Climate Variability and Change—Hydrological Impacts (Proceedings of the Fifth FRIEND World Conference held at Havana, Cuba, November 2006), IAHS Publ. 308, 2006.

Associations between Western European air-masses and river flow regimes

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Abstract This paper identifies and models statistical associations between monthly air-mass frequencies and annual flow regime shape (seasonality) and magnitude for Western Europe, using 141 river and 48 climate stations (1974–1990). The month of regime peak, or month before the peak, is associated with increased (decreased) frequencies of moister (drier) air-masses. Low (high) magnitude regimes are associated with increased (decreased) frequencies of drier air-masses and decreased (increased) frequencies of moister air-masses. An *a priori*, weighted regional model yields the greatest predictive ability for regime shape; either an *a priori*, weighted global or regional model produces "best" predictions for regime magnitude. Overall model skill is lower for regime magnitude than shape, with model accuracy varying regionally. The development of methods and process knowledge, as herein, is vital to assessing climate–river flow sensitivity and predicting water resource variability in a changing climate.

Key words classification; discriminant function analysis; regionalization; statistical prediction; river flow; regimes; climate; air-masses; hydroclimatology; Western Europe

INTRODUCTION

River flow regimes characterize runoff dynamics over the annual cycle, which are driven by climate and moderated by basin factors (Bower *et al.*, 2004). Commonly, flow regimes are constructed based upon mean monthly flows and regarded as static. Previous studies in Europe have regionalized flows to identify spatial structure and/or estimate flows at ungauged sites (e.g. Krasovskaia *et al.*, 1994). This research concentrates on the timing of flows (regime shape) rather than regime magnitude.

Given heightened concerns about climate change/variability and human impacts upon hydrology, there is a pressing need for research to quantify temporal (inter-annual) variability in flow regimes and to establish hydroclimatological (climate–flow) associations as a basis for predicting future water resources. The few studies of year-to-year fluctuations in European flow regimes focus upon magnitude attributes (e.g. Arnell, 1994); this approach contrasts with regionalization work that emphasizes flow seasonality. Hence, there is a gap for research that investigates consistently spatial and inter-annual variability in both flow regime shape and magnitude at the European-scale.

Many climate diagnostics employed to explore atmosphere–land surface links are of limited utility for locations peripheral to the study region centre. The synoptic climatological approach, which relates large-scale air-mass climatology to the surface environment, provides a means to identify and understand climate–flow associations at the continental-scale. However, most air-mass classifications yield daily sequences of atmospheric circulation types on a station-by-station basis, which does not permit easy comparison of climatologies between locations. The Spatial Synoptic Classification (SSC) and its extension (SSC2) have been developed to overcome this problem (Sheridan, 2002). To date, the SSC2 has been applied only to North America; extension of the SSC2 to Europe offers the prospect of more robust spatio-temporal analysis of large-scale climate, and air-mass influence upon flow regimes across this region.

This paper addresses the above research gaps as it aims: (a) to explore associations between air-mass frequencies (derived using a modified SSC2) and annual flow regime shape (form, seasonality) and magnitude (size) classes at the Western European-scale; (b) to identify the flow regimes and regions exhibiting greatest/least flow sensitivity to air-mass climatology; and (c) to evaluate the utility of statistical models to predict annual flow regimes based upon air-mass frequencies.

DATA

River flow

Hydrological research at the continental-scale relies upon international data archives, such as the FRIEND European Water Archive (EWA). Long-term (1974–1991) daily flow data were obtained for 141 river gauges: (a) 137 from the FRIEND-EWA, and (b) four from the Global Runoff Data Centre (http://grdc.bafg.de/). This timeframe was chosen as many FRIEND-EWA time-series end in 1992 and European synoptic climate records (below) begin in 1974. Stations were selected that gauge similar basin areas (100–500 km^2) and provide coverage across Western Europe. Only basins with flows approximating natural conditions are included within the FRIEND-EWA. Monthly averages of daily flows (mm month^{-1}) were calculated and time-series were divided into hydrological years (commencing in October) to characterise annual regimes.

Climate

Synoptic climate data (1974–2000) were provided by the UK Meteorological Office for 48 Western European stations. At each station, six-hourly observations (0300, 0900, 1500 and 2100 hours GMT) were recorded for air temperature, dew point temperature, mean sea level pressure (MSLP), wind direction, wind speed and cloud cover.

METHODS

The analytical procedure is divided into five linked tasks: (a) regionalization of long-term average flow regimes; (b) classification of annual flow regimes for each station-year; (c) classification of daily air-masses at each station; (d) exploration of associations between monthly air-mass frequencies and annual flow regimes; and (e) statistical prediction of annual flow regimes based upon air-mass frequencies, as detailed below.

