SESSION 1
"Global environmental risk"

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Modelling natural risks in the Russian seas

INTRODUCTION

Coastal zones are characterized by extremely high concentration of the World's population (producing >70% of the GWP). Integration of the coastal structures into the economy goes far beyond coastal regions, stresses on the economy and life conditions of the coastal zones crucially impact on the economy and life conditions in the inland regions. All these make coastal zones highly vulnerable to natural hazards with the key concerns being that sea level rise or changes in maritime storms cause flooding resulting in inundation and subsequently land loss. Responses to sea level rise have implications for water resources, and the ecological balance in the coastal zone with its ocean part and the neighboring land part. Increasing population pressure on the coastal zone — more people moving to the coast because of enhanced economic development through increased use for transport infrastructure, tourism, industry settlements — increases the risk and vulnerability. The Russian coastal zones are characterized by strongly different conditions implying large differences in the nature and character of extreme events. This requires very different approaches to the risk assessment of natural hazards in the marginal Arctic coasts and the inland sea coasts in the Baltic, Black, Azov and Caspian seas because approaches relevant for one area may not necessarily be effective for the others.

Marine storminess represents the core of the direct local ocean impacts and originates from the off-shore winds. According to Gulev and Grigorieva [8], during the last several decades there has been a tendency of growing mean and extreme significant wave height (SWH) over the North Atlantic and North Pacific with a maximum of 10-12 cm per decade. Furthermore, in the coastal areas the trends are typically higher than in the open ocean regions, being of up to 20 cm per decade. Importantly, wave extremes typically grow faster compared to the mean values. For instance, for the Barents and Black Seas 99th percentile of SWH was nearly doubled during the last 5-6 decades, while the mean values increased by 20-25%.

Climate model projections show that the midlatitudinal hydroclimate extremes will likely intensify and become more frequent for the 21st century under all emission scenarios [11]. These projections, being quite robust on average, exhibit, however, a very large spread and give little confidence in particular coastal regions. This is not surprising given the large number of mechanisms involved. Even in the advanced climate models such mechanisms as regional water vapor recycling and changing cyclone life cycle are poorly resolved. Thus, scenario climate projections require regionalization or downscaling to regional scale. Importantly, the downscaling is just partly a resolution issue — on small scales there are conceptual drawbacks in large scale climate models. Moreover, realistic adaptation of these models to specific coastal areas requires extensive use of observational data for validation purposes.

To identify and fill the gaps in our understanding the mechanisms and quantifying the intensity of extreme hazardous events in the coastal zones of Russian Federation the Natural Risk Assessment Laboratory (NRAL) were established at the Faculty of Geography, Lomonosov Moscow State University in 2010. During 2010-2016 NRAL implemented a comprehensive research programme of ocean-related extreme events in costal zones, centered on understanding their nonlinear nature and multifactor character. We developed a comprehensive catalogue of climate extremes over coastal zones of European Russia and performed high resolution diagnostic and modelling studies of different types of extreme events resulting in natural hazards, such as extreme wind wave storms, extreme precipitation and associated flash and river flooding, extreme temperature conditions and abrupt changes in the local geochemical balances. In particular, we understood that extreme wind waves may not necessarily follow mean climatological values of wind and wave height and may exhibit strong increases in magnitude even when the mean values are relatively stable, as in the Barents and Kara Seas [7].

Our studies clearly demonstrated that most of the coastal hazards are associated with the compound nature of climate extremes, quantified through hydrological modelling using high resolution models of wave modelling [1] and non-hydrostatic atmospheric modelling. To build an effective system which allows for the synthesis of ocean dynamics and atmospheric dynamics — we implemented at NRAL most advanced wave models (WAWEWATCH and SWAN), high resolution regional ocean model ROMS and the atmospheric high resolution non-hydrostatic model WRF. Never before have all these highly technological numerical tools been employed in a synergistic and holistic way, even at leading operational and forecasting centers.

The present paper highlights some results of a modelling studies of storm waves in some seas near Russia during last decades based on the NCEP/NCAR reanalysis data [12]. The goal of this study was to assess modern climatic parameters of wind waves and storm surges in the Black, Caspian, Baltic and Barents seas and to determine their spatial, annual and seasonal variability.

