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Influence of the North Atlantic Oscillation on spatial and temporal patterns in Eurasian river flows

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Abstract Atmospheric circulation indices can be used to explain the variability of runoff at a continental scale. In Eurasia, besides well-known zonal anomalies of runoff that correlate with phases of the North Atlantic Oscillation (NAO), drifting fields of annual discharge anomalies exist. With the trend of the NAO these fields drift along a longitudinal direction from Western Russia to the Lena River basin in Siberia and back again. Similar observations can also be applied to changing river flow regimes. Drifting fields can be identified by a cluster approach. The centroids of the clusters can be linked to the driving processes of the NAO. Thus, the spatial drifting can be understood as an autoregressive process where the NAO-index determines the drifting direction. This paper describes the origin and causes of these fields which can explain important processes of climate variability in the Northern hemisphere.

Key words Eurasia; North Atlantic Oscillation; discharge anomalies; flow regimes; drifting fields; autoregressive process

INTRODUCTION

Large-scale changes of hydrological processes can be recorded as trends or anomalies in discharge time series. Usually the decadal and multi-decadal discharge variations in large-scale basins are examined by using time series of average annual values. Dettinger & Diaz (2000) introduce a global data set of interannual discharge variability and correlate these data with atmospheric circulation indices such as the El Nino/Southern Oscillation (ENSO) index and the North Atlantic Oscillation (NAO) index. South and North European river basins especially react sensitively to the phases of the NAO (Arnell, 1997; Popova & Shmakin, 2003).

Nevertheless in Eurasia only a quarter (24%) of gauging stations shows significant correlations between annual discharges (period 1950–1990) and the NAO-index (Hurrel, 1995). Thus Fig. 1 reflects only roughly the positive correlations with the NAO in Northern Europe while Southern Europe has negative correlations (for all gauging stations, Fig. 2). Arnell (1997) described such a pattern for the correlation of European winter discharges with the NAO-index.

Long-term correlations of river flows with climate indices presuppose that regions reacting to climatic fluctuations stay spatially stable. Under spatially non-persistent conditions the correlation between large-scale climate variability and river flows can be better explained by a time dependent spatial process.

DATA

In this paper long-term variability of annual discharges and seasonal figures with regard to climate variability of the northern hemisphere is described using 3241 Eurasian discharge time series provided by GRDC (Global Runoff Data Centre), NCAR ds552.1 and ds553.2 (Bodo, 2001) as well as from ArcticRiverNet. Nearly 70% of the time series used are longer than 30 years but 70% contain data before 1984, and 30% data before 1985. For detailed studies the climatological normal period, 1960–1990 was used. In, addition the dfjm NAO-index by Hurrel (1995) was used to describe the phases of the NAO.

METHODS

Anomalies in annual runoff

The first study was made by using annual deviations of the annual sums of the long-term discharge average for all gauging stations in Eurasia. By analysing maps of anomalies of annual discharges, clusters become visible which can be assumed to be a spatial response to the NAO. The driving processes are described in the Results section.

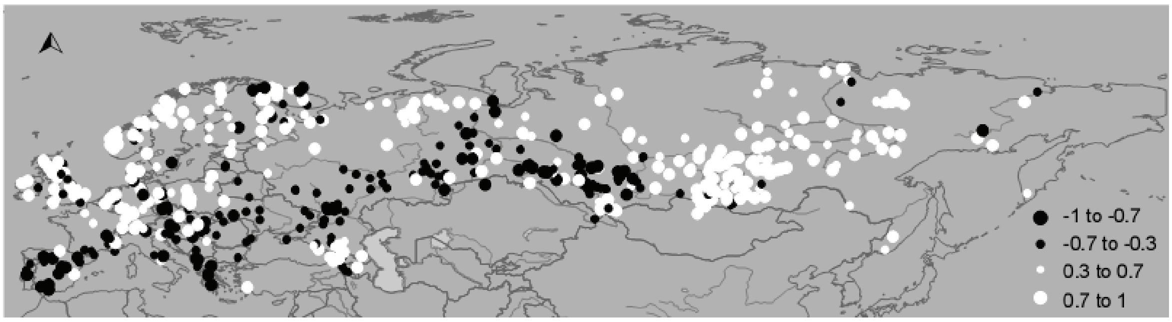

Fig. 1 Significant correlations (> |0.32|) of time series of Eurasian annual discharges with the NAO-index 1950–1990 (Hurrel, 1995).

