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LETTER

Long-range forecasts of UK winter hydrology

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Abstract

Seasonal river flow forecasts are beneficial for planning agricultural activities, river navigation, and for management of reservoirs for public water supply and hydropower generation. In the United Kingdom (UK), skilful seasonal river flow predictions have previously been limited to catchments in lowland (southern and eastern) regions. Here we show that skilful long-range forecasts of winter flows can now be achieved across the whole of the UK. This is due to a remarkable geographical complementarity between the regional geological and meteorological sources of predictability for river flows. Forecast skill derives from the hydrogeological memory of antecedent conditions in southern and eastern parts of the UK and from meteorological predictability in northern and western areas. Specifically, it is the predictions of the atmospheric circulation over the North Atlantic that provides the skill at the seasonal timescale. In addition, significant levels of skill in predicting the frequency of winter high flow events is demonstrated, which has the potential to allow flood adaptation measures to be put in place.

1. Introduction

Year to year variations in river flows govern much of the water supply available to agriculture, industry and the public. Rivers also integrate catchment scale rainfall and determine the risk of disruptive fluvial flooding events with substantial costs to society each year (Environment Agency 2009). While river flow forecasts on timescales of days are highly skilful (Price *et al* 2012), seasonal predictability of extratropical river flows is limited and mainly derives from the initial water storage conditions of the catchment (Bierkens and van Beek 2009, Shukla *et al* 2013, Yang *et al* 2013).

Until recently, seasonal river flow forecast studies in the United Kingdom (UK) were limited to either a few catchments, and/or covered mainly the summer season (e.g. Wilby 2001, Wedgbrow *et al* 2002, Wilby *et al* 2004, Svensson and Prudhomme 2005, Wedgbrow *et al* 2005). The methods comprised empirical relationships between hydrological indicators and climate indices in the preceding months, and were experimental rather than operational. None of them forecast the winter (December to February) hydrology, which is the target season for the present study. Svensson (2014) developed the first nationwide, year-round forecasting system, which showed that river flows in the south-eastern parts of the UK can be successfully predicted at seasonal timescales from persistence of the initial flows. Such persistence occurs because the catchments in this region have a permeable geology and a flow regime dominated by slowly released groundwater.

However, the upland north-west, with its steep slopes and impermeable geology, has so far shown little predictability of seasonal river flows. The influence of the initial hydrological conditions on the fast responding catchments in this area persists for only a short time, and instead these regions are under meteorological control. Skilful long-range flow forecasts for this part of the country are therefore highly dependent on skilful seasonal rainfall forecasts.

Rainfall is in turn largely governed by atmospheric circulation. Numerous studies have identified the North Atlantic Oscillation (NAO) as the single most important pattern of circulation for UK winter rainfall, particularly in western areas (Wilby *et al* 1997)

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and in areas with high relief where both lofting and secondary feedbacks act to amplify the NAO signal in rainfall (Burt and Howden 2013).

In this paper, we build on the recent advancement in forecasting the NAO presented by Scaife *et al* (2014), to improve river flow forecasts in the north and west of the UK. We show how the regional geological and meteorological controls of river flows complement each other geographically, and how skilful river flow forecasts can now be made for the whole of the UK (geolocation 50.0°N–58.7°N, 8.2°W–1.7°E). Moreover, we show that the forecast skill extends to predicting the frequency of winter high flow events. In a wider water resources perspective, winter is the main season for recharge of groundwater and reservoir stocks, and the forecast skill for example groundwater and reservoir levels is also presented.

2. Methods

The approach taken is to first examine the relationship between various hydrological variables and their predictors in a linear regression framework, and then to use more sophisticated conceptual models to forecast winter river flows and groundwater levels from climate model winter rainfall forecasts. Winter is defined as December to February, and analyses were carried out for the 20 winter seasons 1992/93–2011/12 for which climate model hindcasts were available (Scaife *et al* 2014).

