Proceedings of FRIEND-Water 2014, Montpellier, France, October 2014 (IAHS Publ. 363, 2014).

Connecting streamflow and atmospheric conditions in Europe: state-of-the-art review and future directions

DAVID M. HANNAH[1], ANNE K. FLEIG[2], DANIEL G. KINGSTON[3], JAMES H. STAGGE[4] & DONNA WILSON[2]

1 School of Geography, Earth & Environmental Sciences, University of Birmingham, UK
d.m.hannah@bham.ac.uk
2 Hydrological Modelling Section, Norwegian Water Resources & Energy Directorate (NVE), Oslo, Norway
3 Department of Geography, University of Otago, New Zealand
4 Department of Geosciences, University of Oslo, Norway

Abstract Given the issues of climate change and global water-food-energy security, there is an urgent need to improve understanding of climate–streamflow connections at regional scales and beyond. We synthesise pan-European studies: (1) to evaluate current methods for assessing space–time dynamics for different streamflow metrics (annual regimes, low flows and high flows) and for linking flow variability to atmospheric drivers (circulation indices, air-masses, gridded climate fields and vapour flux); and (2) to propose a plan for future research connecting streamflow and the atmospheric conditions in Europe and elsewhere. We highlight the need to consider appropriate atmospheric descriptors (dependent on the target flow metric and region of interest) and to develop analytical techniques that best characterise connections in the ocean–atmosphere–land surface process chain. We call for the need to consider not only atmospheric interactions, but also the role of the river basin-scale terrestrial hydrological processes in modifying the climate signal response of flows.

Key words hydroclimatology; climate; river discharge; regimes; flood; drought; vapour flux; teleconnections

CONTEXT AND AIMS

The United Nations has identified better knowledge of large-scale water cycle processes as essential for socio-economic development and global water-food-energy security (WWAP, 2009). In this context, and given the ever-growing concerns about climate change/variability and human impacts on hydrology, there is an urgent research need: (a) to quantify space–time variability in regional streamflow, and (b) to improve hydroclimatological understanding of climate–flow connections as a basis for identifying current and future water-related issues (Hannah *et al.*, 2011).

This paper draws together findings from studies undertaken at the pan-European scale and aims: (1) to evaluate the current suite of methods used to assess space–time dynamics for different streamflow metrics (annual regimes, low flows and high flows) and for linking flow variability to atmospheric drivers (circulation indices, air-masses, gridded climate fields and vapour flux); and (2) to propose a plan for future research connecting streamflow and atmospheric conditions in Europe and elsewhere. This paper makes a unique contribution to the literature through a systematic inter-comparison of different streamflow metrics and atmospheric descriptors.

ANNUAL STREAMFLOW REGIMES

Streamflow “regimes” describe seasonal behaviour over the annual cycle (hydrological year). Studies of links to atmospheric conditions often include a preliminary stage of streamflow regionalisation (to identify homogeneous regions) and use flow descriptors (estimated for the whole regime or seasons) to characterise space–time patterns. Climate predictors are typically: (a) large-scale circulation indices or climate system diagnostics (e.g. North Atlantic Oscillation, NAO), (b) atmospheric pressure fields, (c) categorical circulation types/air-mass classifications (e.g. Grosswetterlagen), and (d) station-based climate observations (usually temperature and precipitation). The main analytical methods are concurrent/lagged correlation (e.g. Dettinger & Diaz, 2000) with fewer studies using composites (e.g. Kingston *et al.*, 2006), sensitivity analysis (e.g. Bouwer *et al.*, 2008), spectral analysis/wavelets (e.g. Massei *et al.*, 2010), or novel techniques to link categorical data (e.g. Hannah *et al.*, 2006).

