delta\mathrm{NAOI}}$: variation in NAO generally has a larger effect in basins with higher summer flows, which may be significant in relation to water supply and summer drought.

[20] Results shown in Figure 4 were used to project the potential range of double orographic enhancement of UK precipitation and river flows. Figures 6a and 6b show the percentage change in winter precipitation and flow totals

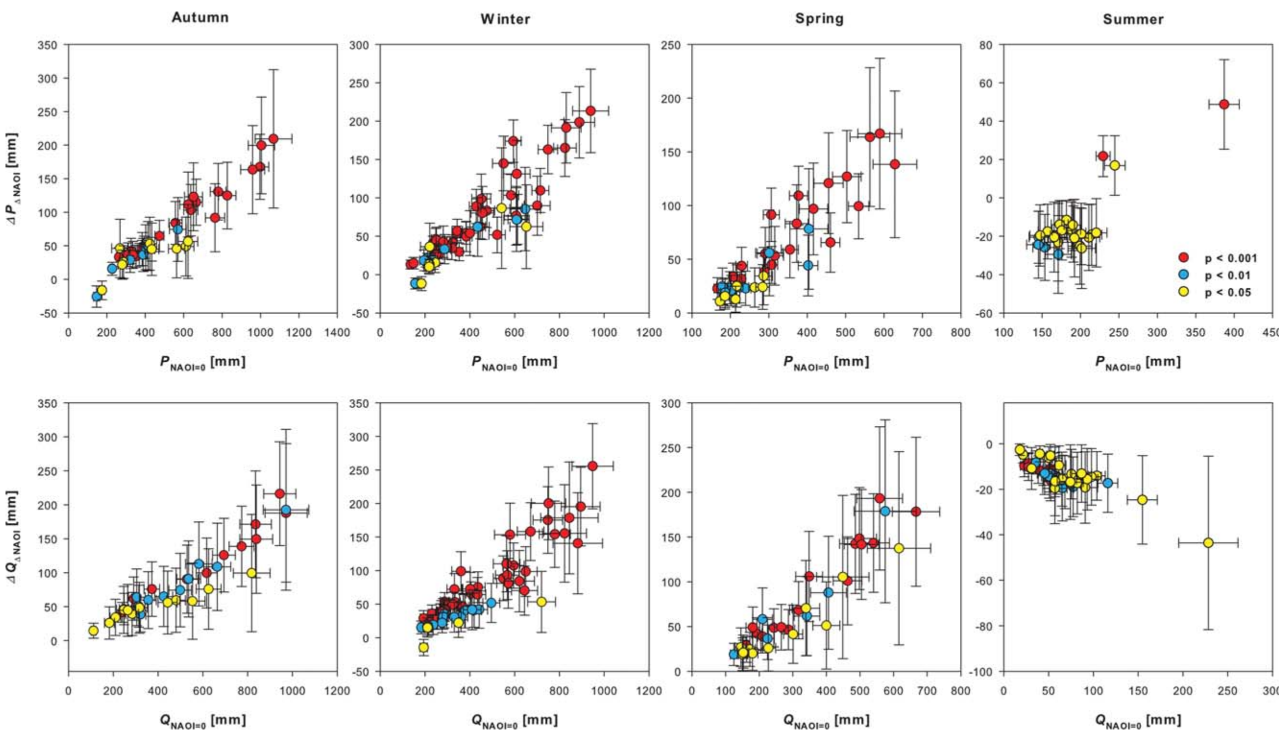

Figure 4. Average seasonal precipitation or average flow for neutral NAO ($R_{\mathrm{NAOI}=0}$, $Q_{\mathrm{NAOI}=0}$), and change in rainfall or river flow per unit change in NAOI ($\Delta R_{\Delta\mathrm{NAOI}}$, $\Delta Q_{\Delta\mathrm{NAOI}}$). Autumn: precipitation $r = +0.9533$, $p = 7.8890\mathrm{e}^{-21}$; flow $r = +0.9393$, $p = 2.0520\mathrm{e}^{-16}$. Winter: precipitation $r = +0.9097$, $p = 2.9385\mathrm{e}^{-22}$; flow $r = +0.8984$, $p = 2.\ 5991\mathrm{e}^{-21}$. Spring: precipitation $r = +0.9186$, $p = 1.1256\mathrm{e}^{-15}$; flow $r = +0.9449$, $p = 1.\ 4517\mathrm{e}^{-17}$. Summer: no significant relationships identified that are consistent across the country.