DATA AND METHODS

Nowadays, numerical modelling seems to be the most appropriate method of generating wind wave data sets. The main advantage of this technique is its flexibility relative to the formulation of initial conditions, the calculated parameters and the resolutions — both temporal and spatial. Another advantage of modelling studies is the possibility to perform hindcast and forecast calculations using archived or forecast wind fields. Operational wave forecasting on different spatial scales is a state-of-the-art field in which numerical modelling is used.These models are relatively well developed and provide the wide range of configurations. However, for every individual region (the Caspian Sea, Baltic Sea, Barents Sea, Black Sea) the choice of the best configuration is an unresolved scientific task dominated by regional features.

A calendar of storm events was derived for the period 1948–2010 for this study. The numerical storm simulator SWAN (Simulating WAves Nearshore) was used, a third generation wave model that was developed at Delft University of Technology. It computes random, short crested wind-generated waves in coastal regions and inland waters [4]. The model is based on the wave action balance equation (or energy balance in the absence of currents), with sources and sinks. It uses typical formulations for wave growth by wind, wave dissipation by white-capping, and four-wave nonlinear interactions Wind forcing data was extracted from NCEP/NCAR reanalysis [12] at the 6-hourly intervals available (0000 UTC, 0600 UTC, 1200 UTC and 1800 UTC). The spatial resolution of the SWAN numerical grid was about 5 km. An overview of numerical simulations is described in [1,2]. For our study, days were chosen when modeled wave height was 4 m or more. The threshold of 4 m is based on the state standard for safety in emergencies [3], which specifies waves of 4 m or more in the coastal zone and 6 m or more in the open sea as hazardous. 412 storm cases were identified for the Baltic Sea, 137 cases for the Black Sea and 94 for the Caspian Sea between 1948 and 2011. Sea floor topography (0.05 × 0.05 degree, rectangular grid) and surface wind speed and its direction are used as model inputs. The wind forcing data set was extracted from NCEP/NCAR reanalysis for the 6-hourly values available at 1.9×1.9 degree. Supercomputers “Chebyshev” and “Lomonosov” of the Moscow State University were used for the numerical experiments.

In contrary to the Black, Caspian and Baltic seas, we need to include swell from the North Atlantic for the analysis of the White and Barents seas. In this paper, we present the evaluation of the effect of the swell generated either in the North Atlantic or in the Barents

Sea, on the waters of the White Sea. It turned out that the effect from the North Atlantic swell on the White Sea is negligible (height up to 0.2 m) for the area.

For the climate projection of storm events we used daily sea level pressure (SLP) fields (0-90°E, 30-80°N) generated by the coupled atmosphere-ocean circulation model of Max Plank Institute ECHAM5/MPI-OM [17] within the framework of CMIP3 project [14]. It consists of models for the atmosphere (ECHAM5) and the ocean (MPI-OM). Global ECHAM5-MPI/OM SLP datasets were taken from the open-source CMIP3 archive at the Program for Climate Model Diagnosis and Intercomparison (PCMDI) [http://www-pcmdi.llnl.gov] for the 1960-2000 and 2046-2065 (SRES, emission scenario A2 [15]).

As shown in [17], ECHAM5-MPI/OM appears to closely reproduce daily mean SLPs and the frequencies in circulation types, especially for the late autumn, winter and early spring periods. This justifies the use of the model because the majority of the storm activity in the Black, Baltic and Caspian Seas is observed in the cold season.

Our approach of atmospheric circulation classification for storm events relies on the understanding that storm waves are mainly the product of wind speed and direction, which determine the value of the flux of momentum from the atmosphere to the sea. Storm wave parameters also greatly depend on the sea size, its depth, bottom relief, coastline configuration etc. But these factors are not results of atmospheric processes on as short a time-scale as one storm. It is the surface wind that plays the most important role in individual storm forcing. Fortunately, the pressure is the most reliable meteorological parameter reproduced by reanalyses and by climate general circulation models, and so a straightforward expansion of the study to model data is possible. SLP has already been used successfully in previous classification procedures, e.g. [10, 18].

