Interactions between large-scale climate and river flow across the northern North Atlantic margin

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Abstract To assess the nature of hydrological sensitivity to climatic change a clear understanding of the cascade of hydroclimatological processes from atmosphere–surface–runoff is necessary, yet this is poorly defined for the northern North Atlantic. This research gap is addressed through a composite analysis of large-scale climatic controls on monthly high and low river flow across this region for 1968–1997. Analyses are structured using hydrological regions defined by cluster analysis, and focus on the month of November. High river flow in all regions is associated with more maritime climatic conditions, driven in northern Europe by a stronger Atlantic pressure gradient and wind-speeds. In eastern North America, high river flow is linked to the opposite conditions. This is suggestive of a positive (negative) relationship between European (North American) river flow and the North Atlantic Oscillation. Additionally, inverse climatic associations between northern European hydrological regions (north *versus* south) appear linked to the Scandinavian pattern.

Key words climate–river flow linkages; composite analysis; hierarchical cluster analysis; North Atlantic Oscillation; northern North Atlantic; Scandinavian pattern

INTRODUCTION

To understand the drivers of hydrological variability, particularly in the context of climate change, fundamental research is required into the process cascade linking the atmosphere and hydrosphere over large spatial domains. The nature of such linkages remains poorly understood, yet such knowledge is crucial for understanding and predicting water resource availability and associated potential stress on society and ecosystems. The ability of atmospheric circulation patterns (such as the North Atlantic Oscillation, NAO) to summarize large-scale climatic variation makes them potentially useful in research on spatial and temporal aspects of climate–environment relationships. To date, the use of such patterns for studying climatic forcing of river flow has been under-utilized (Lawler *et al*., 2003; Kingston *et al*., 2006a). This research gap is addressed through an investigation of the links between large-scale climate and monthly river flow and discussion of possible hydroclimatological mechanisms underlying such associations (i.e. atmospheric circulation patterns). This aim is achieved through a composite analysis of North Atlantic geopotential height and wind vector under monthly high and low river flow conditions for the period 1968–1997. This is conducted on a regional basis, with hydrological regions defined using hierarchical cluster analysis. Analyses are undertaken first for part of the Northern European FRIEND region (Iceland, Scotland, Norway, Sweden, Denmark and Finland), before the study area is extended to the wider northern North Atlantic domain (i.e. northeastern USA and southeastern Canada) to set results in a larger spatial context. In this short paper, results for November are focused upon because previous work (Kingston *et al*., 2006b) has revealed November to be the month with the strongest and most widespread atmospheric links to river flow.

DATA AND METHODOLOGY

Monthly river flow data for Norway, Sweden, Denmark and Finland were primarily sourced from the FRIEND-EWA, supplemented by records from the national hydrometric agencies of these countries. Icelandic data and a small number of Norwegian records were obtained from the Global Runoff Data Centre. Scottish flow data were obtained from the UK National River Flow Archive. The Hydro-Climatic Data Network and Reference Hydrometric Basin Network provided data for the USA and Canada, respectively. A total of 112 river flow records were selected: 69 for northern Europe and 43 for eastern North America. Gauging stations were selected according to the following criteria: (a) gauged basin area between 50 and 1000 km^2; (b) a continuous 30-year record; (c) satisfactory record homogeneity, assessed by detailed visual inspection and double mass curve analysis; (d) maximum spatial coverage of the northern North Atlantic margin. These requirements resulted in a study time period of 1968–1997.

Climate data were obtained from the European Centre for Medium Range Weather Forecasting (ECMWF) ERA-40 re-analysis, which provides gridded data at 2.5º resolution (Simmons & Gibson, 2000). Monthly 500 and 1000 hPa geopotential height and wind vector data for 1968–1997 for the North Atlantic region were extracted for this investigation.

Hierarchical cluster analysis (CA) of river flow time series was used to define hydrological regions within the study domain. Regionalization was undertaken to identify spatial structure within the data set and so facilitate interpretation of inter-regional patterns and processes. Ward's clustering algorithm was used, as this was found to provide the most physically meaningful results (in agreement with Bower *et al*., 2004). Whilst CA is an objective method for regionalization, the user has to make a number of decisions at different stages which influence emergent groups (Bower *et al*., 2004). As such, visual inspection and correlation of individual stations with their regional means, and a check of the geographical expression of each region in terms of physical interpretability, were carried out to validate the final cluster solution.