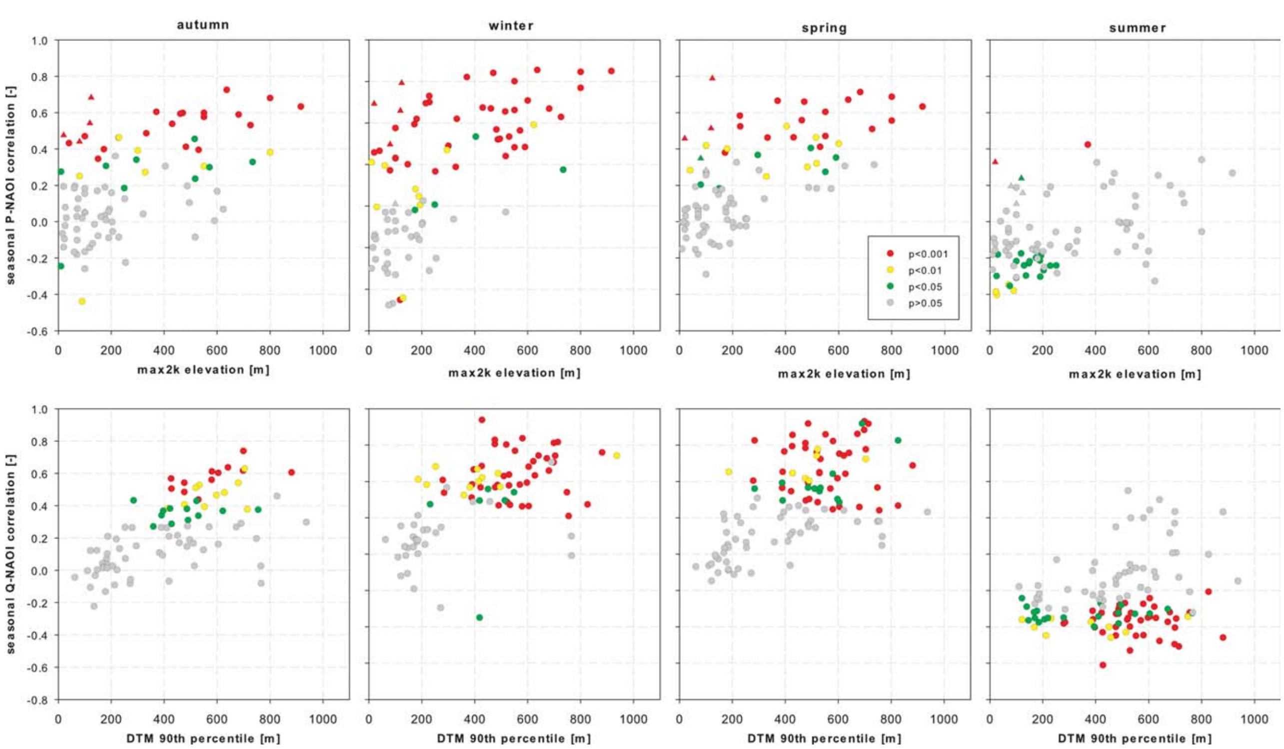

Figure 5. The relationship between generalized elevation and the correlation between precipitation or river flow and NAOI at each site. Table 1 gives relevant results to show that correlations between NAOI and precipitation or river flow increase in strength with altitude.