Several studies have shown seasonal variability in atmospheric circulation to be reflected in European streamflows, with the strongest relationships occurring during winter. For example, Bouwer *et al.* (2008) identified higher annual streamflow correlations for frequency of westerly circulation types than pressure differences described by the NAO index (NAOI; Fig. 1). Similarly, Kingston *et al.* (2006) found high monthly streamflows across northern Europe to be associated with a stronger and more northeasterly Icelandic Low and/ or Azores High, and low monthly streamflow to be associated with weak meridonal winds (Fig. 2). Outside the winter half-year, Kingston *et al.* (2009) revealed an inverse climate–flow relationship between northern and southern Scandinavia, explained by differences in the relative contribution of meltwater to streamflow, latitudinal separation and orographic precipitation effects. Analyses of the full annual streamflow cycle have shown month of regime peak to be associated with increased frequencies of moister air-masses and decreased frequencies of drier air-masses; and low magnitude regimes to be associated with increased frequencies of drier air-masses and decreased frequencies of moister air-masses, and *vice versa* for high magnitude regimes (Hannah *et al.*, 2006).

Annual/seasonal links between atmospheric circulation and streamflow are weaker than for rainfall and evaporation, reflecting complexity in the process chain (Lavers *et al.*, 2010). The seasonal cycle of evaporation determines streamflow timing in eastern parts of Europe while, in other regions, the timing and seasonal amplitude of streamflow depend on the month of maximum precipitation and/or extent of snow and glacier storage (Dettinger & Diaz, 2000).

Fig. 1 Sensitivity of mean annual streamflow to the frequency of westerly circulation weather types for basins >1000 km^2 and record lengths >30 years (Sensitivity (β_1) represents the sensitivity of a particular basin to atmospheric forcing, and indicates the proportional increase in streamflow *per* unit increase (+)/decrease (–) in the normalized index of the frequency of westerly circulation weather types. Only stations with $p < 0.05$ are shown). (After Bouwer *et al.*, 2008.)

LOW FLOWS AND HYDROLOGICAL DROUGHT

"Low flows" are a recurrent element of the natural streamflow regime; and "hydrological drought" can be defined as a period of sustained and regionally extensive below average water availability, normally using a threshold approach (Tallaksen & van Lanen, 2004). When studying links with atmospheric circulation, the most commonly used low flow indices are annual minimum and low flow percentiles, derived from the flow exceedence curve. Low flow percentiles correspond to a discharge equalled or exceeded during a specified percentage of the time, and are often combined with an *n*-day moving window that incorporates severity and duration consistent with the definition of hydrological drought (Tallaksen & van Lanen, 2004).

The primary methods to investigate climate–low streamflow relationships are concurrent and lagged correlation analysis, composites, and frequency analysis. Correlation is most widely used and sometimes employed firstly to screen for promising predictor–predictand associations and lag periods. Predictands may be direct measurements of low flow at a station, a regionalised value, percent area in drought (Stahl & Demuth, 1999), or principal components of the low flow field

(Özger *et al.*, 2009). Early correlation studies focused on circulation indices, such as the NAOI (e.g. Wedgbrow *et al.*, 2002). While simplification of atmospheric conditions to an index provides a convenient time series for correlation, some atmospheric detail is lost. Low flows have also been correlated with the frequency of circulation types, for example Grosswetterlagen (Fleig *et al.*, 2011) or Lamb Weather Types (Jones *et al.*, 2013). Composites of geopotential height, wind speed and other atmospheric fields have been related to low flows (Kingston *et al.*, 2013). Other techniques such as wavelets (e.g. Özger *et al.*, 2009) and fuzzy rule sets of circulation patterns (e.g. Pongracz *et al.*, 1999), have been used to link atmospheric conditions with low flows elsewhere, but have not been applied widely in Europe.

European studies exploring connections between atmospheric conditions and low flows have shown significant correlations between low flows and anticyclonic circulation patterns, generally with high pressure centres persisting over central Europe (e.g. Fleig *et al.*, 2011). Accompanying these patterns are slack meridonal winds (Kingston *et al.*, 2006; Fig. 2). An important lagged correlation exists between summer low flows in Great Britain and the negative phase of the NAOI during the preceding winter (Wedgbrow *et al.*, 2002; Kingston *et al.*, 2013). However, in both cases, the NAO pattern was unable to describe atmospheric variation preceding drought onset fully. Composite analysis of geopotential heights show a much more complex pattern related to streamflow droughts (Kingston *et al.*, 2013). Winter low flows have received less research attention; however, they are related generally to northerly or easterly airflow in Europe, which advects cold, dry air from continental Russia and western Asia (Stahl & Demuth, 1999). Research on atmosphere–low flow connections in Europe has focused on central and northern regions. For southern regions of Europe, precipitation based drought indices are typically used. Thus, additional low flow research is required further south and east, particularly because studies hint that meteorological droughts in the Mediterranean tend to be out of phase with the rest of Europe (Hoerling *et al.*, 2011) and the same may be hypothesised for hydrological droughts.

