DECADAL VARIABILITY OF THE DANUBE RIVER STREAMFLOW IN THE LOWER BASIN IN CONNECTION WITH THE LARGE SCALE ATMOSPHERIC AND OCEANIC CONDITIONS

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Abstract: The main objectives of this paper is the search for and understanding of the large scale physical mechanisms responsible for the Danube river streamflow in the lower basin.
The decadal variability (>5 years) of the Danube river streamflow in the lower basin and its connection with the North Atlantic Oscillation (NAO) is analysed for the period 1931-1995. Associated linkages with precipitation (PP) in the European sector, global sea surface temperature (SST) and atmospheric circulation (SLP) for the period 1931-1991, and the 500 mb geopotential heights (G500) over the northern hemisphere for the period 1948-1995 are also investigated.
The results show that there is an out of phase relationship between the time series of the Danube river streamflow anomalies and the NAO index, and a phase relationship with the time series of a PP index defined as the average of normalized precipitation anomalies over a large area including the Danube basin.
The correlation maps between the river streamflow anomalies and global SST show coherent large scale patterns. A tripol-like SST structure similar to that appearing during the negative phase of the NAO together with a negative SST anomalies in the central North Pacific and positive SST anomalies in the eastern and central tropical Pacific are associated to high values of the Danube river streamflow. Physically consistent sea level pressure and 500 mb geopotential height are found to support these results.
Keywords: Danube river lower basin, North Atlantic Oscillation, decadal variability.

1. Introduction

Research studies show that climate variations influence many components of the climate system. Evidence from long hydrological records shows that periods with anomalous hydrological behaviour (Arnell et al., 1993) are associated with persistent climatic anomalies.

Interannual to decadal variability of the atmosphere over the North Atlantic region is characterised by the North Atlantic Oscillation (NAO) teleconnection pattern (Bjerknes, 1964; Hurrell, 1995). The NAO is a fluctuation in pressure gradients across the North Atlantic with centres of action near the Icelandic low and the Azores high. It is the dominant mode of atmospheric behaviour in the North Atlantic throughout the year, mostly pronounced during winter and a primary climatic factor orchestrating hemispheric scale climatic fluctuations centred over the Atlantic.

Research studies focused on the influence of the NAO on the variability of various climatic elements at time scales ranging from seasonal to interannual and decadal show that the NAO is responsible for generating systematic, large-amplitude patterns in the anomalies of temperature, precipitation, wind speed, latent and sensible heat fluxes, and hence sea surface temperature over much of the extra-tropic North Atlantic (van Loon and Rogers, 1978; Kushnir, 1994; Hurrell and van Loon, 1997). Because the signature of the NAO is strongly regional, a simple index of the NAO has been defined as the difference of the standardized sea level pressure anomaly measured at Lisbon, Portugal, and at Stykkisholmur, Iceland (Hurrell, 1995).

Correlations with hydrological data have shown that when NAO index is high, streamflow (particularly in winter) is above average in northern Europe and below average in the southern Europe (Shorthouse and Arnell, 1997, Dettinger and Diaz, 2000). Because the river flows directly depend on precipitation it is evident that there is a linkage between precipitation anomalies associated to extreme phases of the NAO, and river flows regime in Europe.

At decadal time scale (> 5 year) the North Atlantic Oscillation (NAO) strongly influences the moisture balance (i.e. precipitation minus evaporation) over Europe. During positive phase of the NAO (deep Icelandic Low and strong Azores High) enhanced precipitation over northern Europe associated with less precipitation over central and southern Europe occurs (Hurrell, 1995; Hurrell and van Loon, 1997; Rîmbu et al., 2001). A reverse situation occurs during the negative phase of the NAO.

The Danube river has a very large catchment basin extending from the central Europe (upper basin) to the south-eastern Europe (lower basin). Its flow regime and other hydrologic characteristics are subject to significant influences due to climate variability (Bondar and Buţă, 1995). Based on existing observational data in the Danube river basin many research studies pointed out on the effect of precipitation and temperature changes on the Danube flow regime (Starosolszky and Gauzer, 1998), on the possible climate impacts on the water resources in the Danube river basin (Behr, 1998; Petrovic, 1998) and on changes of hydrological characteristics for selected river basins in the case of climate change scenarios (Dvorak et al., 1997; Stănescu et al., 1998). Because the decadal variability in the NAO has became especially pronounced since the early 1970s and has determined decade-long regional climatic anomalies (winter dry conditions over southern Europe and Mediterranean and wet anomalies from Iceland eastward through Scandinavia (Zorita et al., 1992; Wilby et al., 1997; Werrity and Foster, 1998)) we expect that NAO signal be detected also in the decadal variations of the Danube streamflow in the lower basin.