The long-range meteorological forecasts used here were produced using the Met Office Global Seasonal forecast system (GloSea5) (MacLachlan *et al* 2014). The climate model at the core of this forecast system is HadGEM3 (Scaife *et al* 2014) with atmospheric resolution of 0.83° longitude by 0.55° latitude, 85 quasi-horizontal atmospheric levels and an upper boundary at 85 km near the mesopause. The ocean resolution is 0.25° globally in both latitude and longitude with 75 quasi-horizontal levels. This resolution is necessary to reduce key biases in the ocean and atmosphere and give a realistic winter atmospheric blocking climatology in the model (Scaife *et al* 2011). A 24-member ensemble of forecasts was run for each winter in the period 1992/93–2011/12 with lagged start dates centred on 1 November (25 October, 1 and 9 November) and eight members initialized on each of the three start dates. Members from the same start date differ only by stochastic physics. Initial atmospheric and land surface data were taken from ERA interim observational reanalyses and initial conditions for the global ocean and sea ice concentration were from the FOAM data assimilation system (Storkey *et al* 2010). In addition to the explicit UK winter rainfall forecasts used as input to the hydrological model, rainfall forecasts were also derived through linear regression on the forecast NAO index calculated from the sea level atmospheric pressure fields predicted by the climate model.

The river flow regression analyses were based on data for 92 catchments in the UK (http://ceh.ac.uk/data/nrfa/index.html). Two types of data were used, both derived from daily mean river flow series: (i) winter mean flows, and (ii) number of flood events in each winter. Monthly mean river flows were calculated for each month and log-transformed to obtain a distribution more similar to a Normal distribution. These log-transformed flows were then standardized for each calendar month separately, by subtracting the mean and dividing by the standard deviation. The winter mean was then calculated and again standardized. The predictors to use for each regression model were selected using least absolute shrinkage and selection operator (Efron *et al* 2004), and the final regression equations were obtained through least squares regression. Where the selected model has only one predictor, the regression coefficient is equal to the correlation coefficient, as the input data has been standardized to have mean equal to zero and standard deviation equal to one. Correlations throughout the paper are considered to be significant if they correspond to the 5% significance level or better for a one-sided test (as it is known *a priori* how the NAO affects UK rainfall), except figure 3 which shows a range of significance levels.

Peaks in the daily mean flow series are indicative of the occurrence of instantaneous flow peaks (and thus flood potential), although they will not capture the instantaneous peak magnitude. Flood counts are defined here as the number of independent peaks above a fixed threshold in the daily mean flow series that occurred in each winter. The threshold for each catchment was set so that on average three peaks per season were retrieved. This is a commonly used number (e.g. Madsen *et al* 1997, Svensson *et al* 2005), which strikes a balance between having a large enough dataset for various statistical analyses, while ensuring peak flows are high, although they may not all necessarily go out of bank and cause a flood. The peaks were derived using an approach adapted from that for instantaneous peaks described by Bayliss and Jones (1993). Peaks were selected based on an automated cluster-above-threshold separation criterion, which replaces the two Bayliss and Jones criteria of minimum time separation between instantaneous peaks and minimum discharge in the trough between them. The time-to-peak was estimated for each catchment according to equation (2.10) of Houghton-Carr (1999), multiplied by three and rounded to the nearest whole number of days. Clusters above the threshold then had to be separated by this number of days minus two, or at least one day. The counts data are available for a reduced set of 79 stations, as independent peaks could not be derived for very slowly responding catchments.

For the reservoir level analysis, stocks (as percentage of full capacity) at the end of each month were averaged across the winter season. The monthly stocks data are available at http://ceh.ac.uk/data/nrfa/index.html.

For the hydrological modelling, hydrological initial states were constructed using the distributed 1 km resolution Grid-to-Grid model (Bell *et al* 2009). This provides a high resolution estimate of subsurface water in storage in the unsaturated zone across Great Britain, derived using the most recent observations of daily gridded rainfall and monthly potential evaporation (PE). This is used as the initial condition for a 1 km resolution monthly water-balance model (WBM) forecast of the next three-month subsurface storage and runoff using UK Met Office rainfall ensemble forecasts and climatological PE as input (Bell *et al* 2013). A 24-member ensemble of UK-mean three-monthly resolution winter rainfall forecasts is applied as spatially uniform rainfall anomalies scaled with respect to monthly mean spatially distributed historical rainfall. This ensures a reasonably realistic spatial distribution of rainfall across Great Britain, and rainfall forecasts scaled in this way will have a (monthly) climatological rainfall distribution. Corresponding ensembles of river flow estimates are produced by averaging the monthly WBM runoff forecasts (scaled by the long-term mean at each location) upstream of every 1 km river pixel.

