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COASTAL EROSION AND IMPACT OF EXTREME EVENTS ALONG THE BELGIAN COAST

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ABSTRACT

In coastal areas, storm event is closely related to decreasing air pressure, wind conditions and often generates sea surges. Wind forcing could induce waves contributing to sediment movement and erosion process. Although wind is an important forcing, its characteristics at local and regional (>100 km) scales and its consequences have been rarely investigated during storms. This study aims to assess the impact of wind storm events on local coastal morphological changes in Belgian coast (Northwest Europe) with focus on the erosion phenomena. Wind storm events were extracted from the local wind analyses to understand their characteristics. These were related to the measured net budget of local erosion volume. Based on these considerations, an index for the intensity of the wind storm activity will be built to model this erosion volume. Thus, the erosion index could be a useful tool for coastal managers to predict the sand volume loss caused by extreme storm events.

KEWORDS: Wind storm, local and regional scales, erosion volume.

1 INTRODUCTION

There is a large variety of natural processes acting along the coast over wide ranges of spatial and temporal scales. Their consequences are multiple and some of them can be catastrophic, given the high degree of development of human activities along the coasts (French, 2001). Erosion is an important consequence of these natural processes. In coastal areas, storm event is often associated to a decrease of air pressure and strong wind conditions. Thus, an important low pressure zone provokes high wind speed which in turn generates waves. The combination of the displacement of the low pressure and the wind force eventually drives the generated waves towards the coast where they can reach several meters high causing significant morphological changes at the coast (Masselink *et al.*, 2014). Thus, wind-induced waves contribute to move sediments and to erosion processes. A change in the direction and intensity of the dominant wind might modify the morphology of the coast. Although wind is an important forcing, its characteristics at local and regional (>100 km) scales and its consequences have been rarely investigated during extreme storms. This study aims to assess the impact of wind storm events on local coastal morphological changes in Belgian coast (Northwest Europe) with focus on the erosion phenomena.

2 REGIONAL SETTINGS

The study site is located along the Belgian coast which extends up to 67km (Figure 1). It forms more or less a straight line directed SW to NE from the French Opal coast to the nature reserve Zwin at the border with the Netherlands. In general, the coast consists of a broad gentle sloping sandy beach backed by dykes, while in the shallow continental numerous sand banks occur, the Flemish Banks. The Belgian coast is mainly erosive state (Van Lancker, 1999). Hard and soft engineering schemes are already being implemented to reduce or prevent it.

