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Wave Climate in the Gulf of Gdańsk vs. Open Baltic Sea near Lubiatowo, Poland

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Abstract

The paper analyses long-term variability in the wave climate near Lubiatowo, ca. 15 km east of Łeba harbor, and in the Gulf of Gdańsk, near the Vistula river mouth. The wave climate was reconstructed for the 1958–2001 period by the German Institute for Coastal Research (GKSS). Using basic statistical tools – empirical mean values of significant wave height, estimation of the number of threshold crossings above a prescribed value of that height and conditional empirical probability density functions of wave approach directions – a comparison of wave height at the two locations was executed. A substantial reduction in wave height inside the Gulf (sheltering effect) was measured. Further, the increased storminess over the winter season was estimated for the open sea location. Finally, the analysis of wave approach direction in the open sea location revealed substantial growth in extreme waves from the western sector. Given the geographic configuration of the Gulf and the combined rise in storminess and evolution in extreme wave direction, it can be inferred that the sheltering effect of the Gulf can vary depending on locations within the Gulf. Identification of sheltering patterns in the Gulf emerges as obvious follow-up research. This study could also prove useful in analyses aiming at integrated management of coastal zones in the Gulf, mainly in the implementation of Coastal Protection Law (Apr. 2003), which postulates maintenance of the 2001 shoreline configuration along the entire Polish coast.

Key words: Baltic Sea, climate change, global processes, North Atlantic Oscillation, significant wave height, singular spectrum analysis

1. Introduction

The Baltic Sea is a semi-enclosed water body with a total area of 415,000 km^2 and a volume of 21,700 km^3 (including Kattegat), BACC 2008. It is highly dynamic and strongly influenced by large-scale atmospheric circulation, hydrological processes and by the restricted exchange of water due to its narrow entrance area. Initial efforts aimed at reconstruction of the wave climate in the Baltic Sea were based on parametric models fed by stationary and homogeneous wind inputs (Paszkiewicz 1988, Zeidler et al 1995). In the next stage, the so called 2nd generation wave models were applied

(Blomgren et al 2001, Gayer et al 1995 or Jönsson et al 2002). Then, the availability of wind fields over the Baltic Sea allowed for the application of 3rd generation WAM4 models (WAMDI group 1988). Finally, global meteorological re-analyses, briefly described below, provided an input for long-term reconstruction of wave fields of the whole Baltic Sea for the 1958–2001 period with high resolution and precision. This was achieved in the FP5 HIPOCAS project (Hindcast of Dynamic Processes of the Ocean and Coastal Areas of Europe, EVK2-1999-00038). The extensive reconstruction procedure is described in detail by Weisse et al (2009). Briefly, the National Center for Environmental Prediction – National Center for Atmospheric Research (NCEP–NCAR) global reanalysis (Kalnay et al 1996), was applied in combination with the spectral nudging technique (von Storch et al 2000) as the input to the **RE**gional **MO**del (REMO) that is based on the numerical weather prediction model EM of the German Weather Forecast Service (DWD) (Feser et al 2001, Jacob and Podzun 1997). In this way the near-surface (10 m height) marine wind (velocity and direction) and pressure fields were obtained. The atmospheric reconstruction was provided on a rotated $0.5° \times 0.5°$ grid with the equator passing nearby the study area. In the next step, the results of the REMO model were fed into the Wave Analysis Model (WAM) (WAMDI group 1988, Weisse, Günther 2007), to arrive at the wave climate hindcast of the North Sea in a nested grid of 50×50 km resolution. The same procedure was applied for hindcasting of the Baltic Sea wave climate with the spatial resolution of approximately 5.5×5.5 km, without nesting and using the North Sea hindcast as a boundary condition near the Danish Straits (Weisse, Günther 2007). The reconstruction of wave climate there was based on the high resolution WAM4 modeling framework. The computed wave climate parameters comprise hourly estimates of significant wave and swell height, wave and swell direction, wind direction and wave period.