The goal of the present study is to investigate the role of the NAO on decadal variability of the Danube river streamflow in the lower basin and its connections with the atmospheric circulation and sea surface temperature at global scale based on observed data.

The paper is organised as follows. After the Introduction a brief climate description of the Danube river basin is given in section 2. The data and methods are shortly described in Sections 3 and 4, respectively. The decadal variability of river streamflow and its relation with the NAO and precipitation in the European sector, and with global sea surface temperature (SST), sea level pressure (SLP) and 500 mb geopotential height (G500) are presented in section 5.

2. Brief climate characteristics of the Danube basin

The climate of the Danube basin is very diverse. There is an influence of Atlantic climate in the western part of the upper basin, Mediterranean influence in the southern part of central and lower basin, while the rest has a continental climate.

The Danube river streamflow is determined in principal by precipitation and evaporation processes from the Danube catchment basin. The mean quantity of precipitation which falls in a certain area of the Danube catchment basin is strongly dependent on the orography. Because one third of the basin is formed by mountains while the remaining consists of hills and plains, the annual precipitation total ranges from about 2000 mm per year in the high regions while in the plains it is only about 500 mm per year. Evaporation is also important for the water balance in the Danube catchment basin, especially in the lower regions where the mean annual evaporation varies between 450 mm and 650 mm per year.

3. Data

The annual mean streamflow was calculated from monthly mean streamflow time series of Danube river measured at six hydrological stations located in the lower basin, on the Romanian border. The names of the stations, their locations (latitude and longitude) as well as some simple statistical characteristics of the river streamflow for the period 1931-1995 are presented in Table 1.

Monthly precipitation data (PP) for land areas were extracted from Hulme data set

(Hulme, 1992, 1994). The sea surface temperature (SST) data set is extracted from the global analyses derived from in situ data (Kaplan et al.,1997). The spatial resolution of PP and SST data sets is 5° lat×5°lon.

Sea level pressure (SLP) data over the ocean (horizontal resolution 4°lat×4°lon) were extracted from the Comprehensive Ocean-Atmosphere Data Set (COADS). The anomalies were calculated with respect to the climatological annual cycle for the period 1951-1980 (Kaplan et al., 2000). Both for SST and SLP, we have analysed the period 1931-1991.

The 500 mb geopotential heights (G500) for horizontal resolution 2.5°lat×2.5°lon were taken from the NCEP/NCAR reanalyses data set (Kalnay et al., 1996). The selected period is 1948-1995.

Table 1. The hydrological stations form the Danube river lower basin, their coordinates and some simple statistical characteristics

Station	Coordinates	Annual mean streamflow (m^3s^{-1})	Standard deviation (m^3/s)		Variance[a] (%)	Coeff. of variability[b]
			Original	Decadal		
Orşova	22°22'E; 44°40'N	5441	940	519	30.48	9.54
Corabia	24°35'E; 43°46'N	5716	954	573	36.07	10.02
Turnu Măgurele	24°53'E; 43°42'N	6062	1032	618	35.86	10.19
Giurgiu	25°56'E; 43°53'N	5944	974	534	30.06	8.98
Călăraşi	27°00'E; 44°10'N	6086	1080	658	37.12	10.81
Ceatal Izmail	28°48'E; 45°20'N	6372	1160	670	33.36	10.51

[a]Decadal/original
[b](Decadal st.dev./annual mean)x100.

4. Methods

All data were processed in the same way. First, annual means were calculated from monthly means. Then, annual anomalies with respect to the mean and normalised by local standard deviation estimated for the period 1931-1995 were produced. The annual normalised anomalies were smoothed with a five-year running mean filter to obtain the decadal component of the series.

To explain the decadal variability of the Danube river streamflow we drawn composite maps. All maps corresponding to the times when the normalised streamflow anomaly was lower (higher) than one standard deviation were averaged. The map of difference between high flow and low flow averaged maps was used to identify the large scale precipitation and atmospheric circulation anomalies associated with decadal variability of the Danube river streamflow in its lower basin.

Correlation maps between the time series of decadal anomalies of river streamflow and the global SST and SLP have been produced to investigate possible coherent large scale connections.

