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Multi-decadal Evolution and North Atlantic Oscillation Influences on the Dynamics of the Danube Delta Shoreline

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ABSTRACT

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A comprehensive analysis of data collected over the last five decades on the Danube delta coast (topographic maps, satellite imagery, GPS surveys and beach profiles) revealed two different shoreline dynamics patterns: (1) high mobility during 1961-1979 interval with high retreating and; (2) advancing rates and low mobility afterwards (1979-2006). The divergence zones in the longshore sediment transport system experienced the highest rates of retreat (~20 m/yr and ~10 m/yr in the first/second time interval), whereas the shoreline advanced fastest along the coast of active lobes (i.e., Chilia and Sf. Gheorghe lobes). During the second interval the decrease of shoreline changes rates was similar for the erosive beaches (with 55-66%) and non-uniform for the accretionary coasts (20-61% for open beaches and 80% for the sheltered secondary deltas). Wind data analysis reveals a good connection between multi-decadal winter storm frequency along the Danube delta coast and negative NAO phases (r = -0.76). The results of the present study clearly show that shoreline changes at decadal time scales are also ultimately driven by the NAO which controls the storminess on the Danube delta coast.

ADDITIONAL INDEX WORDS: *shoreline retreat/advance, longshore sediment transport (LST), storms, multi-decadal climate variability, Black Sea*

INTRODUCTION

On wave-dominated deltaic coasts, a prominent role in the evolution of the shoreline is played by the wave climate and the wave-driven nearshore circulation, in addition to the sediment discharged by the delta-forming river (Coleman and Wright, 1975; Bhattacharya and Giosan, 2003). Along the tideless and wave-dominated Danube delta coast, due to a strong asymmetry in wave attack relative to shoreline orientation, the longshore sediment transport (LST) was found to be the primary control on shoreline mobility (Giosan et al., 1999). Recent LST estimates for the Danube delta coast highlight the major role played by high-energy events. Thus, the LST computations for 1991-2000 interval point to an average amount of 1.25×10^6 m^3/yr of sediment mobilised alongshore by storms, which is 62% of the total LST; more important is the resultant LST during storms, which is responsible for 78% of the net southward LST due to the high frequency of northern and north-eastern storms (Vespremeanu-Stroe, 2004).

The strong influence of storms on the nearshore sediment transport, together with the high correlation between the North Atlantic Oscillation (NAO) and storminess on the Danube delta coast (Vespremeanu-Stroe and Tătui, 2005), prompted the study to examine the possible control exerted by climate variability on shoreline change. NAO is the meridional oscillation in atmospheric mass between the subtropical high and the polar low.

This oscillation is the dominant mode of winter climate variability in the North Atlantic region, extending from central North America, to Europe, and into northern Asia (Hurrell et al., 2001; Hurrell, 2003). The NAO index has been defined as the difference in the sea level air pressure (SLP) between the Icelandic low and the Azores high (Van Loon and Rogers, 1978). The index varies from year to year, but also exhibits a tendency to remain in one phase for intervals lasting several years (Hurrell and van Loon, 1997)

The goal of the present study is to investigate the role of the climate variability (expressed by NAO) upon the Danube delta shoreline mobility. The study focused on 1961-2006 period when NAO index exhibited the largest negative/positive phases (corresponding to 1961-1972 / 1980-2002 intervals) for the entire period when direct measurements exist for the index to be computed (mid 19th century to present).

STUDY AREA

The study area is a 162 km low-lying coast including the coast of the Danube delta in Romania as well as the coast located south of the delta proper to Cape Midia (Figure 1), which is dynamically linked to the development of the delta (Giosan et al., 2006). Due to no comparable topographical database being available for the delta coast, located north of the Musura mouth in Ukraine, this region was excluded from our analysis.

The study area consists of five littoral cells, most of them being dominated by erosion. The dry temperate climate of the region (i.e., 345 mm/yr of precipitation) supports only a sparse vegetation cover in the backshore zone, which favours strong aeolian transport and preservation of an aerodynamic morphology of the foredunes with small heights (VESPREMEANU-STROE and PREOTEASA, 2006). Along the stable and prograding sectors, the subaerial beaches have a seasonally-controlled morphology, displaying 15-25 m widths at the beginning of the spring and 30-50 m at the end of the summer due to the seasonal differences in wave climate and sea level oscillations dependent on the Danube discharge. On rapidly retreating sectors, the narrow beaches are backed by washover fans (VESPREMEANU et al., 2004).

