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Prediction of hydrological extremes by air circulation indices

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Abstract The study of air circulation variability is important for a better understanding of river runoff. Research presented in this paper describes an attempt to find a link between air circulation on a large regional scale, and hydrological extremes of Carpathian river discharges in warm and cold seasons. The relationship between the North Atlantic Oscillation in winter, the Scandinavian baric system, and maximum and minimum river discharges was investigated over the period 1951–2000. Multiple correlation analysis was used. Some interesting relationships were found and multiple correlation formulae were developed for a few Carpathian basins. They may be used for hydrological forecasts of Carpathian extreme river discharges and they may allow the implementation of a warning system for extreme river events.

Key words Carpathian Mountains; hydrological extremes; multiple regression; North Atlantic Oscillation; river discharge; SCAND; teleconnections; winter Hurrell index

INTRODUCTION

The North Atlantic Oscillation (NAO) is one of the most important regional systems steering the weather and climate over the middle and high latitudes of the Northern Hemisphere (Bonsal *et al.*, 2001; Hurrell *et al.*, 2002; Hurrell & Van Loon, 1997, Shabbar *et al.*, 1997). The meteorological conditions in Poland are influenced by the NAO, particularly during the winter season (Bryś & Bryś, 2002; Kożuchowski & Degirmendžic 2002; Łupikasza 2000; Marsz & Styszyńska, 2001; Styszyńska, 2001; Wibig, 2000). The interactions between the NAO and river discharge in European and Polish rivers were discussed by Stahl & Demuth (2001) and introduced by Kaczmarek (2002), Pociask-Karteczka *et al.* (2002) and Styszyńska (2002). Adler *et al.* (1999) investigated the synoptic situations that lead to droughts in the Carpathian region in Romania. The most important conclusions of this research are as follows:

(a) The relationship between the NAO and river runoff is not very strong. However, it is statistically significant in many cases, hence NAO plays an important role as an indirect factor influencing river runoff.

(b) Some synchronic and asynchronic relations between the NAO and river discharges can be observed: the positive NAO phase in winter is associated with high river discharge during winter and with low discharge in August and at the beginning of autumn.

(c) Floods during the meltwater season are associated with very low winter NAO index.

According to these analyses, the relationships between NAO and river discharge have not been strong, contrary to expectations (Fig. 1). There might be two reasons for this: genetic non-homogeneity of data sets, and many other circulation and geographical factors controlling river runoff. The most interesting from human, economic and hydrological points of view, are relationships between the air circulation conditions controlling the meteorological phenomena and extreme river discharges. Hydrological extreme events (drought and flood) affect all factors of human life.

NAO refers to the redistribution of atmospheric masses over North Atlantic and neighbouring continents. In central Europe, the intensity of its influence may be weakened, and even blocked, by the local baric system over Scandinavia or west Russia, called SCAND. The positive phase of SCAND plays a very important role during the cold season, causing lower precipitation than usual over the Scandinavian part of Europe, and higher precipitation than usual over southern Europe. In this paper the relationship between the North Atlantic Oscillation, Scandinavian baric system and river maximum and minimum discharges of the Carpathian rivers is empirically examined by multiple correlation analysis. Using the results obtained so far, the aim is to find answers to the following questions:

(a) What is the relationship between the NAO in winter, the Scandinavian baric system and extreme river discharges?

(b) Is there any possibility of forecasting the extreme river discharges in the Polish Carpathians on the basis of Hurrell's NAO and SCAND indices?

These studies try to find a link between extreme hydrological events and large-scale climatic phenomena. It might be interesting to examine the relationships between macroscale air circulation phenomena and river response.

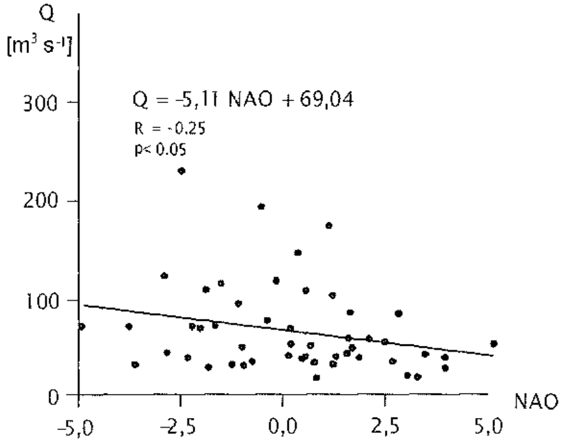

Fig. 1 Relationship between the Dunajec River mean discharge in August and winter NAO index (1951–2000).