5. Results

In this section we present the results of the analysis of the relationship between decadal variations of the Danube river streamflow and precipitation in the river catchment basin, global sea surface temperature (SST) and atmospheric circulation (SLP), and the 500 mb geopotential heights (G500) over the northern hemisphere.

5.1 Linkage with PP in the European sector and the NAO

To have a quantitative measure of the strength of decadal (> 5 year period) variations of the Danube river streamflow, the variance both for original (annual means) and decadal time series of the annual mean streamflow measured at selected hydrological stations has been calculated. The ratio between decadal and original variance for each station is presented in Table 1. Consistent with partition of variance between interannual and decadal time scales of the river streamflows in Europe (Dettinger et Diaz, 2000) more than 30% of the mean annual streamflow variability is contained in the decadal component at all selected stations in the Danube lower basin.

The time series of annual means of Danube streamflow recorded at selected hydrological stations during the period 1931-1995 are represented in Figure 1 (thin line). The solid line represents the decadal component obtained by smoothing the series with a 5-year running mean filter. A simple visual inspection of these time series shows that the decadal variations at all stations are quite similar. A decreasing trend is evident at all stations during the last two decades.

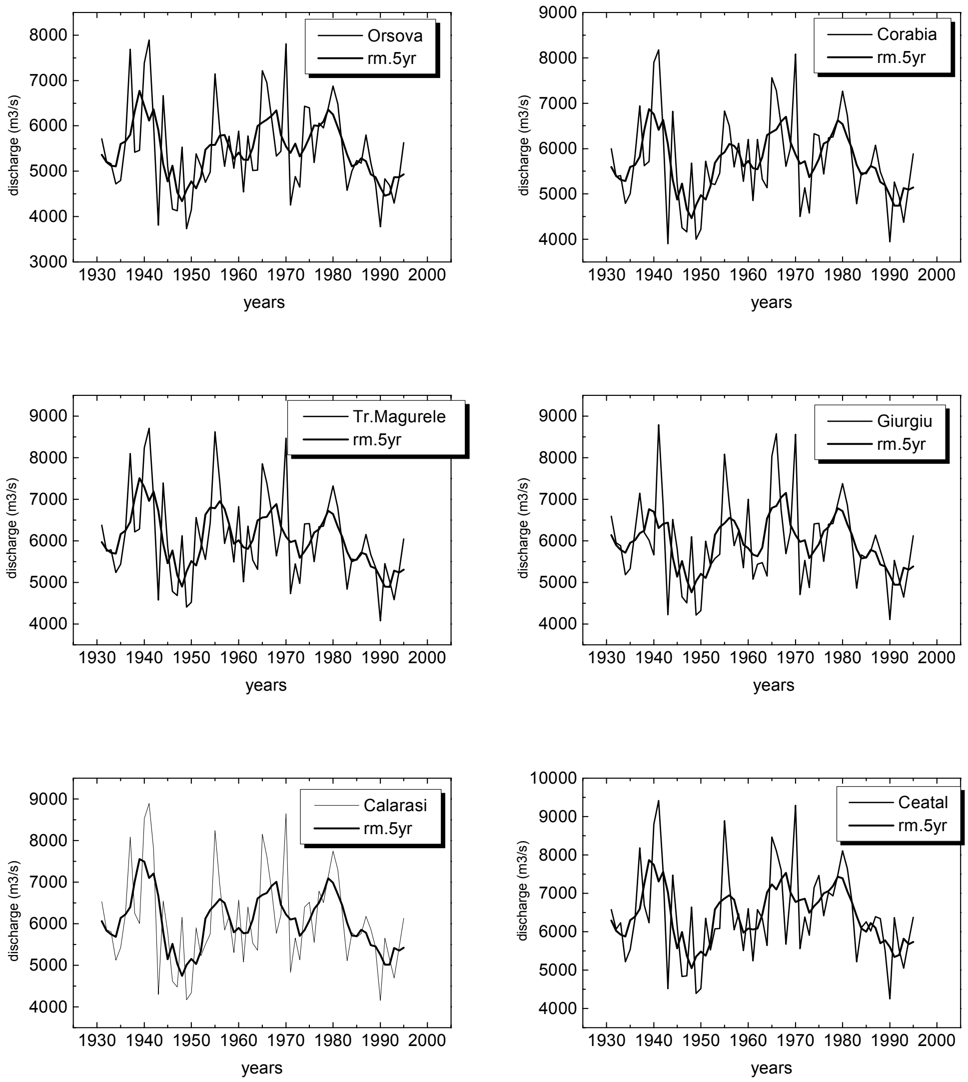


Figure 1. The time series of annual means of the Danube river streamflow in the lower basin (thin line) measured at hydrological stations presented in Table 1 for the period 1931-1995. The solid line represents the decadal component obtained by smoothing the series with a 5-year running mean filter. Unit is m^3/s.