The steps of our study were the following: to classify SLP grids accompanying storm events (from now on referred to as storm SLP); to extract the main features of circulation patterns for every type; to evaluate the frequency of every type for the modern climate and possible changes in frequency in the future. The circulation types are obtained by cluster analysis (k–means approach, e.g., [11]) preprocessed by Empirical Orthogonal Function (EOF) analysis, e.g., [16] to reveal few leading modes determining the most part of variance. These techniques of EOF decomposition and k-means cluster analysis, together or in combination with other techniques, are widely used in circulation type classifications, e.g., [5, 18]. Firstly a dataset consisting of 30 daily SLP grids was prepared for every storm from the calendar, including 15 days before and 15 days after each storm day. After EOF decomposition of daily SLP grids, the first three eigenvectors were retained, describing more than 70% of the variability. Therefore, high frequency perturbations were filtered out. EOF fields of sea level pressure for storm days (according to the storm calendar of the sea) were used as input variables to classify circulation patterns. Definition of circulation types was carried out using the k-means cluster analysis. In this study, cluster centroids (ensemble mean of cluster members) were constructed for each circulation type by averaging the SLP grids of all days that belonged to the same circulation type.

The same procedure was also applied to the model data for the period 2046-2065, i.e. the correlation was calculated between daily model SLP and reanalysis SLP fields from the storm calendar. Before this correlation procedure, the model data were interpolated on the reanalysis grid.

RESULTS AND DISCUSSION

Storm events (with $H \geq 4$ m) modeled by SWAN were included into our storm calendar to classify the synoptic patterns that accompany Black, Caspian, White and Baltic Sea storms. For example, time series of annual storm frequency for the Baltic Sea (Fig. 1) demonstrated noticeable interannual and decadal variability. The relatively stable regime of 1950s and 1960s was replaced by a positive trend in the 1970s which, while briefly interrupted at the end of the 1980s, continued on until the first part of the 1990s. We also revealed an increase in storm activity in 1979-1989, maximum in 1992-1994, sharp decrease till 2000 and a gradual increase until 2010 for the White Sea. No valuable in the amount of storm situations were observed in this basin. The alternation of relative calm and stormy periods as well as

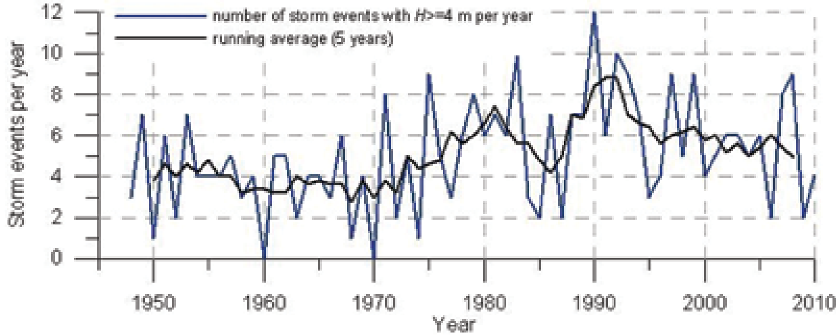

Fig. 1. Time series of storm events (H ≥ 4 m) in the Baltic Sea from SWAN results.

the increase of storminess in approx. 1960–1975 is a typical feature not only for the Black Sea, but also for other European seas, e.g. the North and Baltic Seas as shown by Matulla et al. [13].

Four main circulation types of SLP daily fields were revealed for the Baltic Sea (Fig. 2). Types 1, 2 and 4 have several common features, the main one being the dipole structure of SLP with negative

