Impacts of the North Atlantic Oscillation and the El Niño–Southern Oscillation on Danube river flow variability

N. Rimbu,[1,2] M. Dima,[1,2] G. Lohmann,[1,3] and S. Stefan[4]

Received 19 May 2004; revised 27 October 2004; accepted 29 October 2004; published 7 December 2004.

[1] Based on analysis of observational data we show that the impact of the North Atlantic Oscillation (NAO) and El Niño–Southern Oscillation (ENSO) on the Danube river flow variability shows important decadal variations. A lag-correlation analysis reveals that winter SST from tropical Pacific and some regions from the North Atlantic are significantly correlated with the streamflow variations from spring and summer suggesting a possible predictive skill of the Danube river flow anomalies in these seasons using winter SST as a predictor. *INDEX TERMS:* 1655 Global Change: Water cycles (1836); 1704 History of Geophysics: Atmospheric sciences; 1854 Hydrology: Precipitation (3354); 1860 Hydrology: Runoff and streamflow; 3309 Meteorology and Atmospheric Dynamics: Climatology (1620). **Citation:** Rimbu, N., M. Dima, G. Lohmann, and S. Stefan (2004), Impacts of the North Atlantic Oscillation and the El Niño–Southern Oscillation on Danube river flow variability, *Geophys. Res. Lett.*, *31*, L23203, doi:10.1029/2004GL020559.

1. Introduction

[2] Interannual to decadal variability in streamflow play an important role in the development and management of water resources in most regions. Such variations occur in connection to changes in regional atmospheric circulation, which often are related to large scale processes [*Dettinger and Diaz*, 2000; *Rimbu et al.*, 2002]. Two of the most important phenomena that influence the streamflow variability at regional and global scale are the North Atlantic Oscillation (NAO) and the El Niño–Southern Oscillation (ENSO) [*Dettinger and Diaz*, 2000; *Cullen et al.*, 2002].

[3] The positive phase of the NAO is associated with above-normal precipitation (PP) over northern Europe and Scandinavia and below-normal PP over southern and central Europe. Opposite pattern of PP anomalies is observed during the negative phase of the NAO. Consistent with these PP patterns streamflow in northernmost Europe is lower (higher) than usual and streamflow in most of the rest of Europe is higher (lower) than normal during the negative (positive) NAO phase [*Dettinger and Diaz*, 2000]. The El Niño–Southern Oscillation (ENSO) influences significantly the precipitation over Europe. The annual mean PP anomaly pattern associated to El Niño shows positive PP anomalies over central and southern Europe [*Dai et al.*, 1997]. Consistent with the ENSO related PP pattern over Europe, during El Niño events, large streamflows are usually recorded in most rivers from Europe. Broadly opposite patterns occur during La Niña years [*Dettinger and Diaz*, 2000].

[4] In this study we investigate the ENSO and NAO teleconnections in Danube river flow variability for the period 1840 to 1998. We show that the teleconnections of these two phenomena strongly influence the Danube river flow variability.

2. Data

[5] The primary quantity analyzed in this study is the Danube river flow. The Danube is one of the most important European waterways, flowing 2857 kilometers across the continent from the Schwarzwald (Black Forest) Mountains in Germany down to the Black Sea. The Danube basin extends to 817 000 km^2 with many countries sharing the Danube catchment area. The time series of Danube river flow used in this study is recorded at Orsova hydrological station (44.40°N;22.22°E). The data were provided by the National Institute for Meteorology and Hydrology (NIMH) from Bucharest, Romania. The streamflow data covers the period 1840 to 1998 with monthly resolution. Our study is focused on the relation between the winter (January/February) ENSO and NAO and streamflow variability recorded at this hydrological station.

[6] The time series of the annual mean Danube flow for the period 1840–1998 (Figure 1) shows strong interannual to decadal variations. The mean Danube flow during this period is 5441 m^{3}s^{-1} and the mean standard deviation is 940 m^{3}s^{-1}. To verify the accuracy of the streamflow data we calculate a precipitation (PP) index by averaging the annual PP over the area (40°N–55°N;10°E–30°E) which covers the entire Danube drainage basin. The PP data were extracted from the gridded PP data set (2.5° lat × 3.75° lon) constructed at CRU [*Hulme and New*, 1997], covering the period 1900 to 1998. This index, abbreviated as PP-D, follows temporal variations similar to those of the Danube flow (Figure 1).