The correlation coefficients between the decadal streamflow time series at Ceatal Izmail and the rest of the five stations from the Danube lower basin have been calculated and presented in Table 2. Because the six time series of Danube decadal streamflow are highly correlated each other (the correlation coefficients are greater than 0.91) in the following we have considered, for simplicity, only the time series of river streamflow at Ceatal Izmail as representative for the Danube river lower basin and have referred it as the Danube river streamflow.

Table 2. The linear correlation coefficients between the time series of annual streamflow at Ceatal Izmail station and five hydrological stations from the Danube river lower basin.

	Correlation coefficient				
	Orşova	Corabia	Tr. Măgurele	Giurgiu	Călăraşi
Ceatal Izmail	0.978	0.971	0.914	0.938	0.975

The streamflow behaviour has been analysed in connection with precipitation field and the NAO.

The composite PP map (Fig. 2) shows that high values of precipitation over the Danube basin occur in association with high values of Danube river streamflow. It is interesting to note that higher precipitation anomalies are located in the upper and central basins that are the regions with the main tributaries to the total Danube streamflow in the lower basin. Accordingly, the decadal variability of river streamflow in the lower basin reflects mainly the decadal variability of precipitation from the upper and central catchment basins.

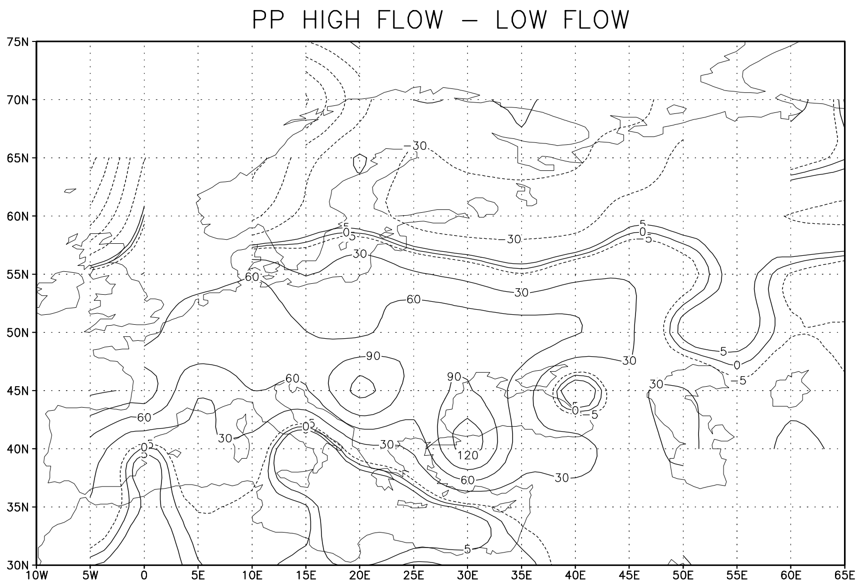


Figure 2. The composite map of precipitation in the European sector based on decadal component of Danube river streamflow for which the normalized anomaly was less/greater than one standard deviation. Unit is mm

Based on PP pattern represented in Figure 2 a PP index has been defined by averaging the normalised PP anomalies from the region (5°E-35°E; 40°N-55°N). This domain includes the whole Danube river catchment basin. The correlation coefficient between the time series of normalised streamflow anomalies and the time series of PP index is 0.80. The values of coefficient of variability (i.e. standard deviation/mean*100) of streamflow (about 10%) and of precipitation over Danube river catchment basin (about 7%) suggest that decadal PP and streamflow variability is dominant.

Many research studies showed that decadal precipitation variability over Europe is related to the decadal variability of the NAO (Hurrell, 1995; Rîmbu et al., 2001). Therefore, the NAO signal should be present in the European river streamflow time series.

We have represented in Figure 3 the decadal time series of the NAO index (thin line), the normalised Danube river streamflow anomalies (solid line) and the PP index (dotted line). It is evident from this figure that there is an out of phase relationship between the Danube river streamflow and the NAO index. The correlation coefficient between these time series is -0.75, consistent with other studies (Shorthouse and Arnell, 1999; Dettinger and Diaz, 2000) that showed that the river streamflows tend to be lower than normal in central and southern Europe and higher than normal in the northernmost Europe when NAO is in its positive phase. As Fig. 3 shows, since 1970 NAO index run an upward trend while the Danube river streamflow was continuously decreasing. A simple visual inspection shows that the time series of the Danube river streamflow and the PP index present similar decadal variations with precipitation leading the streamflow.