The groundwater level forecasts were produced using AquiMod, a parsimonious lumped conceptual groundwater model that uses monthly rainfall and potential evapotranspiration time series to simulate monthly groundwater levels at individual observation boreholes (Mackay *et al* 2014). It consists of three separate modules: (i) a soil moisture balance model to produce time series of soil drainage; (ii) a Weibull transfer function to attenuate soil drainage to the water table as recharge; and (iii) a layered Darcian groundwater flow model that simulates groundwater discharge and storage. Each module has a number of parameters (16 in total) that can be fixed or calibrated. For this study, 8 of the 16 parameters were calibrated to available monthly groundwater level time series data outside of the forecasting time frame using a Monte-Carlo optimization procedure. Each borehole model achieved an acceptable Nash–Sutcliffe efficiency (Nash and Sutcliffe 1970) of >0.6 and was able to match the non-seasonal component of the hydrograph with a $R^2 > 0.5$ when driven by observed rainfall.

3. Results

Figures 1(a) and (b) show the observed impact of the NAO on UK winter (December–February) rainfall. As expected, positive NAO, with associated increased westerly flow and increased delivery of rainbearing cyclonic weather systems into northern Europe, produces increased rainfall over large areas of Northern Ireland, western England, Wales and Scotland. UK winter rainfall is well correlated with the NAO (figure 1(b)) and differences between positive and negative phases of the NAO exceed 100 mm per winter in many places (figure 1(a)). The differences reach over 300 mm per winter over steep orography, where they are comparable to year to year differences in mean winter rainfall.

This topographic modulation of the influence of the NAO on rainfall is similar across timescales and across other regions of northern Europe where the NAO is a key driver of winter rainfall variability from both year to year and decade to decade (Hurrel 1995), including the frequency of heavy rainfall over timescales of a few days relevant to river catchments (Scaife *et al* 2008). Note however, that the influence of the NAO is weak in southern and eastern England where catchments are in the 'rain shadow' from westerly winds.

Although seasonal rainfall is fairly evenly distributed across the year, evapotranspiration decreases as temperatures fall, and soil wetness and groundwater stores generally replenish as autumn and winter progress. Catchments in general therefore become particularly susceptible to flood events in winter (Bayliss and Jones 1993). For permeable catchments, the flow hydrograph tends to become dominated by a pronounced seasonal peak, as the recharged groundwater stores slowly release their water into the rivers. High river flows in such catchments can be long-lasting (months). Equally, if soil and groundwater stores are depleted it can take several weeks for river flows to recover. This persistence of either high or low flows provides a baseline source of prediction skill for seasonal flow forecasting purposes and is quantified below in forecasts initialized with observed flows.

Figures 2(a) and (b) show the predictors for linear regression models of the mean winter river flows in 92 UK catchments. The models were based on either or both of the observed mean river flow in the preceding November, and a seasonal prediction of the NAO by the UK Met Office Global Seasonal forecast system (GloSea5) (MacLachlan *et al* 2014). GloSea5 produced skilful seasonal predictions for the winter NAO with a correlation score of 0.62 when correlating the mean of the ensemble prediction with the observed NAO index (Scaife *et al* 2014).

Consistent with the influence of the NAO in figures 1(a) and (b), figure 2(a) shows that river flow predictions in the north and west rely on the predicted NAO, whereas flow predictions in the south and east rely on the preceding month's river flow (figure 2(b)). The striking geographical complementarity of the two predictors reveals two distinct regions of the UK, roughly corresponding to upland and lowland Britain, allowing skilful winter river flow predictions throughout the UK.

