The Impact of Large-Scale Atmospheric Forcing on the Dynamics of Water Turbidity in the Danube Delta Coastal Area

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Abstract. Large scale climatic changes can have important impacts on regional and local environments, especially on fragile ecosystems like wetlands and coastal areas. In order to better quantify the magnitude of such impacts on marine areas in front of Danube Delta, specific indicators can be correlated with locally determined parameters. The analyzed climatic indicators within this study are the North Atlantic Oscillation (NAO) and the East Atlantic / West Russia (EAWR) indices. Their dynamics are linked to local processes (waves and currents), which can influence the variability of total suspended matter in the water column, crucial for all the geomorphological processes that take place in coastal areas. In this context, turbidity products derived from long time series of satellite data are used as an expression of sediment loads in the upper water layers. Analyzing 12 years of remote sensed turbidity values shows the relationship between large-scale atmospheric forcing systems and regional dynamics of suspended sediments. The results show a medium degree of correlation between the two parameters during winter seasons, while for the rest of the year no such relationship is to be found.

Keywords: turbidity, MODIS, Danube Delta, NAO, EAWR

1. Introduction

Coastal areas are fragile ecosystems that require intense monitoring in order to obtain the necessary information for proper management action plans to be conducted. Out of all the techniques available today, remote sensing represents the only way to have a synoptic overview for large study areas, like wetlands or marine basins (IOCCG, 2000). Multiple oceanographic parameters can be quantified using remote sensing data, such as chlorophyll concentration, water turbidity or total suspended matter. The last two can be used in order to monitor and analyze the evolution of sediment dynamics in coastal areas, since both are strongly linked to such processes. Availability of sediments is the first order concern for delta maintenance (Giosan *et al.*, 2013). Turbidity represents an optical property of the water, determined by the scattering (and to a lesser degree by absorption) of light by suspended particles inside the water column (Anderson, 2005). By comparison, the amount of total suspended matter (TSM) represents an exact quantitative measure of the solid matter per unit of volume (Kemker, 2014). For coastal areas dominated by the river's solid discharge, the relationship between turbidity and TSM is a very strong one. Although the optical properties of water (turbidity) can also be influenced by other factors, such as chlorophyll concentration or colored dissolved organic matter, in coastal areas dominated by river's input (such as the deltaic coastal zone) the main cause for large turbidity units is represented by inorganic matter from river particulate discharge or caused by resuspension processes (IOCCG, 2000).

It can be therefore concluded that both turbidity and TSM can be used as parameters based on which the evolution of sediment dynamics can be evaluated. Detailed knowledge of this type of processes is crucial for understanding the mechanisms that govern specific geomorphological characteristics, such as formation and evolution of barrier islands or submerged bars. The sedimentary balance also dictates the evolution of the entire delta shoreline, through appearance of erosion/ accumulative sectors, mainly depending on the amount of solid particulates at specific time periods and locations. The spatial distribution of turbid waters has also an influence on the primary production, by modifying the characteristics and vertical extension of the photic zone.

The goal of this study is to investigate if there is any correlation between water turbidity and teleconnection patterns in the Danube Delta coastal area, at monthly time scale. The main index involved in the analysis is NAO (North-Atlantic Oscillation), but also EAWR (East Atlantic / West Russia) was taken into consideration. This hypothetical relationship between coastal turbidity and large-scale atmospheric forcing was tested for different spatial extents and for multiple time intervals (for all the months and also only for specific seasons - winter).

For the Black Sea basin, the effects of climatic teleconnection on the marine environment were studied mainly taking into consideration parameters such as chlorophyll concentration or sea surface temperature (Oguz, 2005). For the Danube Delta coastal areas, NAO influence was accounted for in terms of shoreline dynamics (Vespremeanu-Stroe *et al.*, 2007) or in correlation with the overall Danube hydrological status (by determining the precipitation anomalies in the drainage basin), that must be considered when analyzing the geomorphological changes that occur at river mouths and in the delta plain (Giosan *et al.*, 2005).