The reconstructed waves were validated against available records of actual wave measurements near Lubiatowo (Cieślikiewicz, Paplińska-Swerpel 2005). The validation showed a good agreement between measurements and hindcasts; the correlation coefficient between the hindcast and measured *in-situ* significant wave height at Lubiatowo was high and equalled 0.82. Even though extreme values of significant wave height were slightly overestimated by the hindcasting procedure, it was concluded that the goodness of fit is satisfactory enough to use the hindcast quantities for research purposes (Cieślikiewicz, Paplińska-Swerpel 2005). For example (Różyński 2010), using deepwater hindcast significant wave height ($h \approx 20$ m) near Lubiatowo, PL, found a certain coupling between the reconstructed waves and North Atlantic Oscillation for the winter months of January and February.

The current study is devoted to comparison of the same wave climate near Lubiatowo (open sea location) to a point near the Vistula river mouth, far within the Gulf of Gdańsk ($h \approx 90$ m). The main purpose of this comparison is the assessment of the sheltering effect in the Gulf, expressed by the ratios of average monthly significant wave heights, reconstructed at both locations. Due to the geographic configuration of the Gulf, the sheltering can vary from place to place. Thus, the results should be treated as the first step towards the mapping of the sheltering effect in the whole Gulf. Such mapping is intended to provide input for ICZM studies on sustainable development of various coastal segments in the Gulf. The second goal is the assessment of the variation in storminess at both locations throughout the study period.

2. Study Area

The point selected for the analysis of waves near the Lubiatowo station has the following geographic coordinates: 17.8506 E and 54.9079 N. It represents a deepwater open sea location ($h \approx 20$ m). To quantify the wave climate there, monthly mean values of significant wave height H_s were computed from hourly hindcasts. This parameter was selected because of a straightforward relationship with wave energy and thus connection with erosion potential. The same parameter was selected for the second location, 19.0126 E and 54.4163 N, *i.e.* a deepwater point near the current Vistula river mouth, near the village of Jantar ($h \approx 90$ m). This point is situated deep within the Gulf and therefore a large sheltering effect can be expected. A visual representation of both sites is presented in Fig. 1.

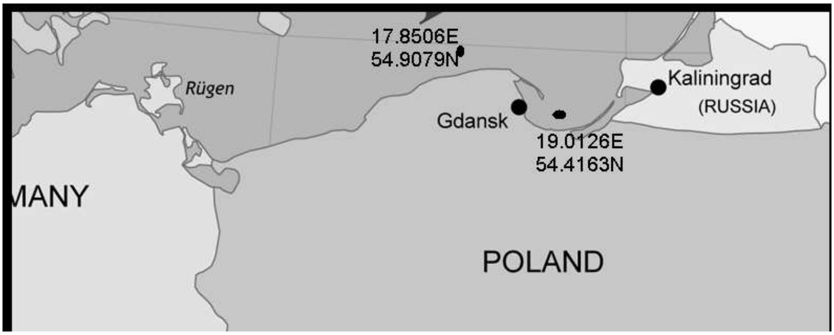


Fig. 1. Two study locations: at open sea near Lubiatowo and in Gulf of Gdańsk

3. Analysis

The entire significant wave height reconstruction time series (hourly estimates) was partitioned into 12 subsets containing wave information for each month. Then, mean values were computed for each subset from 1958 until 2001. The results are plotted in Fig. 2. The most immediate observation to be deduced from Fig. 2 is the substantial relative reduction in wave height within the Gulf. This reduction is largest for the winter months (ca. 45%) (January, February, November, December). In summer it is also significant and amounts to at least 33% (May). This indicates a considerable fall in wave attack potential near the Vistula river mouth and points to the fact the mouth is river dominated because reduced waves have little power to vastly remodel