A similar result can be achieved using hydrological rainfall-runoff models. Figure 3 shows correlations between observed and forecast mean winter river

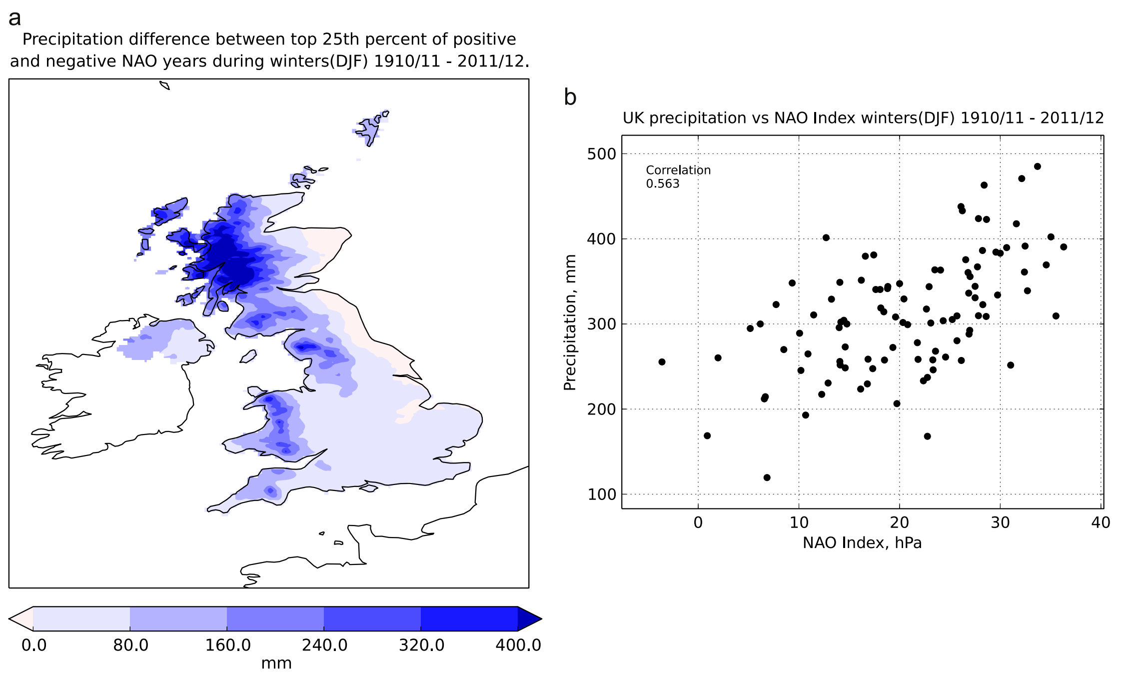

Figure 1. Influence of the NAO on seasonal UK winter rainfall as shown by (a) the difference in precipitation (mm) between the top 25% of positive and negative NAO winters, 1910-2011, across the UK, and (b) the UK-mean winter precipitation versus winter NAO.