The submerged beach of erosive/accretionary and stable sectors has a slightly concave/convex cross-shore profile with 1-3 nearshore bars which migrate offshore independent of shoreline behaviour (VESPREMEANU-STROE et al., *in press*).

The coast is virtually tideless, with a maximum tidal range of 0.12 m at spring tide (BONDAR et al., 1973). The wave climate is medium-energy with a significant wave height of 0.9 m in deep water. Frequent waves from the northeast quadrant induce a strong net longshore sediment transport of $0.85\text{-}1\times10^6$ m^3/ yr (GIOSAN et al., 1999; VESPREMEANU-STROE, 2004).

METHODOLOGY

The primary data used in this study consist of successive shoreline positions covering the last 45 years and was obtained from topographical surveys, maps, aerial photos, and satellite images. Topographical data included maps at the 1:25000 scale for 1961 and 1979, annual measurements of shoreline movement relative to a benchmark in a network covering all the deltaic coast from 1962 until present, as well as GPS shoreline surveys for the interval 2004-2006. The 1989 and 2006 shoreline positions were reconstructed by combining LandSat and Aster satellite images with topographical surveys. Based on these datasets, the Danube delta coast evolution was analysed using 123 cross-shore profiles, spaced alongshore at 0.5-2 km intervals. On each profile, the annual rates of shoreline changes were computed for the time intervals of interest.

In order to assess the influence of NAO via storms on coastal process variability we used: (1) hourly wind data at Sulina and Sf. Gheorghe meteorological stations, and (2) Hurrell's NAO index defined as the difference of normalized sea level pressure (SLP) between Lisbon, Portugal and Stykkisholmur, Iceland (HURRELL, 1995). Data covering the interval between January 1961 and September 2006 were processed in the same way. The annual mean was first calculated and then normalized by extracting from