Table 1. Effect of Altitude on the Strength of Correlation Between NAOI and Seasonal Precipitation and Streamflow

	Correlation	% Increase in Correlation Per 100 m Increase in Altitude	Correlation at Zero Altitude
Precipitation			
Winter	0.581	4.5	0.373
Spring	0.539	3.6	0.302
Summer	0.504	5.2	−0.336
Autumn	0.523	3.9	0.262
River Flow			
Winter	0.474	4.7	0.340
Spring	0.479	4.5	0.267
Summer	0.214	0.89	−0.410
Autumn	0.517	4.6	0.215

compared with NAO-neutral conditions for a range of NAOI (±4.0). This clearly shows the dipole signal: the double orographic enhancement effect is reversed in drier areas. As $P_{\mathrm{NAOI}=0}$ increases, so too does the percentage enhancement due to NAO, tending to a constant at high values of $P_{\mathrm{NAOI}=0}$. Figures 6c and 6d further use the relationships from Figure 4 to estimate winter rainfall and river flow for the maximum and minimum winter NAOI values since 1825 (Figure 6e): this indicates a range of 150% at the wettest locations compared to the NAOI-neutral total. Figure 6f shows the frequency distribution for winter NAOI; since the mean winter value is slightly positive, it is to be expected that positive enhancement of seasonal precipitation and flow totals will more usually be evident. The tails of the distribution imply that extreme DOE will occur in 12% of winters (NAOI > 2), while very low rainfall and flow will occur in about 11% of winters (NAOI < −1). Similar patterns exist for both precipitation and flow in spring and autumn, the only difference being in the exact position of the dipole. In summer, NAO influence disappears in the uplands, but clear impacts remain for northwest coasts and southeast lowlands.

3.4. Impact of Record Length on the Results

[21] It was considered whether length of record (24–181 years for rainfall and 23–125 years for river flow) might affect the results and whether there were changes in the relationship between NAOI and precipitation or river flow totals over the period of study. Correlations for long series were compared with those for a fixed period: 1971–2000,