[7] Large scale SLP patterns associated to the river flow variability are based on the updated version of the SLP data set constructed by *Trenberth and Paolino* [1980]. This data set covers the period 1899 to present with a resolution of 5° lat × 5° lon. The SST patterns associated to the streamflow variability are based on the global SST data set constructed by *Kaplan et al.* [1998]. The SST data set has 5° lat × 5° lon resolution covering the period 1856 to 2000. The Niño3 index, which is used as a measure of the amplitude and phase of the ENSO is defined as the monthly SST averaged over the eastern half of the tropical Pacific (5°S–5°N,

[1]Department of Geosciences, Bremen University, Bremen, Germany.
[2]Also at Department of Atmospheric Sciences, Bucharest University, Bucharest-Magurele, Romania.
[3]Also at Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany.
[4]Department of Atmospheric Sciences, Bucharest University, Bucharest-Magurele, Romania.

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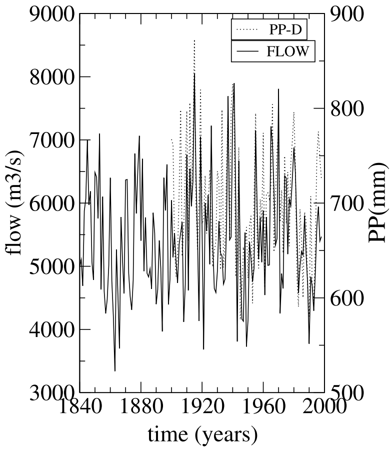

Figure 1. The time series of the annual mean Danube river flow recorded at hydrological station Orsova (44.40°N–22.22°E) for the period 1840 to 1998 (159 years) (solid line), and the time series of the annual precipitation over the Danube drainage basin for the period 1900–1998 (dotted line). Units are m^3s^{-1} and mm.

90°W–150°W). The index used here is the version prepared by *Kaplan et al.* [1998]. For investigation of the NAO signature in streamflow variability we used the time series of the NAO index, defined as the normalized pressure difference recorded at Reykjavik (southwest Iceland) and Gibraltar, prepared at CRU [*Jones et al.*, 1997].

[8] Quantitative comparison between streamflow and climate variables are made using conventional linear correlation analysis. The level of significance of correlations is established by means of Student's t test [*von Storch and Zwiers*, 1999]. The anomalies associated with climatic indices or streamflow are derived using composite analysis. The composite maps are defined by averages of climatic fields when climatic indices or the streamflow were greater (smaller) than +0.75(−0.75) standard deviation. This threshold was chosen as a compromise between the strength of the climate anomalies associated to flow anomalies and the number of maps which satisfy this criteria. Further analysis has shown that the results are not sensitive to the exact threshold value used for our composite analysis.

3. Results

3.1. NAO and ENSO Signature on the Streamflow Variability

[9] The composite map of annual PP anomalies based on the winter NAO index (Figure 2a) shows a pattern similar to that associated to the NAO during the winter season [e.g., *Cullen et al.*, 2002]. This pattern shows a monopolar structure over the Danube drainage basin. Positive (negative) phase of winter NAO is associated with negative (positive) annual PP anomalies over entire Danube drainage basin. The PP-D index defined above is significantly negative correlated ($r = -0.27$) with the winter NAO index, consistent with the PP pattern associated to the winter NAO (Figure 2a). The annual mean streamflow anomaly time series is significantly positive correlated ($r = +0.70$) with the PP-D index as well as significantly negative correlated ($r = -0.34$) with the winter NAO index.

