NORTH ATLANTIC OSCILLATION DRIVES DOUBLE OROGRAPHIC ENHANCEMENT OF PRECIPITATION AND RIVER FLOW IN UPLAND BRITAIN

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ABSTRACT

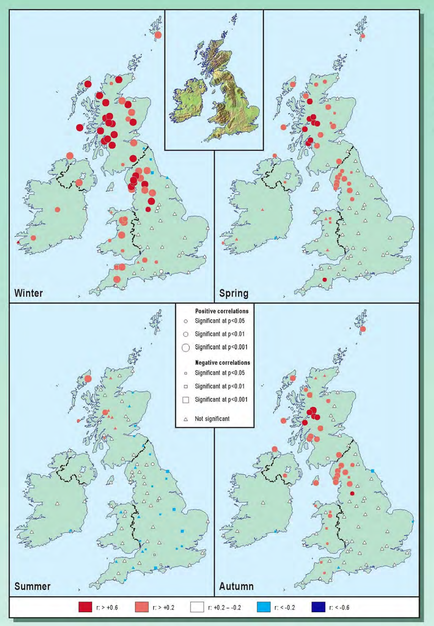
Large-scale climatic variability in the North Atlantic region modulates seasonal rainfall and river flow across the British Isles. We show how the North Atlantic Oscillation (NAO) dramatically affects orographic enhancement of upland precipitation. NAO variations cause large differences in seasonal precipitation 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 autumn, winter and spring, there is a strong positive relationship between upland precipitation and NAO; this is not seen at low altitude except on north-west coasts. In summer, significant negative relationships are evident in the English lowlands. These precipitation patterns directly translate to seasonal runoff. Our findings significantly revise our understanding of the hydroclimatology of rainfall and river flow in upland areas; we argue that the effects observed are of global significance, not merely a local result. Preliminary analysis of precipitation in the Pacific North West of the USA confirms the ubiquity of the effect. Identified effects are large enough to have major implications for water resources and flood risk.

Methodology

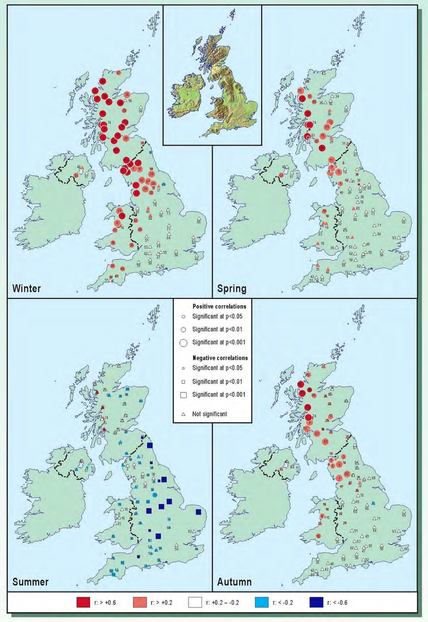
- We used precipitation data from the British Atmospheric Data Centre (BADC) MIDAS database (http://badc.nerc.ac.uk/) and the UK Meteorological Office (UKMO) historic station database (http://www.metoffice.gov.uk/climate/uk/stationdata/), together with other available long records such as Durham [Burt and Horton, 2007] and Oxford [Burt and Howden, 2011].
- We calculated seasonal precipitation totals for 89 stations of lengths between 24 and 181 years (mean: 74 years).
- **We used daily flow records and associated metadata from the UK's National River Flow Archive (http://www.ceh.ac.uk/data/nrfa/) and calculated seasonal flow totals at 84 river gauging stations of lengths between 23 and 125 years (mean length 45 years).**
- 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. For each regression we confirmed that our assumption of linearity was valid through an analysis of residuals.

Results

1. 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". These precipitation patterns directly translate to seasonal runoff.
2. 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.
3. Preliminary analyses of precipitation for sites the Pacific North West of the USA in relation to ENSO replicate the pattern of response seen in the UK uplands in relation to NAO.
4. These findings modify our understanding of underlying processes that control the hydroclimatology of rainfall and river flow in upland areas on an inter-annual time scale. Identified effects are large enough to have major implications for water resources and flood risk.
5. We are not in a position to add to the debate about global warming and increased frequency of intense precipitation (e.g. Min et al., 2011; Pall et al, 2011), except to make the point that, on an inter-annual timescale, ocean-atmosphere drivers like NAO and ENSO provide first-order control of variability in precipitation totals, as demonstrated here.