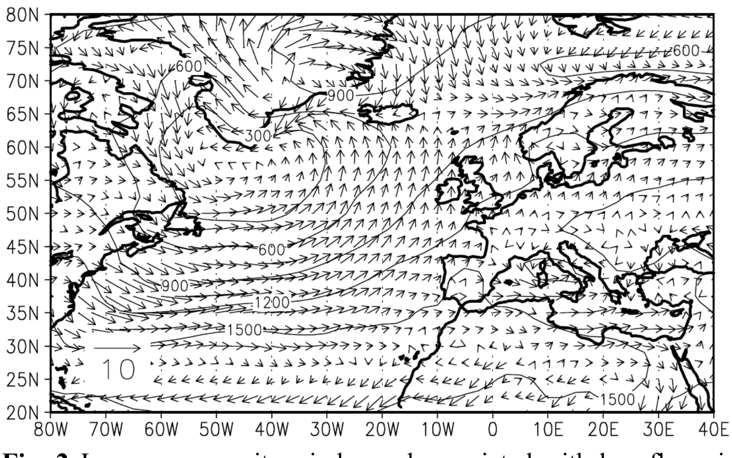

Fig. 2 January composite wind speed associated with low flows in northern Britain (Arrow length is proportional to wind speed in m s^{-1}; see scale bar inset equivalent to 10 m s^{-1}, after Kingston *et al.*, 2006.).

HIGH FLOWS AND FLOODS

Floods may be defined hydrologically as short-term peak streamflow events, generally identified by annual maximum or peak-over-threshold series. These so-called "high flows" may be related to an immediate atmospheric cause (e.g. intense or prolonged rainfall, and/or rapid snowmelt). However, antecedent basin properties may also play an important role in conditioning the climate–runoff signal; hence, analysis of drivers of floods has been undertaken over longer scales (to account for basin priming) as well as the event-scale. For individual basins in Europe, numerous researchers have investigated the meteorological conditions behind major flood events empirically and modelled climate–flood relationships (e.g. Hundecha & Merz, 2012).

At the pan-European scale, typical approaches for linking climate to high streamflows are correlation, regression and composite analysis. Correlation and regression are applied when exploring a single or few atmospheric variables whereas composites are used to explore gridded atmospheric fields. The most common atmospheric predictors tend to be circulation types (CTs). Prudhomme & Genevier (2011) investigated CT–flood linkages across Europe and showed hydroclimatological connections to be more spatially coherent in winter than summer. Jacobeit *et al.* (2006) combined CTs at lead times up to 7 days with analysis of cyclone tracks to understand atmospheric controls on flooding in central Europe. Their results indicated the CTs and cyclone tracks generating high flows differ seasonally and between regions. Correspondingly, Mudelsee *et al.* (2004) found the Vb-cyclone track to be associated with severe floods in central Europe over the last 500 years (Fig. 3). There is also evidence that flood severity varies in response to different atmospheric conditions (e.g. Parajka *et al.*, 2010). Thus, the climatic drivers of European floods may differ between season and region, and severity of the analysed flood event.

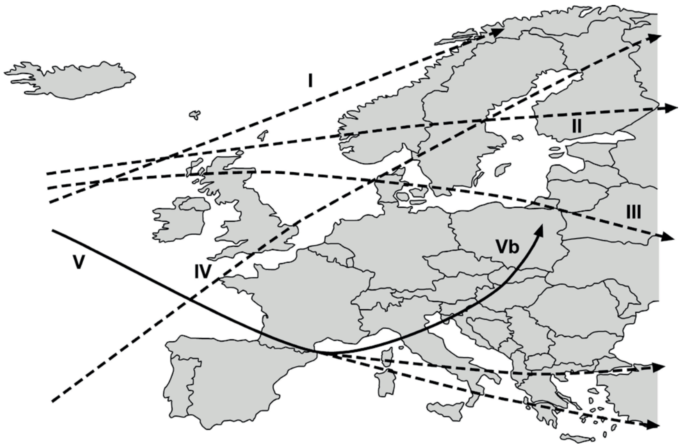

Fig. 3 Van Bebber classification of cyclone tracks in Europe (The Vb track has been linked to extreme flooding in Central Europe, after Roald, 2008).