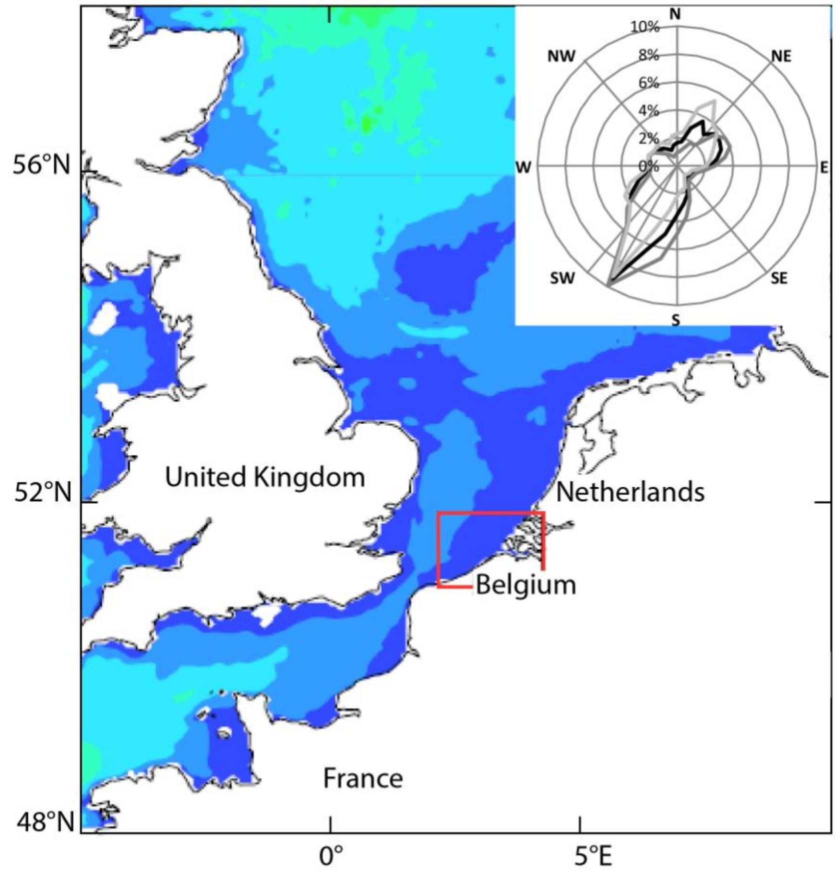

Figure 1. Location of the Belgian coast. The inset presents the local wind regime with the black, dark grey and light grey lines corresponding to annual, winter and summer winds respectively.

Throughout the region, the tides are a semi-diurnal and macro-tidal with a range between 3.5m at neap tide and 5m at spring tide. The wind regime is characterized by typical wind speeds between 3 and 8m/s, largely coming from SW (Figure 1). There are no significant changes in wind regime between summer and winter except for the intensity of winds. The strongest period is between November and February (Van den Eynde *et al.*, 2012). High wind speeds (> 10m/s) are generally coming from WSW to NW, which are susceptible to have a devastating impact considering the coastline orientation since wind would produce piling up of water at the coast. Verwaest *et al.* (2008) have found that the wind direction is strongly correlated with the wave directions. Along the coast, the wave climate is typically characterized by wave height from 0.5 to 1m, and with wave periods of 6s.

3 METHODS

In this study, time series of local wind records, the Lamb daily Circulation Weather type (CWT) and the winter North-Atlantic Oscillation (NAO) index were used to investigate the impact of the wind storm events. Time serie of available wind records from the Meteopark of Zeebrugge were examined to identify wind storm event along the study site. Ten-minute measurements of the averaged wind speed and direction were obtained for the period from 01/06/1993 to 31/10/2014 (total duration: 21.4 years). The data were recorded throughout the Flemish Banks Monitoring Network of the Flemish Government. To focus on the most extreme events, threshold criteria were established in order to filter wind storm events out of the original time series. The data series were first filtered with a minimum average wind speed of 15.5m/s. This velocity was way higher than the average velocity (8.3m/s) but not too low to avoid excluding erosion events that would eventually not be characterized by strong winds. Then, an independency criterion of at least 12h between two isolated events was imposed; and all events shorter than 3h were discarded. Furthermore, water level was measured at five-minute interval from the tide gauge in Ostend harbor for the study period. The analysis consisted to extract water levels at high tides from the data. The high tide water levels were then filtered to extract only the highest values going over the usual range of tide (*i.e.* 4.39m TAW, *Tweede Algemene Waterpassing*). Also, a threshold at ≥ 5m TAW was chosen, corresponding to the lower limit of high water found by Haerens *et al*. (2012) as one of the criteria for significant morphological changes at the Belgian coast.

In addition, the wind storm events were analyzed regarding to their characteristics at regional scale through the CWT and the winter NAO index. A method of classifying the CWT of the British Isles was described by Lamb (1972), in which the daily atmospheric pressure charts are used to examine the surface airflow pattern and steering of the circulation system. This was further developed by Jenkinson and Collison (1977) and Jones *et al*. (1993) who extended this classification based on mean sea level pressure measured at 16 fixed locations covering the British Isles and surrounding area. Eight main directional types in the classification are recognized as the directional types North (N), North-West (NW), West (W), South-West (SW), South (S), South-East (SE), East (E) and North-East (NE). In addition, there are 2 non-directional types: Anticyclonic (A), Cyclonic (C), and also an unclassified type which is not considered in this study. For this study, the daily CWT data above the North Sea basin measured at synoptic 12h were collected from the Climate Research Unit of the University of East Anglia (UK). For the 10-types classification, each hybrid day was counted as half a day for one type and half a day for the other type (*e.g.* an 'Anticyclonic North-East type ANE' day counts for 0.5 day for type A and 0.5 day for type NE). Further investigation was carried out using the NAO which is a large-scale mode of atmospheric pressure variation that governs the climate variability in mid-latitudes of the North Atlantic Ocean (Hurrell, 1995). The NAO is present the whole year, but its influence is particularly visible during winter season. The NAO index is computed from regional differences in normalized pressure anomalies difference between the Icelandic Low and the Azores High and is used to quantify its state. Positive phases in the index often correspond to wet and stormy weather in Northwest Europe, dominated by strong mid-latitude westerlies, while negative phases are associated with dry, calm weather in Northwest Europe (Hurrell, 1995). Time series of standardized monthly NAO index were provided from the National Oceanic and Atmospheric Administration. The winter NAO index was here calculated for each winter corresponding to the period from October to March.