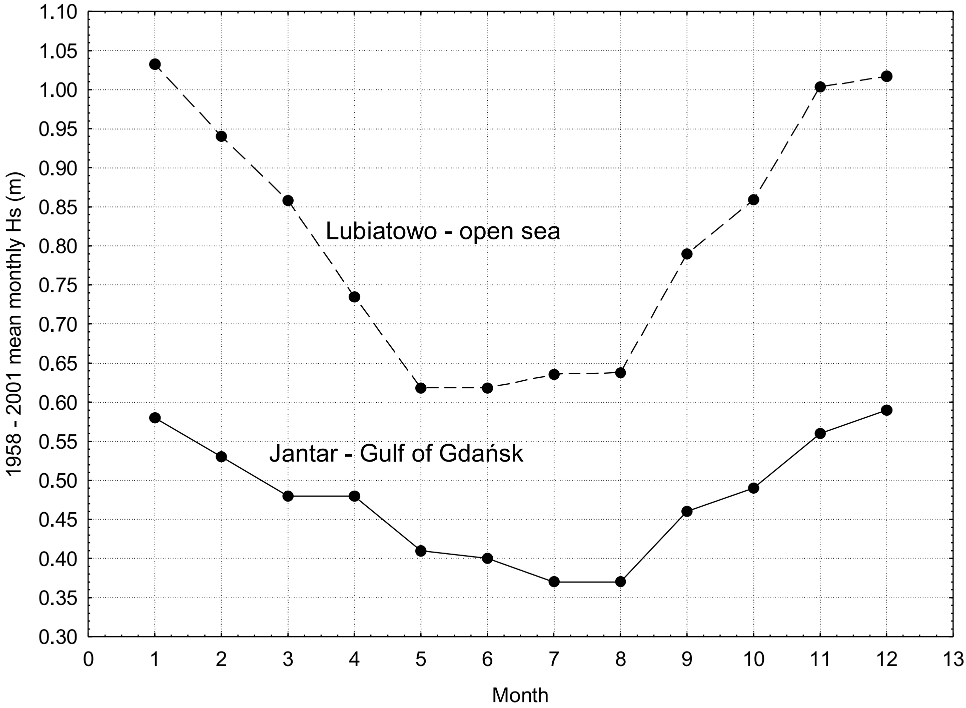
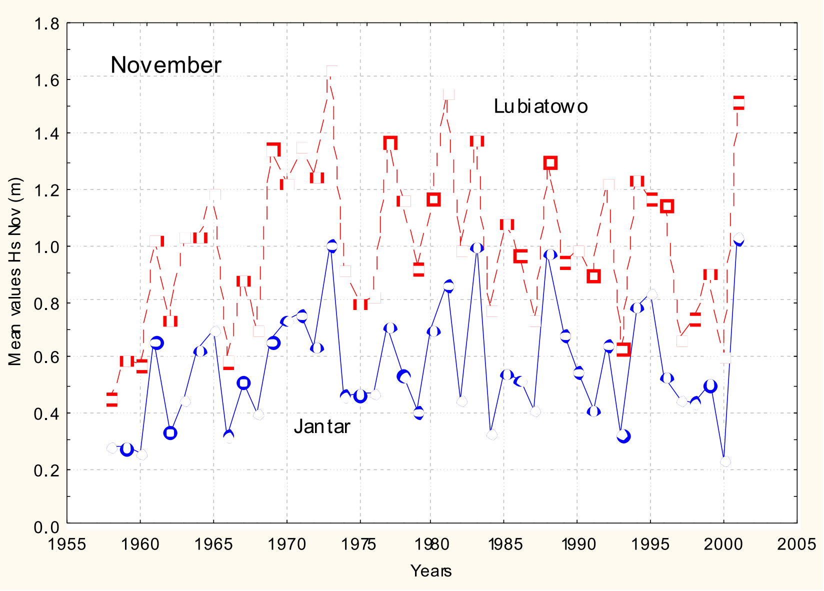


Fig. 2. Mean monthly H_s at Lubiatowo and Vistula river mouth

the alluvial fan. The fan's evolution is dominated by constant flux of riverine sediment and periodic 'flushes' by extreme river discharges; severe storms can only play a secondary role because the approaching waves cannot carry much energy into the fan area.

The information on waves at both locations was assessed by visual inspection of plots shown in Fig. 3, which present monthly mean H_s values for each November, December, January and February in the 1958–2001 period. It can immediately be seen that the wave climate in the Gulf varies almost 100% consistently with the open sea location, with the only difference being a reduced wave height. Therefore, apart from wave height/energy reduction in the Gulf, wave climate reconstruction gives the same information as the open sea hindcast. For this reason, further analysis was based solely on the open sea location.

