**Viktoria Grigorieva[1], Sergey K. Gulev[2*] and K. Peter Koltermann[3]**

[1] P.P.Shirshov Institute of Oceanology, 36 Nakhimovsky ave. 117997 Moscow, Russia;
    e-mail: vika@sail.msk.ru

[2*] P.P.Shirshov Institute of Oceanology, 36 Nakhimovsky ave. 117997 Moscow, Russia;
    tel.: +7 499 1247985, fax: +7 499 1245983; e-mail: gul@sail.msk.ru
    (**Corresponding author**)

[3] Moscow State University, Moscow Russia

# EXTREME WAVES IN THE MARGINAL RUSSIAN SEAS: UNCERTAINTY OF ESTIMATION AND CLIMATE VARIABILITY

**ABSTRACT.** An analysis of extreme characteristics of surface wind waves in the three marginal Russian seas (Barents, Black and the Sea of Okhotsk) was performed using visual wave observations. Estimates of extreme seas, swell and significant wave heights were computed using the initial value distribution method and the peak over threshold method. Due to the use of large samples compiled for the entire seas the differences between the two methods are considerably smaller than those that would be expected for grid-cell estimates. This implies a relatively high reliability of the results. In the Barents Sea both methods demonstrate growing tendencies for the extreme wind waves, while mean values do not exhibit any significant trends. This hints at a considerable modification of the statistical distribution of wind wave heights rather than on general growth of wind seas. Some further perspectives of the analysis of regional wind wave extremes are discussed.

**KEY WORDS:** ocean wind waves, extreme events, probability distributions

## INTRODUCTION

Global information about ocean wind waves is currently available from different sources, namely long-term wind wave hindcasts performed with numerical wave models driven by reanalyses winds [e.g. Sterl and Caires 2005, Wang et al. 2004], satellite altimetry [Young et al. 2011] and visual observations by marine officers [e.g. Gulev et al. 2003, Gulev and Grigorieva 2004, 2006]. Among these three sources, the latter provides the longest time series available with however, very inhomogeneous coverage of observations over global oceans. Furthermore, these data are subject to a number of biases and uncertainties associated with observational errors and sampling inhomogeneity. Careful pre-processing of these data [e.g. Gulev et al. 2003, Gulev and Grigorieva 2006] helps, however, to minimize these biases and allows for the development of homogenized regional time series. Thus for selected well sampled regions Voluntary Observing Ship (VOS) data provide quite reliable information on surface wind waves and allow for estimation of extreme waves and their climate variability. In this context, marginal seas give a very good prospect of using visual VOS data, since they are characterized by a much higher number of samples compared to the open ocean regions. Analysis of changing storminess in marginal seas is highly important due to the potentially very high impact of changes in wind wave parameters on the operations of marine transport carriers and off-shore structures. In this paper we assemble VOS visual data for the Barents, Okhotsk and Black Seas and analyse centennial time series of wind wave parameters with a focus on estimation of extreme wind waves.

## DATA AND METHODS

We used the latest update of the global archive of visual wind wave data based on the ICOADS [International Comprehensive Ocean-Atmosphere Data Set, Worley et al. 2005] collection of marine meteorological observations. This data set covers the period from 1784 onwards with wave information starting from 1880. However, the global data coverage is provided for the period starting from 1950. During earlier decades, wave data are available only for the major ship routes with spatially and temporary varying sampling. Visual data provide separate estimates of the wind sea and swell only for the period after 1960. In the decades prior to 1960, officers reported the highest wave component. Comprehensive description of the data processing, coding systems, changes in data formats, ad-hoc corrections of biases and estimates of the uncertainties can be found in Gulev et al. [2003]. The major biases in wind sea height (hw), swell height (hs) and SWH, which have been considerably reduced in the climatology of Gulev et al. [2003] and its latest updates [Gulev and Grigorieva 2004, 2006], were the overestimation of small wave heights and poor separation of sea and swell