[10] The composite map of annual PP anomalies associated to the winter Niño3 index (Figure 2b) shows a monopolar structure over the Danube drainage basin (Figure 1). High (low) PP over the Danube drainage basin are detected during El Niño (La Niña) years. A similar pattern over Europe appears in the first Empirical Orthogonal Function (EOF) of global annual mean precipitation anomalies over land area, which is strongly related to ENSO [*Dai et al.*, 1997]. The winter Niño3 index is significantly positive correlated both with PP-D index ($r = +0.25$) and annual mean stramflow time series ($r = +0.30$), consistent with the PP pattern associated to ENSO (Figure 2b).

[11] To better asses the relation of NAO and ENSO with Danube flow we construct the composite maps of winter Northern Hemisphere SLP and global SST based on annual mean Danube flow anomalies. The composite analysis reveals that the streamflow variability is controlled by a coherent large-scale atmospheric circulation pattern that contain elements of PNA and NAO in opposite phases (Figure 3a). The corresponding SST pattern (Figure 3b) project well on the ENSO and NAO related SST patterns. These SST and SLP patterns are consistent with the correlations of Niño3 and NAO indices with the streamflow.

[12] Recent studies [*Mariotti et al.*, 2002; *Knippertz et al.*, 2003] identified decadal variations in the correlations of ENSO indices with European rainfall. Consistent variations of the ENSO-related SLP anomalies over Europe during the last century were also detected [*Rimbu et al.*, 2003]. Motivated by the above mentioned studies we investigate the variability of the correlation of the winter NAO and

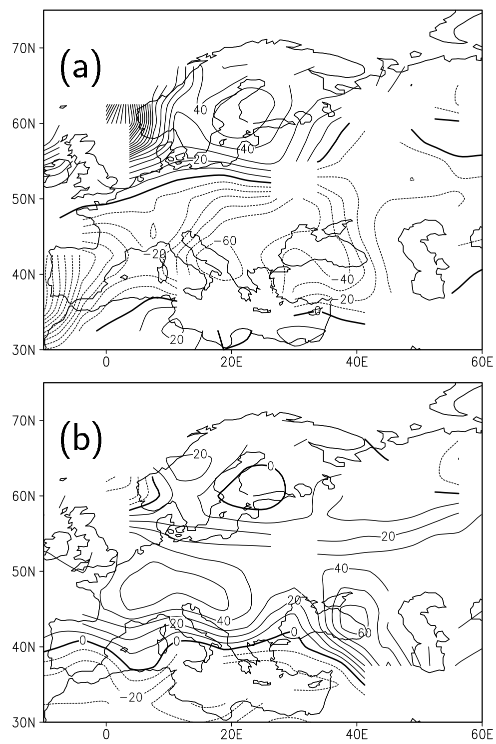

Figure 2. The composite map of annual precipitation anomalies with respect to winter (January/February) a) NAO and b) Niño3 indices for the period 1900–1998. Units are mm.

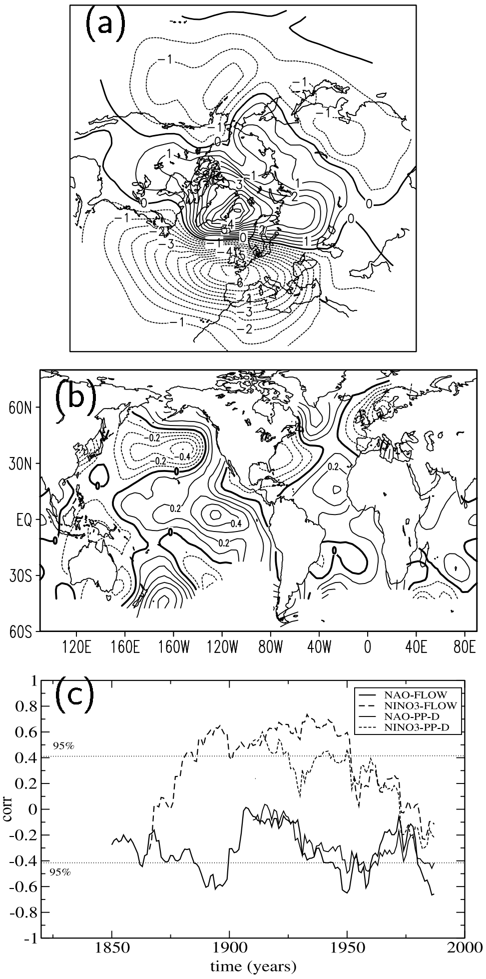

Figure 3. Composite map of winter a) sea level pressure, and b) sea surface temperature based on annual mean Danube flow anomalies for the period 1900–1998. Units are hPa and °C. c) The correlation of winter (January/February) NAO and Niño3 indices with annual mean Danube river flow (thick lines) and with average annual precipitation anomalies over the Danube drainage basin (thin lines) in a 21-year moving window.