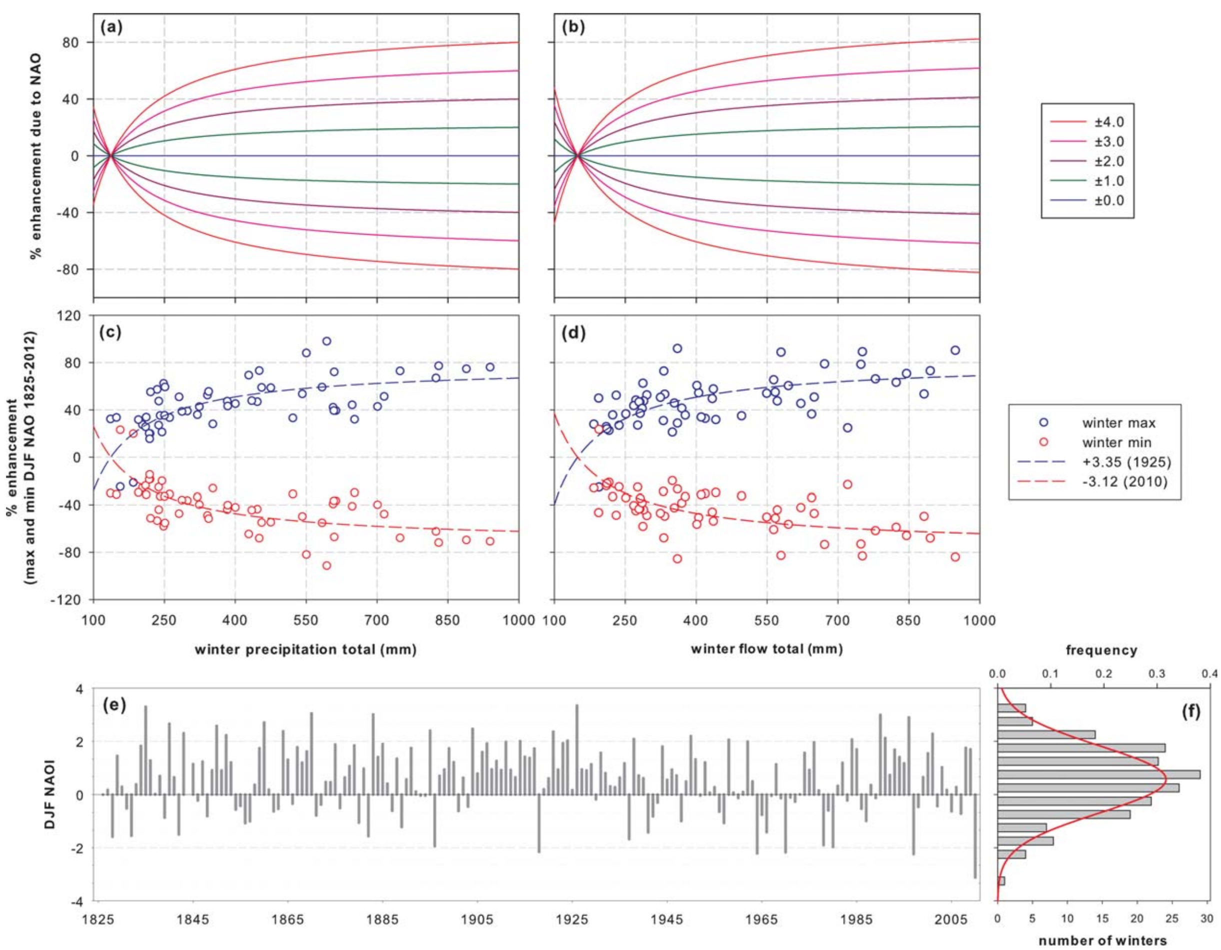

Figure 6. Projected range of double orographic enhancement in winter in relation to variations in NAOI. Percentage variations for the NAO range ±4.0 for (a) precipitation and (b) river flow. Estimates of (c) winter precipitation totals and (d) winter river flow for the maximum and minimum observed winter NAOI values since 1825. (e) Winter NAOI values since 1825. (f) Distribution of winter NAOI values since 1825.

Table 2. Comparison of Precipitation Results for Long Series With the 30 Year Period, 1971–2000[a]

Significance in 1971–2000 Series	Significance in "Long" Series n.s.	<0.05	<0.01	<0.001
Winter Precipitation				
n.s.	31	3	1	6
<0.05		2	4	4
<0.01		1	1	5
<0.001				21
Spring Precipitation				
n.s.	46	3	3	1
<0.05	1	1	2	
<0.01		2	3	2
<0.001			2	13
Summer Precipitation				
n.s.	56	13	4	
<0.05	1	2		1
<0.01				1
<0.001				
Autumn Precipitation				
n.s.	44	6	4	4
<0.05	1	2	1	4
<0.01			2	4
<0.001				6

[a]Numbers in the leading diagonal show where results are unchanged between the two analyses. Results above the leading diagonal show reduced significance, and vice versa, for the shorter period.

chosen because many of the flow records started in the 1960s. A few records that started after 1971 or finished before 2000 were discarded. For precipitation, Table 2 indicates a tendency for significant correlations to be weaker or nonexistent in shorter records, although particularly strong ones remain so, especially in winter and spring. For river flow (Table 3), it is interesting that some correlations become stronger; this may perhaps relate to lag effects already mentioned earlier. It is clear that long records are required to elucidate the relationships shown in Figures 1 and 2; given local hydroclimatological variability, even a 30 year record may be insufficient to identify long-term coupling of NAO to hydrological systems, given that 30 years would in any case be too short to capture the influence of slowly varying North Atlantic sea-surface temperatures on seasonal rainfall anomalies.

Table 3. Comparison of River Flow Results for Long Series With the 30 Year Period, 1971–2000[a]

Significance in 1971–2000 Series	Significance in "Long" Series n.s.	<0.05	<0.01	<0.001
Winter River Flow				
n.s.	22	5	8	2
<0.05		1		3
<0.01			1	3
<0.001				18
Spring River Flow				
n.s.	37	2		1
<0.05	4	2		
<0.01	1	4	3	1
<0.001	2	1	1	7
Summer River Flow				
n.s.	29	17	8	3
<0.05	1	1	1	4
<0.01				
<0.001				
Autumn River Flow				
n.s.	38	2	1	
<0.05	3	6	1	
<0.01	1	2	4	3
<0.001				3

[a]Explanation as for Table 1.