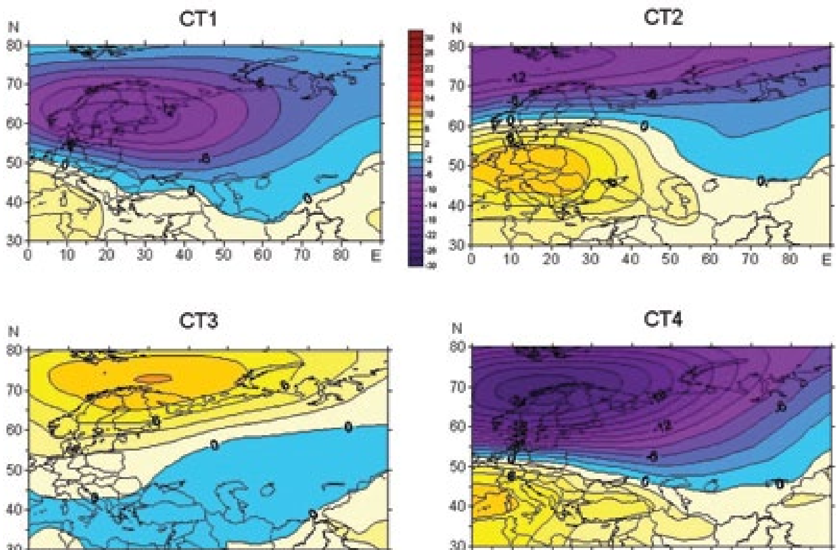

Fig. 2. Patterns of the four wintertime SLP circulation regimes for the Baltic Sea, anomalies from 1961–2000 (hPa).

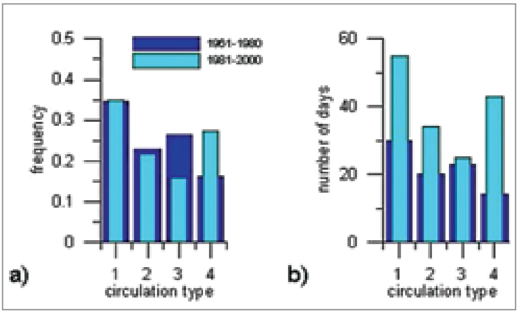

Fig. 3. Relative (a) and absolute (b) frequency of storm days in the Baltic Sea with wave height H ≥ 4 m, circulation types as in Fig. 2.

anomalies in the North and positive in the South. Despite likenesses they differ clearly in the position of their negative anomaly centers which shows the diversity of prevailing tracks of Atlantic mid-latitude cyclones. Types 1, 2 and 4 exhibit the influence of westerly air flow and cyclones moving with them towards the Baltic Sea along different trajectories. In case of CT 1, the center of cyclones is located over the Baltic Sea, for CT 2 it is over the Norwegian Sea, and for CT 4 it is over the North of Scandinavian peninsula. Circulation Type 3 is meanwhile completely opposite to others. This regime is often referred to as Scandinavian blocking and is characterized by a strong positive height anomaly over Northern Europe.

Storms in the Baltic Sea occur mainly in winter whereas summer is relatively calm. The main trend for the two time periods 1961–1980 and 1981–2000 was an increase in storm numbers, especially under the CT 4 weather regime with its high cyclonic activity. The comparison of CT regime for two periods, 1961–1980 and 1981–2000 revealed both an increase of the storm activity in the second period and a redistribution of storm frequency (Fig. 3). Further analysis showed weakening of CT 3 anticyclonic influence for the storm activity and at the same time, an increase of cyclonic CT 1, CT 2and CT 4 importance.

Within the variety of the atmospheric circulation governing the climate of the Black Sea, there are two main types of sea level pressure field derived by cluster analysis and associated with SWAN storm days (Fig. 4). For the first circulation type CT 1 (57% of events), the trough moves to the Black Sea from the eastern Mediterranean Sea, and often forms an independent local cyclone over the Black Sea.

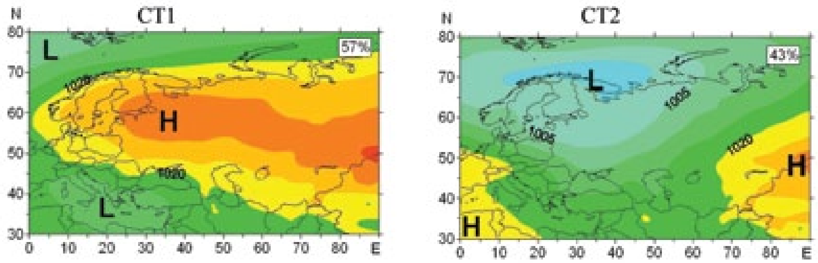

Fig. 4. Patterns of the two wintertime SLP circulation regimes (hPa) for the Black Sea.

