

Multidecadal Fluctuations of Storminess of Black Sea Due to Teleconnection Patterns on the Base of Modelling and Field Wave Data



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Abstract The connections of Black Sea storminess activity with teleconnection patterns (climatic indexes) were performed on the base of visual wave observations (Voluntary Observing Ship) and WAM modelling. The annual maximal waves are more affected by AMO and PDO, but annual mean waves by NAO. It is shown that for qualitative analysis of climatic variability of waves on short- and middle-time periods, in general, one can use numerical simulation data even at one point of sea combining classical correlation analysis with wavelet analysis methods and parametric spectral analysis. In WAM modelling data, a long-term periodicity cannot be defined.

Keywords Teleconnection patterns · Storminess variability · Black Sea North Atlantic oscillation · Pacific decadal oscillation
Atlantic multidecadal oscillation

1 Introduction

Storminess variability is one of the key importance for many marine applications, naval and coastal engineering. Recent investigation had shown that extreme wave climate and coastal hazards are strongly affected by teleconnection patterns of atmospheric and oceanic variability on interannual and multidecadal timescales [1–3]. The teleconnection pattern defines a recurring and permanent, large-scale pattern of

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pressure and circulation anomalies that span some geographical areas [4, 5]. Teleconnection patterns are also defined as preferred modes of low-frequency (or long timescale) variability of the atmospheric circulation. Detailed description of teleconnection patterns, its calculating and importance can be found, for example, on <http://www.cpc.ncep.noaa.gov>. Studying the evolution of storminess along with large-scale atmospheric connection patterns and being able to predict them is crucial in the context of problem of global climate change. This is the main aim of the work on example of Black Sea's wave climate.

2 Teleconnections Patterns

For analysis of multidecadal fluctuations of storminess of Black Sea such teleconnection patterns as North Atlantic oscillation (NAO), Pacific decadal oscillation (PDO), Arctic oscillation (AO), East Atlantic–West Russian and Atlantic multidecadal oscillation (AMO) were chosen. The North Atlantic oscillation (NAO) index is calculated on the surface sea-level pressure difference between the Subtropical (Azores) High and the Subpolar Low. The Pacific decadal oscillation (PDO) indicates a long-lived El Niño-like pattern of Pacific climate variability. The Atlantic multidecadal oscillation (AMO) is a coherent mode of natural variability occurring in the North Atlantic Ocean with long-time period of 60–80 years. It is based on the average anomalies of sea surface temperatures in the basin of North Atlantic and associated with such important climate impacts as the variability of hurricane activity in Atlantic basin, changes of European summer climate and northern hemispheric mean surface temperature. The Arctic oscillation (AO) is a climate pattern characterized by winds circulating counterclockwise around the Arctic at around 55°N latitude. AO reflects the climate variability connected with a penetration of colder arctic air and increasing storminess into the mid-latitudes. The East Atlantic/West Russia (EA/WR) pattern affects Eurasia throughout year. The main surface temperature anomalies associated with the positive phase of the EATL/WRUS pattern reflect above-average temperatures over Eastern Asia and below-average temperatures over large portions of western Russia and north-eastern Africa.

3 Wave Data

The Black Sea is the inner sea of Atlantic Ocean located between Eastern Europe and Western Asia. The Black Sea connects with the Mediterranean Sea and then with the Atlantic Ocean, through the Aegean Sea and various straits. According to classification suggested in [6], the Black Sea can be divided into five regions differed by wind-wave activity (Fig. 1). The main problem of analysing the variability of wave climate is long-term wave data. Usually, there are no such data of measurements and modelling data are analysed. But there are some questions about modelling data: (a)



Fig. 1 Black Sea region, characteristic parts of Black Sea, points of modelling data (O1) and hydrometeorological service observation (O)

how many modelling data we need or how many points of investigated region we need and (b) how does an accuracy of modelling influence on analysis and predictions of wave climate variability? To answer these questions, we will compare three types of data for one of the regions of Black Sea and data for all sea.