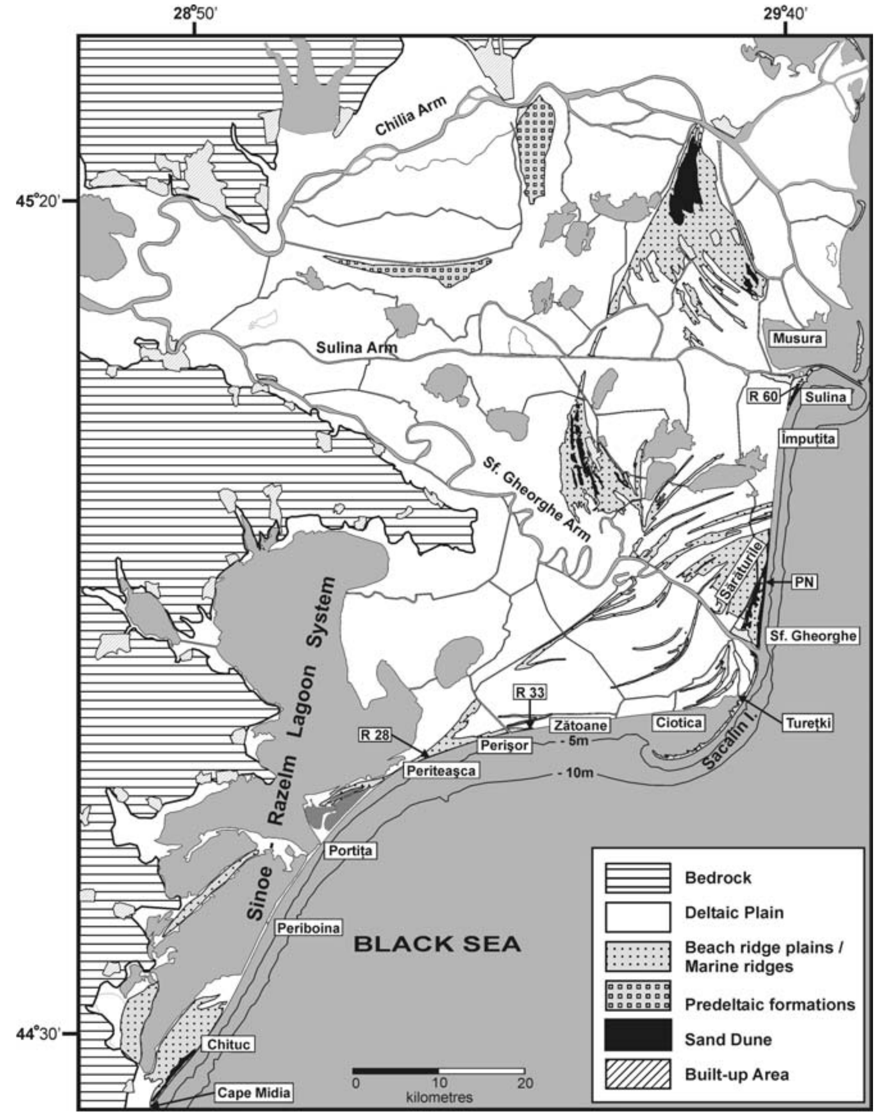

Figure 1. The Danube delta coast. The position of the toponyms used to delimitate the coastal sectors and of the benchmarks in the paper is shown on the map in black rectangles

each value the mean for the entire study period (1961-2006) and dividing it by the standard deviation. The annual normalized anomalies were smoothed with a three-year running mean filter to obtain a multi-annual component of the series. In the present study, a storm was defined by winds at speeds over 10 m/s that persisted for at least 24 hours (VESPREMEANU, 1987).