Spatial clusters of positive and negative discharge anomalies were detected by hierarchical cluster analysis using latitude, longitude and discharge anomalies. For each year the standardized anomalies were classified using Squared Euclidian distance and Complete linkage. Subsequently, the spatial centroids of each cluster were determined by computing the weighted average of latitude and longitude. Anomalies of more than 0.5 were weighted with a factor 0.6, anomalies of more than 0.25 were weighted with a factor 0.3. All other anomalies of more than 0.1 were weighted with a factor 0.1. The computed longitudes of the centroids are visible in Figs 3 and 4.

Time dependent varying seasonal figures

In addition to the seasonally varying discharge curve, the discharge regime is overlaid by the long-term variability of the discharge regimes themselves. Thus, it is possible to detect climate fluctuations by using time series of discharge regimes. Under the influence of climatically varying boundary conditions, discharge regimes will react and show modifications. Besides a temporal variability of annual discharges, Burn & Soulis (1992) focused on seasonal discharge variability as well as on the appearance of extreme discharges and snowmelt induced floods. The latter reflect the climatic variability of hydrological processes clearest.

Elimination of impoundment effects

Many runoff time series are affected by impoundments. To assess the intensity of the impoundment impact on each gauging station their impoundment coefficients were computed. The impoundment coefficient can be calculated as the ratio of cumulated upstream dam capacity to annual discharge. Therefore all dams from the ICOLD database (ICOLD, 1998) in Europe and Russia were geo-referenced. The relevant upstream dams and their cumulated capacity were determined by using a digital elevation model and a digital river network (Rödel & Hoffmann, 2005).

Figure 2 shows the impoundment coefficients for Eurasia in 1990. For further analysis of temporal variability of flow regimes, 354 gauging stations classified as dam influenced (impoundment coefficients >0.001) were removed from the data set.

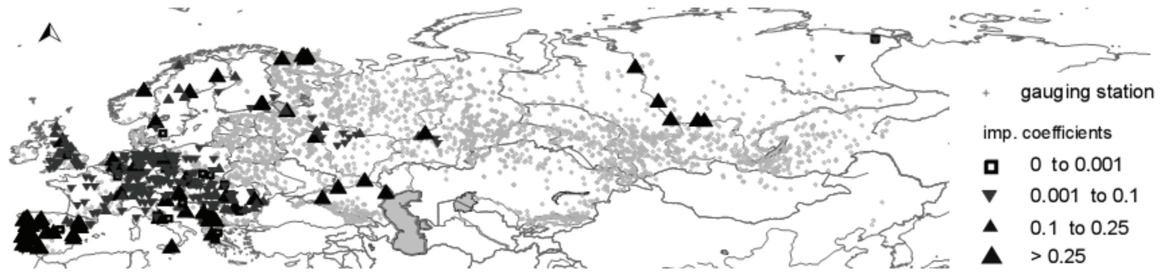

Fig. 2 Impoundment coefficients for Eurasia in 1990.

Balance point drift of discharge regimes

For analysing regime changes, annual flow regimes were determined as an order of discharge coefficients, q_i (equation (1)):

$$q_i = Q_i / Q_{Year} \text{ with } \sum_{i=1}^{n} q_i = 1 \qquad q_i \geq 0, \qquad i = 1, \ldots, 12 \tag{1}$$

where Q_{Year} is the annual discharge and Q_i is the monthly discharge. When the monthly discharges are standardized in this way, the transitions between the regimes of successive years appear abrupt. Unless the discharge sums of two successive years are virtually the same, the last month of year one and the first month of year two will have different coefficients, even if discharge is the same in both months. To minimize this distortion, the one-year period that the description of the runoff regimes was based on, was delimited in a way resembling the method used for hydrological years. The beginning of the annual cycle was defined by that month i which had the lowest square deviation from its average discharge value over the whole time series:

$$\sum \left(Q_i - \overline{Q_i} \right)^2 \rightarrow Min! \tag{2}$$

Finally, changes in flow regimes were determined as an interannual shift of the balance point. The balance point is reached in that month i for which equation (3) is valid:

$$\sum_{1}^{i} q_i \geq 0.5 \tag{3}$$

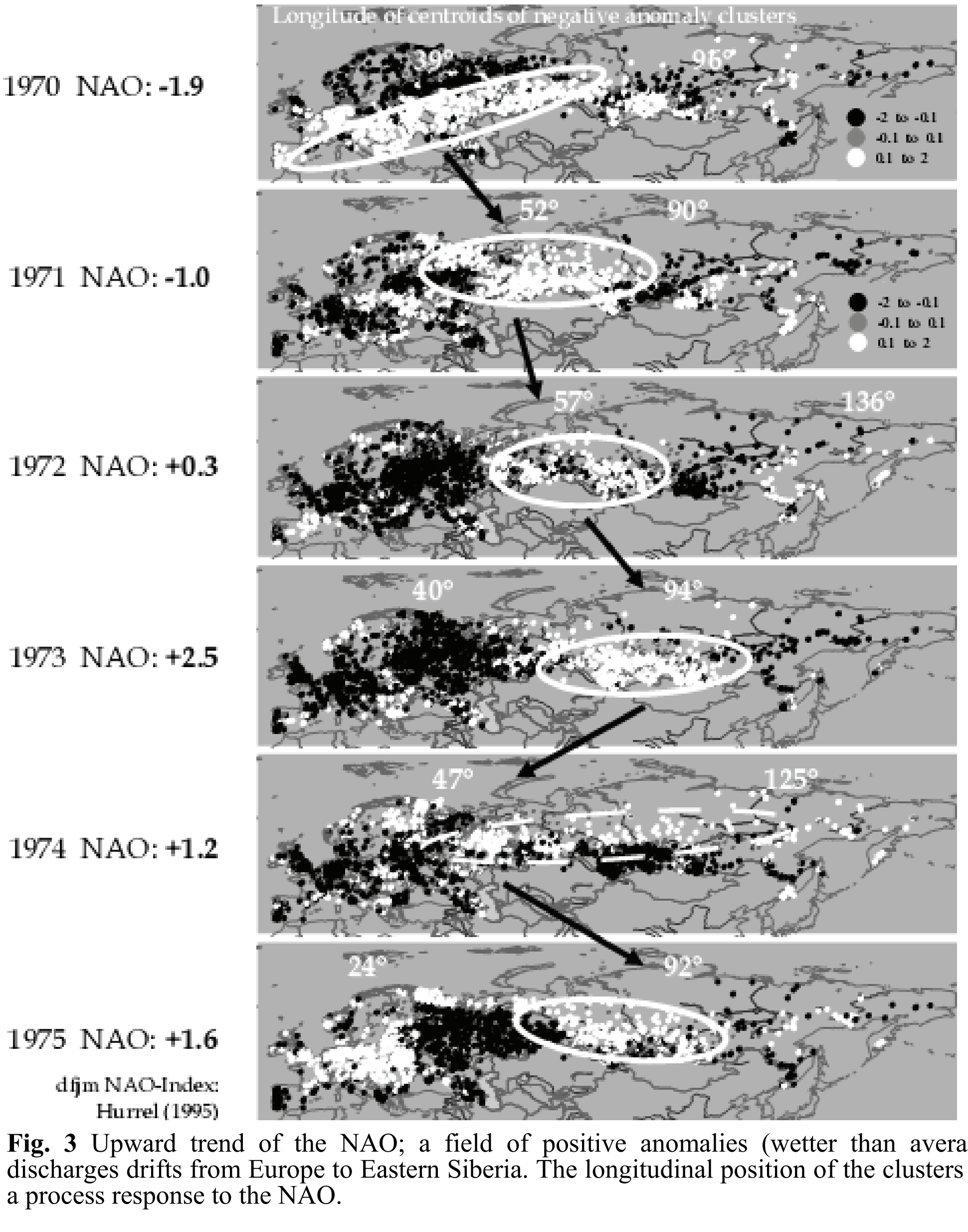

Fig. 3 Upward trend of the NAO; a field of positive anomalies (wetter than average) of the annual discharges drifts from Europe to Eastern Siberia. The longitudinal position of the clusters can be assumed as a process response to the NAO.