The analysis of Black Sea storminess activity was performed on the base of:

- (a) Visual wave observations (Voluntary Observing Ship or VOS data) for the period 1955–2007 years [7, 8]. In total for this period for all parts of Black Sea, there are 125,142 observations available for analysis. Wave data of swell and wind-driven sea are registered separately;
- (b) Open-source data of anomalies (A_i) of heights of maximal waves:

$$A_i = (H_i - \text{mean}(H))/\text{std}(H), \quad (1)$$

where $H = H(\text{year})$ —height of maximum wave in year, i —year, std —standard deviation, based on visual and semi-instrumental observations on hydrometeorological station on Black Sea near Khersoness lighthouse (Fig. 1) for the period 1955–2007 years [9];

- (c) Hindcasting wave data was modelled using the spectral wave model WAM Cycle 4 [10]. Historical wind data for the Black Sea region for 59-year period (1948–2006) were extracted from NCEP global reanalysis [11]. The modelling was performed on a regular spherical grid, covering the Black Sea basin at 0.5° spatial resolution. During modelling, following source terms in wave action equation were taken into account: wind input, quadruplet nonlinear interactions and white capping. Previously validated WAMC4 model for the Black Sea had

shown a good agreement between the modelling results and observations [12]. Continuous hourly time series of root-mean-square wave height are simulated. From all massive of modelling data for analysis, the wave data in one point were chosen (Fig. 1). VOS data annual means and annual maximal heights of wind-driven seas and swell were investigated separately. For all data, the wavelet analysis with wavelet function Morlet and the parametric spectral analysis using Yule-Walker method were applied.

4 Discussion of Results

In Fig. 2, the wavelet transforms of all teleconnection indices are shown. It is well visible that changes all of indices are non-stationary process. There are trends of changes in frequency, which are not resolved by spectral analysis. But long-term variability of indices is well visible on wavelet transforms.

In Fig. 3, the changes of maximal annual wave heights of swell and wind-driven sea for all Black Sea and wavelet transforms are shown. The same data for mean annual waves are in Fig. 4. It is well visible that for all analysed wave data of maximal and mean annual waves have on average the same trends of change: since the mid-1980s, there has been a sharp decrease in the heights of waves. For annual mean wave heights of wind-driven sea, this decreasing is not so clear pronounced, especially for wind waves. For annual mean wave heights, the general increasing of wave height in period of 1955–2007 and heights of swell waves increase more than wind waves. In general, increasing of heights of mean annual height of swell waves was 25%. The average mean annual wave height for period of 1955–2007 years is 1.1 m for wind waves and 1.486 m for swell. The average annual maximal height of wind waves is 8.88 m, and swell waves are 9.18 m.

The decreasing of heights of annual maximal waves beginning in the mid-1980s is described in [13]. In this work, it is associated with the 50-year period of the Atlantic multidecadal oscillation (AMO). Also it is pointed out that the Pacific decadal oscillation (PDO) also affects the change in storm conditions and wave heights in the Black Sea, especially when both PDO and AMO are in the negative phase. Our analysis showed that (1) a sharp change in the heights of waves occurs when the PDO is in the maximum phase and the AMO is still in the negative phase, and (2) if the sharp change in the maximum wave heights is due to the minimum phase of the low-frequency AMO fluctuation, a time delay is about 4–5 years.

Wavelet analysis of variability of heights of waves shown that the characteristic periods of fluctuations in the heights of annual mean and maximal waves, on the whole, are non-stationary (Figs. 3 and 4).