Table 4. Moving-Window Analysis of Pearson Correlations Between Winter Precipitation Totals and NAOI for Successive 30 Year Periods[a]

Decade	Armagh	Fort William	Holehird	Ullscarf	Stornaway
1841–1870	0.207				
1851–1880	0.178				
1861–1890	0.257				
1871–1900	0.311				0.530
1881–1910	0.503			**0.648**	0.558
1891–1920	0.510			**0.738**	**0.617**
1901–1930	0.460		**0.661**	**0.669**	**0.738**
1911–1940	0.524		**0.775**	**0.691**	**0.792**
1921–1950	0.484		**0.713**	**0.606**	**0.842**
1931–1960	0.432	**0.830**	0.543	**0.596**	**0.634**
1941–1970	*0.380*	**0.828**	0.542	**0.618**	**0.664**
1951–1980	0.189	**0.785**	0.480	0.543	**0.647**
1961–1990	0.157	**0.830**	0.564	**0.640**	**0.796**
1971–2000	0.168	**0.826**	**0.667**	**0.629**	**0.772**
1981–2010	0.436	**0.814**			**0.739**

[a]Italicized r values are significant at $p < 0.05$, underlined at $p < 0.01$, and bold at $p < 0.001$.

[22] Moving-window analysis [*Burt et al.*, 2008; *Howden et al.*, 2011] was used to explore the changing nature of the NAO-total relationship over time. Table 4 shows results for five long series, with correlations between winter precipitation total and NAOI by decade. For the three upland rain gauges (Fort William, Holehird, and Ullscarf), the correlations remain highly significant, notwithstanding some variation over time. A similar conclusion can be drawn for Stornaway, a low-altitude site but further northwest than any other site included here. At Armagh, a lowland site, there are several decades when the correlation is not significant, including the period 1971–2000. We conclude that choice of 30 year period could be significant for lowland sites where the relationship is weak at the best of times, but much less relevant for upland gauges where the relationship remains very strong irrespective of the period selected. Our choice of 1971–2000 for the fixed-period analysis reported earlier seems secure therefore, but we note that the decade 1951–1980 had relatively lower correlations and would not therefore have been an ideal choice as a baseline for analysis given its exceptional nature.

[23] It is clear that record length has some influence on our findings. The moving-window analysis shows that there have been changes in the relationship between NAO and precipitation over time. Comparison of results for long records and the fixed period 1971–2000 show that even a 30 year record may provide misleading results about underlying system behavior [cf. *Howden et al.*, 2011]. Given the long timescales required to detect significant changes in the frequency of heavy precipitation, this underlines the need for long-term environmental monitoring and reporting of climate change indices at "benchmark" locations [*Burt*, 1994; *Fowler and Wilby*, 2010].

Table 5. Relationship Between the NINO3 Index and Rainfall Total for Two Gauges in Sri Lanka for the SW Monsoon (March-April) and the NE Monsoon (October-December) Periods, 1976–2003 Inclusive

Location	Period	Intercept	Regression Coefficient	r	p	n
SW coast (Mapalana)	SW Monsoon	270.77	−70.28	0.382	0.044	28
Mountain (Ratnapura)	SW Monsoon	581.11	−109.35	0.409	0.031	28
E coast (Ampara)	SW Monsoon	152.22	−59.10	0.464	0.014	26
Coast (Mapalana)	NE Monsoon	80.49	682.47	0.370	0.052	28
Mountain (Ratnapura)	NE Monsoon	1097.42	122.07	0.484	0.012	26
E coast (Ampara)	NE Monsoon	840.20	63.20	0.340	0.089	26

4. Discussion

[24] These results cast a new light on rainfall variability in upland Britain and have implications worldwide, for any mountainous region where significant orographic precipitation is generated. Of course, rainfall increases with altitude: this is well known, and the topographical and climatological controls on the distribution of orographic rainfall in space and time been studied for many decades [e.g., *Shaw*, 1962; *Chuan and Lockwood*, 1974; *Burt*, 1980]. What is novel here is the identification of large-scale interannual variability in seasonal precipitation and river flow totals across the British uplands controlled by the varying strength of atmospheric circulation in the North Atlantic region.