in visual observations. Gulev et al. [2003] also provided global estimates of random observational errors in hw and hs, estimates of day-night differences and estimates of sampling uncertainties. Sampling errors were found to be large in the poorly sampled Southern Ocean, where they dominate over the other error sources. Here we consider the period starting from 1958 to 2007 for which visual wave data are massively available. Considering Russian Seas, sampling is not homogeneous everywhere being reasonably higher in the regions of the active ship traffic and exploration of oil and gas. For example, the total number of reports for the period 1958–2007 is 46 505 for the Black Sea, 99 119 for the Barents Sea, more than 100 000 in the Sea of Okhotsk, and only 22 503 observations for the Caspian Sea.

Fig. 1 shows changes in the number of observations over the Barents and Black seas during the last century. There is a drastic increase of the reports in the Barents Sea, after the 1960s being 5–6 times higher than in previous decades. At the same time in the Black sea the number of reports during the last decades is generally similar to that for the decades of 1920s and 1930s. The
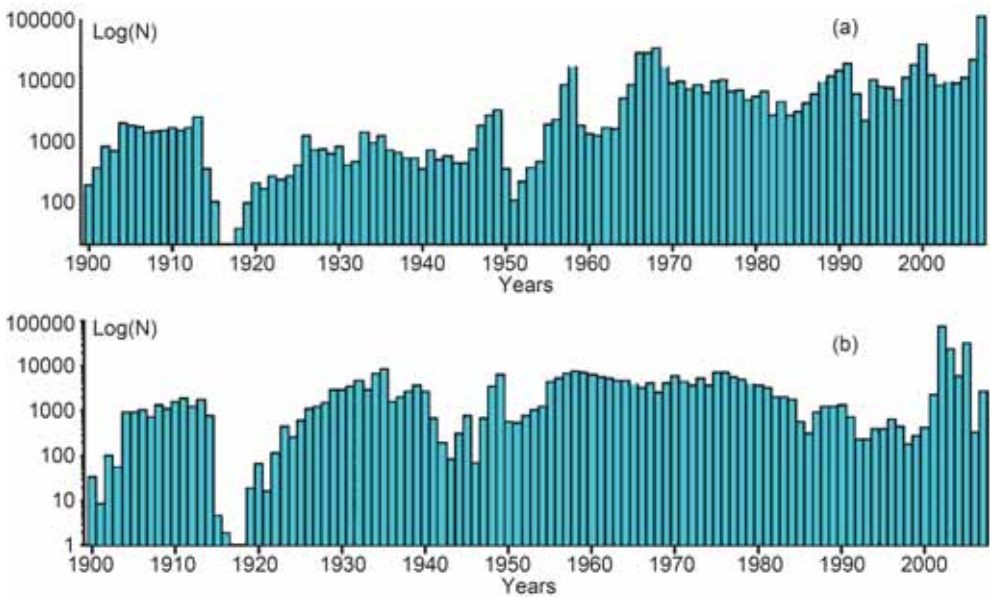


**Fig. 1. Annual number of reports containing visual wave data over the Barents Sea (*a*) and the Black Sea (*b*). The number of reports is shown in logarithmic scale (y-axis)**

situation in the Sea of Okhotsk is even more remarkable than in the Barents Sea with nearly no reports before the 1950s.

To accurately estimate wind wave extremes from the VOS data one has to account for inhomogeneous sampling. This makes it difficult for the direct application of the so-called peak over threshold (POT) method for estimating extremes because visual data in a given grid cell may not necessarily form the regular time series allowing for identification of exceedances over the thresholds. Thus, for the further estimation of extreme wave characteristics we first used the method of initial value distributions (IVD) and then adopted the POT method to the VOS data. In the IVD method the extreme wave statistics were estimated from the tails of distribution functions fitted to all wave observations for different seas. For fitting data we used the Weibull distribution whose parameters were estimated from the maximum likelihood method. The choice of large domains allows us to achieve a reasonable sampling size for the further estimation of the Weibull probability density function (PDF) and the cumulative distribution function (CDF).