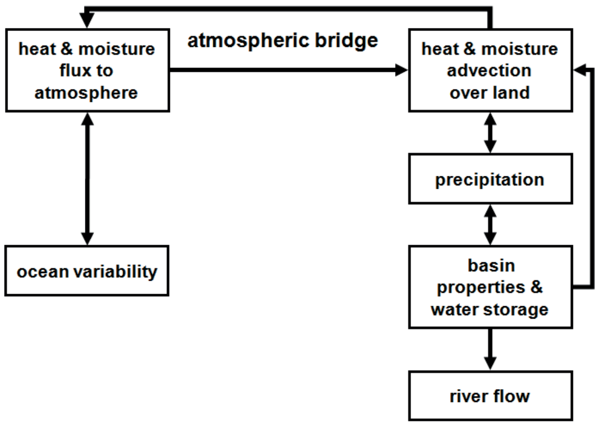

Fig. 4 A conceptual model of the links between ocean–atmosphere–land–river flow.

Large-scale climate indices have been linked to flood frequencies, particularly in the winter half-year when the NAO exerts most influence on European hydroclimatology (e.g. Bouwer *et al.*, 2008). A few recent studies have considered gridded atmospheric fields such as geopotential height or water vapour (e.g. Lavers *et al.* 2012, as discussed below). As with low flows and droughts, CTs and gridded analyses appear to hold greater potential to understand the atmospheric processes forcing high flow events. Large-scale climate diagnostics (such as the NAO) mask more intricate and seasonally dynamic underlying climate patterns (Kingston *et al.*, 2006); but such indices may be informative in long-term studies of changing flood frequencies.

ROLE OF ATMOSPHERIC WATER VAPOUR

Understanding exactly where water evaporates from and how evaporated water arrives over a basin prior to precipitation (i.e. the atmospheric bridge of the hydrological cycle) is critical to understanding the ocean–atmosphere processes driving variation in river flow (Fig. 4). Previous investigation of atmospheric water vapour as a driver of streamflow variability may be split broadly into: (a) analyses of atmospheric water vapour time series from station records or large-scale gridded datasets; and (b) specific pathways of vapour transport through the atmosphere, identified using back-trajectory analysis.

Analysis of water vapour climate may provide important additional information to the analysis of atmospheric circulation (reviewed above). For example, Lawler *et al.* (2003) combined measures of atmospheric circulation and moisture to calculate water vapour flux, which helped to unravel the process chain linking meridional vapour flux, local temperatures, precipitation and streamflow in southern Iceland. Similarly, Kingston *et al.* (2013) linked antecedent sea surface temperatures (SSTs) and atmospheric circulation to the development of streamflow drought in Britain through water vapour flux anomaly patterns.

A notable advance in understanding large-scale climate-flow connections has been the identification of so-called “atmospheric rivers”: intense bands of atmospheric water vapour flux, with total transport rates exceeding those of the largest terrestrial river systems. Lavers *et al.* (2012) have demonstrated the importance of atmospheric rivers in generating 10 major floods in the UK. They examined geopotential height fields and atmospheric circulation patterns associated with the atmospheric rivers, and found some connection to the Scandinavian atmospheric teleconnection pattern.

An alternative to analysing vapour flux for stations or gridded data is to track movement of individual parcels of air moisture through the atmosphere over time (i.e. back-trajectory analysis). This approach has been used to understand where the primary moisture sources (i.e. evaporative source regions) are for precipitation over particular land surface regions. For example, Gimeno *et al.* (2010) identified that the most important moisture source regions for the Iberian Peninsula were the Peninsula itself, the surrounding Mediterranean, and a corridor extending from the Gulf of Mexico to the Peninsula. Other studies have used back-trajectory analysis to extend the moisture source region–trajectory–precipitation process cascade to consider streamflow too. For example, Stohl & James (2004) revealed the moisture sources and trajectories generating the August 2002 central European floods. Similarly, Stohl *et al.* (2008) combined trajectory analysis of the September 2005 flood in western Norway with analysis of atmospheric water vapour fields to identify the strong influence of atmospheric rivers (combined with two ex-tropical cyclones) during this particular high flow event.