Long-term reconstruction of wave climate also allowed for the assessment of the evolution of storminess. Fig. 4 presents the number of hindcast hours where the estimated significant wave height near Lubiatowo exceeded 1 m in two sub-periods: 1958–1979 and 1980–2001. We can see a spectacular growth in storminess in January and less vivid augmentation in February, October, November and December. More information on the nature of the growth in storminess was found in conditional



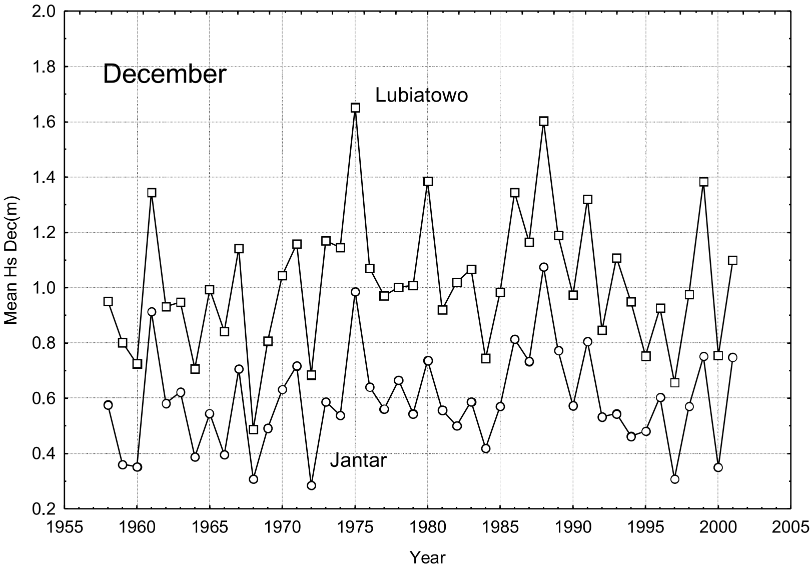


Fig. 3. Monthly H_s for Novembers and Decembers 1958–2001