Before regionalization was performed, two steps were taken to ensure that underlying time-series variation was the primary factor determining the definition of river flow regions. Initially, the seasonal cycle was removed. Secondly, river flow time series were standardized (*z*-score transformation) to enable meaningful comparison of time series from basins with different absolute discharge magnitudes. After determination of hydrologically similar regions, monthly data for each region were averaged to produce regional time series, which formed the basis for subsequent composite analysis.

Composites of geopotential height and wind vector across the North Atlantic region were produced based on high and low flow episodes for each monthly regional river flow series. High and low flow are defined as the upper and lower quartiles of river flow for each month over the 1968–1997 study period (equating to eight high flow and eight low flow years). These threshold levels were chosen as the best compromise between sample size and sampling only genuinely high and low flow years. T-tests were used to test for statistical significance of climatic differences between high and low flow composites.

RESULTS

Seven hydrological regions were defined (Fig. 1): four in the Northern European FRIEND area (Regions 1–4) and three in North America (Regions 5–7). Region 1 represents rivers in central Scandinavia, Region 2 northern Scandinavia and Iceland, Region 3 southern Scandinavia and northeast Scotland, and Region 4 southern and central Scotland. For North America, Region 5 includes rivers in central and northern New England, southeastern Quebec, New Brunswick and one in northern Newfoundland. Region 6 covers rivers in Nova Scotia and southern Newfoundland, while Regions 7 represents rivers from southern New England. Although a range of basin sizes has been used herein, no statistically significant ($p = 0.05$) differences in basin size were found between the regions (using analysis of variance).

Composite analysis

Regions 1–4 (northern Europe) High river flow in Regions 1 and 4 is associated with a stronger and more northwesterly positioned Icelandic Low (IL) and Azores High (AH) (e.g. Fig. 2). The resultant enhanced pressure gradient between the IL and AH causes greater wind speeds and increased advection of moist maritime air masses over Regions 1 and 4 (Fig. 3(a)). Low river flow is associated with decreased wind-speeds over northwest Europe, resulting from weaker pressure gradients in the zone upwind of Regions 1 and 4 (Fig. 3(b)).

For Region 2, geopotential height differences between high and low river flow consist of a positive anomaly over Britain and southwest Scandinavia and a negative anomaly affecting north-east Scandinavia, as part of a circumpolar wave of alternating positive and negative geopotential

Fig. 1 Locations of river flow gauging stations and hydrological regions.

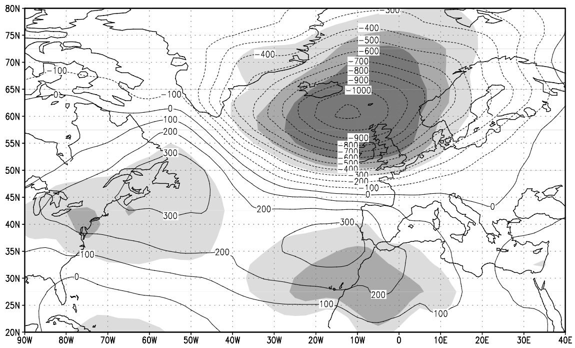

Fig. 2 High minus low flow November 1000 hPa geopotential height for Region 4. (Dotted lines indicate greater geopotential height for low flow; solid lines where greater for high flow. Shading indicates statistical significance at $p = 0.05$, 0.01 and 0.001 from light to dark.)