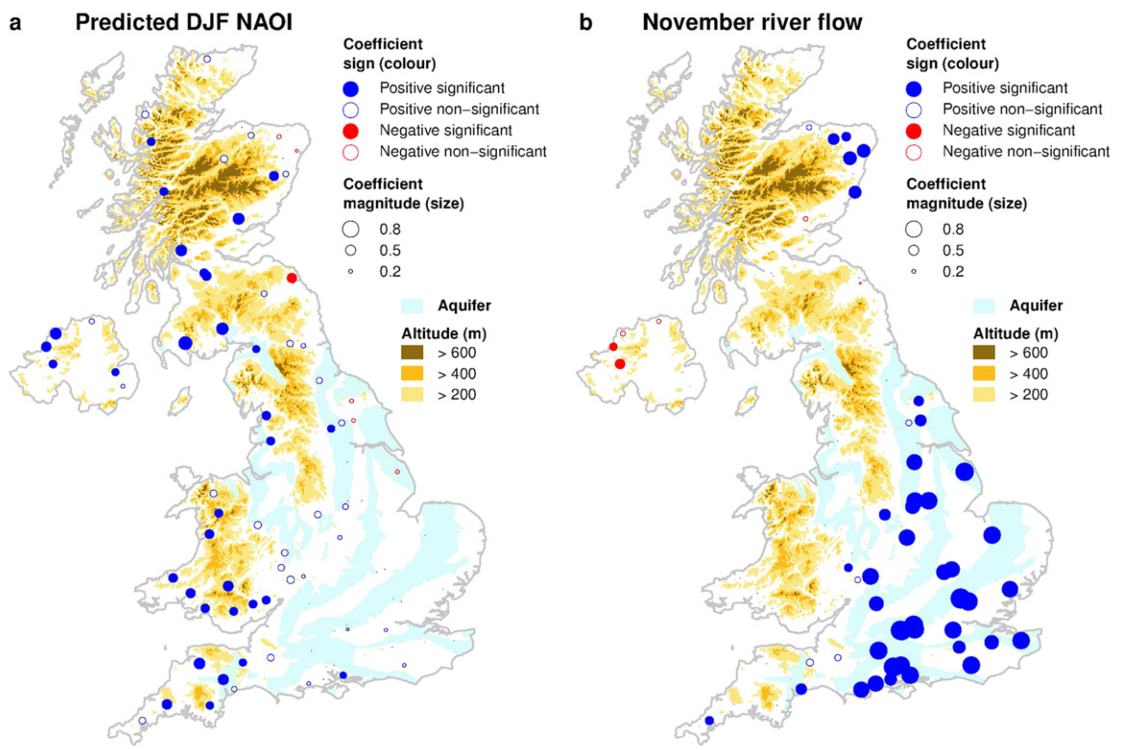

Figure 2. Sources of predictability of winter river flows as reflected by the coefficients for a regression model of winter river flow on either or both of two predictors: long-range forecasts of atmospheric circulation over the North Atlantic as characterized by the NAO index (a), and observed monthly mean river flow for November (b). The aquifer outcrop areas (light blue shading) show where groundwater makes an important contribution to river flows.

flows, averaged across regions of Great Britain. For figure 3(a) the forecast river flows are derived by persisting the flow anomaly from the end of the previous month, as modelled by the Grid-to-Grid hydrological model (Bell *et al* 2009, 2013). It can be seen that this performs well across the southeast. For figures 3(b)–(d), a simple grid-based WBM has been used, initialized using subsurface storage information from the Grid-to-Grid hydrological model and long-range seasonal rainfall predictions from the Met Office GloSea5