4.1. Implications for River Flow

[25] There are major implications for river flow: there is an increased risk of flooding during wet winters when the NAO is strongly positive; the most damaging floods in Britain are generated in upland, headwater basins where the combination of heavy falls of intense rain falling on steep catchments with low infiltration capacity produce rapid flood runoff [e.g., *Sibley*, 2010]. Conversely, the densely populated southeast has a higher risk of drought when the NAO is strongly positive. When the NAO is highly negative, precipitation is greater in the southeast, but the uplands will be unusually dry and surface water reservoirs may not refill in winter, leading to water shortages the following summer for nearby cities such as Manchester, Leeds, or Glasgow. This was a feature of the extreme droughts of both 1975–1976 [*Doornkamp et al*., 1980] and 1995–1996 [*Wilby et al*., 1997]. These conclusions are particularly noteworthy because of the long records used in the analysis: our findings therefore relate to long-term climatic trends and not simply to shorter-term variability [*Howden et al*., 2011]. The results imply that as forecasting skill for NAOI and similar indices improves, it should be possible to mitigate the worst effects of rainfall variability through careful management of regional water resources.

4.2. Is the Double Orographic Enhancement Phenomenon Ubiquitous?

[26] There can be nothing unique about the processes involved, simply variation in their frequency and intensity as atmospheric circulation varies in strength. To see if the same sort of effect is seen in other areas of the world where secular variations in the strength of atmospheric circulation are known to occur, we undertook preliminary analyses of precipitation in Sri Lanka (Table 5) and the PNW of the USA (Figure 5). It is well established that the El Niño-Southern Oscillation (ENSO) is a significant influence on Sri Lankan rainfall [*Rasmussen and Carpenter*, 1983; *Zubair et al*., 2008]. We used the sea-surface temperature index for the NINO 3 region of the Pacific Ocean (NINO3) index [*Kaplan et al*., 1998] to predict rainfall totals at Ratnapura (mountains), Mapalana (south coast), and Ampara (east coast) for the period 1976–2006. For the SW Monsoon (March-April), the regression coefficient is larger (more negative) in the mountains than at the upwind coast, suggesting that double orographic enhancement is occurring in line with variations in the strength of ENSO, However, for the NE Monsoon (October-December), Mapalana is in the rain shadow of the mountains, which may be why the regression coefficient (not significant at $p = 0.05$) is larger than at Ratnapura. However, for Ampara on the east coast, the regression coefficient (not significant) *is* smaller than at Ratnapura for the NE Monsoon, further evidence of an enhanced orographic effect in downwind uplands.

[27] For the PNW, we analyzed 19 long records from northern Oregon and southern Washington for the extended winter period, November-May, when most of the annual precipitation is received; the area considered extended from the Pacific coast east to the Cascade Range. Again, this is a region in which ENSO is known to have a clear influence on variations in precipitation [*Hamlet and Lettenmaier*, 2007]. At the coast, there is no significant correlation between the NINO34 index and precipitation totals. Highly significant regressions are found for both the Coast Range and the Cascades, with less strong (but still significant) correlations in the Willamette Valley in between. For the 13 gauges where there is a significant relationship between NINO34 and rainfall total, and using maximum altitude within 8 km of the gauge (max8k) as the effective height of local topography (a different measure was used, given the much greater scale of relief involved in the PNW), we found that ENSO-neutral precipitation increases very significantly with altitude ($r = +0.670$, $p = 0.012$), while the regression coefficient is even more strongly correlated with max8k ($r = +0.694$, $p = 0.0086$). Figure 7 confirms that PNW precipitation varies with the changing strength of ENSO compared to ENSO-neutral conditions; once again, the orographic enhancement effect is seen to be amplified at altitude. Of course, much more work would be needed to identify the precise nature and extent of such influence, but these preliminary results help confirm that the UK results are not a local phenomenon but have global significance.