River flow regime classification

Since it is important to assess the timing and size of flows over the entire water year, multivariate statistical techniques were employed to separately classify regime shape and magnitude (Bower *et al.*, 2004). The shape classification identifies stations or station-years with similar regime form, regardless of magnitude (i.e. dimensionless, z-scored regimes). The magnitude classification is based upon four indices (i.e. mean, minimum, maximum and standard deviation) derived from long-term mean monthly values or monthly mean values for each station or station-year, regardless of timing.

The flow classification is applied in two modes: (a) to identify regions based upon long-term average regimes at a station; and (b) to assess year-to-year variability in annual regimes using 12-monthly observations for each station-year. It is important to note that: (a) regimes are not interchangeable between long-term and station-year classifications, as analyses are performed upon different data matrices; and (b) magnitude classes for regionalization identify absolute differences between stations, whereas inter-annual magnitude classes identify relative variations at a station.

Air-mass classification

A new weather typing scheme for Western Europe based upon the Spatial Synoptic Classification-2 (SSC2-WE) was developed that classifies daily air-masses into one of six categories based upon nine variables derived from six-hourly synoptic climate observations. SSC2-WE is a modified version of Sheridan's (2002) method. Bower *et al.* (2006) detail analytical procedures for SSC2-WE and evaluate its application.

SSC2-WE identifies temporal air-mass variability on a station-by-station basis but, because the six daily categories are common to all locations, it permits ready spatial comparison of atmospheric conditions. The classes are: (a) Dry Polar (DP): cool or cold, dry and little cloud; (b) Dry Moderate (DM): mild and dry; (c) Dry Tropical (DT): hot, dry and little cloud; (d) Moist Polar (MP): cold, humid and cloudy; (e) Moist Moderate (MM): warm, humid and cloudy; and (f) Warm Tropical (MT): warm, very humid and cloudy in winter or partially cloudy in summer. A transitional category (TR) is identified for days with changes in MSLP, dew point depression and maximum wind shift that indicate a major switch in air-mass climatology.

Air-mass – river flow regime associations

Associations between monthly air-mass frequencies and annual flow regimes are investigated by matching river gauges with the nearest climate station. Data are pooled by long-term flow regime regions; this is valid as SSC2-WE yields the same air-mass types for each location. Flow regimes associated with anomalous air-mass occurrence (i.e. monthly air-mass frequencies above (+) and below (-) 2.5 times the median for shape and 1.5 times the median for magnitude) are identified to highlight the most climatically sensitive links for months and regions.

Prediction of flow regimes using air-mass frequencies

Multiple discriminant function analysis (MDFA; Klecka, 1980) provides a statistical model of the associations between monthly air-mass frequencies and annual flow regime classes. Air-masses are input as the discriminating variables, with MDFA scores predicting the most probable flow regime. Four MDFA models are developed: (a) global (all 141 river gauges), equal probability (GE), (b) regional, equal probability (RE), (c) global, *a priori* weighted (GW), and (d) regional, *a priori* weighted (RW). Weights are applied based upon frequencies of flow regime classes over the calibration period for the even years (1974, 1976, ...). The "best" models are selected to predict flow regimes from air-mass frequencies for the odd years (1975, 1977, ...). Models are evaluated based upon % correct predictions.

RESULTS AND DISCUSSION

River flow regions and annual regimes

It is beyond this paper's scope to detail results of flow regionalization or spatio-temporal flow regime/air-mass dynamics. Regionalization is used to structure the analyses. Six regime shape regions were identified: (A) January peak with secondary March peak, 17 stations in the western UK; (B) December–March peak, 39 stations across the eastern UK, Denmark and northeast continental Europe; (C) December–April peak, 42 station in the south–east UK and a belt from northern/central France, Germany to Poland; (D) April peak, 16 stations in a more southerly belt than C from Spain to Belarus; (E) April–May peak, 7 stations in southern Norway, Finland, Slovakia and Austria; and (F) May–June peak, 20 stations in Austria and Norway. The regions identify a maritime-continental gradient in the timing of the flow regime peaks (lagged from the Atlantic rim); and summer regime peaks in Region F indicate snow and glacier melt contributions. Five magnitude regime regions were apparent: (1) low mean and seasonality, 77 stations across a wide latitudinal range; (2) low-intermediate mean and seasonality, 33 stations mainly in the western UK, Austria and Switzerland; (3) intermediate mean and high seasonality, 10 stations in Norway, Sweden and Finland; (4) moderately high mean and intermediate seasonality, 16 stations in the western UK, the Alps, southern Norway and northern Spain; and (5) high mean and seasonality, five stations in Austria, Norway and Scotland. These regions map broadly onto patterns of annual average rainfall, although magnitude seasonality is moderated by winter precipitation storage as snow/ ice and summer meltwater release.