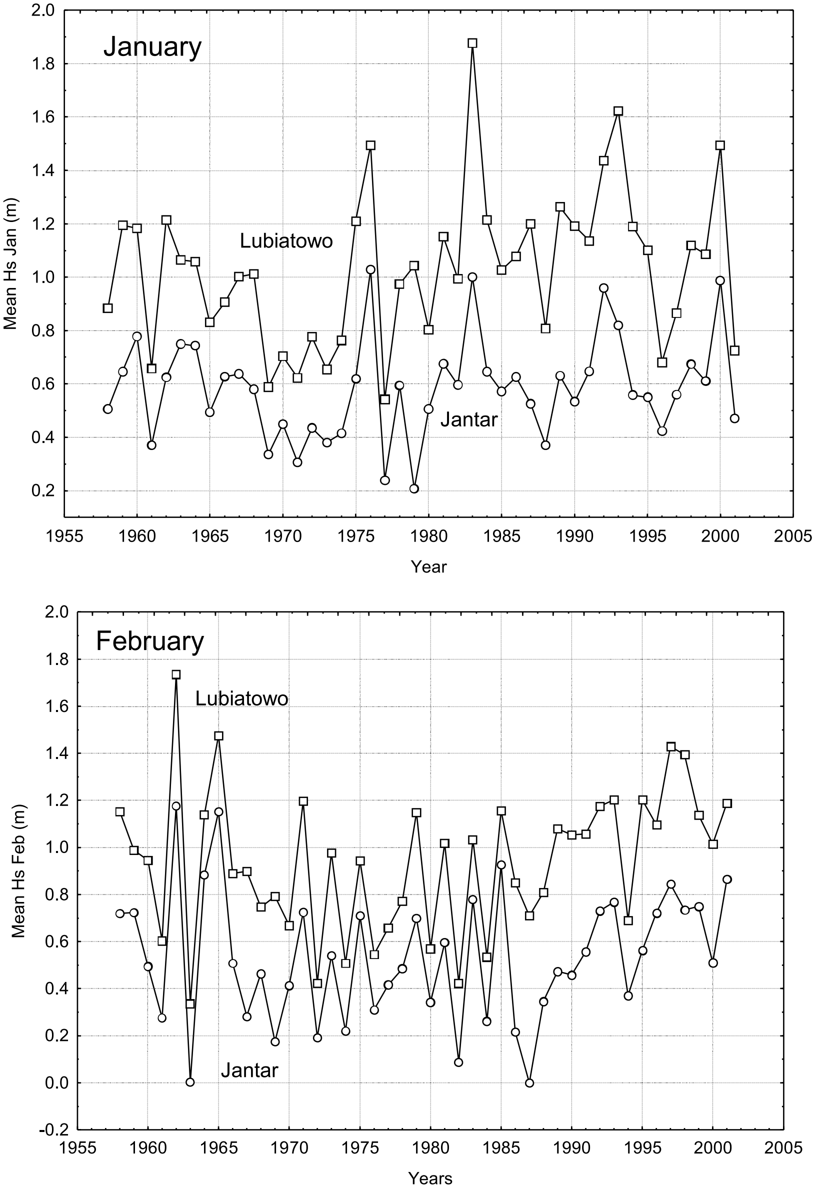


Fig. 3a. Monthly H_s for Januaries and Februaries 1958–2001

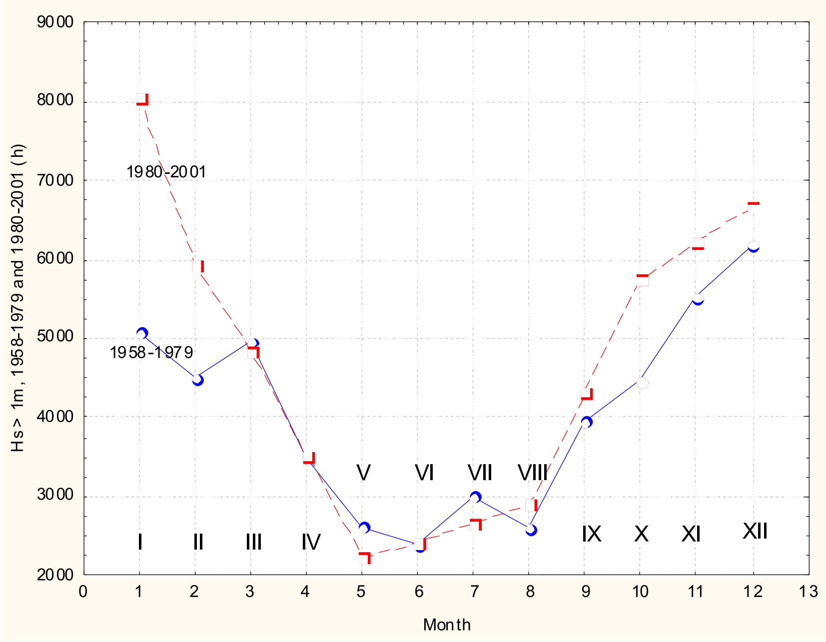


Fig. 4. Growth in storminess in winter season over reconstruction period

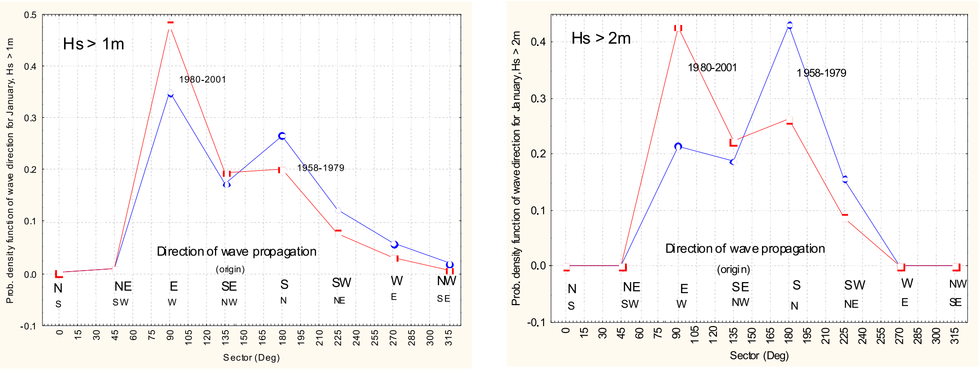


Fig. 5. Growth of extreme waves from western sector in January: empirical, conditional ($H_s > 1$ m and $H_s > 2$ m) probability distribution functions of wave direction

empirical probability density functions of wave approach directions, estimated for the location near Lubiatowo and shown in Fig. 5.