Alternatively, we applied for the first time data the POT method [Caires and Sterl 2005] to irregularly sampled VOS data. In this method only storm peak values of wind sea, swell and SWH were considered. For this all VOS reports were matched to 6-hourly time steps for every domain. In the case where more than one report matches a given time moment, the median value was considered. Unsampled time steps imply the undersampling of the monthly time series. As in the case with altimeter data which are also characterized by undersampling, sparse data do not necessarily record the biggest exceedances at a point. However, the distribution of any exceedance provides the estimation of the probability of the largest one. According to the experience of application of POT to the altimeter data (Challenor and Woolf, personal communication) undersampling will lead to an underestimate of the extremes by about

10–15%. Nevertheless, to avoid strong impact of the undersampling onto estimation of extreme wave characteristics, we excluded from the analysis monthly composed time series which covered have less than 40% of month. The first-guess thresholds were established as 50% exceedance of the monthly time series of wave parameter considered. Then the search between the adjacent time moments was applied to retain only peak values in the record. The search was based on the consideration of storm durations (derived from the analysis of the regularly sampled WAM data) and on the use of filtering procedures. Finally the peak values identified were approximated by the Generalized Pareto Distribution in order to further estimate percentiles and return values of wave parameters. Using both IVD and POT methods we estimated 90th and 99th percentiles of wave characteristics as well as 100-year return values. Estimation was performed for individual decades that allowed for the further analysis of the decadal variability of wave statistics.

## RESULTS
Table 1 and Table 2 show estimates of the 99th percentile for the Barents Sea and the Sea of Okhotsk for different wind wave components derived using IVD along with the confident limits. Estimates we derived for the period from 1960 to 1999 as well as for individual decades that allows for assessing interdecadal variability in extreme wind wave characteristics. In winter in the Barents Sea 99th percentile of SWH amounts to nearly 8.8 meters with interdecadal variations ranging from 7.2 to 9.2 meters. Over the 30-yr period estimates of the extreme SWH show a decline in the decade of 1980s and growth in 1990s up to 9.2 meters. Extreme seas are ranging from 5.5 to 6.4 meters with the 30-yr average of 99th percentile being 6.9 meters. Extreme swells are typically 10 to 15% higher compared to the extreme wind seas and are coordinated with sea and SWH interdecadal changes. This is not surprising because fetches in the Barents Sea are quite limited and most swells typically originate from the local storm systems,

**Table 1. Barents Sea Initial Value Distribution 99th, decade values**

| Winter season | Wind sea | Swell | Significant wave height |
|---|---|---|---|
| 1960–1969 | – | – | – |
| 1970–1979 | 6.35 (1.59) | 8.70 (1.39) | 8.39 (2.02) |
| 1980–1989 | 5.46 (0.80) | 6.50 (1.49) | 7.20 (1.37) |
| 1990–1999 | 7.43 (0.79) | 7.94 (1.91) | 9.28 (1.80) |
| **1960–1999** | **6.90 (1.00)** | **7.34 (1.71)** | **8.84 (1.93)** |
| Summer season | Wind sea | Swell | Significant wave height |
| 1960–1969 | 3.88 (1.03) | 6.75 (1.98) | 7.45 (2.03) |
| 1970–1979 | 4.27 (0.88) | 5.77 (2.04) | 6.57 (2.32) |
| 1980–1989 | 4.22 (0.91) | 4.50 (1.28) | 5.27 (1.26) |
| 1990–1999 | 3.97 (0.65) | 5.19 (1.57) | 5.57 (1.47) |
| **1960–1999** | **4.01 (0.80)** | **4.98 (1.89)** | **5.58 (1.76)** |

thus, unlikely to exhibit large-scale variability different from that demonstrated by the wind sea as in the case of the Eastern North Atlantic demonstrated by Gulev and Grigorieva [2006]. Summer estimates of extreme waves in the Barents Sea are 20 to 25% smaller compared to the winter values with climatological values of 99th percentile being 4 meters for the wind sea, nearly 5 meters for swell and 5.4 meters for SWH. In contrast to the winter, interdecadal changes in the extremes of different wave components in summer are not co-ordinated with each other. Thus, the decade of the 1970s clearly demonstrates the highest estimates of extremes of wind sea, while the highest values of extreme swell and SWH were observed in the decade of 1960s. During summer, the impact of swell systems propagating from remote regions is much higher compared to winter because of the enlargement of the ice-free areas of the Arctic Ocean.