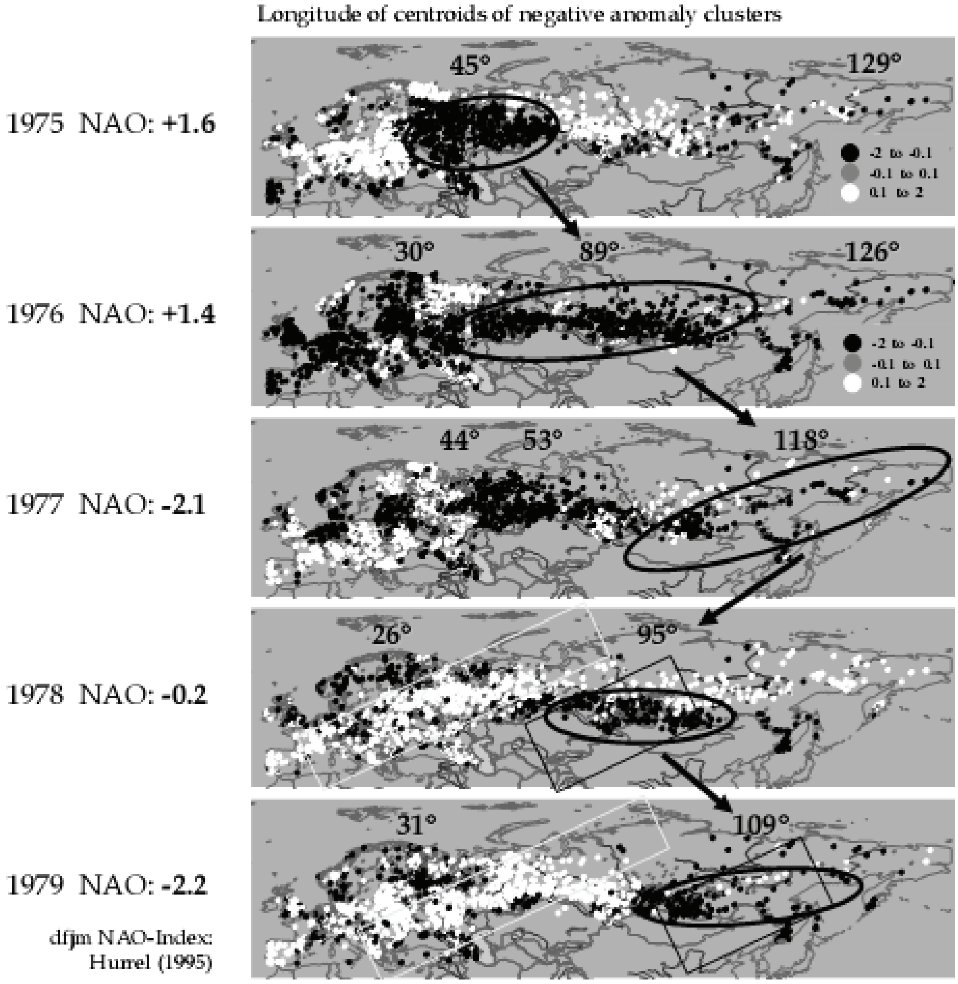

Fig. 4 Downward trend of the NAO; a field of negative anomalies (dryer than average) of the annual runoff drifts from western Siberia to eastern Siberia. The longitudinal position of the clusters can be assumed as process response to the NAO. Note the rectangles in the lower two pictures; these reflect the dipole-structure of the NAO reaction in river flows (Arnell, 1997), which is rotated and drifted eastward.

If the monthly discharge is constant (1/12 of the annual discharge), the balance point falls exactly in the sixth month of the cycle. To analyse the long-term variability of the balance point, the mode of balance points was calculated for each time series. Annual deviations from the mode were treated as positive or negative shifts of the balance point.

Negative balance point shifts co-occur with steep-shaped or earlier-than-usual runoff maximum peaks. Negative shifts are typical for years with an above-average temperature and an earlier-than-usual snowmelt in Northern Eurasia. Positive balance point shifts are typical for flat-shaped runoff maximum peaks that occur later in the year than usual. In Northern Eurasia, these shifts frequently occur in years in which the temperature is relatively low during the flood formation phase (snowmelt).

RESULTS

Large scale patterns in annual runoff

Figures 3 and 4 show deviations of long-term annual discharges during a downward trend and an upward trend of the NAO. Besides the dipole structure with higher runoff in Northern Europe and lower runoff in Southern Europe during a significantly positive NAO phase (Arnell, 1997), drifting fields of anomalies in annual runoff can be detected. These fields drift with the trend of the NAO along a longitudinal direction.