The left plot in this figure shows that for significant waves exceeding 1 m there was an increase in waves coming from the western sector. When the wave threshold is lifted to 2 m, we can see that the increasing number of westerly waves coincides with a simultaneous fall in northerly waves. Fig. 5 thus illustrates a substantial growth in the number of extreme waves from the western sector. In other words, extreme events have become more frequently driven by wind and pressure fields from that sector. The origin of those fields should be sought in large meteorological patterns over the Atlantic Ocean; Różyński (2010) found a gentle coupling between long-term trends of significant waves and North Atlantic oscillation (NAO) in January. Still, the results of that study have only a preliminary character and more in-depth analyses with more accurate data are required to pinpoint the NAO-wave height relationship with greater precision and accuracy.

The growth in storminess in January (most energetic month) denotes a greater susceptibility of sandy beaches to erosion. Interestingly, the growth in westerly wind circulation also means a rise in temperatures in January, frequently above freezing. Hence, the risk of beach losses due to more powerful westerly winds is further magnified by the related rise in temperature and the resulting reduction in ice armor, which would normally defend soft beaches from excessive wave action in winter. All of this suggests severe implications for ICZM actions, plans and strategies, which will have to accommodate more severe hydrodynamic regimes occurring without ice protection.

The second implication of the growth in storminess and particularly the observed change in dominant wave directions is related to the mapping of the sheltering effect of the Gulf of Gdańsk. Greater exposure to westerly waves on easterly beaches in the Gulf, mainly situated in the Kaliningrad region, means that beaches there will be enjoying less sheltering than the westerly parts in the vicinity of the cities of Gdańsk and Gdynia. From a research perspective this shows an urgent need to calculate the sheltering effect at several key locations in the eastern part of the Gulf.

4. Conclusions

– The study quantified reduced wave attack (sheltering effect) in the Gulf of Gdańsk near the Vistula river mouth,

– The most effective sheltering was observed in winter – significant wave height in December, January and February was reduced by almost a half.

– Substantial sheltering explains long-term observations that coastal areas near the Vistula mouth are not seriously endangered by direct wave attack; the inundation of coastal areas usually results from storm surge induced backwatering in Vistula and other smaller rivers, creeks and canals having direct or indirect connection with the Gulf,

– The plots of monthly wave heights at both locations show nearly 100% resemblance; the only information extracted from the Gulf wave climate that was not available at the open sea location was wave reduction, probably due to short fetch; this illustrates limitations in wave climate reconstructions from air pressure and wind velocity fields, which are usually based on coarser resolution than the WAM4 resolution,

- The sheltering effect also explains why the Vistula's alluvial fan is river dominated; smaller waves have no energy to remodel the fan substantially and its evolution is shaped by constant delivery of riverine sediment and 'flushes' during peak discharges – snowmelt and heavy rainfalls upstream,
- The mapping of the sheltering effect in the Gulf can be obtained by determination of wave height reduction at other locations there, knowing that eastern beaches are exposed to direct head-on wave attack, whereas southern and western segments are protected by geographic configuration of the Gulf,
- The identified growth in storminess, particularly in January, and the combined growth of westerly waves in winter months indicate that eastern beaches in the Gulf will have to cope with significantly higher energies, posing a risk of accelerated erosion there; maps of the sheltering effect should reflect this climate-change related evolution,
- Results of wave climate reconstruction, including growing winter storminess and the changing direction of extreme waves, can be used in ICZM plans of coastal zones situated in the Gulf; such analyses will be particularly vital in eastern regions, where intensified head-on wave attack becomes more likely.

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