Niño3 indices with the annual mean Danube flow anomaly time series during the period 1856–1998.

[13] The correlation curves (21-year moving window) (Figure 3c) show important multidecadal variations. Both winter Niño3 and NAO indices are significantly correlated with annual mean flow anomalies for the windows centered during 1930s to 1950s consistent with significant correlation between ENSO and NAO during this period [*Rimbu et al.*, 2003; *Knippertz et al.*, 2003]. A relatively small period when both NAO and ENSO were significantly related to streamflow appear also around 1890. The streamflow is significantly correlated only with Niño3 during 1900s to 1930s and only with the NAO for the windows centered around 1960 and after 1980s. There are also windows when the streamflow was not significantly correlated either with NAO or Niño3. More precisely, for the period 1856–1998 the annual mean streamflow anomalies are significantly correlated (95% level) both with the NAO and Niño3 for 20% of the windows, only with the NAO for 15% of the windows, only with the Niño3 for 34% of the windows, and neither with NAO nor with Niño3 for 31% of the windows. These percentages are robust against the exact definition of the NAO and ENSO indices, respectively. The PP-D index show similar decadal variations in the correlation with NAO and Niño3 indices as the streamflow (Figure 3c).

3.2. Potential Predictability of Danube Flow Variability From Winter SST

[14] Recent studies [*Oldenborgh et al.*, 2000; *Knippertz et al.*, 2003] show that the ENSO influence on European rainfall appears to be strongest for a delay of one season. A lag-correlation analysis reveals a strong relationship between winter SST and Danube flow anomalies during boreal spring and summer seasons. The correlation between boreal spring (MA) streamflow and global winter SST (Figure 4a) shows a coherent global pattern with positive correlations over almost the entire tropical region. Negative correlations appear in the central North Pacific, western subtropical North Atlantic and eastern North Atlantic. The SST pattern is very similar to the SST pattern associated to the annual mean Danube flow anomalies (Figure 3b).

[15] Based on the correlation pattern represented in Figure 4a we define four SST indices by averaging the normalized winter SST anomalies over the (0°–20°E;40°N–70°N), (70°W–50°W;20°N–40°N), (60°W–10°W;0°–20°N) and (180°W–100°W;10°S–10°N) which are referred as SST1, SST2, SST3 and SST4, respectively. The spring streamflow and winter SST indices defined above are significantly correlated for the period 1856 to 1998. However, the running correlation coefficients (21-year window) between these indices and spring streamflow show

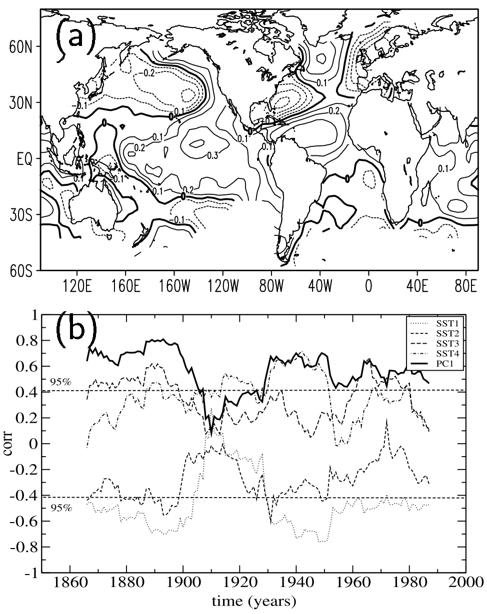

Figure 4. a) The correlation map of spring (March/April) Danube flow anomalies and winter (January/February) sea surface temperature (SST) for the period 1856–1998. b) The running correlations (21-year window) of the four SST indices (see text for the definition) and time coefficients of the first EOF of these indices (PC1) with spring (March/April) Danube flow anomalies.