NAO is defined as the difference in air pressure at sea level between the Icelandic low and Azores high pressure centers (Van Loon & Rogers, 1978). EAWR pattern consists of four main anomaly centers. Positive height anomalies over Europe and northern China and negative height anomalies located over the central North Atlantic and north of the Caspian Sea correspond to a positive phase. Both patterns affect their influence area throughout year.

Although NAO has the general tendency to vary from one year to another, periods of several years without any shifts between positive and negative phase were recorded. For the Romanian deltaic coastal area, a strong inverse relationship exists between NAO and the occurrence of storms, together with high wave and wind energy. This is defined by a correlation coefficient of R=-0,76 for meteorological data (wind) recorded at Sulina station and R=-0.77 for Sfântu Gheorghe (Vespremeanu-Stroe *et al.*, 2007). All this translates in a higher probability for storms to occur during periods with strong negative NAO values, which can lead to high impact on the shoreline by increasing the expansion of erosive sectors. Such changes are heavily dictated on decadal scales by NAO phases (Vespremeanu-Stroe *et al.*, 2007). Also, the resuspension processes in shallow waters are favored by strong winds, waves and currents. This indirectly affects the values of turbidity by increasing the sources for suspended sediments in the water column. Changes in wind energy can contribute not only to higher resuspension processes and shoreline erosion, but also to a larger spatial distribution of sediment plume at the surface of the water column, thus leading to a much wider area with high turbidity values observed from space.

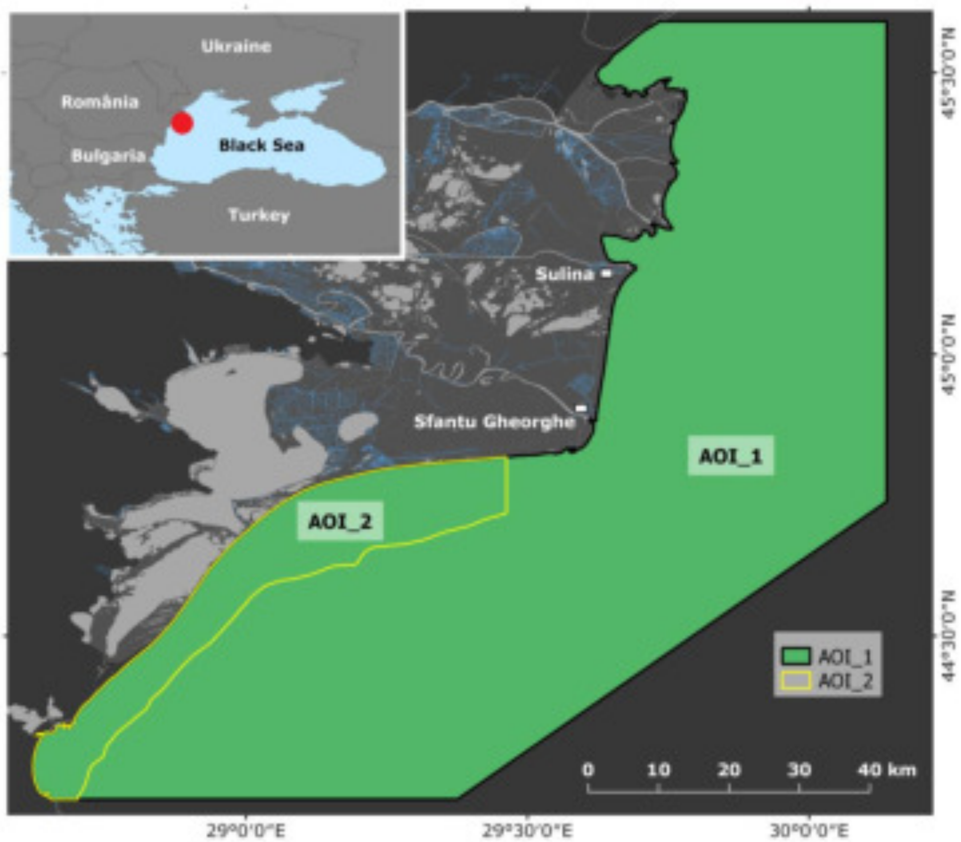

Fig. 1. **Location of the study area; two distinct Areas of Interest (AOI_1 and AOI_2) were selected**