Estimates of extreme wind waves in the Sea of Okhotsk (Table 2) are typically slightly smaller compared to the Barents Sea. Climatological winter values of the 99th percentile amount to

**Table 2. Sea of Okhotsk Initial Value Distribution 99th, decade values**

| Winter season | Wind sea | Swell | Significant wave height |
|---|---|---|---|
| 1960–1969 | 6.87 (0.87) | 8.97 (1.71) | 9.87 (1.96) |
| 1970–1979 | 5.70 (0.60) | 8.53 (1.24) | 9.64 (1.68) |
| 1980–1989 | 5.37 (1.14) | 6.01 (1.27) | 7.25 (1.64) |
| 1990–1999 | 4.94 (0.93) | 5.46 (1.15) | 6.69 (1.42) |
| **1960–1999** | **5.34 (0.89)** | **6.61 (1.29)** | **7.29 (1.14)** |
| Summer season | Wind sea | Swell | Significant wave height |
| 1960–1969 | 4.50 (0.87) | 5.30 (0.99) | 5.66 (1.12) |
| 1970–1979 | 4.43 (0.87) | 5.41 (1.71) | 6.07 (1.52) |
| 1980–1989 | 3.50 (0.64) | 4.39 (1.28) | 4.96 (1.24) |
| 1990–1999 | 4.40 (1.17) | 5.10 (1.49) | 6.17 (1.58) |
| **1960–1999** | **3.93 (0.86)** | **5.42 (1.79)** | **6.21 (1.67)** |

5.3 meters for the wind sea, 6.6 meters for swell and 7.3 meters for SWH. On interdecadal time scales there is a tendency of the slowly declining extremes of all components which is largely provided by the contribution of swell. In summer, estimates of extreme waves are smaller compared to winter as in the case of Barents Sea. In both winter and summer in the Sea of Okhotsk interdecadal changes in the extreme values of wind wave characteristics are coordinated with each other. This is not surprising since the sea of Okhotsk represents semi-enclosed basin separated from the Pacific by the Kuril islands. Thus, sea and swell are provided here by the local storm systems and should go hand in hand with each other.

To validate the reliability of the estimates derived from the IVD method and to provide estimates over longer periods we also estimated annual maxima and analysed time series of these maxima. Annual maxima were estimated by taking maxima of wave heights from the whole annual sample. Importantly, estimating maxima we did not account for the waves reported with code figure "49" corresponding to 24.5 meter waves. In the VOS collection this code figure occurs suspiciously frequently implying artificial overestimation of extremely high waves. Some discussion of this bias is provided in Gulev and Grigorieva [2006], although the nature of this artefact in the collection of visual observations is not fully clear. Fig. 2 shows time series of the annual maxima values for the period from 1960 to 2005 computed for the Barents Sea, Sea of Okhotsk and the Black Sea.