Annual classes are used to identify and predict links between flow regimes and monthly air-mass frequencies. Six annual shape regimes were found: (A) November–January peak = 504 station-years; (B) January peak = 321 station-years; (C) February peak = 421 station-years; (D) March peak = 279 station-years; (E) April peak = 463 station-years; and (F) May–June peak = 409 station-years. Five annual magnitude regimes were found: (1) low mean and seasonality = 677 station-years; (2) low-intermediate = 650 station-years; (3) intermediate mean with high seasonality = 414 station-years; (4) intermediate = 457 station years; and (5) high = 199 station-years.

Air-mass – river flow regime associations

In this short paper, it is only possible to outline key generic and region-specific associations. For regime shape (Fig. 1), the main generic finding is increased frequencies of moister air-masses (i.e.

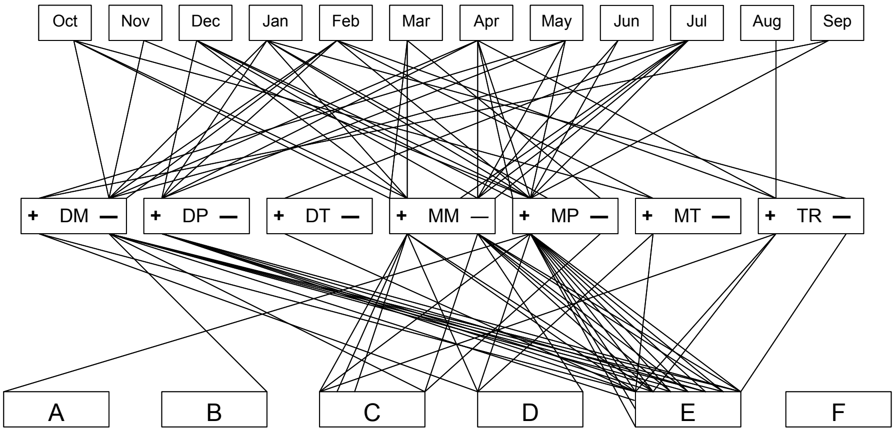

Fig. 1 River flow shape regimes associated with increased or decreased (2.5 ≤ median ≥ 2.5) monthly air-mass frequencies in Region A.

MM, MP and MT) and decreased occurrence of drier air-masses (i.e. DM, DP and DT) during the month of regime peak (month *T*), or the month before peak (month *T* – 1). This suggests advection of moist air causes regimes to peak in the same month, or the following month due to a lag between climatic drivers and runoff response as moderated by basin conditions. Increases (decreases) in drier (moister) air-masses are found to delay timing of regime peaks (i.e. no peak in month *T* or *T* + 1) due to less moisture advection. A second generic finding is that some regimes occur typically in the absence of anomalous air-mass frequencies (i.e. climatological average). Regimes associated with average air-mass occurrence differ between regions, reflecting the climatic situation and secondarily basin characteristics. Notable region-specific associations include: (a) Region A: April peak regimes with an increase in polar air-masses in several months, suggesting increased snow storage and spring melt, (b) Region C: January peak regimes with a decrease in MM in month *T* + 1, which influences recession onset rather than the peak; (c) Region C: April peak regimes with an increase of polar in month *T* – 1 and then hot (DT) in month *T* air-masses, indicating probable snow storage and melt; (d) Region E: April peak regime with increase in DP in January, which may deliver snow for spring melt; and (e) Region E: May–June peak with decrease in MM in month *T* – 1, possibly delaying spring melt onset.

For regime magnitude (Fig. 2), the main generic association is low (high) magnitude regimes with increased (decreased) frequencies of drier air-masses and decreased (increased) frequencies of moister air-masses. Intermediate regimes show least association with anomalous air-mass occurrence, implying these flows occur under average climatologies. There are few region-specific associations that depart from these generic links. However, in Regions 2 to 5, high magnitude regimes are associated with a summer increase (decrease) in dry (moist) air-masses, implying meltwater release.