The study area covers 8125 km^2 in front of Danube Delta (Fig. 1), overlapping a shelf zone with low depths, up to maximum approximately -60 m. The large interest area was noted as AOI_1, and it encompasses a smaller one, noted AOI_2, situated South-West of Sfântu Gheorghe mouth, and delimited by the 0 and -20 m isobaths. The main reason for choosing two AOIs was to capture the turbidity patterns in areas dominated by distinct factors. While for AOI_1 the turbidity is determined mainly by the Danube solid input, in AOI_2 the resuspension processes can play a more important role. Statistics were computed for each of the two AOIs.

2. Methodology and used datasets

Large volumes of archived satellite data can now be used to analyze trends of the impact that large-scale atmospheric forcing can have on specific local ecosystems, like coastal environments. In the near future, climatic observations will also be possible to be tackled based on the same input information type (Earth Observation data), but this will most probably require solid and validated processing schemes, especially in terms of sensor inter-calibration. This is mainly due to the fact that long periods of time are usually covered by data coming from different satellites with sensors that have distinct radiometric and spectral characteristics. For this specific study, only data coming from one sensor, MODIS, mounted on two platforms, Terra and Aqua, were used. The period of time for which the analysis was performed is covering 12 years, from 2003 up to 2014.

Level 1A satellite data was acquired from NASA Ocean Biology Processing Group. Using SeaDAS 7.1 software, Level 2 reflectance products were computed, using the MUMM algorithm for atmospheric corrections (Ruddick *et al.*, 2000). These products were translated into turbidity maps based on a local determined relationship between satellite reflectance and turbidity (Constantin *et al.*, 2015). For every month during the 2003-2014 period, composite products were processed by averaging all the available turbidity maps from that specific time interval. NAO and EAWR monthly index values were available from NOAA Climate Prediction Center.

3. Results and discussions

The location of AOI_1 (Fig. 1) was set as to cover all the area with overall high turbidity values. In what concerns AOI_2, its extension was chosen in order to have more information on how the turbidity varies as a result of resuspension processes alone. After analyzing all the monthly turbidity maps, it was observed that the shallow waters South-West of Sfântu Gheorghe mouth are more prone to such events than others, during winter periods, when storm occurrence is higher and also the wind and wave energy are grater. Although some spring months are characterized by an overall higher turbidity average (for AOI_1), the suspended sediment load in AOI_2 is much lower than in winter (Fig. 2). This is mainly because the turbidity plume extension is more influenced now by the river discharge than during winter, when resuspension plays a key role in the close proximity of the coast.