AREA OF INVESTIGATION

The Carpathian Mountains are located in central Europe and spread from northwest to southeast as an arch of length about 1300 km and width of –120 to 350 km. The investigated area includes the highest part of these mountains with Gerlach (2655 m a.s.l.). The area spreads through southern Poland, northern Slovakia and eastern Ukraine. The location of the Carpathians is noticeable and distinctive: they form a border between two different influences of NAO. The strong positive phase of NAO causes higher precipitation than usual on the northern side of the Carpathians, and lower precipitation than usual on the southern side.

River basins were chosen that drain the northern slopes of the Carpathians and belong to the upper Wisła basin. Six rivers were analysed with eight water gauging sites (Table 1, Fig. 2). They represent typical mountain flow regimes with two maximum peaks (Chełmicki *et. al.*, 1998–99). The first maximum occurs during the meltwater period—usually in April or March, and the second one occurs during the summer rains period—usually in July or August. However, the western part of the

Table 1 The area of investigated basins.

River	Water gauging site	Area (km^2)
Raba	Stróża	644
Poprad	Stary Sącz	2 071
Wisłoka	Mielec	3 915
Wisłok	Tryńcza	3 516
San	Jarosław	7 041
San	Radomyśl	16 824
Wisła	Sandomierz	31 846
Wisła	Zawichost	50 732

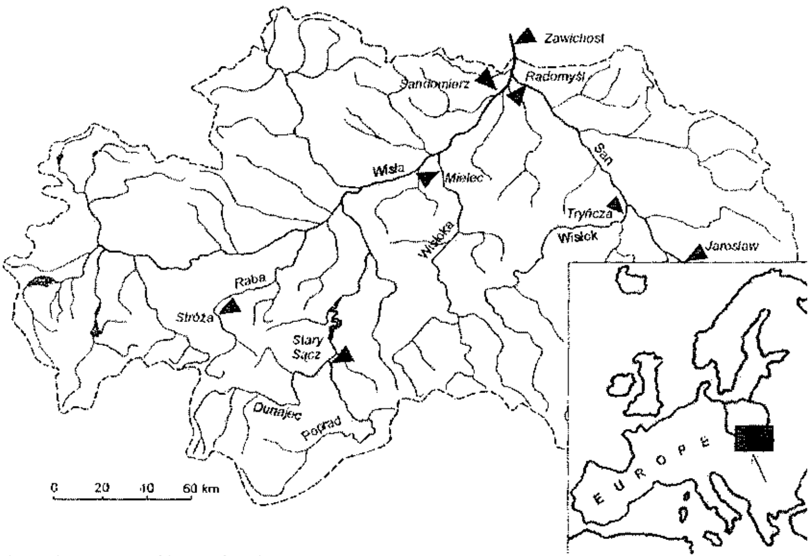

Fig. 2 The area of investigation.

investigated area represents the pluvio-nival pattern of flow regime, with a very distinctive maximum in summer, and the eastern part represents the nivo-pluvial flow regime with a very distinctive maximum in April or March. The low flow occurs during late autumn and in winter (usually from October to January).

DATA

Data sets of maximum and minimum discharge in the warm season (May–October) and in the cold season (November–April) for the period 1951–2000 have been taken into consideration. These data sets are genetically homogeneous. Winter Hurrell's NAO index (one value for the period from December to March) and the SCAND index (monthly values for the whole year except June and July) were employed in this study.

RESULTS AND DISCUSSION

Comparison of the results of linear and multiple correlation analyses presented in Table 2 showed that correlation coefficients between hydrological extremes in warm and cold seasons and winter NAO and SCAND indices are higher than between hydrological extremes and winter NAO index.

Next, the analysis of multiple correlation was performed between hydrological extremes in warm and cold seasons and winter NAO index and SCAND indexes in particular months separately. There are some remarkable correlations between:

(a) maximum discharge in the cold season and winter NAO index and SCAND indices in all analysed months (for San (Jarosław) and Wisłok (Tryńcza) basins);
(b) minimum discharge in the cold season and winter NAO index and SCAND indices in all analysed months (for San (Jarosław), San (Radomyśl), Wisła (Sandomierz) and Wisłok (Tryńcza) basins);

Table 2 Correlation coefficient between maximum (R_{max}) and minimum (R_{min}) discharges in warm and cold seasons and winter NAO index (linear correlation), and between maximum (R_{max}) and minimum (R_{min}) discharges in warm and cold seasons and winter NAO index and SCAND index* (multiple correlation).