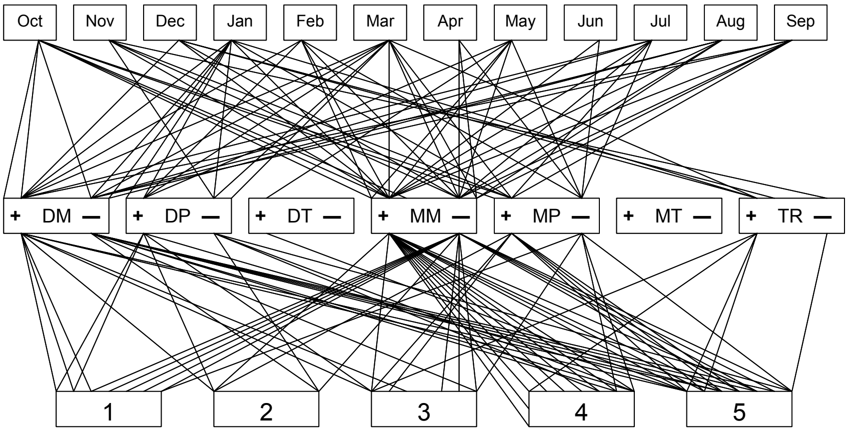

Fig. 2 River flow magnitude regimes associated with increased or decreased (1.5 ≤ median ≥ 1.5) monthly air-mass frequencies in Region 5.

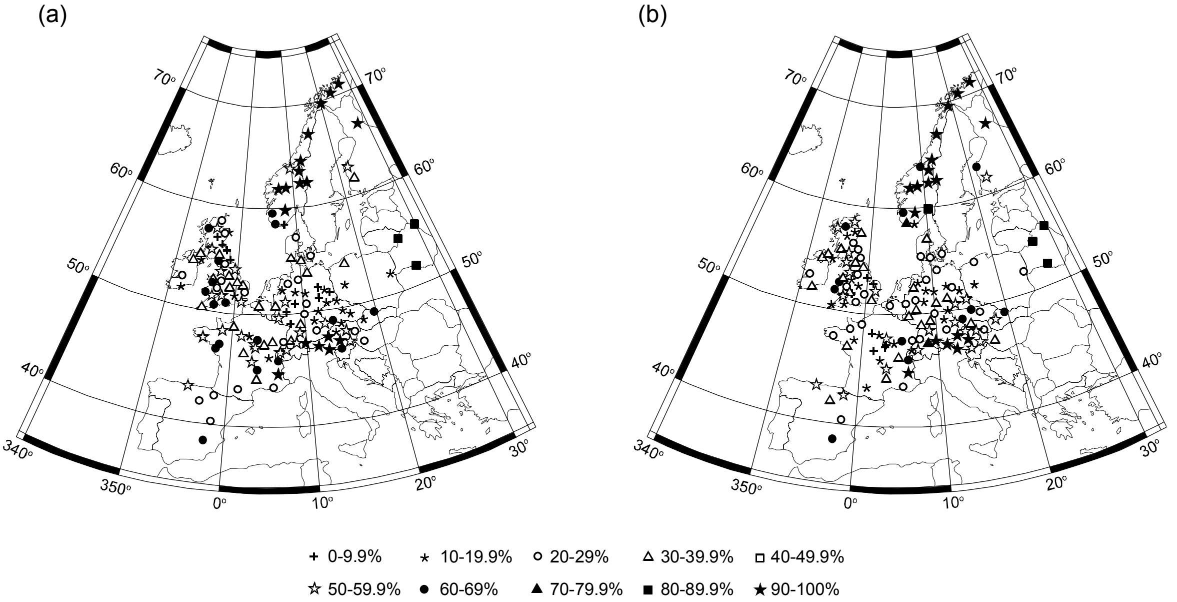

Fig. 3 Spatial pattern in predictive accuracy (% correct) of annual flow regime shape based upon monthly air-mass frequencies: (a) October and (b) April.

Prediction of flow regimes using air-mass frequencies

For regime shape, the *a priori*, weighted regional model yields greatest predictive ability overall; but model accuracy varies regionally (Fig. 3). The most skilful models by far are achieved for Region F (88–96% correct). Regions A, D and E attain similar accuracy levels to one another (27–55% correct). Regions B and C give the least accurate models (14–34% correct). Thus, models show highest predictability for regions characterised by a clear peak in: (a) spring or summer (i.e. snow- and glacier-fed rivers, with limited year-to-year regime variability) and (b) winter (i.e. concurrent rainfall–runoff response). The least predictable regions have broad regime peaks (i.e. December to March (B) or April (C)) and include basins with major aquifers (e.g. the southeast UK), which may weaken direct climate-flow links due to groundwater buffering.