4 CHARACTERISTICS OF THE WIND STORM EVENTS

The number of wind storm events extracted from the local records at Zeebrugge was of 263 between 01/06/1993 and 31/10/2014 and most of them occur in winter. The distribution of durations is shown in Figure 2. The majority of these extreme events lasts between 3 and 6 hours and the distribution rapidly decreases, but there is a non-negligible amount of wind storms which are particularly long. There are 101 events longer than 12 hours and 29 longer than 24 hours; and the longest event lasts 72 hours occurring on 12/02/2005. The duration of the wind storm events is relatively similar to the observed storm surges causing significant morphological changes of Belgian sandy beaches reported by Haerens *et al*. (2012). They reported that one of the criteria for a storm event to cause erosion is to last at least 12 hours.

The high tide water levels (≥ 5m TAW) associated with the wind storm events are not particularly extreme. Figure 2 compares the total distribution of high tide water levels to the one of only the wind storm events, with bins of 20cm width. There is a shift of about 20cm towards higher water level values from the overall distribution. It implies that the local wind is capable of increasing the water level, significantly enough to lead to more erosive conditions. Indeed, the average high tide level of the wind storm events is of 4.54m TAW, *i.e.* located in the supratidal beach (≥ 4.39m TAW), while it is only 4.34m TAW for the total distribution.

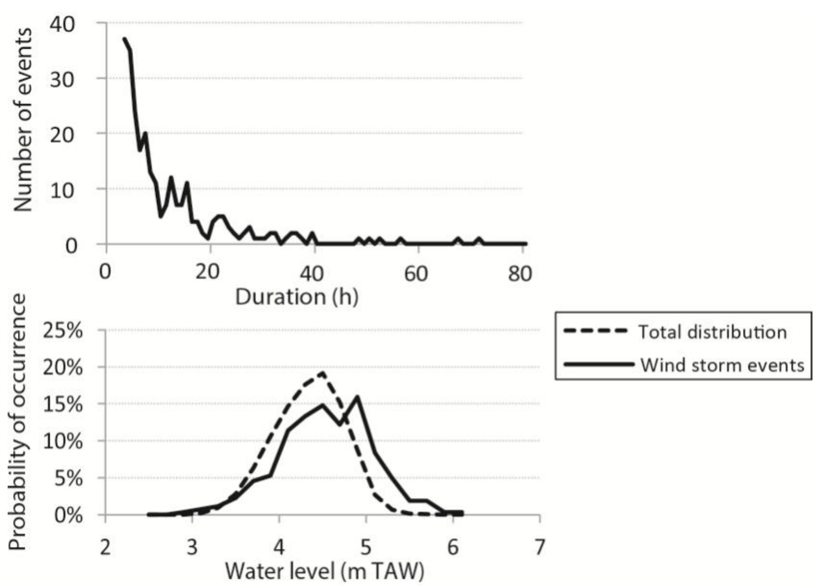

Figure 2. Distribution of the durations of the wind storm events (upper panel). Distribution of the high (tide) water levels and the wind storm events for the period from 1993-2014 (lower panel).