River	Water gauging site	Linear correlation:				Multiple correlation:			
		Warm season:		Cold season:		Warm season:		Cold season:	
		R_{max}	R_{min}	R_{max}	R_{min}	R_{max}	R_{min}	R_{max}	R_{min}
Raba	Stróża	–0.23	–0.22	–0.02	0.17	*0.34*	0.30	0.05	0.22
Poprad	Stary Sącz	–0.08	–0.04	–0.17	0.11	0.13	006	0.25	0.13
Wisłok	Tryńcza	–0.05	–0.10	–0.26	*0.32*	0.06	0.16	*0.39*	**0.42**
Wisłoka	Mielec	–0.05	–0.10	–0.05	0.17	0.05	0.15	0.09	0.23
San	Jarosław	–0.09	0.20	*–0.29*	**0.41**	0.12	0.28	**0.43**	**0.55**
San	Radomyśl	–0.11	0.09	–0.20	*0.29*	0.15	0.13	0.30	*0.39*
Wisła	Sandomierz	–0.19	–0.10	–0.10	*0.30*	0.28	0.15	0.17	*0.40*
Wisła	Zawichost	–0.07	–0.14	–0.16	0.18	0.10	0.20	026	024

*mean value for the period January–May and August–December.
bold: $P < 0.001$; **bold**: $P < 0.01$; *italic*: $P < 0.05$.

(c) maximum discharge in the warm season and winter NAO index and SCAND indices in all analysed months (for Raba (Stróża) basin);
(d) minimum discharge in the warm season and winter NAO index and SCAND indices in all analysed months (for Raba (Stróża) basin);
(e) minimum discharge in the warm season and winter NAO index and SCAND index in January (for San (Jarosław) basin).

In some cases, the statistical relationship—mainly asynchronic ones—does not guarantee a physical cause and effect. The most interesting, from a prognostic point of view, are correlations presented in Table 3. Some of them may be applied for the development of a formula to calculate hydrological extreme discharges:

$$Q_{EX} = f(\text{NAO, SCAND}) \tag{1}$$

where Q_{EX} is maximum or minimum river discharge in warm or cold seasons, NAO is Hurrell's NAO index, and SCAND is the air circulation index in a particular month.

To derive hydrological extremes Q_{EX}, the multiple linear regression may be defined as:

$$Q_{EX} = a + b\text{NAO} + c\text{SCAND} \tag{2}$$

where a, b and c are multiple linear regression coefficients.

Verification of calculated models was performed and errors of estimation E were derived:

$$E = \frac{100\sum_{1}^{50}(Q'_{EX} - Q_{EX})}{n\bar{Q}} \tag{3}$$

Table 3 Multiple correlation coefficient between hydrological extremes and winter NAO index and SCAND* index in particular months.

River	Water gauging site	Index	Warm season:		Cold season:	
			R_{max}	R_{min}	R_{max}	R_{min}
Raba	Stróża	NAO, SCAND3	*0.34*	0.30	0.03	0.23
		NAO, SCAND5	0.33	0.31	0.04	0.23
		NAO, SCAND8	0.32	0.31	0.31	0.24
		NAO, SCAND12	0.33	0.31	0.02	0.20
Poprad	Stary Sącz	NAO, SCAND3	0.12	0.06	0.25	0.14
Wisłok	Tryńcza	NAO, SCAND3	0.06	0.14	*0.37*	**0.43**
		NAO, SCAND4	0.07	0.14	*0.37*	**0.45**
Wisłoka	Mielec	NAO, SCAND3	0.06	0.13	0.09	0.24
San	Jarosław	NAO, SCAND1	0.11	0.31	**0.43**	**0.56**
		NAO, SCAND3	0.12	0.29	*0.41*	**0.59**
		NAO, SCAND4	0.12	0.29	*0.41*	**0.57**
		NAO, SCAND8	0.12	0.28	*0.40*	**0.56**
San	Radomyśl	NAO, SCAND3	0.14	0.14	0.29	*0.40*
		NAO, SCAND4	0.15	0.14	0.29	*0.41*
Wisła	Sandomierz	NAO, SCAND3	0.27	0.14	0.16	*0.41*
		NAO, SCAND4	0.26	0.13	0.16	**0.43**
Wisła	Zawichost	NAO, SCAND3	0.10	0.20	0.25	0.25

*number means particular month (i.e. 1 = January, 2 = February, etc.).
bold: $P < 0.001$; **bold**: $P < 0.01$; *italic*: $P < 0.05$.