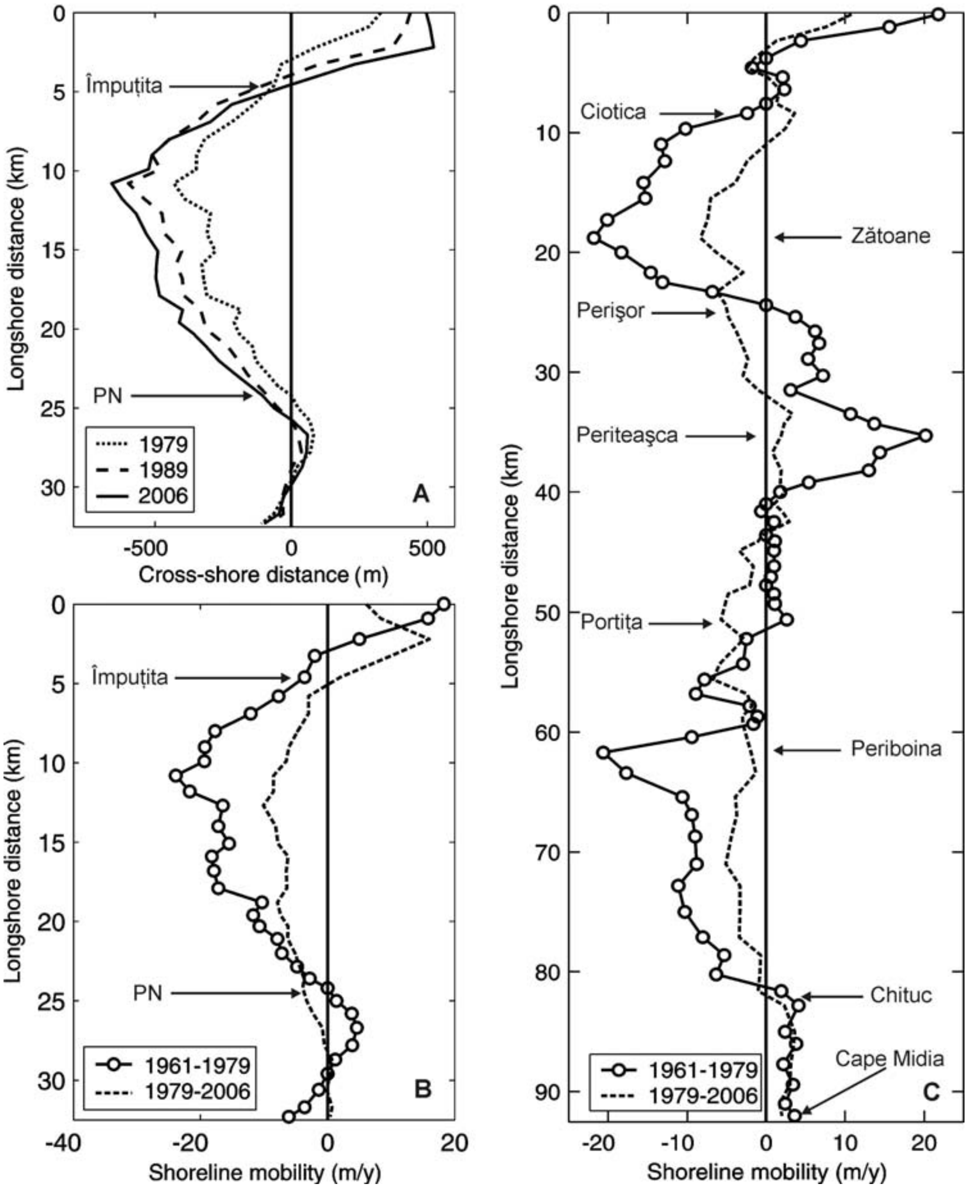

Figure 2. Shoreline evolution between 1961 – 2006 (**A**, **B**: Sulina (0 km) – Sf. Gheorghe (32 km) sector; **C**: Tureţki (0 km) – Cape Midia (92 km) sector). In panel A, the “0” line represents the shoreline reference position in 1961, while in panels B and C, the “0” line indicates no changes in shoreline position, dividing the retreating (-) and accretionary (+) coastal sectors.

RESULTS

During the last five decades, the shoreline in the area under study was primarily erosive. Retreating sectors account for ~90 km out of 162 km (55.6%), whereas advancing and stable sectors extend for ~48 km (29.6%) and ~24 km (14.8%), respectively.

Prograding sectors generally occur either along secondary deltas built by Danube distributaries (i.e., Chilia and Sf. Gheorghe) or to the downdrift areas (South Sacalin Island, Chituc – Cape Midia) or stretches of coast where the LST is convergent due to changes in coast orientation (Periteaşca) and around engineering structures (Sulina); erosive coasts represent the updrift and central segments of the littoral cells. The spatial distribution of both the prograding and retreating coasts preserves the position from the 19th century despite an alongshore migration recorded in the second half of 20th century (Figure 2). Four coastal sectors that were defined as stable (the shoreline changes are small and non-directional) for the 1961

Table 1: Mean and maximum rates of shoreline mobility for erosional (E1-E4) and accretional (A1-A5) coastal sectors (1961 – 2006). The coastal sectors are presented from North to South.

Coastal sectors	Time interval	1961 - 1979		1979 - 2006	
		Mean value (m/yr)	Max. value (m/yr)	Mean value (m/yr)	Max. value (m/yr)
Erosional sectors	**E1** (Împuţita – PN)	**-14.0**	-24.0	**-6.3**	-10.1
	E2 (Sacalin I.)	**-23**	-37.2	**-17.7**	-26.9
	E3 (Zătoane)	**-14.7**	-21.8	**-4.9**	-8.2
	E4 (Portiţa – Chituc)	**-8.3**	-20.5	**-3.0**	-6.7
Accretional sectors	**A1** (Musura)	**52.8**	91.6	**10.4**	15.6
	A2 (Sulina)	**12.4**	15.8	**8.1**	10.8
	A3 (Sf. Georghe – Tureţki)	**16.9**	21.8	**3.7**	6.6
	A4 (Periteaşca)	**6.0**	20.2	**2.3**	4.8
	A5 (Chituc – Cape Midia)	**2.8**	4.1	**2.3**	3.5

to present time period were either prograding (Musura-Sulina, Sf. Gheorghe) or retreating (Ciotica, South Periteaşca) prior to 1961.