The dominant directions of the wind storm events are shown in Figure 3 for both local (Zeebrugge records) and regional (CWT data) scales. The comparison between these two highlights the importance of the local effects: most of the events which are located in the W-NW-N sectors at regional scale are redirected in the SW direction at local scale. One also notices the rarity of events in the NE-E-SE sector at both scales. However, the SW direction does not remain the dominant one when the events are filtered with a minimum high tide water level of 5m TAW. With this limit, on the contrary, the NW sector is dominant at local scale. The shift between the two scales also looks less precise: the directions at regional scale are well focused in the W-NW-N sectors while they are much more spread over the SW-W-NW-N-NE sectors at local scale. The SW dominance is thus not a feature of the strongest events. Thus, this suggests that the wind storm events from the W-NW-N sectors are the most threatening. These observations are in agreement with previous studies which found that the most devastating local winds and waves along the Belgian coast are known to come from the W-N-NW directions (Verwaest *et al*., 2008, Haerens *et al.*, 2012).

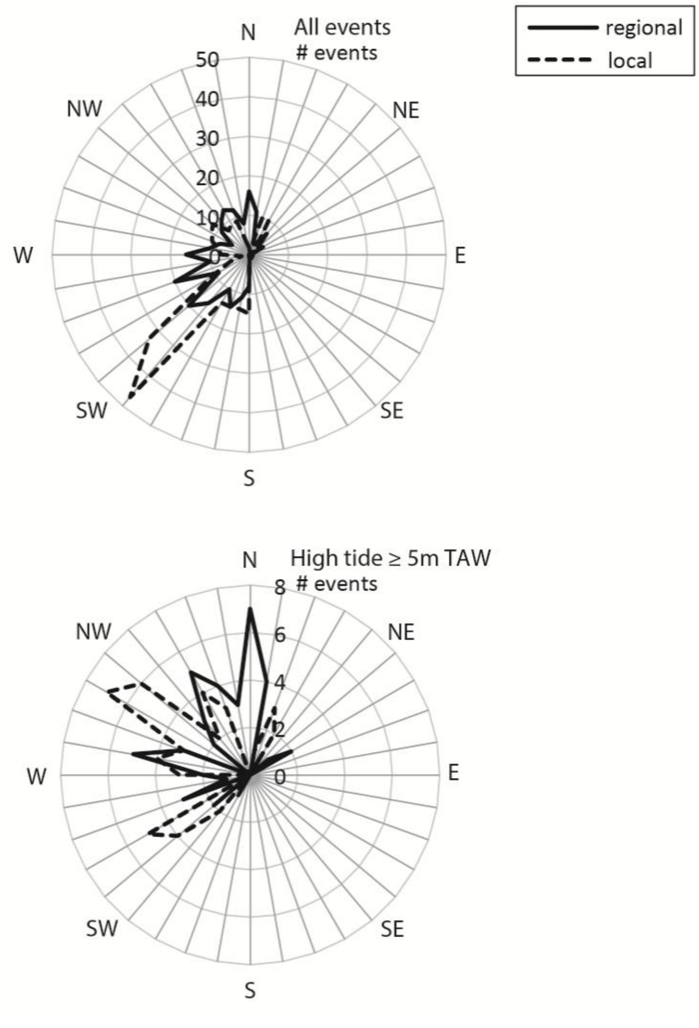

Figure 3. Distribution of local and regional wind directions of the wind storm events: all events (upper panel) and events with high tide water level ≥ 5m TAW (lower panel).

The occurrence of each CWT type among the wind storm events for the period from 1993-2014 is presented in Table 1. The SW-W-NW-N sector is dominant partly due to the generally high frequencies of these types. The cyclonic type is also particularly frequent. This is coherent since a cyclonic day often goes with lower air pressures and thus attracts high wind speeds. On the contrary, the NE-E-SE-S sector almost never appears. This can be again partly explained by the very low frequency of these types in general.

Table 1. Number of wind storm events per weather type.

Weather type	Number of events
A	13
NE	12
E	3.5
SE	1
S	12
SW	40
W	33.5
NW	25
N	29.5
C	92.5

Concerning the synoptic scale, the values of the NAO index are centered on a neutral phase with a frequenc of 56% (Table 2). Compared to the wind storm events distribution, the values are shifted towards more positive phases. The average value is 0.16 for the wind storm events. This fits the conclusion of Donat *et al.* (2010) for Central Europe that a slightly positive phase of NAO seems to represent optimum conditions for the occurrence of winter storms.