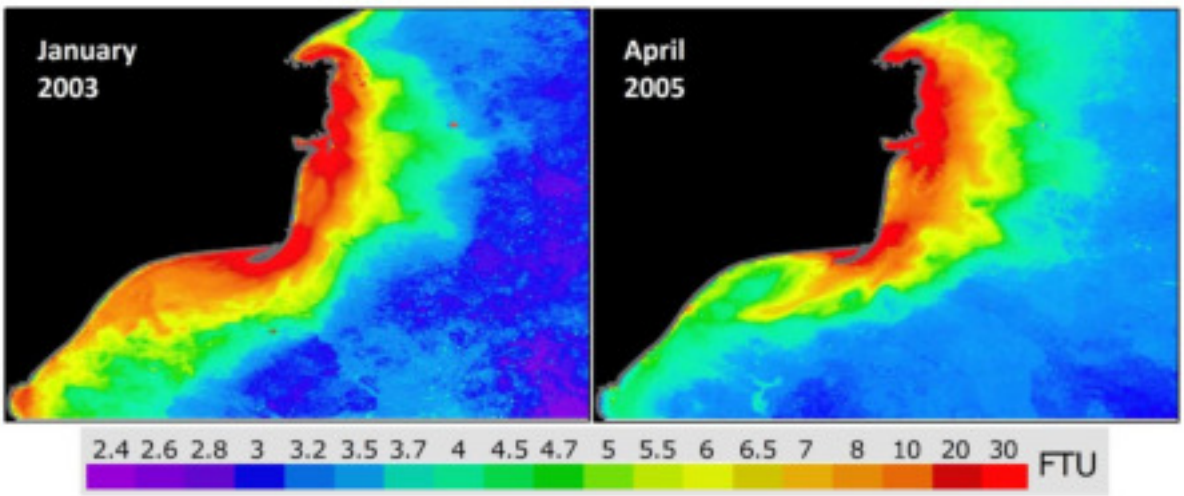

Fig. 2. **Different distribution of high turbidity values between winter and spring months, especially in the South-Western part of the AOI_1**

For the analyzed time period, a high oscillation of NAO index was observed, with some long intervals with negative values, such as the one between the end of 2009 and beginning of 2011 (more than one year). EAWR is mostly negative, with short periods when positive values are recorded. The relationship between NAO and EAWR is not a strong one, with a correlation coefficient of just R=0.106.

One of the first steps in our analysis was to determine if and how coastal water turbidity alternates in parallel with NAO and EAWR. For this specific purpose, the correlation coefficients between the two parameters of interest for AOI_1 and AOI_2 were computed, for all the 144 months taken into consideration. A synthetic overview is given in table 1. All the values are lower than ±0.06, which strongly indicates that there is no evident relationship between turbidity and climatic teleconnection patterns for all year round in the Danube Delta coastal area.

Since this low correlation is mainly caused by the fact that turbidity is influenced by river discharge more than by resuspension (due to strong winds and waves), when all seasons are considered, the next step was to choose only those time periods when NAO and EAWR are supposed to have a more significant impact. Therefore, we performed the same analysis taking into consideration only winter months (December, January and February). For EAWR, the correlation coefficients were found still to be very low (R=-0.159 for AOI_1 and R=-0.189 for AOI_2), which clearly shows that turbidity dynamics are not directly influenced by changes that occur in EAWR behavior.

Regarding NAO, it was found out that the same correlation coefficients are increasing considerably during winter (R=-0.50 for AOI_1 and R=-0.57 for AOI_2) (Fig. 3). High negative NAO values correspond to significant increase of turbidity units. This is the case during December 2009 and the winter of 2010, when the turbidity monthly averages were the highest one recorded, of more than 10 FTU in average for AOI_1 (maximum of 13.2 FTU), and more than 15.2 FTU for AOI_2 (maximum 19.9 FTU). The average turbidity values for all winter months are 6.3 FTU for AOI_1 and 8 FTU for AOI_2. During time periods when NAO has the highest positive recordings (December 2011), the values of turbidity are also some of the lowest ones (3.5 and 3.7 FTU for AOI_1, respectively AOI_2). The graphic from figure 3 shows an evident larger fluctuation for turbidity in AOI_2 than in AOI_1 when NAO index drops to negative values, which proves that our initial hypothesis concerning different magnitudes on resuspension processes inside the two AOIs (grater in AOI_2) is correct.