The low-frequency changes in annual maximal waves, both wind-driven and swell, are affected mainly by the AMO index, and influence of the PDO index is also traced. The changes in wind waves are followed also (a) by AMO in decreasing frequency 0.09; (b) by AO, especially after 1970, at the scale of 17 years—frequency 0.06; and (c) NAO with decreasing frequency of fluctuations from 0.08 to 1.2. It can be

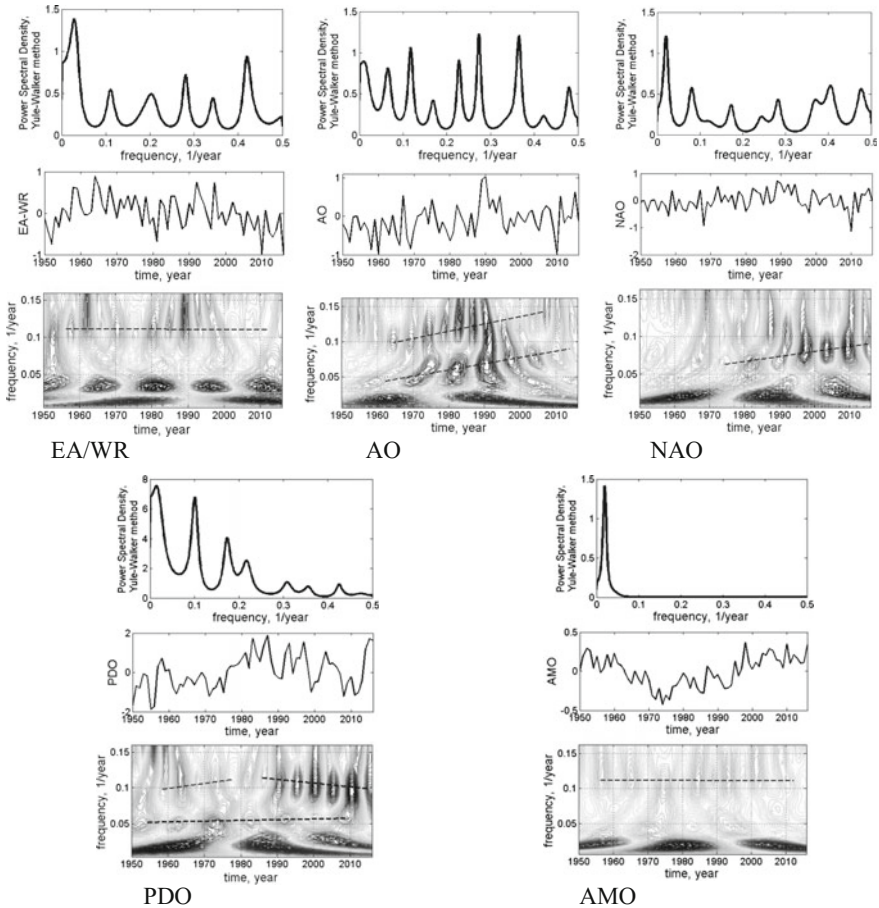


Fig. 2 Teleconnection patterns, its spectra and wavelet transforms. Some trends in frequency variability are shown by dotted lines

said that until the mid-1980s, AMO had a greater influence and now index NAO. In swell waves, the changes are in the antiphase with PDO (the frequency scale of 0.05). But fluctuations with this frequency scale are not observed in wind-driven sea waves. Until 1980, the frequency scale about 1.2–1.5 associated with AMO is clearly traced.

The changes in annual mean wind-driven waves are connected with the PDO on frequency 0.05 which increases, starting from the 80 s, to frequency about 0.1, that can be connected with fluctuations of AMO. The low-frequency fluctuations associated with the AMO are not traced. The influence of NAO (especially in 2000s) is traced. The changes in annual mean swell waves are on frequencies 0.03 (connected with fluctuations of EA/WR index), 0.06 (with AO) and 0.1 (with AMO). Wavelet analysis had shown that the relationship between the variation of the wave heights and