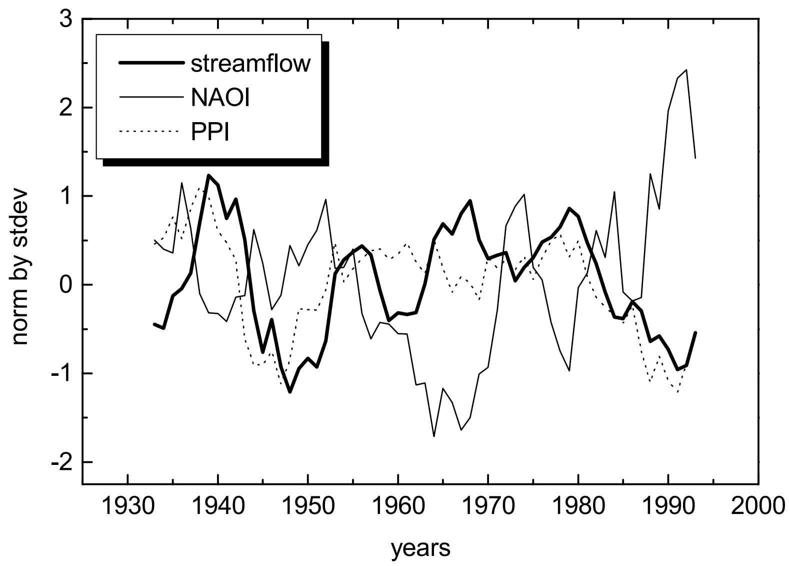


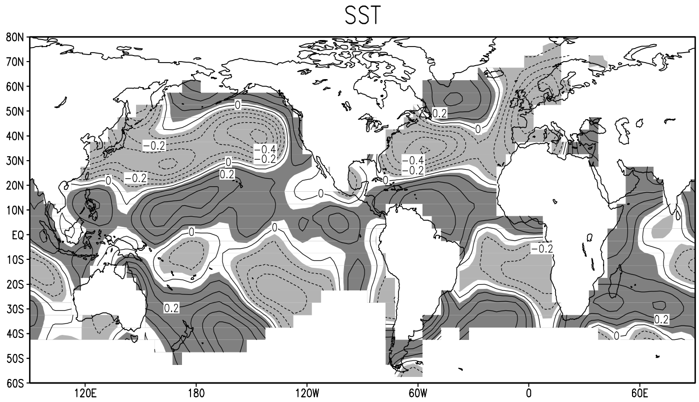
Figure 3. The time series of normalized anomalies of Danube river streamflow at Ceatal Izmail station (solid line), NAO index (thin line), PP index (dashed line). All time series were normalised and smoothed with a 5-year running mean filter.

5.2 Linkage with global SST and SLP

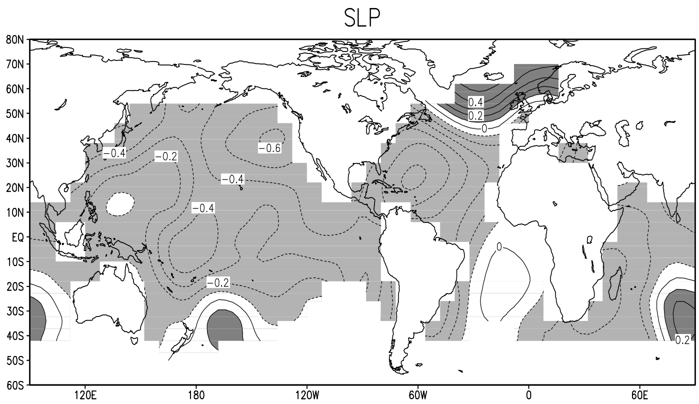
According to the results presented in the previous sections the decadal variations of the Danube river streamflow can be related to the NAO in the extent to which NAO controls the precipitation regime in the Atlantic European sector (Hurrell and van Loon, 1997; Rîmbu et al., 2001). Although our analysis was focused on the NAO influence on the Danube river streamflow in the lower basin, we looked at some atmospheric and ocean field associations at global scale.