Between 1961 and 1979, on the interdistributary Sulina - Sf. Gheorghe coast, erosion reached a maximum of -24 m/yr close to km 11 (Figure 2A and B). As the beach immediately south of the Sulina mouth jetties continuously prograded, the erosion maximum moved downdrift to km 13, but diminished considerably to -10.1 m/yr after 1979 (Table 1).

The average retreat rate for the erosive sector from the Sulina – Sf. Gheorghe coast shows a similarly large (55%) decrease from -14 m/yr to -6.3 m/yr between the two time intervals. For the same time interval, on the Ciotica – Cape Midia coast, the rate of shoreline retreat along erosive sectors (Figure 2C), reduced from -14.7 to -4.9 m/yr for Zătoane beach (66%) and from -8.3 to -3 m/yr for Portiţa – Chituc (64%). Compared to the relatively homogeneous behaviour of the retreating sectors of Danube delta coast, the prograding coasts show dissimilar rates among them. On the marshy coasts of Musura and Sf. Gheorghe secondary deltas, which are protected by barriers and/or extensive flat nearshore zones, the advance rate decreased by 80%, whereas on the open prograding beaches the decrease varied between 20% along the Chituc-Cape Midia shore, 35% at Sulina and 61% at Periteaşca.

In spite of the different magnitudes of LST and wave energy during the two time intervals, the comparative analysis of shoreline position indicates that coastal areas affected by accelerated erosion, during the 1961-1979 interval, did not extend their length. On the contrary, an alongshore expansion (13.4 km) of these retreating sectors occurred during the more stable 1979-2006 interval.

The NAO variability during the 20th century was characterized by periods of persistent positive-phase with more frequent and stronger winter storms over northern Europe and with less and weaker storms over central and southern Europe (HURRELL and VAN LOON). This is a somewhat unusual situation, which occurred in the past only prior to 1650 (COOK and D'ARRIGO, 2001). The NAO index shows a larger variability since the 1960s (between -4.89 and 5.08) in comparison with the previous 100 years of the recorded NAO index time series (between -3.97 and 3.89).

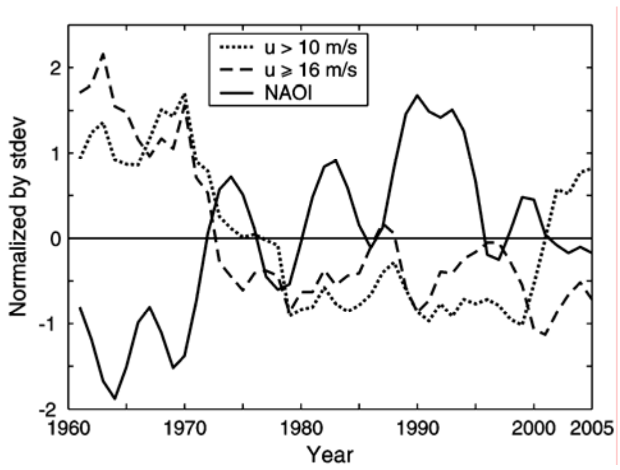

Figure 3. Time evolution of storm incidence and Hurrel's NAO index for Sulina meteorological station

On the Danube delta coast, a strong NAO signal is found in the wind regime whereby there is a high correlation established between the NAO index and the storm frequency at Sulina (r = -0.76) and Sfântu Gheorghe (r = -0.77) meteorological stations.

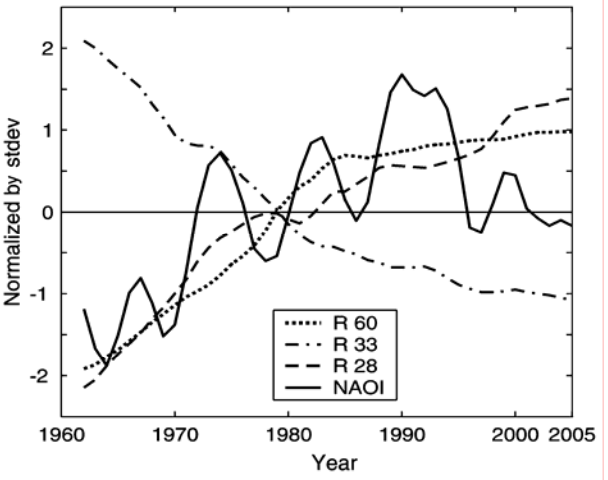

Figure 4. Time evolution of shoreline mobility at R 60, R 33 and R 28 benchmarks and Hurrel's NAO index