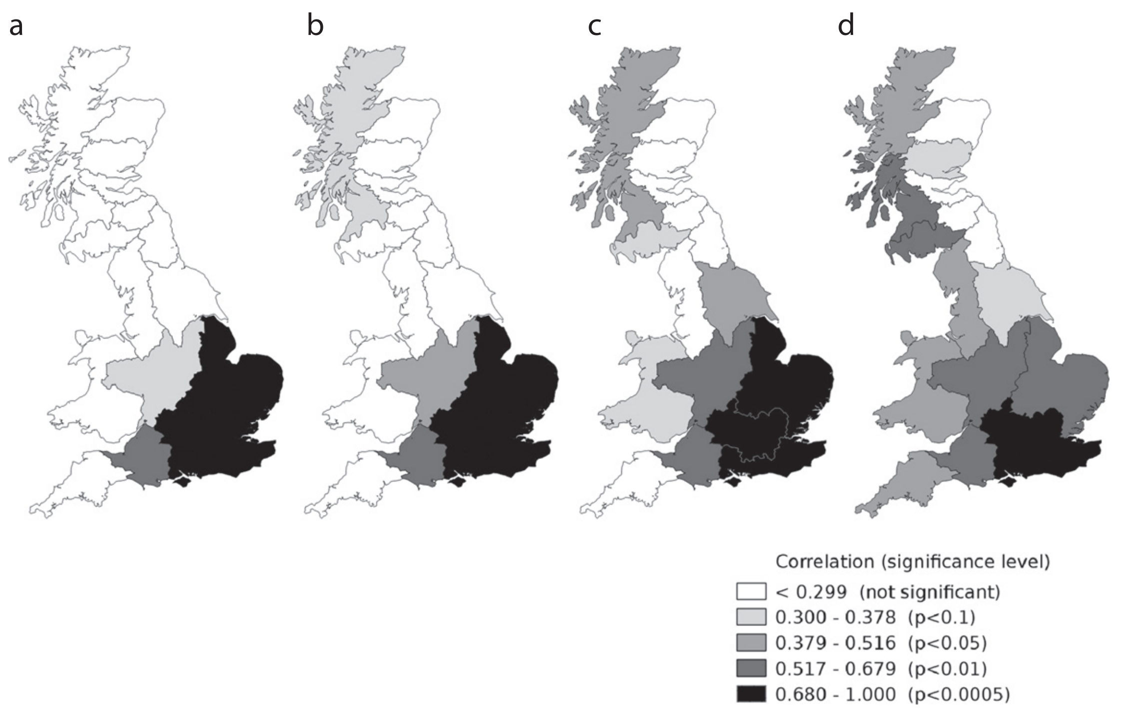

Figure 3. Correlations between predictions and observations of winter river flows, averaged across regions. Predictions are based on (a) persistence of previous month's flow, (b) climatological rainfall, (c) the mean of a 24-member ensemble of rainfall predictions from GloSea5 and (d) a rainfall prediction derived from the mean of a 24-member ensemble of NAO index predictions from GloSea5.

system. The result of different strategies for seasonal rainfall input are shown: (b) the seasonal mean rainfall (climatology), (c) the mean of a 24-member ensemble of rainfall predictions from GloSea5, (d) using rainfall estimated through regression onto the predicted NAO. Compared with simply persisting the river flows, forecasts for the northwest are improved when using the WBM, even when the rainfall input is climatology. This is because the model uses subsurface water storage to initialize the river flow predictions. However, the most skilful UK-wide forecasts result when the predicted atmospheric circulation anomaly from the NAO is used as a proxy for forecast rainfall. The median correlation for the UK is 0.45, which is significant at the 5% level. The reason why the NAO is a better predictor of UK rainfall than the rainfall from GloSea5 is at least partly due to the fact that although UK rainfall is strongly related to the NAO, it depends also on other factors which are less predictable by the climate model. Further discussion regarding the size of the predictable signal relative to unpredictable chaos is provided by Scaife *et al* (2014). See also Eade *et al* (2014).

For groundwater, the new NAO-based rainfall forecasts improve groundwater forecast skill marginally in the northwest, compared with using the standard rainfall forecasts. However, the bulk of aquifers are located in the southeast where the NAO is less influential and control (as elsewhere) is exerted mainly by persistence.

The complex management of reservoir systems means that climatic influences are less pronounced than for more natural systems like rivers. Nevertheless, direct forecasts of reservoir levels are possible within the main area of NAO-influence. For example, for the Loch Katrine group of reservoirs in west Scotland, which supplies water for Glasgow, the correlation with the predicted winter NAO index amounts to 0.47. For the observed NAO this rises to 0.66 (both figures are significant at the 5% level). However, for most reservoirs a combination of forecasts of river inflow and water demand need to be used.

For river flows, the methodology can be extended from prediction of winter average conditions to the more specific prediction of numbers of winter flood events. In the northwest, severe floods can occur in a matter of hours because of the combination of steep slopes, thin soils and largely impermeable geology on the one hand, and orographic enhancement of frontal rainfall in the predominantly westerly air flow on the other. Across much of the southeast, flood peaks tend to occur superposed on already seasonally high winter river flows, the latter being largely driven by the seasonally high groundwater contribution to flows. Figure 4(a) shows correlations between the predicted and observed winter flood peak counts for river flow stations across the UK. Skilful forecasts of the number of winter flood events are possible using the seasonal forecast NAO (mainly affecting the northwest) and initial flow conditions (mainly affecting the southeast). The correlations are significant for 43 stations,