SYNTHESIS AND FUTURE DIRECTIONS

We have undertaken a systematic inter-comparison of different streamflow metrics and atmospheric descriptors to evaluate the current state-of-the-art, and propose future directions for research on connecting streamflow and the atmospheric conditions in Europe. For annual streamflow regimes (seasonal behaviour and seasonal/annual averages), links with climate have been investigated using circulation indices, air-masses, atmospheric pressure fields and station-based climate observations. The main methods of analysis are concurrent and (to a lesser extent) lagged correlation with a few recent studies using composite or spectral/wavelet analysis. Studies of low flow and hydrological drought (characterised variously using severity threshold and duration, and often based on regional time-series) have tended to focus on correlation with circulation indices and air-masses, but rarely use gridded climate fields or composite analysis. Floods and high flows have been related to circulation indices, air-masses and atmospheric fields using correlation, regression and composite analysis. Notably, the analysis of vapour flux and so-called “atmospheric rivers” offers a physically interpretable means of hydroclimatological flood analysis; but this approach has not been applied to other flow metrics.

With regard to future research directions, we suggest there is a need to identify appropriate atmospheric descriptors (dependent on the target flow metric and region of interest) and to develop analytical techniques that best characterise connections in the ocean–atmosphere–land surface process chain. We call for the need to quantify not just atmosphere interactions, but also the role of the river basin-scale terrestrial hydrological processes in modifying the climate signal response of streamflows.

REFERENCES

Bouwer, L. M., Vermaat, J. E. & Aerts, J. C. J. H. (2008) Regional sensitivities of mean and peak river discharge to climate variability in Europe. *J. Geophys. Res.* 113, D19103.

Dettinger, M. D. & Diaz, H. F. (2000) Global characteristics of streamflow seasonality and variability. *J. Hydrometeorology* 1, 289–310.

Fleig, A. K., Tallaksen, L. M., Hisdal, H. & Hannah, D. M. (2011) Regional hydrological drought in north-western Europe: linking a new Regional Drought Area Index with weather types. *Hydrol. Processes* 25, 1163–1179.

Gimeno, L., Nieto, R., Trigo, R. M., Vicente-Serrano, S. M. & Lopez-Moreno, J. I. (2012) Where does the Iberian Peninsula moisture come from? An answer based on a Lagrangian approach. *J. Hydrometeorology* 11, 421–436.

Gimeno, L., Stohl, A., Trigo, R. M., Dominguez, F., Yoshimura, K., Yu, L., Drummond, A., Duran-Quesada, A. M. & Nieto, R. (2012) Oceanic and terrestrial sources of precipitation. *Reviews of Geophysics* 50. RG4003.

Hannah, D. M., Bower, D. & McGregor, G. R. (2006) Association between Western European air-masses and river flow regimes, In: *Climate Variability and Change-Hydrological Impacts* (ed. by S. Demuth, A. Gustard, E. Planos, F. Scatena & E. Servat), 344–349. IAHS Publ. 308. IAHS Press, Wallingford, UK.

Hannah, D. M., Demuth, S., van Lanen, H. A. J., Looser, U., Prudhomme, C., Rees, G., Stahl, K. & Tallaksen, L. M. (2011) Large-scale river flow archives: importance, current status and future needs. *Hydrol. Processes* 25, 1191–1200.

Hoerling, M., Eischeid, J., Perlwitz, J., Quan, X. W., Zhang, T. & Pegion P. (2011) On the increased frequency of Mediterranean drought. *J. Climate* 25, 2146–2161.

Hundecha, Y. & Merz, B. (2012) Exploring the relationship between changes in climate and floods using a model-based analysis. *Water Resour. Res.* 48, W04512.

Jacobeit, J., Philipp, A. & Nonnenmacher, M. (2006) Atmospheric circulation dynamics linked with prominent discharge events in Central Europe. *Hydrol. Sci. J.* 51(5), 946–965.

Jones, P. D., Harpham, C. & Briffa, K. R. (2013) Lamb weather types derived from reanalysis products. *Int. J. Climatol.* 33, 1129–1139.