During a downward trend of the NAO, fields of reduced discharges (represented as negative anomalies of the long-term average of the annual discharges) drift eastward from Western Russia up to the Lena catchment area in Eastern Siberia (Fig. 4).

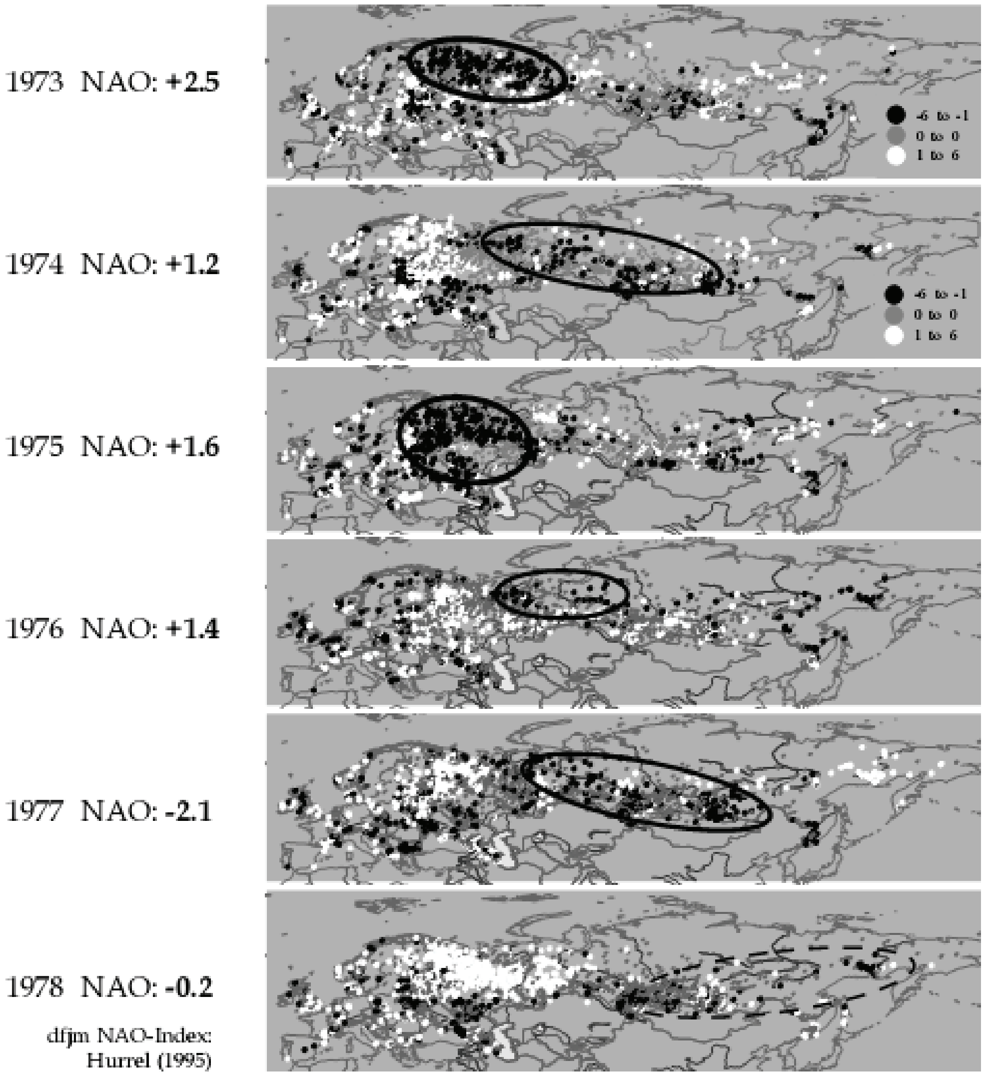

Fig. 5 Downward trend of the NAO; a field of negative shifted balance points in flow regimes (shown is shifting of balance points in each year in relation to the most frequent balance point) drifts from north-western Russia to Eastern Siberia. Strong runoff maxima which occur earlier than normal, drift to eastern Siberia.