important decadal variations (Figure 4b). Interestingly, during the period 1900s to 1930s the spring (MA) streamflow anomalies are significantly correlated only with tropical Pacific SST anomalies. During this period the annual mean streamflow was significantly correlated with the winter Niño3 but not with the winter NAO (Figure 3c). The first EOF of the four SST indices defined above is consistent with the correlation map represented in Figure 4b and describes 39% of the variance (not shown). The correlation of the time coefficients of this EOF (PC1) and spring Danube flow anomalies in a 21-year sliding window shows relatively weak decadal variations (Figure 4b). The correlations are positive and highly significant, excepting the windows centered during 1900s to 1930s (Figure 4b).

[16] Considering the period 1856–1998, the correlation between PC1 of the four winter SST indices defined above and winter streamflow is +0.36. The correlation is greatest when PC1 is correlated with spring Danube flow anomaly time series (r = +0.57) and remains significant (at 95% level) also for May/June (r = +0.48) and July/August (r = +0.27). These significant correlations suggests a possible use of the winter SSTs to predict a part of Danube flow anomalies with several months in advance using winter SST as a predictor.

4. Discussion and Conclusions

[17] In this paper we have investigated the relation between variability of Danube river flow anomalies with the NAO and ENSO. We showed that both NAO and ENSO strongly influence the river flow variability. Considering the 1900–1998 period negative (positive) phase of the winter NAO is associated with positive (negative) annual mean Danube flow anomalies. On the other hand, El Niño (La Niña) conditions in the tropical Pacific during winter are associated with positive (negative) annual mean Danube flow anomalies. These results are consistent with the mean NAO and ENSO precipitation patterns over Europe [*Cullen et al.*, 2002; *Dai et al.*, 1997]. However the ENSO and NAO PP patterns presented here represent only the climatological mean. Individual ENSO or NAO events may vary substantially from these mean patterns.

[18] We detected important decadal variations of the NAO and ENSO teleconnections on the Danube flow variability. The similar variations in the NAO and ENSO correlations with PP from the Danube drainage basin suggest that the observed variations on ENSO and NAO impact on Danube flow variability have natural causes. The impact of ENSO on European climate could be dependent on the strength of the ENSO anomalies [*van Loon and Madden*, 1981] or on the asymmetric impact of El Niño versus La Niña [*Pozo-Vásquez et al.*, 2001]. Still, it is not clear what are the physical mechanisms behind NAO-ENSO interactions and their variable impact on European climate. However, it cannot be ruled out that the observed variations in NAO and ENSO correlations with the streamflow are due to stochastic fluctuations rather than long-term physical changes in the climate system.

[19] We detected significant correlations between winter SST and streamflow anomalies during MA, MJ and JA, suggesting a possible prediction of Danube flow anomalies during these months using winter SST as a predictor. Consistent with this result, the winter Niño3 index is greatest correlated with spring European PP anomalies [*Oldenborgh et al.*, 2000; *Knippertz et al.*, 2003]. These significant lag-correlations could be attributed to the delay between ENSO impact on European rainfall as well as to the delay between PP anomalies and streamflow anomalies.

[20] In conclusion, the variability as well as the predictability of Danube river flow is strongly related on the impact of ENSO and NAO on European climate. Future research will establish the physical mechanisms responsible for the ENSO and NAO impact on Danube flow as presented in our study.

[21] **Acknowledgment.** This work is part of the DEKLIM project funded by the German Federal Ministry for Education and Research (BMBF) and the Romanian project PNCDI/CERES 3/105.

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N. Rimbu, M. Dima, and G. Lohmann, Department of Geosciences, University of Bremen, Klagenfurter Str., D-28334, Bremen, Germany. (nrim@palmod.uni-bremen.de)

S. Stefan, Department of Atmospheric Sciences, Bucharest University, 70709 Bucharest-Magurele, Romania.