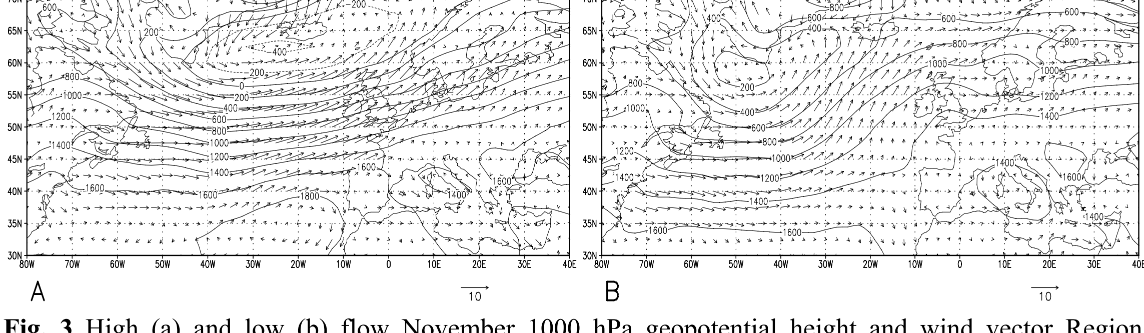

Fig. 3 High (a) and low (b) flow November 1000 hPa geopotential height and wind vector Region 4 composites. (Arrow length indicates wind speed in m s^{-1} – see scale at bottom right.)

height departures (Fig. 4). In high flow situations these pressure differences are associated with an IL displaying two geopotential height minima, a weaker western low and a deeper centre north of

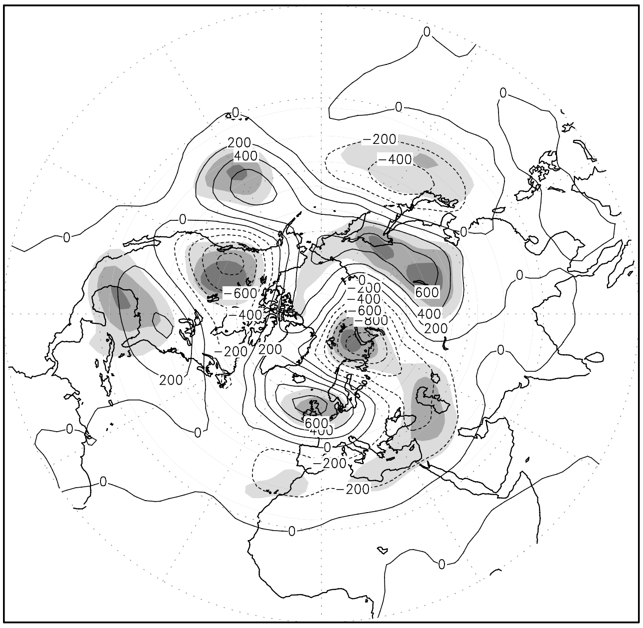

Fig. 4 High minus low flow November 500 hPa geopotential height for Region 2 (lines and shading as Fig. 2)

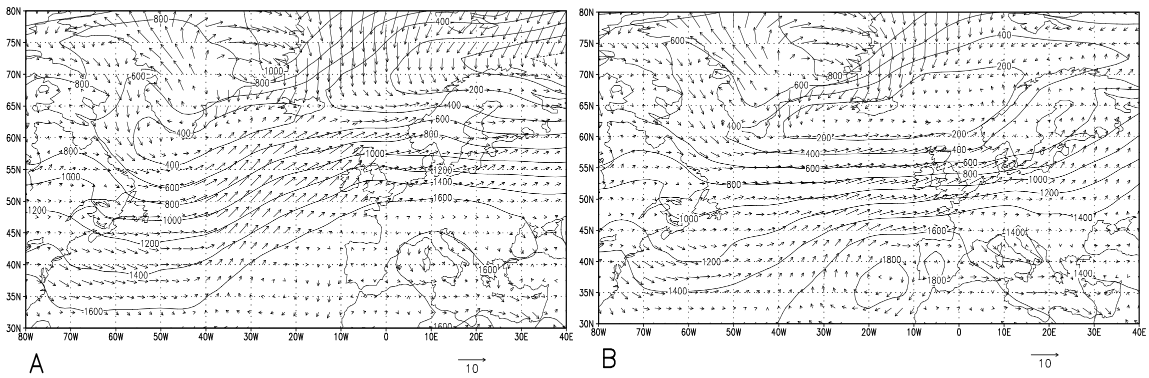

Fig. 5 High (a) and low (b) flow November 1000 hPa geopotential height and wind vector Region 2 composites. (Arrow length indicates wind speed in m s^{-1} – see scale at bottom right.)

Scandinavia. This is associated with strong northerly winds over the north of Region 2 and southwesterly winds in the south of this region (Fig. 5(a)). The low flow composite shows an IL position between Iceland and Scotland, resulting in a relatively strong pressure gradient and wind-speeds south of Region 2, over Britain and southern Scandinavia (Fig. 5(b)). Differences in geo-potential height and wind vector between high and low flow for Region 3 (southern Scandinavia and northeast Scotland) are less apparent but in general show the opposite patterns to Region 2.