Despite the data available starting from the late 1950s, the decade of the 1960s is still influenced by inadequate sampling and large
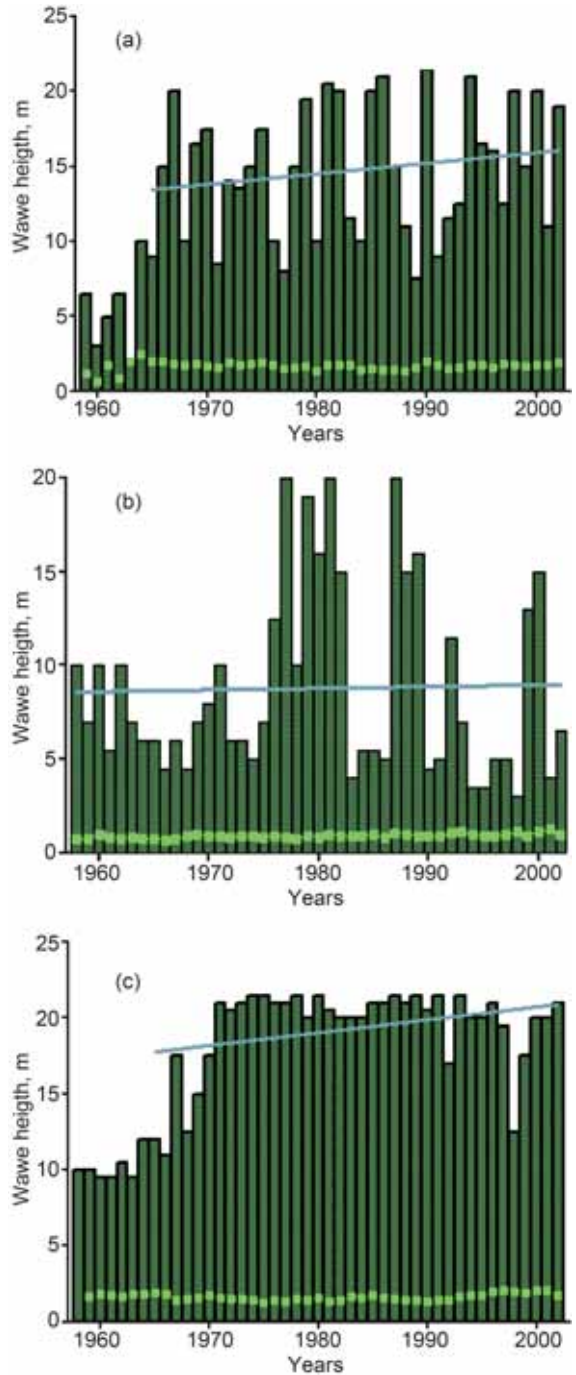


**Fig. 2. Time series of the annual maxima SWH (dark green bars) in the Barents Sea (*a*), Black Sea (*b*) and the Sea of Okhotsk (*c*).**

*Light green dotted lines show annual mean SWH estimates for the same seas. Blue straight lines show linear trends estimated by least squares for the period when data are characterized by adequate sampling and are free from biases associated with the coding system changes*

uncertainties associated with the changes in observational practices and coding systems. Thus, the statistical analysis of the time series has been performed for the period after 1968. The Barents Sea is characterized by the strongest short period interannual variability of annual maxima SWH with the highest waves ranging between 17 and 22 meters. There is a visible linear trend in the annual maxima implying a growing tendency of about 2.2 meters over 35 years. In the Black Sea the decade from the mid-1970s to the early 1980s is characterized by the highest annual maxima, approaching 20 meters in some years. During earlier periods and later decades the annual maxima typically do not exceed 10 meters except for 1987–1898 and 1999–2000. In the Sea of Okhotsk starting from the early 1970s, annual maxima wave heights amount to 20 meters nearly every year showing the smallest (compared to the Black and Barents seas) interannual variability. No statistically significant linear trends were identified in the Black and Barents Seas.