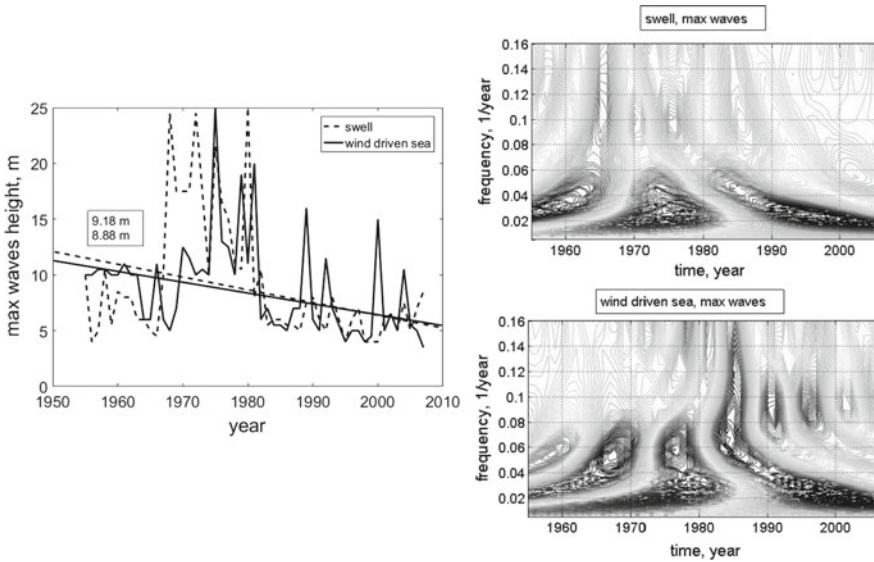


Fig. 3 Variability of heights of annual maximal swell and wind-driven sea waves (left) and its wavelet transforms (right), swell—upper, wind-driven sea—lower

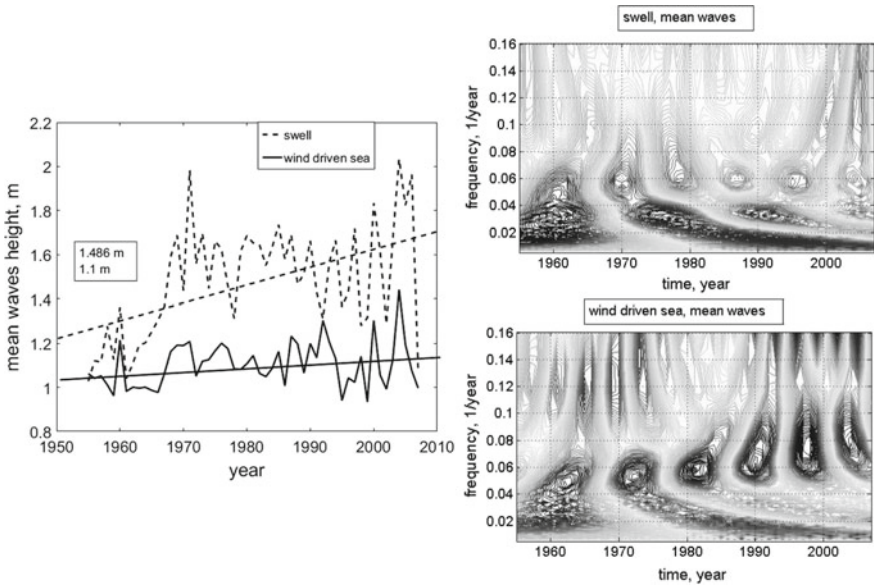


Fig. 4 Variability of mean heights of swell and wind-driven sea waves in year (left) and wavelet transforms of variability of mean heights of waves in year (right), swell—upper, wind-driven sea—lower

Table 1 Correlation coefficients with indices and height of annual maximal and mean waves