Marine storm distribution during the last half of 20th century exhibited a very active interval between 1961 and 1972 that coincides with the strongest negative NAO phase and a relatively quiet period with low variability between 1979 and 2000, which overlaps a strongly positive NAO phase (Figure 3). During the 1970s a gradual decrease in storm frequency was recorded. In the last few years (2000-2005), when the NAO index was close to zero, the large storm frequency was very low, whereas the occurrence of medium-intensity storms increased considerably.

Time series data of three benchmarks representative for the corresponding dynamic sectors (R 60 and R 28 for the accretionary Sulina and Periteaşca beaches; R 33 for the retreating Zătoane beach) were compared with NAO index to assess its influence on the inter-annual shoreline evolution (Figure 1). A comparison of the shoreline behaviour at these three benchmarks shows an accentuated advance/retreat in the 1960s and 1970s followed by an obvious shift toward less dynamic beaches during 1978–1985 interval (Figure 4). The shift occurred in 1978 for R 28, in 1982 for R 33, and in 1985 for R 60. The NAO index records a similar shift from dominantly negative to dominantly positive sometime between 1970 and 1980.

Thus, the shoreline evolution on both the prograding and retreating sectors appears to be negatively correlated with the NAO index (Figure 4).

DISCUSSION AND CONCLUSION

Recent studies on macrotidal coasts suggest that the impact of storm surges can be satisfactory assessed only on a short-term scale, when shoreline changes represent an almost immediate response to meteorological and oceanographic forcings. At decadal scale, no direct relationship was observed between storminess and coastline evolution (CHAVEROT et al., 2006). As the impact of storms highly depends on the tide level at the moment of the storm event, microtidal and tideless coasts are appropriate locations to investigate the potential effects of climatic-modulated storms on shoreline change. Moreover, the low-lying Danube delta coast is considered to be one of the best locations, as besides the favourable tidal regime, it benefits from a higher correlation between storm frequency and NAO index, than on the European Atlantic coast (LOZANO et al., 2004; VESPREMEANU-STROE and TĂTUI, 2005). Another conducive factor is given by the temperate-dry climate which inhibits the high foredune development and indirectly enables the shoreline mobility. The study also advocates the use of a lower limit for storm threshold accompanied by a minimum duration (e.g., u>10 m/s for T≥24 hours instead of the usual u≥16 m/s with no time limit), which will extend analyses into a more realistic range of morphodynamically-effective events and not just to exceptional events as previously considered.

Some expected consequences of global climate change that will potentially impact the coastal landscape in the 21st century include an accelerated sea-level rise and an increase in storminess, which could result in an intensification of coastal erosion and more frequent flooding of low-lying coasts (FRENCH et al., 1995; WASA, 1998; PIRAZZOLI et al., 2004). Besides the sea-level rise, which is a common phenomenon for most coasts, the storminess on the Romanian Black Sea Coast is strongly coupled with the NAO phases. Similarly on other coasts, storminess could vary as a function of the local climatic variability, ultimately controlling the intensity of the coastal dynamics (LOZANO et al., 2004). On coasts where longshore transport is dominant, the concept of “accelerated coastal erosion”, associated with the periods of high storminess, needs to be thought of in association with “accelerated coastal progradation”, as these phenomena compensate for each other in every given littoral cell. Due to this conservation of sediment mass, eroding coastal sectors are not necessarily more extensive during intervals with high storminess than during intervals with low storminess.

A previous analysis of wind regime on the Romanian Black Sea coast points out that the positive winter wind speed anomalies are associated with NAO negative phases (VESPREMEANU-STROE and TĂTUI, 2005). The present study clearly shows that shoreline changes and storminess are connected at short-time scale whereas the coastline medium-term (decadal) evolution is controlled by the NAO phases.

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