For flow magnitude, either the *a priori*, weighted global or regional model produces the "best" predictions. The global model performs better for the prediction of flow regime magnitude than for

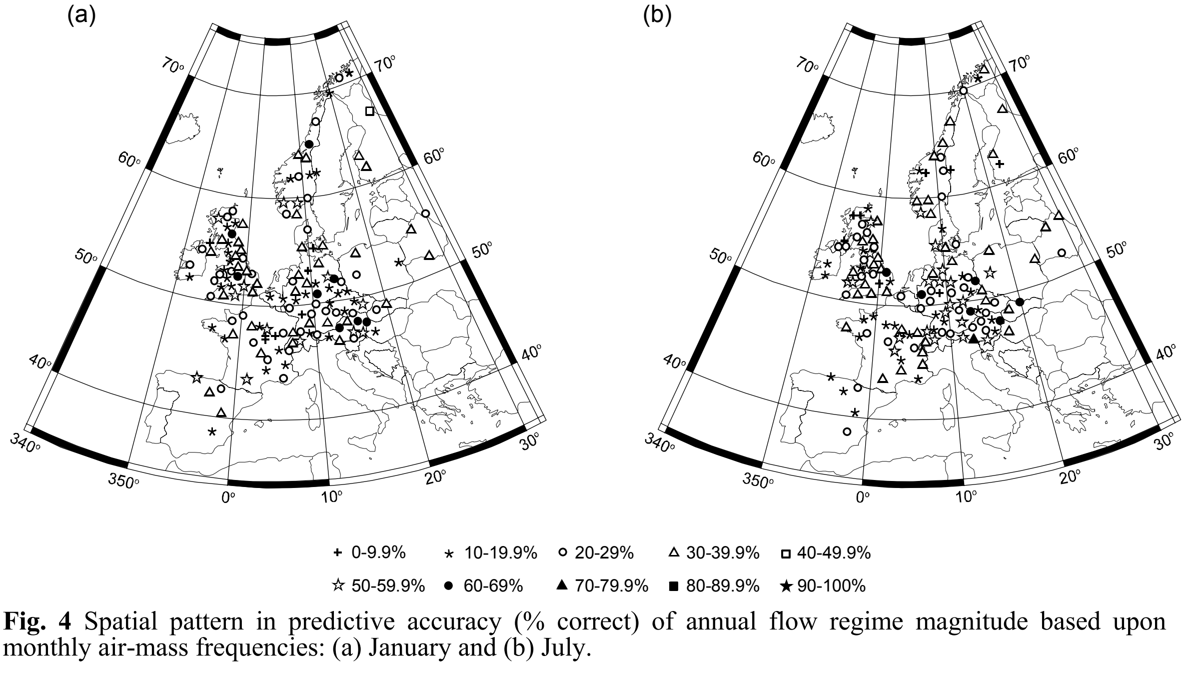

Fig. 4 Spatial pattern in predictive accuracy (% correct) of annual flow regime magnitude based upon monthly air-mass frequencies: (a) January and (b) July.

shape, possibly because annual magnitude classes are relative (not absolute) at a station and/or pooling of data for 141 stations improves regime sampling and statistical robustness. Predictive ability is relatively low across all regions (15–45% correct; Fig. 4); and overall skill is lower than for regime shape. However, some months show greater predictability of specific regimes, with these key months and regimes varying regionally. For example, the following models predict >60% correct: (a) Region 1: November/August = regime 1; (b) Region 3: January–March/May/June/August = 2; (c) Region 4: March = 2; and (d) Region 5: November = 1 and January/February/March = 2. Generally, models are better at predicting lower (i.e. regimes 1 and 2) than higher magnitude regimes, possibly because high magnitude regimes are less frequent and/or due to the complexity of high flow generating mechanisms (e.g. frontal, convective or orographic precipitation, plus snow or glacier melt). Model predictions are high for individual stations (up to 88%), with 12 basins yielding >75% accuracy. These findings indicate further detailed analysis is required of air-mass—flow predictions at a regime-by-regime and station-by-station level for both magnitude and shape regimes.

CONCLUSION

This paper advances methods of wider applicability in the assessment of large-scale hydroclimatological interactions and it provides an insight into climatic drivers of flow regimes at the Western European-scale. The development of such techniques and process knowledge is vital to assessing climate-river flow sensitivity and predicting water resource variability in a changing climate.

Acknowledgements D. Bower was funded by a NERC studentship GTNER/S/A/ 2000/03936 based at the University of Birmingham. G. Rees and I. Akram at the Centre for Ecology and Hydrology, UK, extracted data from the FRIEND-EWA. We are grateful to S. C. Sheridan for collaboration in developing the SSC2-WE.

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