Several studies have established that large scale SST fluctuations can be linked to atmospheric circulations that produce precipitation fluctuations (Dai et al., 1997; Latif et al., 2000). One of the most widely studied phenomenon is El Niño-Southern Oscillation (ENSO) that generates coherent anomaly patterns of temperature and precipitation in regions all over the globe (Dai and Wigley, 2000). However, the direct impact of ENSO on the North Atlantic and Europe appears to be weak.

The correlation map between the time series of the Danube river streamflow and global SST represented in Figure 4a emphasizes coherent large scale patterns. In the North Atlantic a tripole-like SST pattern similar to the SST pattern associated with negative phase of the NAO (Hurrell, 1995) appears in connection with positive anomalies of the Danube river streamflow. The centres of the tripole anomaly SST pattern appears to be displaced towards the eastern coast of North America comparative to the SST pattern in the North Atlantic associated to the NAO. Higher than average values of Danube river streamflow tend to be associated with cooler than average SST anomalies in the central North Pacific and warmer than average SSTs along the western coast of North America, eastern and central tropical Pacific. Our results are compatible with the negative correlation between North Pacific SSTs and river streamflows throughout North America, tropical Africa, central and southern Europe reported by Dettinger and Diaz (2000).



a)



b)

Figure 4. a) The correlation map between the time series of decadal component of the Danube river streamflow measured at Ceatal Izmail station and sea surface temperature.
b) As in a) but for sea level pressure.

The correlation map between the time series of the Danube river streamflow and the sea level pressure over the North Atlantic (Fig. 4b) emphasises coherent large scales SLP patterns consistent with the corresponding SST patterns (Fig 4a). Over the North Atlantic, high values of the Danube streamflow are related to a dipole-like pattern of SLP anomalies similar to that corresponding to negative phase of the NAO, and are consistent with the negative correlation between NAO index and the Danube streamflow. In agreement with SST anomalies, the central North Pacific is dominated by negative SLP anomalies. It is evident from Figure 4b that the SLP anomaly pattern over the central and eastern Pacific does not present an out of phase relation with the SLP anomalies over the western tropical Pacific as in the case of interannual ENSO phenomenon. This pattern might suggests that the SST and SLP anomalies from the tropical Pacific are not generated through atmosphere-ocean interaction processes that produce the typical interannual ENSO, and that their impact on decadal variability of Danube river is small.

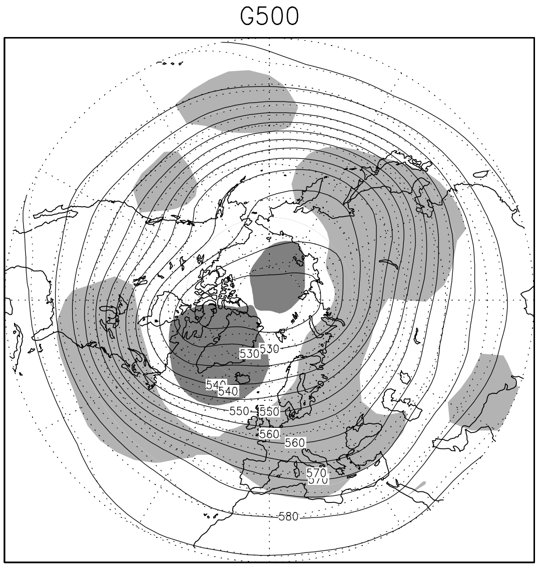


Figure 5. The composite map of the northern hemisphere geopotential height at 500 mb (G500) based on the time series of decadal Danube river streamflow. Solid line corresponds to high flow and dashed line to low flow. The regions where the difference between the composite G500 maps corresponding to high flow and low flow is higher (lower) than 10 gpm are shaded (light shaded). The contour interval is 10 dam.

5.3 Linkage with the Northern Hemisphere G500

The composite map of G500 (Figure 5) emphasises a dipole-like pattern in the North Atlantic that is characteristic to the negative phase of the NAO, and a large area of negative G500 anomalies in the north Pacific that are consistent with the corresponding SLP patterns presented in Figure 4b. The G500 variations corresponding to the difference between the high values and low values of the Danube river streamflow are higher in the North Atlantic than the corresponding variations over the North Pacific. Low values of G500 over central and southern Europe associated to high values of the river streamflow are consistent with increasing precipitation over a large area that includes the entire Danube river catchment basin (Rîmbu et al., 2001) and confirm our supposition that the North Atlantic processes (i.e. the NAO) play the principal role in generating the Danube river streamflow decadal variations.

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