1. Derived relationships between NAOI and seasonal precipitation totals. The derived intercept and slope parameters at each station denote the average seasonal precipitation when the NAO is neutral ($R_{NAOI=0}$) and the change in precipitation per unit change in NAOI ($\Delta R_{\Delta NAOI}$), respectively. Maps show the significance levels for the derived regression equation at each site.



2. Derived relationships between NAOI and seasonal river flow totals. The derived intercept and slope parameters at each station denote the average river flow when the NAO is neutral ($Q_{NAOI=0}$) and the change in river flow per unit change in NAOI ($\Delta Q_{\Delta NAOI}$), respectively. Maps show the significance levels for the derived regression equation at each site.

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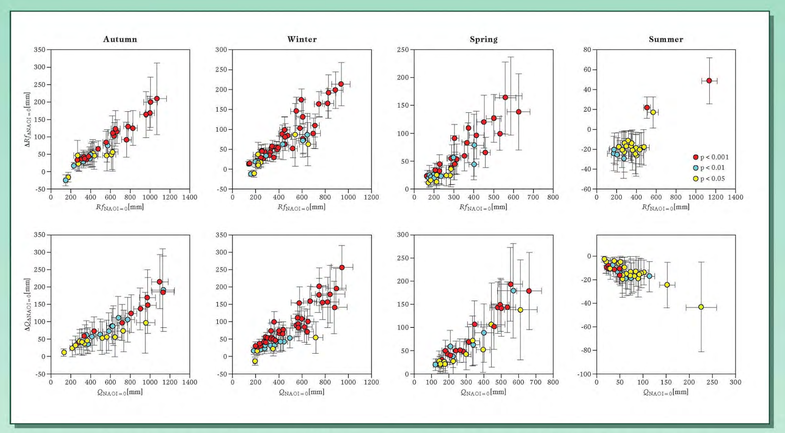
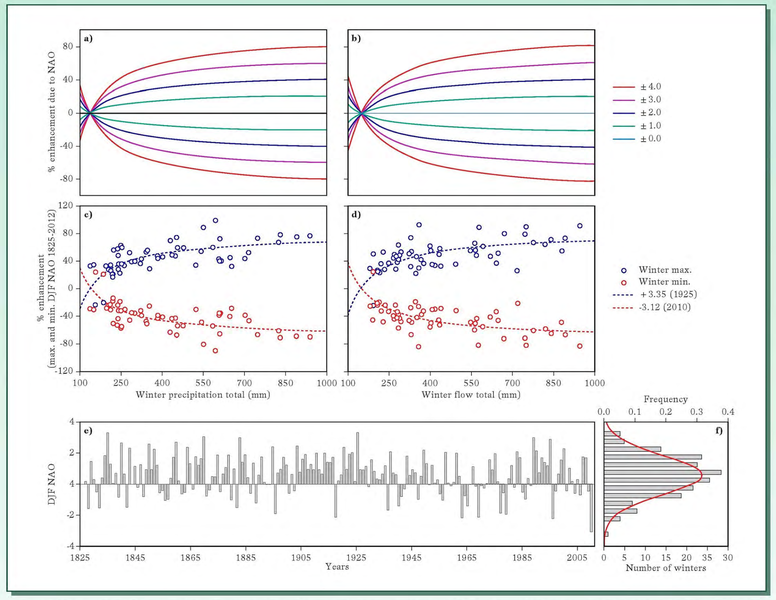


3. Average seasonal precipitation or average flow for neutral NAO ($R_{NAOI=0}$, $Q_{NAOI=0}$), and change in rainfall or river flow per unit change in NAOI ($\Delta R_{\Delta NAOI}$, $\Delta Q_{\Delta NAOI}$). Autumn: precipitation r = +0.9533, p = 7.8890e-21; flow r = +0.9393, p = 2.0520e-16. Winter: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



4. 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.

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