Finally, we developed estimates of different percentiles of wave height using the POT method according to the guidelines provided in Section 2. Figure 3 shows time series of 95th and 99th percentiles of wind sea for January for the Barents Sea. Remarkably, POT-based estimates of the higher order percentiles of wind sea are somewhat higher than similar estimates derived using the IVD method. Compared to Table 1, deviations may amount to 0.5–1 meter, implying 15 to 20% differences between the two methodologies. Another interesting observation is related to the variability of extreme wind seas. On short period interannual time scales the mean wind sea 95th and 99th percentiles are closely correlated with each other. However, if we consider interdecadal time scales, the linear trend in the mean wind sea will be slightly negative (however not statistically significant), while both 95th and 99th percentiles indicate statistically significant positive trends. This hints at the considerable change in the shape of the probability distribution of wind waves in this region with the mean remaining relatively stable and waves of rare occurrences being growing. The largest growth of about 0.7–0.9 meters per decade for e.g. the 99th percentile is observed during the period after 1988, when a strong increase of the poleward deflection of the cyclone trajectories has been reported and the number of midlatitudinal lows in the Barents Sea has increased [e.g. Loeptien et al. 2008].
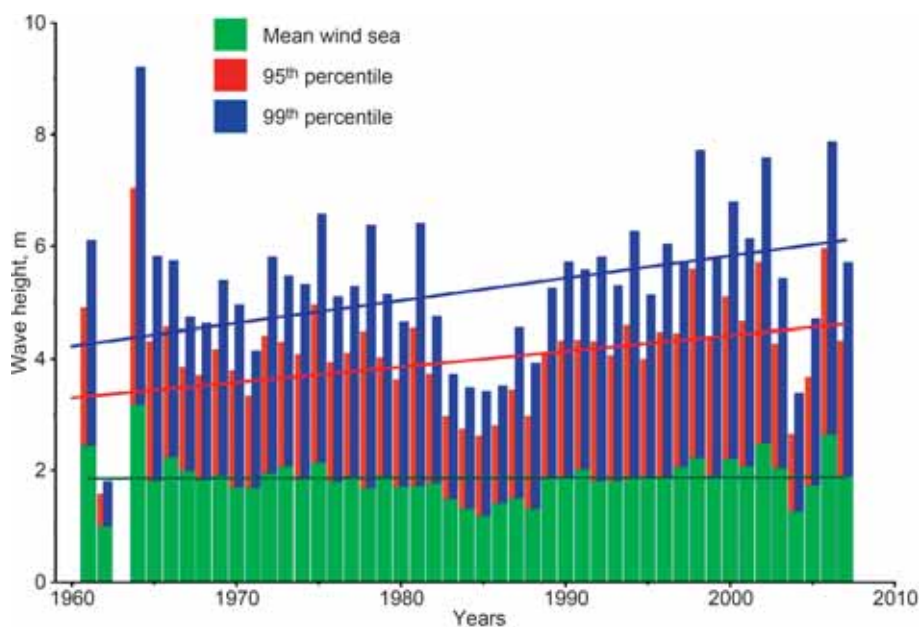


**Fig. 3. Time series of the mean wind sea (green), 95th percentile (red) and 99th percentile (blue) for the winter season in the Barents Sea. Straight lines show linear trends estimated by least squares**

## CONCLUSIONS

The main purpose of this study was to obtain realistic estimates of extreme wave heights in the three marginal seas of Russia and to analyse their interannual variability. Quantitative estimates were computed using IVD and POT methods which typically provide different estimates of high order percentiles of extreme waves. However, in our case the differences between the two estimates were smaller than expected. The reasons for this may lie in the fact that we designed estimates for the whole seas, thus using very large samples for computing statistics. When similar approaches are used for the small samples (e.g. for individual grid cells) poor sampling immediately results in very heavy tails of statistical distributions of extreme waves and provides large overestimation of wave extremes computed by POT method. Thus our results, although overall estimates for the seas, seem to be highly reliable.

In the future, similar estimates can be developed for specific sea regions characterized by dense off-shore activities. From a practical view point, it is highly important to know precisely whether the extreme waves occur primarily in the areas where the major ship routes and oil platforms are located. At the same time, we have to stress that estimates presented here have their own value. They are based on the visual observations which are collected exactly along the ship routes and in the locations of the platforms. Thus, inhomogeneous sampling frequently considered to be a drawback for the VOS data may be considered here to some extent as an advantage, since it provides a better coverage of the regions of high activity. For more detailed coverage of the spatial distribution of statistical characteristics of extreme waves implementation of one of the advanced numerical wave models will be useful. Model hindcasts performed for individual seas with these models forced by the modern era reanalyses such as NCEP-CFSR, ERA-Interim or MERRA can then be validated against visual observations. Finally, additional useful information on the variability of extreme wave parameters in Russian seas can be obtained from satellite records provided by altimeter measurements [e.g. Young et al. 2011]. These data, although limited in coverage for the last few decades, have very homogeneous sampling and are not suffering from the changes in observational practices. Consolidation of different data sets for accurate estimation of wind wave extremes can make it possible the delivery of highly accurate wind wave statistics with reasonably high resolution for different sea domains.