Teleconnection patterns	Annual maximal height of waves		Annual mean heights of waves	
	Wind-driven sea	Swell	Wind-driven sea	Swell
NAO	0.45	0.45	0.4	0.4
AO	0.3	0.38	0.35	0.35
AMO	0.40	0.56	0.32	0.4
PDO	0.40	0.46	0.3	0.4
EA/WR	0.30	0.37	0.3	0.35

climatic indices is rather complicated. It can be said that all fluctuations in climatic indices are reflected in changes in the heights of wind waves. However, for changes of mean annual waves, a connection with NAO index fluctuations is typical, with a period of 12–14 years and 3–4 years. For annual maximal wave heights, a low-frequency variability is more characteristic with large periods (about 45–50 years), which is mainly influenced by the Atlantic (AMO) and Pacific (PDO) oscillations. The connection with the NAO is weaker. It should also be noted that the use of spectral and classical correlation analysis to establish these relationships is complicated by the non-stationarity of the analysed data; classical correlation analysis will give lower values of correlation coefficients (Table 1).

Let us compare data of annual maximal and mean wave heights for wind waves of modelling and observed data for region 1 of Black Sea. It should be mentioned that in general, modelling data have wave heights of annual maximal waves that are twice lower than observed. For observed and modelled annual mean wave height, the difference is not so significant. But comparisons of anomalies (1) of wave heights of modelling data, HMS observations and VOS data have a good agreement (Fig. 5). Wavelet analysis demonstrates that in general, the fluctuations of wave heights are similar for modelled and observed waves. The fluctuations of modelled annual maximal waves better correspond to visual observation, than of modelled mean waves. For region 1 of Black Sea, there are correlations between NAO, EA/WR and PDO indices (correlation coefficients about 0.4). However for modelled data, correlation coefficients with all indices are less than 0.33. Using wavelet transform and parametric spectral analysis is possible to define similar periods of fluctuations in indices and heights of waves, but predominantly in middle and short periodicity. No clear low-frequency periodicity and no connections with AMO and PDO low-frequency variability are observed in modelling data. Wavelet structure of annual maximal and mean modelling waves is similar on EA-WR index wavelet transform. Wavelet structure of field observed and modelled waves has time lags practically in all frequency scales.

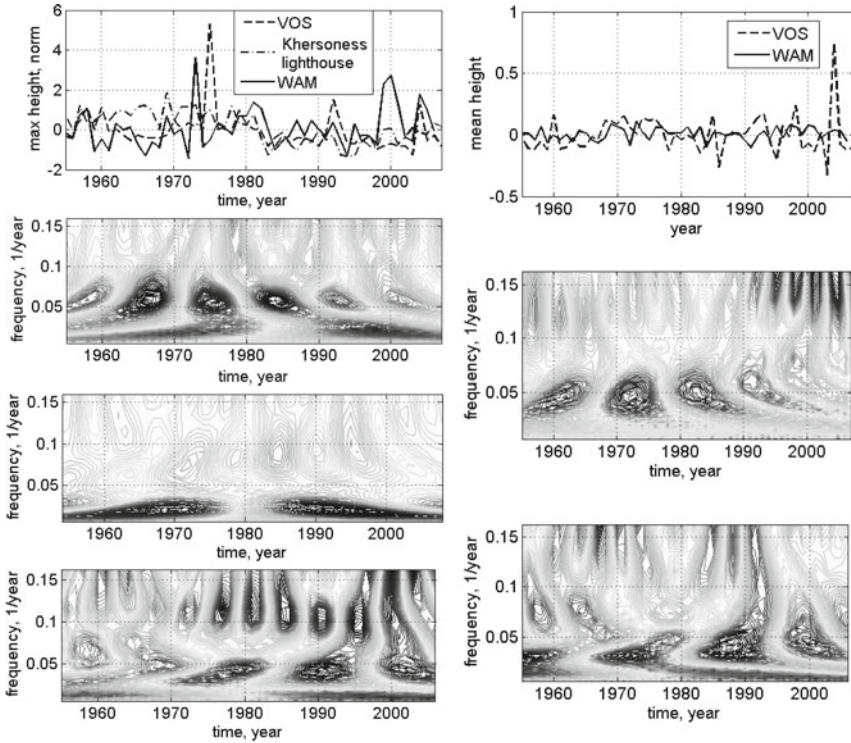


Fig. 5 Variability of heights of mean waves in year relatively its average height (left) and anomalies of maximum wind-driven sea waves (right) in year of modelling (WAM) and field observation data (VOS, HMS) and its wavelet transforms