Kingston, D. G., Fleig, A. K., Tallaksen, L. M. & Hannah, D. M. (2013) Ocean-atmosphere forcing of summer streamflow drought in Great Britain. *J. Hydrometeorology* 14, 331–343.

Kingston, D. G., Hannah, D. M., Lawler, D. M. & McGregor, G. R. (2009) Climate-river flow relationships across montane and lowland environments in northern Europe, *Hydrol. Processes* 23, 985–996.

Kingston, D. G., McGregor, G. R., Hannah, D. M. & Lawler, D. M. (2006) River flow teleconnections across the northern North Atlantic region. *Geophys. Res. Lett.*, 33(14), L14705.

Lavers, D., Prudhomme, C. & Hannah, D. M. (2010),= Large-scale climate, precipitation and British river flows: identifying hydroclimatological connections and dynamics, *J. Hydrol.* 395, 242–255.

Lavers, D. A., Villarini, G., Allan, R. P., Wood, E. F. & Wade, A. J. (2012), The detection of atmospheric rivers in atmospheric reanalyses and their links to British winter floods and the large-scale atmospheric circulation. *J. Geophys. Res.* 117, D20106.

Lawler, D. M., McGregor, G. R. & Phillips, I. D. (2003) Influence of atmospheric circulation changes and regional climate variability on river flow and suspended sediment fluxes in southern Iceland. *Hydrol. Processes* 17, 3195–3223.

Massei, N., Laignel, B., Deloffre, J., Mesquita, J., Motelay, A., Lafite, R. & Durand, A. (2010) Long-term hydrological changes of the Seine River flow (France) and their relation to the North Atlantic Oscillation over the period 1950–2008. *Int. J. Climatol.* 30, 2146–2154.

Mudelsee, M., Borngen, M., Tetzlaff, G. & Grunewald, U. (2004) Extreme floods in central Europe over the past 500 years: Role of cyclone pathway Zugstrasse Vb. *J. Geophys. Res.*, 109, D23101.

Özger, M., Mishra, A. K. & Singh, V. P. (2009) Low frequency drought variability associated with climate indices. *J. Hydrology* 364, 152–162.

Parajka, J., Kohnova, S., Balint, G., Barbuc, M., Borga, Claps, P., Cheval, S., Dumitrescu, A., Gaume, E., Merz, R., Hlavcova, K., Pfaundler, M., Stancalie, G., Szolgay, J. & Bloschl, G. (2010) Seasonal characteristics of flood regimes across the Alpine-Carpathian range. *J. Hydrol.* 394, 78–89.

Pongracz, R., Bogardi, I. & Duckstein, L. (1999) Application of fuzzy rule-based modeling technique to regional drought. *J.Hydrol.* 224, 100–114.

Prudhomme, C. & Genevier, M. (2011) Can atmospheric circulation be linked to flooding in Europe? *Hydrol. Processes.* 25, 1180–1190.

Roald, R. A. (2008) *Rainfall Floods and Weather Patterns*, Norwegian Water Resources & Energy Directorate (NVE).

Stahl, K. & Demuth, S. (1999) Linking streamflow drought to the occurrence of atmospheric circulation patterns. *Hydrol. Sci. J.* 44, 467–482.

Stohl, A. & James, P. (2005) A Lagrangian analysis of the atmospheric branch of the global water cycle. Part II: Earth's river catchments, ocean basins, and moisture transports between them. *J. Hydrometeorology* 6, 961–984.

Stohl, A., Forster, C. & Sodemann, H. (2008) Remote sources of water vapour forming precipitation on the Norwegian west coast at 60 °N - a tale of hurricanes and an atmospheric river. *J. Geophys. Res.* 113, D05102.

Tallaksen, L. M. & van Lanen, H. A. (2004) *Hydrological Drought: Processes and Estimation Methods for Streamflow and Groundwater*. Elsevier.

Wedgbrow, C. S., Wilby, R. L., Fox, H. R. & O'Hare, G. (2002) Prospects for seasonal forecasting of summer drought and low river flow anomalies in England and Wales. *Int. J. Climatol.* 22, 219–236.

WWAP (World Water Assessment Programme). (2009) *The United Nations World Water Development Report 3: Water in a Changing World*. UNESCO-Earthscan.