	R (NAO vs TURBIDITY)	R (EAWR vs TURBIDITY)
AOI_1	-0.058	0.040
AOI_2	-0.012	-0.020

Table 1. **Correlation coefficients between turbidity and large-scale atmospheric forcing indices**

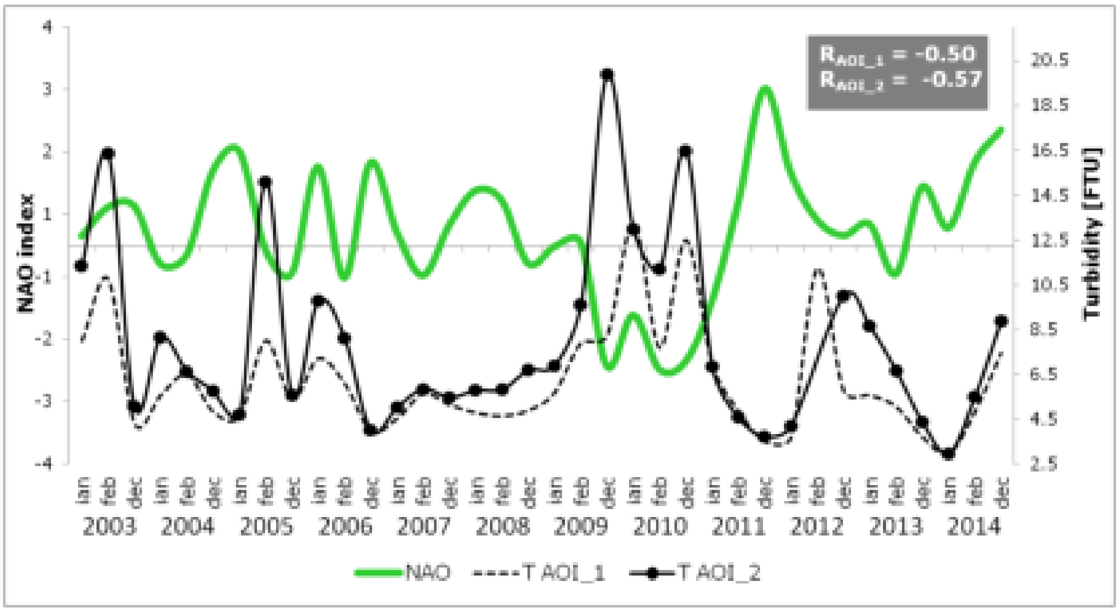

Fig. 3. **Relationship between turbidity (T, in AOI_1 and AOI_2) and NAO index**

This moderately strong relationship between turbidity and NAO shows that the large-scale atmospheric forcing phenomenon can have an indirect impact on sediment dynamics, but other factors must be accounted for when trying to understand the turbidity spatial extension and magnitude. In this context, not only winds and waves are to be considered, but also Danube discharge rates, marine currents behavior or even algal bloom events. The correlation between the two analyzed parameters might increase if only months with high prevalence of storms should be considered, out of the selected period.

4. Conclusions

This current study must be considered as a first attempt to use remote sensed oceanographic parameters (turbidity) in order to establish a connection between climatic and meteorological patterns and geomorphological processes at local scales in the Danube Delta coastal area. Of course, longer periods of time should be taken into consideration in order to have a better understanding of the phenomenon, which is one of our main directions of research for the future. Also, these results must be treated with caution since during winter, because of high cloud cover over the AOIs, the number of satellite data decreases compared to the rest of the year and therefore less information is available for analysis. These observations remain to be further augmented by other similar studies that might introduce into analysis also modeled datasets.

Nevertheless, it is obvious that changes in atmospheric conditions at larger scales can have an indirect impact on the distribution and dynamics of the sediments in the coastal areas. But, as already mentioned, other factors (such as river discharge or algal blooms) might have more significance in specific areas. For the entire year, NAO cannot be hold responsible for turbidity spatial distributions, although it influences the precipitation rates within Danube hydrographic basin which in turn reflects into higher discharge rates at river mouths. Only for winter periods, the coefficient correlation was found to be R=-0.50 (AOI_1) and R=-0.57 (AOI_2) between turbidity averages and NAO, which indicates a moderate relationship between the two parameters during seasons with high resuspension occurrence.

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