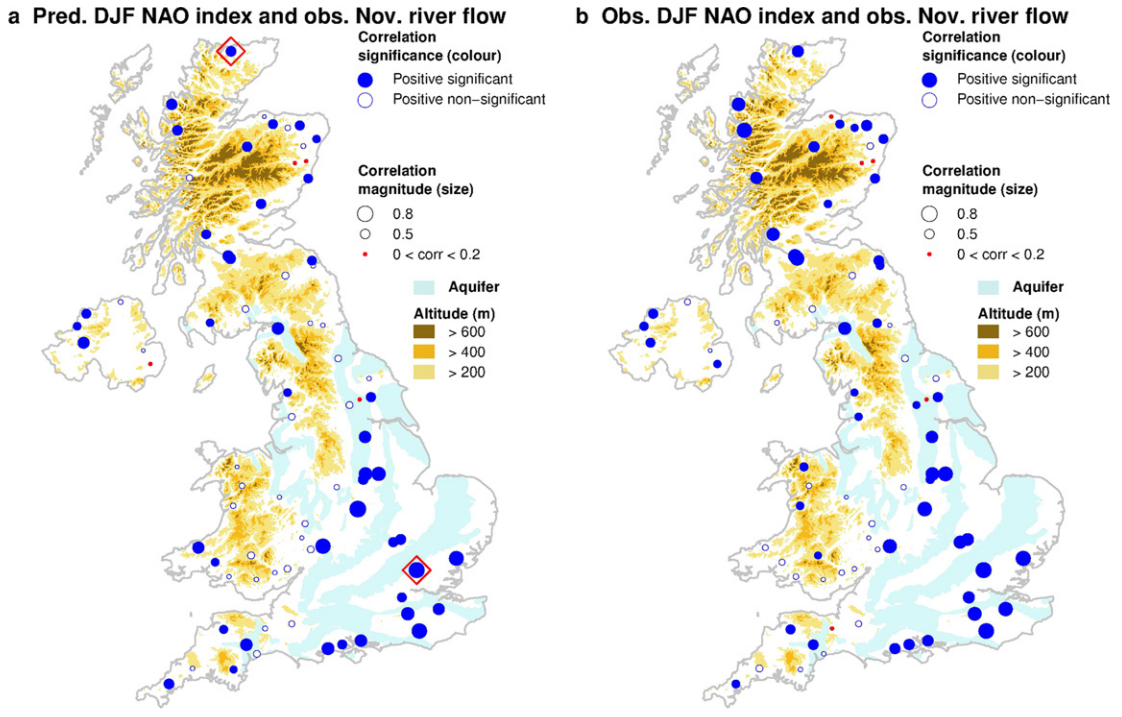

Figure 4. Catchment scale correlation scores between predicted and observed counts of winter flood events. Predictions are from regression models of flood counts on either or both of the preceding November's mean river flow and the December–February NAO index (NAO index predicted by the climate model (a), and observed NAO index (b)).