If there is an upward trend of the NAO, a field of increased discharges drifts to the area of the Lena River basin. The westward drifting fields of higher runoff can be seen in context with an increased runoff in Northern Europe during a positive NAO phase (Arnell, 1997; Timmermann & Latif, 1998).

The NAO as the driver of large-scale pattern variations

The periodical increase of the discharges in Eastern Siberia seems to explain the dependence between the NAO variability and the variability of discharges. Mysak (1999) stated that fluctuations of annual discharge in large-scale basins are strongly correlated with decadal climate fluctuations and show response processes with them. He postulates that the long-term varying discharge volumes of the Mackenzie basin as a major reason for the formation of great ice and salt anomalies (GISA) in the North Atlantic. These anomalies influence the intensity of the oceanic circulation with a delay of 3–4 years and control the climate of the Northern hemisphere via the NAO and AO. Reduced salinity can be seen as control pulse for a weaker thermohaline circulation in the North Atlantic during negative NAO-index periods (Timmermann & Latif, 1998). Although focusing on increased discharges in the Mackenzie basin, Mysak (1999) also emphasizes that increased discharges from Siberian streams favour the setting up of ice cover in the Arctic Ocean.

Large scale spatial patterns for varying seasonal figures

Figure 5 shows that shifts in balance points of flow regimes can also be observed as drifting fields. During a downward trend of the NAO, a field of negative shifts of the balance point drifts eastward and reaches the Lena River basin.

The balance points of flow regimes were shifted into the preceding months during mild winters or flow regimes are characterized by steep-curved runoff maxima. If the pattern of a positive NAO (dipole of annual discharges in Europe) dissolves itself, the field of negative shifted balance points drifts eastward. This can be seen in relation to the more southern position of the higher discharges and negative shifted balance points in the case of the negative NAO-index. Assuming a southeastward direction of drifting, the fields can be thought of as moving on a southwest–northeast axis which generally drifts southward in correlation with the NAO-Index. During an upward trend of the NAO, the opposite situation can be observed. Fields of negative shifted balance points drift back westward from Eastern Siberia. At the same time increased annual discharges are visible in Northern Europe.

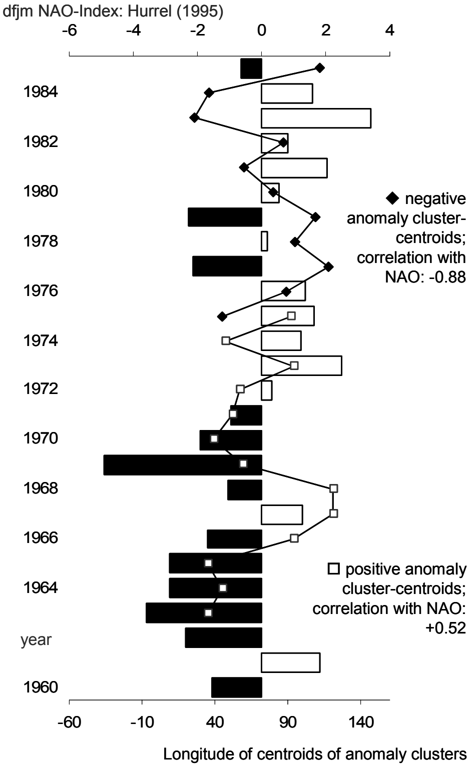

Fig. 6 Longitudinal drifting of large-scale patterns of discharge anomalies in Eurasia (lines) and the NAO-index (bars).

CONCLUSION

Assuming that the NAO is the driving process for drifting fields of discharge anomalies and that discharge represents the response of river flow to the NAO, the centroid longitudes of discharge anomaly clusters were identified (cf. Fig. 3 and 4). Fig. 6 shows the correlation between NAO and the centroid longitudes of anomaly clusters. This leads to an understanding of cluster shifting as an autoregressive process. Thus, the location of a cluster can be determined from its location at $t - 1$ and the drifting direction. The drifting direction itself can be obtained from the NAO-index. The results presented here lead to the hypothesis that discharge variability reflects large-scale hemispheric climate variability better than previously assumed (cf. Arnell, 1997; Dettinger & Diaz, 2000). Anomalies in annual discharges and shifts of the balance points of annual flow regimes point to those regions which are important for the processes of climate variability in the northern hemisphere. The NAO provides a basis for explaining large-scale anomalies of the annual discharges and of the river flow regimes in Eurasia.

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