4.3. Driving Forces for the NAO and Links to Double Orographic Enhancement

[28] There is a growing body of evidence that the Atlantic Ocean is a key driver of decadal variability in the

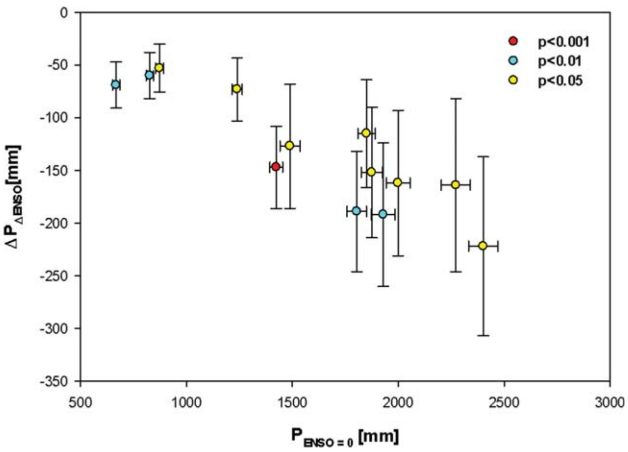

Figure 7. Average winter precipitation for neutral ENSO ($R_{\mathrm{ENSO}=0}$) and change in rainfall per unit change in the NINO34 index ($\Delta R_{\Delta\mathrm{ENSO}}$) for sites in the PNW of the USA.

climate of Europe [*Sutton and Dong*, 2012]. Like *Sutton and Dong* [2012], the focus here has been on impacts (of the NAO in this case) rather than drivers, but we can speculate as to what variations in the NAO may reflect, since this may help to explain observed variations in orographic enhancement. While the NAOI is a relatively simple measure, the difference in atmospheric pressure between Iceland and the Azores, it is strongly correlated to weather types. Data for Lamb Weather Types and circulation patterns over the British Isles [*Jones et al*., 1993] were correlated with NAOI, precipitation totals at Fort William (Scottish highlands), and precipitation totals and mean air temperature (MAT) at Durham (east coast) for the winter period (data supplied by the Climatic Research Unit (CRU): 1872–2011, $n = 140$, for which the critical value of r at $p = 0.001$ is ± 0.287). NAOI is strongly correlated to the frequency of westerly winds ($r = 0.812$) and the strength of the resultant flow ($r = 0.740$). At Fort William, where the winter precipitation total is strongly correlated with NAOI ($r = 0.762$), there are even stronger correlations with the frequency of westerly winds ($r = 0.827$) and the strength of the resultant flow ($r = 0.773$). Our primary hypothesis is therefore that the driving force linking NAO to double orographic enhancement is the strength of atmospheric circulation in the North Atlantic: when the NAO is strongly positive, this means an increased frequency of westerlies conveying maritime air masses across the British Isles and vice versa. Moreover, it may be that these westerly flows are more humid when the NAO is positive: in winter, MAT tends to be strongly correlated with NAOI right across the British Isles. This implies that positive NAO means an increased frequency of warmer, and by implication more humid, westerly winds. Thus, the mechanism for double orographic enhancement may relate both to the strength and frequency of westerly winds and to their enhanced moisture content.

[29] It is worth noting that at Durham, in the east, winter precipitation totals are negatively correlated with NAOI ($r = -0.253$) but more strongly correlated to the frequency of anticyclonic ($r = -0.461$) and cyclonic ($r = 0.599$) conditions and to the total shear velocity ($r = 0.639$), itself a measure of the degree of cyclonicity [*Conway et al*., 1996]. Winter precipitation totals at Durham, in the lee of the Pennine Hills, therefore tend to be higher when the atmospheric circulation is more stagnant. It is possible that the negative correlation of winter precipitation and NAOI at Durham indicates an enhancement of the rain-shadow effect when NAO is positive [cf. *Siler et al*., 2013]. The rain shadow to the east of the British uplands has been well known for a long time [e.g., *Shaw*, 1962; *Burt*, 1980], but detailed analysis of the effect is lacking. This would seem to merit further investigation, including analysis of large-scale atmospheric circulation patterns during individual events but is beyond the scope of this study. If indeed NAO does have a significant influence on the rain-shadow effect, this may explain the lack of significant correlations in autumn, winter, and spring for some rivers to the east of the Cairngorm mountains in Scotland, notably the Dee (12002) and Avon (8004).