The second type CT 2 (the other 43% of events) is characterized by a low pressure center over the Barents or Norwegian seas. The leading edge of the trough develops quickly and trails southeast rapidly from a northern low pressure center. When this cold air reaches the Black Sea in winter, a local cyclone may be generated.

These two circulation types are the most effective for the formation of storms. The configuration of the pressure field is such that the high wind flow has the largest distance over the open sea to accelerate and to induce storm waves. In these cases, storms cover a large part of the sea. Both observations and modeling in previous studies, e.g., [21, 22, 23] agree that the number of storm events in the Black Sea does not increase by the end of the twentieth century and may even reduce. The same tendency is seen in SWAN results (Fig. 5). Analysis of CT frequency shows that the proportion of the two CTs is redistributed slightly between the periods 1961–1980 and 1981–2000, with the frequency of CT 1 events becoming higher than CT 2 in the latter period.

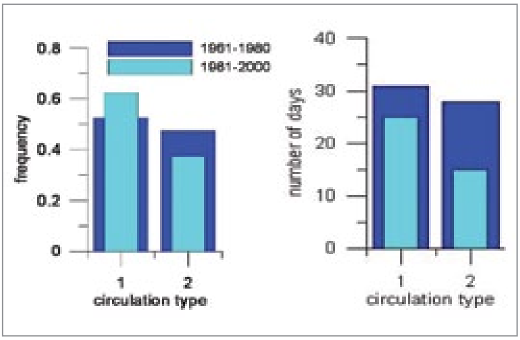

Fig. 5. Relative (a) and absolute (b) frequency of storm days in the Black Sea with wave height H ≥ 4 m, circulation types as in Fig. 4.

When comparing SLP fields of ECHAM5-MPI/OM and NCEP/NCAR for 1961–2000, the threshold for the correlation coefficient:

r ≥ 0.95 were chosen. Previous paper [39] showed that r ≥ 0.95 is enough for ECHAM5-MPI/OM and reanalysis results to have good agreement in the number of days with wind speed of 15 m/s and more, which is considered to be the threshold for storm-wave development in the investigated seas.

To analyze possible changes in storm SLP frequency in the future, we used ECHAM5 results from modeling the A2 SRES emission scenario [15], the most negative variant of human impact to the climate including high greenhouse gas emissions, non-effective land use, fast population growth etc. SRES A2 scenario has the highest temperature increase by the end of the 21st century, about 3.5° [11]. According to the ECHAM5-MPI/OM results, projected mean global temperature will increase by about 1.5°C by 2050 and by 4°C by 2100 relative to 1980–1999 [11].

Storm activity in the Black Sea will be strongly reduced by the middle of the 21st century, and so the tendency of the previous decades will continue: number of storm days will reduce from 250-350 cases for CT1 before 2000 to 200 in 2045-2064 and from 100-150 cases to less than 50 for CT2. According to an IPCC report [11], the multimodel ensemble mean SLP projection shows SLP increase over the Mediterranean Sea and Black Sea, especially between December and February. This may explain why storm activity is projected to weaken in our results. The same reduction of storm activity is expected for the Caspian Sea due to pressure increase over its surroundings.

CONCLUSION

This paper shows the results of a hindcast study of wind waves on the Black, Baltic, Caspian and White seas based on a continuous numerical calculation for the period between 1949 and 2011. The large time span of this period makes it possible to obtain reliable statistical and extreme parameters of wind waves, as well as to assess the evolution of the wave climate. A storm events calendar was prepared based on numerical experiments with the wave model SWAN and only storms with a significant wave height of 4 m or greater were chosen. Additionally, an assessment of interannual variability of storms on the Baltic, Black, Caspian and White seas was carried out. It was shown that by the end of the 20th century the storm activity in the Baltic Sea had increased, while Black and Caspian seas revealed negative trend and the White Sea absence of any trend. It was also found that the frequency of circulation types was redistributed in 1981–2000 compared to 1961–1980. This result provides an important foundation for the statistical climate projection of storm activity in future research.

The results reported in this paper could be further applied in research with the use of other data sets and methods such as meteorological hindcasts having a finer temporal and/or spatial resolution, unstructured numerical grids and coupled models permitting the calculation of both waves and hydrodynamic parameters. The latter are expected to be especially useful for studies of the characteristics in coastal areas, bays and straits.

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