Regions 5–7 (North America) As for Regions 1 and 4, river flow in Regions 5 and 6 appears closely related to variation in the IL and AH. In contrast to the European regions, high flow in Regions 5 and 6 is linked to a relatively weak IL and AH and consequently a reversal of the meridional pattern of pressure differences shown for Regions 1 and 4. These changes are linked to a stronger pressure gradient in the western Atlantic in low flow composites and associated stronger wind-speeds over Regions 5 and 6.

For Region 7, differences in pressure gradient and wind-speed between high and low river flow are similar to those of Regions 5 and 6. Instead of being primarily related to changes in the IL and AH, however, variation in the East Coast pressure trough appears more influential, with this trough weaker in high flow situations and deeper under low flow conditions. This is shown to be related to a hemispheric wave pattern of alternating positive and negative geopotential height departures (but different to that of Region 2).

DISCUSSION

Interactions between large-scale climate and river flow in November have been revealed for hydrological regions within the Northern European FRIEND region and eastern North America. High river flow for all regions is associated with an increased maritime influence on climate. This is thought to result in greater river flow by directing rain-bearing maritime weather systems (i.e. mid-latitude depressions) over these regions with greater frequency and causing milder temperatures. Milder temperatures are thought to influence river flow primarily through reducing the snow-to-rain ratio, making precipitation more likely to influence river flow concurrently.

The atmospheric mechanisms driving differences in the degree of maritime influence on climate are found to vary between hydrological regions. Regions 5 and 6 show opposing relationships with the IL and AH compared to Regions 1 and 4, yet both experience a more maritime/less continental climate in high flow situations. This apparent discrepancy is linked to the opposite locations of these two groups on the North Atlantic periphery. Thus for Regions 5 and 6 on the lee side of the North American continent a reduction in the prevailing mid-latitude westerly winds results in a reduced continental influence, while the reverse is true for Regions 1 and 4 on the windward side of northern Europe.

Differences in the IL, AH and intervening pressure gradient between high and low river flow for Regions 1 and 4 (Fig. 2), and 5 and 6, are typical of those associated with the NAO (Hurrell, 1995). Region 1 and 4 geopotential height differences are consistent with a positive relationship between river flow and the NAO, while those for Regions 5 and 6 suggest an inverse relationship with the NAO. These findings support previous studies on European NAO-river flow relationships (Kingston *et al*., 2006a), although are contradictory to suggestions of a positive NAO-river flow association in northeastern USA (Bradbury *et al*., 2002). This apparent discrepancy may arise because Regions 5 and 6 straddle zones typically believed to be under opposing NAO centres of influence (Hurrell, 1995), although it should be noted that relatively few studies have considered spatial patterns of NAO-climate linkages outside of the December-March winter season.

The contrast in climatic influences on river flow between Regions 2 and 3 is linked to their latitudinal separation causing these regions to be affected in opposite ways by certain weather systems. The consequent geopotential height anomaly dipole between northern and southern Scandinavia in the Region 2 pattern (Fig. 4) (and to a lesser extent in the Region 3 pattern) appears linked to the Scandinavian teleconnection pattern (CPC, 2006), previously referred to as the Eurasia-1 pattern (Barnston & Livezey, 1987). The positive phase of this pattern is associated with a blocking anticyclone over northern Scandinavia and western Russia, and consequent lower temperatures and precipitation over this area (Kauker & Meier, 2003). As such, this apparent connection provides a potential mechanism for river flow variation between Regions 2 and 3, with geopotential height departures consistent with a negative correlation between Region 2 river flow and the Scandinavian pattern and a positive correlation for Region 3.

The association between November high river flow across the northern North Atlantic periphery and a more maritime climate has been shown to be linked to large-scale climatic changes. In a number of cases, these changes appear to be related to atmospheric circulation patterns (the NAO and Scandinavian patterns), with river flow in different hydrological regions associated with opposing phases of these circulation patterns. As such, the relationships defined here represent a promising approach for enhancing understanding of historical discharge behaviour and potential future climate-driven changes.

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