Table 2. Distribution of the winter NAO index for the period from 1993-2014 and for the wind storm events.

Phase	Frequency (%)
NAO--	0
NAO-	15
NAO0	56
NAO+	29
NAO++	0

5 COMPARISON WITH THE EROSION VOLUMES AND SET-UP OF AN EROSION INDEX

The Belgian coast is mainly erosive. From 50 to 60% of the shoreline would be erosive if there were no human intervention to protect it and there would be a progressive landward retreat. The erosion volumes from 1984 to 2007 from the supratidal beach to the dune foot, corrected for soft defence measures (beach nourishment volumes) were calculated by (Haerens *et al.*, 2012) using different remote sensing data collected from either field RTK-GPS or LiDAR surveys data. The erosion volumes are the supratidal beach volume losses along ten areas between De Panne and Zeebrugge, covering a total length of 12.2km along the Belgian coast. The measurement error is evaluated to 5m³/m, which leads to 61,000 m³ per data. Figure 5 indicates that years 1987, 1990 and 1994 were particularly erosive, whereas no sand loss was measured in 1986, 1991, 1992, 2003 and 2005.

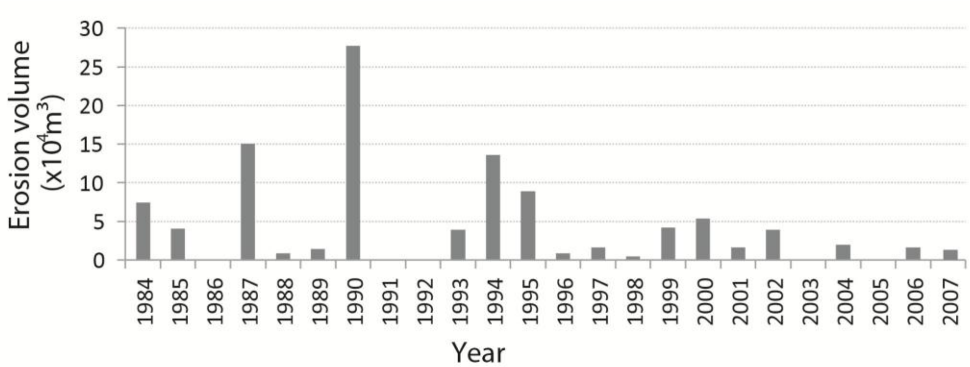

Figure 5. Erosion volumes along a part of the Belgian coast (extracted from Haerens *et al.*, 2012).

Of all the characteristics of the wind storm events described above, one needs to extract the ones to which the erosion capacity is sensitive. In order to identify them, the erosion volumes calculated by Haerens *et al*. (2012) were used from 1994-2007. During the study period, the linear correlation coefficient between the erosion volumes and the winter NAO index is 0.47. The NAO is thus believed to have a significant impact on the coastal erosion. The winter NAO index is often used as a proxy for storminess in coastal studies (e.g. Esteves *et al.* 2011, Thomas *et al*., 2011). One can distinguish two periods of 11 years (Figure 6). From 1984 to 1995, the NAO index is almost always positive. During this period, the erosion volumes reach higher values than from 1996 to 2007, but only during some specific years, (i.e. in decreasing order: 1990, 1987, 1994, 1995 and 1984). Erosion was weak for the other years. A sole positive NAO index is thus not sufficient to provoke high amounts of erosion. Haerens *et al*. (2012) mention for instance the exceptional storminess of year 1990, which has not the highest NAO index of the series. From 1996 to 2007, the NAO index oscillates between slightly positive and negative values and the erosion volumes seem to follow these oscillations. Therefore, a slightly positive NAO index is favourable to erosion but is not sufficient to explain it. When the NAO is closer to zero, the volumes seem more sensitive to its value. These results are in agreement with Donat *et al*. (2010) who reported that a slightly positive phase of the NAO could represent the optimum condition for the occurrence of winter storms in Europe.