5 Conclusions

The connections of Black Sea storminess activity with teleconnection patterns (climatic indexes) were performed on the base of visual wave observations (Voluntary Observing Ship) and WAM modelling results for the periods 1955–2007. The indexes NAO, PDO, and AMO are that well correlated the maximal and mean annual wave heights as the swell of wind-driven sea. The annual maximal waves are more affected by AMO and PDO, but annual mean waves by NAO. Wavelet analysis had shown that fluctuations of teleconnection patterns and heights of waves are non-stationary processes, so application of classical correlation analysis is not correct in this case. Wavelet analysis demonstrates also good correlation between variability of wave heights and fluctuations of AO and EA/WR teleconnection patterns. There are regional differences in connection of variability of wave heights with teleconnection patterns. The wind-driven sea waves at region 1 of the Black Sea are better connected with the index EA-WR, NAO and PDO. The variability of heights of swell waves is better connected with the fluctuation of index AMO and NAO. It is shown

that for qualitative analysis of climatic variability of waves on short- and middle-time periods, in general, one can use numerical simulation data even at one point of region combining classical correlation analysis with wavelet analysis methods and parametric spectral analysis. But in modelling data, a long-term periodicity cannot be defined.

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References

1. Bromirski PD, Cayan DR (2015) Wave power variability and trends across the North Atlantic influenced by decadal climate patterns. *J Geophys Res Oceans* 120:3419–3443. <https://doi.org/10.1002/2014JC010440>
2. Masselink G et al (2014) Role of wave forcing, storms and NAO in outer bar dynamics on a high-energy, macro-tidal beach. *Geomorphology* 226:76–93
3. Hurrell JW, Deser C (2009) North Atlantic climate variability: the role of the North Atlantic oscillation. *J Mar Syst* 78(1):28–41
4. Barnston AG, Livezey RE (1987) Classification, seasonality and persistence of low-frequency atmospheric circulation patterns. *Mon Weather Rev* 115:1083–1126
5. Wallace JM, Gutzler DS (1981) Teleconnections in the geopotential height field during the northern hemisphere winter. *Mon Weather Rev* 109:784–812
6. Lopatuhin LI (2006) Reference data on the regime of wind and waves in the Baltic, Northern, Black, Azov and Mediterranean seas. Saint-Petersburg, Russian maritime register of shipping, 450 p (in Russian)
7. Gulev S, Grigorieva V (2016) World oceans waves (WOW). www.sail.msk/wow
8. Grigorieva VG, Gulev SK, Gavrikov AV (2017) Global historical archive of wind waves based on voluntary observing ship data. *Oceanology* 57(2):229–231
9. Naumova VA et al (2010) Wind-wave conditions of the Azov-Black Sea coast of Ukraine. *Nauk UkrNDGMI*, vol 259, pp 263–283 (in Russian)
10. Günther H, Hasselmann S, Janssen PAEM (1992) Wave model cycle 4: technical report no. 4. In: Modellberatungsgruppe Hamburg (ed) *Deutsches Klima Rechen Zentrum*, Germany, p 102
11. Kalnay E et al (1996) The NCEP/NCAR reanalysis project. *Bull Am Meteorol Soc* 77:437–471
12. Cherneva Z et al (2008) Validation of the WAMC4 model for the Black Sea. *Coast Eng* 55:881–893
13. Polonsky A et al (2014). Low-frequency variability of storms in the northern Black Sea and associated processes in the ocean-atmosphere system. In: *The regional environmental change*, vol 14, issue 5, pp 1861–1871