[30] Negative correlations show that summer rainfall totals in the lowland southeast are higher when the NAO is weaker: the Azores high is less dominant so that midlatitude cyclonic systems can track further south than usual. It remains unclear why, in summer, (negative) correlations for river flow tend to be stronger and more numerous than for precipitation; this contradicts the findings of *Lavers et al*. [2010], but they included very few lowland sites. The pattern is too widespread to be basin-dependent [cf. *Lavers et al*., 2010]. It may be that correlations between NAO and river flow are affected by lagged responses between rainfall and runoff in some catchments [*Wedgbrow et al*., 2002]. However, while there is some evidence of lagged corrections between winter or spring NAOI and summer river flow, the results presented here indicate a direct correlation between summer NAOI and summer river flow. There might also be some connection with evaporation losses, but summer temperatures are not correlated with NAOI, and further work is needed in this respect. A further possibility, as noted earlier, is that NAO amplifies the rain-shadow effect, causing some negative correlations on the lee side of the uplands.

[31] Recent research has established a link between anthropogenic climate change and increased frequency of

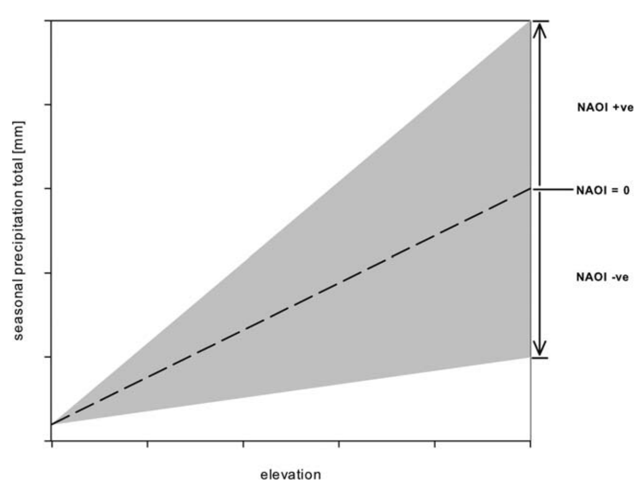

Figure 8. Schematic of the double orographic enhancement effect.

intense precipitation [*Min et al*., 2011; *Pall et al*., 2011]. We are not in a position to add to that debate, except to make the point that on an interannual timescale, ocean-atmosphere drivers like NAO and ENSO will have more immediate effect on extreme precipitation, as demonstrated here. How these drivers behave in the longer term in response to anthropogenic climate change is beyond the scope of this work, but clearly an issue of some significance.

5. Conclusions

[32] We draw three main conclusions:

[33] NAO variations cause large differences in seasonal precipitation totals compared to NAO-neutral conditions, an effect amplified with altitude (up to 150%). These precipitation patterns directly translate to seasonal runoff. Identified effects are large enough to have major implications for water resources and flood risk. Figure 8 provides a schematic summary of the double orographic effect. We conclude that observed orographic enhancement results from two processes: increased precipitation with altitude assuming NAOI = 0, modulated by variation in NAO. Hence, double orographic enhancement occurs at high altitude at times of strongly positive NAO.

[34] In autumn, winter, and spring, there is a strong positive relationship between upland precipitation and NAO; this is not seen at low altitude except on NW coasts. In summer, significant negative relationships are evident in the English lowlands.

[35] Preliminary analyses of precipitation for sites in Sri Lanka and the PNW of the USA in relation to ENSO replicate the pattern of response seen in the UK uplands in relation to NAO.

[36] NAOI is strongly correlated to the frequency and strength of westerly airflow over the British Isles. Since NAOI tends to be positively correlated with MAT, especially in winter, it seems likely that the moisture content of westerly air masses will also increase when the NAO is strongly positive, amplifying the impact of increased airflow.

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