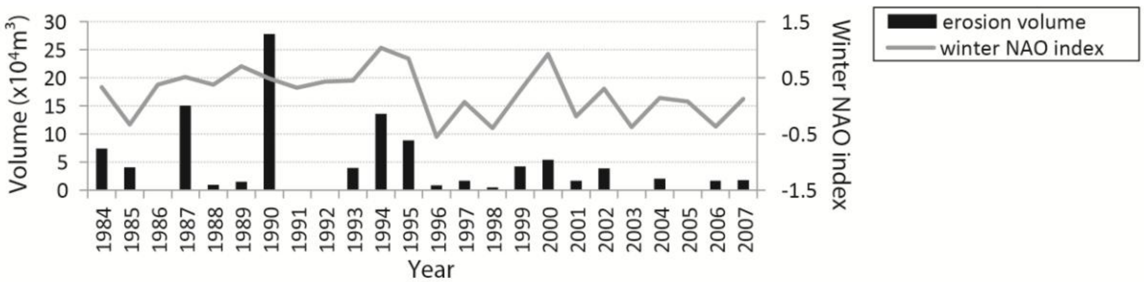

Figure 6. Erosion volumes and winter NAO index from 1984 to 2007.

In addition, the comparison with the wind storm events covers the period 1994- 2007 (Table 3). Over this period, the most erosive years were in decreasing order: 1994, 1995, 2000, 1999, 2002 and 2004. Also, the number of wind storm events extracted per year or per season. These ranged from 6 to 27 events per year, occurring mainly in winter. As expected, annual significant erosion volumes happened when the number of wind storm event was relatively high. For instance, the greatest erosion volume in 1994 took place when 12 wind storm events occurred in winter. However, 27 events were measured in 2007 while the erosion volume was only 17700m^3. This is probably due to the characteristic of the wind storm (magnitude, direction and duration) but also on the coastal state of the beach before the event. Previous studies have reported that the pre-storm morphology is critical to the beach response (*e.g.* Morton, 2002, Houser *et al*., 2008).

Table 3. Erosion volumes and annual and seasonal number of wind storm events compared to the measured erosion volumes from 1994-2007. Significant erosion volume is italic.

		Number of wind storm event		
Year	Erosion volume (m^3)	Year	Winter	Summer
1994	*135700*	*12*	*12*	*0*
1995	*88800*	*11*	*9*	*2*
1996	8500	6	2	4
1997	16100	10	10	0
1998	4500	13	12	1
1999	*42100*	*10*	*10*	*0*
2000	*53600*	*14*	*11*	*3*
2001	16100	9	4	5
2002	*38800*	*18*	*16*	*2*
2003	0	9	6	3
2004	*19800*	*20*	*18*	*2*
2005	0	12	10	2
2006	16100	10	7	3
2007	17700	27	21	6

An index K will be built based on our previous results to attempt to link the wind parameters at all scales and the high tide water level with the erosion volumes. Its goal will be to estimate from these parameters, which erosion volumes can be expected. From the analyses presented above, the NAO index will be chosen as the dominant regulator for the index K. The duration of each event will be also considered. In addition, the index will incorporate the most relevant CWT types of wind events. A condition on the seasonality will be applied since there is a stronger impact of a winter event compared to a summer event. Summer events are much less frequent than winter events and give in general weaker wind speeds. Finally, a minimum high tide water level will be imposed to require that the water reaches, or at least, gets close to the supratidal beach.

6 CONCLUSIONS

In coastal areas, wind is an important component of extreme storm event causing morphological changes. Wind storm events occurred along the Belgian coast were identified from local wind records and their characteristics were further examined at local and regional scales. Results have shown that the significant erosion volumes happened when the number of wind storm event was relatively high. Also, analyses have suggested that the extreme wind storm event is likely to be determined by the winter NAO index; and the SW-W-NW-N weather types are favourable for their occurrence. Based on these considerations and combined with the erosion volume from 1994-2007, an index for the intensity of the wind storm activity will be set up and calibrated. It will allow us to predict the erosion volume over one year caused by extreme events. A reliable and robust erosion index could be a useful tool for coastal managers to predict the sand volume loss volume caused by extreme storm events.

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