## REFERENCES

1. Caires, S. and Sterl, A. (2005): 100-year return value estimates for wind speed and significant wave height from the ERA-40 data. J. Climate, 18, 1032–1048.

2. Gulev, S.K., Grigorieva, V. Sterl, A. and Woolf, D. (2003a): Assessment of the reliability of wave observations from voluntary observing ships: Insights from the validation of a global wind wave climatology based on voluntary observing ship data. J. Geophys. Res., 108, 3236, doi:10.1029/2002JC001437.

3. Gulev, S.K. and Grigorieva, V. (2004): Last century changes in ocean wind wave height from global visual wave data. Geophys. Res. Lett., 31, L24302, doi: 10.1029/2004GL021040.

4. Gulev, S. K., and Grigorieva, V. (2006): Variability of the winter wind waves and swell in the North Atlantic and North Pacific as revealed by the voluntary observing ship data. Journal of Climate, 19, 5667–5685.

5. Loeptien, U., Zolina, O., Gulev, S.K., Latif, M. and Soloviov, V. (2008): Cyclone life cycle characteristics over the Northern Hemisphere in coupled GCMs. Climate Dyn., 31, doi:10.1007/s00382-007-0355-5.

6. Sterl, A. and Caires, S. (2005): Climatology, Variability and Extrema of Ocean Waves – The Web-based KNMI/ERA-40 Wave Atlas. Int. J. Climatol., 25, 963–977, doi: 10.1002/joc.1175.

7. Wang, X.L., Zwiers, F.W. and Swail, V.R. (2004): North Atlantic Ocean Wave Climate Change Scenarios for the Twenty-First Century. Journal of Climate, 17, 2368–2383.

8. Worley, S.J., Woodruff, S.D., Reynolds, R.W., Lubker, S.J. and Lott, N. (2005): ICOADS release 2.1 data and products, Int. J. Climatol., 25, DOI: 10.1002/joc.1166.

9. Young, I.R., Zieger, S. and Babanin, A.V. (2011): Global Trends in Wind Speed and Wave Height. Science, doi: 10.1126/science.1197219.

**Viktoria Grigorieva,** Senior Researcher, P.P. Shirshov Institute of Oceanology, RAS, developed the most complete data base of visual ocean wave observations and produced global climatology of ocean wave parameters including extreme waves. Recognized expert in marine climatology, data processing and metadata attribution.



**Sergey K. Gulev,** Professor, Moscow State University, Head Sea-Air Interaction and Climate Lab (SAIL) of P.P. Shirshov Institute of Oceanology. Recognized oceanographer and meteorologist, developer of widely used global surface flux, wave and cyclone activity products. Research over nearly 30 years contributed to understanding mechanisms and parameterization of air-sea energy exchanges at different scales, ocean modeling, diagnostics of atmospheric dynamics, author of more than 80 peer reviewed articles in leading international journals.



**Klaus Peter Koltermann,** Professor, Moscow State University, Head Natural Risk Assessment Laboratory, Faculty of Geography, Moscow State University, Moscow, Russia. Former Head Tsunami Unit, Intergovernmental Oceanographic Commission of UNESCO, Paris, France. Former Section Head Environmental Assessment and Policy, Bundesamt für Seeschifffahrt, Hamburg, Germany. Former Director WOCE International Project Office, Wormley, UK. Expert in ocean circulation, climate system, hydrography, water masses, tsunami early warning systems, risk assessment.