Table 4 Formulae for calculating maximum and minimum river discharges in the warm season.

River	Water gauging site	Formula	Variability of discharge* (%)	Error of estimation (%)
Raba	Stróża	(1) $Q_{max} = 196.35 - 18.32NAO - 36.70SCAND3$ (2) $Q_{min} = 1.8 + 0.02NAO - 0.03SCAND5$	11.6 9.6	±80.6 ±33.9

* explained by variability of NAO and SCAND.

where E is the error of estimation (%), Q'_{EX} is calculated river discharge; Q_{EX} is observed river discharge; and $\overline{Q}$ is the mean value of observed discharge.

The linear multiple regression formulae were calculated for maximum and minimum river discharges. The summer floods occur in July or August; therefore, the formulae for the warm season consider the winter NAO index and SCAND index in the month preceding the hydrological extreme event. Only the formula for the Raba (Stróża) basin was calculated, because the multiple correlation coefficients for the rest of the basins were not high and significant (Table 4). The Raba (Stróża) basin is located in the western part of the Polish Carpathians, where the river regime is mostly influenced by western oceanic air masses, both in warm and cold seasons. Basins located in the eastern Polish Carpathians are strongly influenced by continental air masses.

The formulae for the cold season consider the winter NAO index and SCAND index in March. The SCAND index in April was not taken into consideration, although the correlation coefficients were remarkable. Maximum discharges in Carpathian rivers in the meltwater season usually occur in April. However, they may occur also in March, and it would then be too late to predict river extremes in early spring. The formulae are presented in Table 5. Formula have been developed for four basins. The San (Jarosław, Radomyśl) and Wisłok (Tryńcza) basins are located in the eastern part of the investigated area, and the Wisła (Sandomierz) basin includes almost the whole upper Wisła basin, except the San River (Fig. 2). Variability of discharge values, explained by NAO and SCAND, are not high (13.7–34.8%), nevertheless it gives approximate information on the dimension of maximum or minimum river discharges. The error of estimation of river discharge by the presented formula is differentiated (26.5–80.6%). For minimum discharges it is unexpectedly small: 26.5–37.3% (Tables 4, 5).

The Hurrell's winter NAO index refers to four months, and it is possible that air circulation in one particular month is responsible for weather and hydrological conditions in early spring or during the summer rain period. Hence, it is recommended that

Table 5 Formulae for calculating maximum and minimum river discharges in the cold season.

River	Water gauging site	Formula	Variability of discharge* (%)	Error of estimation (%)
Wisłok	Tryńcza	(3) $Q_{max} = 175.98 - 10.49NAO - 14.59SCAND3$ (4) $Q_{min} = 7.53 + 0.40NAO - 0.26SCAND3$	13.7 18.5	±47.2 ±36.3
San	Jarosław	(5) $Q_{max} = 510.89 - 48.78NAO - 41.14SCAND3$ (6) $Q_{min} = 20.61 + 1.47NAO - 0.21SCAND3$	16.8 34.8	±69.5 ±34.9
San	Radomyśl	(7) $Q_{min} = 43.06 + 2.13NAO - 0.49SCAND3$	16.0	±37.3
Wisła	Sandomierz	(8) $Q_{min} = 106.47 + 3.80NAO - 2.85SCAND3$	16.8	±26.5

* explained by variability of NAO and SCAND.

similar analysis considering Jones's NAO index for particular months be carried out, which correlate with weather conditions in Poland better than the Rogers NAO index (Marsz & Styszyńska, 2001). It is also possible, that more remarkable relationships between the North Atlantic Oscillation and river runoff can be obtained, in particular atmospheric circulation periods distinguished on the basis of NAO index variability.

CONCLUSIONS

A river flow regime is generated by the action of various processes at local, regional and global scales, and river regime reflects the climate and physiographic conditions of a basin. The knowledge of the contribution of these processes—in particular climatic ones—is important for explaining and forecasting hydrological extreme events. The Carpathian Mountain climatic conditions are influenced by the North Atlantic Oscillation and the Scandinavia baric system. According to the analysis above, the relationships between maximum and minimum river discharges have not been strong, contrary to expectations. However, some interesting relationships have been described and a few linear multiple regression formulae have been developed. They may be used for hydrological forecasting of Carpathians extreme river discharges in warm and cold seasons and they may allow the implementation of a warning system for dangerous maximum or minimum discharges. It would contribute to prevention and mitigation of drought and flood damage.

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