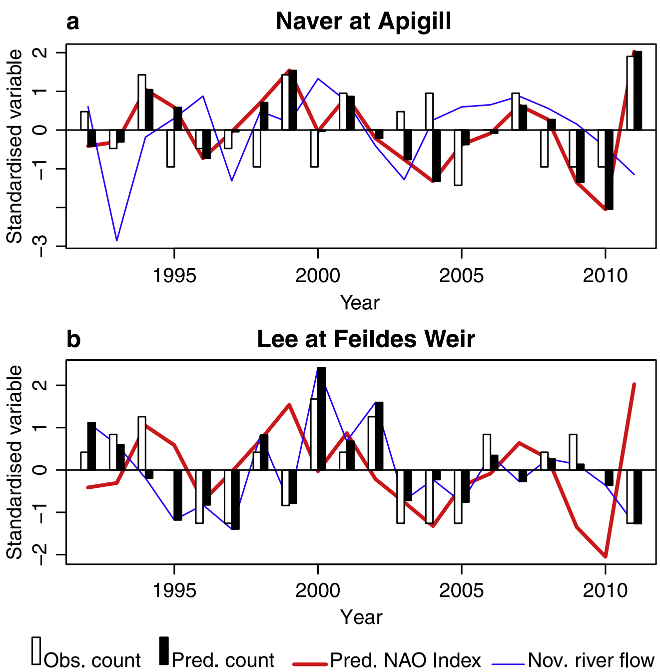

Figure 5. Time series of the predictors for the model in figure 4(a), and predicted and observed number of river flow peaks at the Naver at Apigill in the north (a), and at the Lee at Feildes Weir in the southeast (b). The locations of the two river flow stations are shown by red diamond markers in figure 4(a).

and of the 36 non-significant correlations four have a magnitude <0.2. In figure 4(b) the NAO prediction has been replaced by the observed NAO, and this shows the potential upper limit of skill if the NAO forecasts were perfect. The best correlation in the northwest increases from 0.61 for the predicted NAO to 0.76 for the observed NAO. The number of stations with significant correlations rises to 50, with five of the 29 non-significant correlations amounting to <0.2.

Figures 5(a) and (b) show time series of predicted and observed number of flow peaks for the river Naver at Apigill in the north and for the river Lee at Feildes

Weir in the southeast (see location markers in figure 4(a)). It can be seen how the predicted and observed counts of flow peaks follow the NAO at the Naver, and how they follow the preceding November's river flow at the Lee. The forecasts for the Naver are poorer than those for the Lee. The discussion around figure 3 suggests that knowledge of the antecedent sub-surface water storage improves the winter mean flow forecast in the northwest, and had it been available as a predictor for the linear model it may have improved the flood count forecasts as well.

4. Discussion and conclusion

The results presented here show how geographical complementarity between skilful winter rainfall forecasts for the north and west, and strong persistence of initial hydrological conditions in the south and east, lead to skilful winter river flow forecasts across the whole of the UK. This geographical complementarity is to some degree inevitable due to the permeable geology of lowland Britain, the impermeable geology of the mountainous northern and western regions, and the country's location in the mid-latitude belt of predominantly westerly airflow. There are of course limitations to these results. The NAO is not the only control on rainfall in the UK. Moreover, its influence is weak in the southeast where catchments are sheltered from the westerlies, and successful forecasts rely on flow persistence. At a smaller scale persistence forecasts may be less skilful because of geological heterogeneity (e.g. Laizé and Hannah 2010, Chiverton *et al* 2015). Even within aquifer outcrop areas there will be variation, as local catchment characteristics such as higher degrees of aquifer fracturing, impermeable superficial deposits or urbanization may increase responsiveness.

Skilful seasonal predictions of UK river flows are now a viable proposition and have recently become available for the UK on a year-round, national scale (http://hydoutuk.net/). These consist of predictions based on flow persistence, historical flow analogues and hydrological modelling. For one and three month forecast horizons, seasonal rainfall forecasts (MacLachlan *et al* 2014) are used as input to a state of the art hydrological modelling system (Bell *et al* 2009, 2013). Longer outlooks are also made up to 12 months ahead using a range of hydrological models with a climatology ensemble of historical rainfall scenarios as input. When in a drought, using such an ensemble of climatology as input attempts to answer the question 'How long will it take until hydrological conditions are likely to be back in the normal range again?'.

Given its dependence on the seasonal forecast skill of the NAO, hydrological outlooks will likely become more skilful as the prediction skill of the NAO is improved, as has already been done on timescales of a few days using improved weather forecasts. This could in principle already be achieved through increased forecast ensemble size to better capture the forecast NAO signal (Eade *et al* 2014, Scaife *et al* 2014) assuming the availability of increased computing resources. With winter rainfall projected to increase in future, increasing the risk of extreme events such as those of winter 2013/14 (Huntingford *et al* 2014, Lewis *et al* 2015), the skill demonstrated here for early warning of flood risk will likely be important also for adaption to climate change. Finally, as the NAO affects climate across large parts of western Europe, skilful winter river flow forecasts may also be possible for this wider area.

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