Problems of environmental management on Russia’s coasts in the context of global sea level rise

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Abstract. This study addresses some issues related to environmental management on Russia’s coasts in the context of ongoing global warming and subsequent sea-level rise. The attention to this problem is drawn due to the great extent of Russia’s coastline and high economic potential of certain coastal zones, inundation of which would be detrimental for the economy and the population dwelling there. The research seeks to answer the question as to how seriously global warming contributes to sea-level rise in Russia’s seas and whether or not highly developed coastal zones may be threatened. The study is primarily aimed at identification of statistical correlation between sea-surface temperatures, influenced by global warming, and variations in sea topography that can possibly lead to inundations. As a secondary goal, the areas exhibiting highest sea-level rise rates in the modern period are revealed. The results obtained show that most of the economically developed coastal zones are unlikely to face serious risks of inundation in the near future, however certain areas do need close attention, among them being the seacoasts of Kaliningrad Oblast due to high rates of mean sea-level rise and northeastern coasts of the Sea of Azov due to possible intensification of surge effects. Based on the findings, measures to deal with the potential inundation risks are discussed.

1. Introduction and background

A great amount of natural resources consumed by humankind is concentrated in coastal zones. According to the latest research [1–9], the global mean sea-level (MSL) is steadily rising with accelerating rates, hence in the near future we are to expect inundation of certain parts of seacoasts, which will substantially limit our access to their resources. Measures to prevent or slow down coastal flooding therefore need to be developed, which is a topical issue of modern environmental management.

Flooding of coastal areas is of key concern for the countries with extensive coastlines. Russia is one of them. Its northern coastal zones and Arctic continental shelf are now being intensively developed and further explored for hydrocarbons and other minerals, whereas coasts of the southern seas have long been used for recreational purposes. Russia’s seas are known for intense shipping and fishing. Large seaports are located on their coasts; a great number of population are directly involved in sea-related activities. Hence, the problem of preventing (or at least minimizing the risks of) the sea-level rise-induced inundation of Russia’s coastal territories is about to transit from theoretical into practical field.
The extent of Russia’s coasts is so vast that the construction of flood protection systems (walls, dams or similar barriers) all along the coastline will never be a practical option. Hence, it is important to identify the most threatened parts of the coast whose inundation will be highly likely in the near future and at the same time associated with major economic, social, environmental and other risks.

Our future is not set, neither is the scenario of MSL rise at a particular coast [1–4]. Therefore, identification of most threatened coastal areas and their subsequent flood protection have to be carried out systematically based on the latest scientific insights and prognoses.

Modern theories suggest that on monthly to decadal time scales, MSL variations are caused predominantly by climate changes that account for redistribution of heat and water balances over oceanic regions and cause variations in patterns of the general atmospheric circulation [1, 2].

Global warming leads to an increase in mean temperatures of mixed layers (ML) of water basins. This, in turn, results in thermal expansion of their waters, which, all other factors being equal, causes MSL to rise. The effect is the more noticeable, the greater the thicknesses of MLs. Since mixed layers are quasi-homogeneous, variations in their mean surface temperatures occur nearly synchronously with thermal variations of their interlayers.

Another substantial manifestation of global warming are variations in wind patterns over a particular sea that govern the frequency and intensity of surge effects on the seacoasts. Despite the fact that surges rarely last longer than several days and therefore do not noticeably affect monthly means of sea surface heights (SSH), their input into interannual variability of these indicators is not to be neglected. Since surge-driven variations in levels of near-coastal water areas can be up to several meters, the frequency and intensity of surges can influence variability of SSH monthly means quite significantly [10].

Thermal and surge factors affect SSH variations of a particular body of water differently – depending on its geographical position, climate, oceanographic, geomorphological and other characteristics. In some seas, these factors will both contribute to the MSL rise, while in others the cumulative effect can be opposite [1, 11].

Global warming will also lead to variations in the global hydrological cycle, which will eventually influence the behavior of water balances and sea levels of near-coastal ocean areas as well.

The above mentioned factors, as well as other minor factors acting on the background, affect the sea topography cumulatively. As a result, no constant rate of global MSL rise exists. This indicator differs depending on the location, with some coastal areas already facing inundation threats.

Variations in sea surface topography on Russia’s coasts have been monitored for decades [12–14]. However, little attention has been paid to establishing the areas featuring potential risks of inundation, which complicates planning timely response to the emerging threats.

This study addresses the issues of environmental management on those Russia’s coasts which are likely to face inundation in next two or three decades provided the global sea level continues to rise. The tasks to be tackled include:

i) finding the near-coastal areas of the seas adjacent to Russia’s coasts that exhibit significant statistical correlation between interannual variations in sea surface temperatures (SST) and sea surface heights;

ii) finding the areas featuring the highest rates of sea level rise;

iii) analyzing the results and proposing possible countermeasures.

2. Materials and methods
To obtain data on spatio-temporal variability of SSH and SST in the seas adjacent to Russia’s coasts, we turned to the global reanalysis supported by Integrated Climate Data Center (ICDC) of the University of Hamburg [15, 16]. The reanalysis contains modelled data on monthly means of the above indicators throughout the World Ocean for 1979–2017 period for grid points presented in 13x13 km horizontal resolution. Other reanalyses, including more precise ones (e.g. AVISO), are also available; however, the priority was given to ICDC due to the longest time span of its modelled data.
The applicability of ICDC reanalysis for the seas in question was verified by comparing its data with the analogous data provided by AVISO [17] and actual monitoring records obtained from tide gauges [18]. The verification was performed using correlation analysis and Student’s t-test [19]. Systematic and absolute discrepancies for each water area were estimated.

As an illustration of the method, in table 1 we present the values of the correlation coefficient (CC) describing statistical relationship between interannual variations in monthly means of SSH in the near-coastal parts of the Baltic Sea in 1979–2017 period derived from ICDC reanalysis and the same parameters obtained by use of tide gauge monitoring data corresponding to the same period. The CC threshold level corresponding to 95% confidence interval according to the t-test is 0.32.

Table 1. Correlation between the time series of SSH monthly means as obtained from ICDC reanalysis and the same parameters derived from actual monitoring data collected from the Baltic Sea tide gauges

| Month       | Kronstadt (60N, 29.8E) | Vyborg (60.7N, 28.7E) | Baltiysk (54.6N, 19.9E) | Otkrytoe (54.5N, 21.0E) |
|-------------|------------------------|-----------------------|------------------------|------------------------|
| January     | 0.97                   | 0.96                  | 0.91                   | 0.83                   |
| February    | 0.95                   | 0.96                  | 0.91                   | 0.75                   |
| March       | 0.93                   | 0.94                  | 0.89                   | 0.84                   |
| April       | 0.92                   | 0.9                   | 0.81                   | 0.36                   |
| May         | 0.86                   | 0.82                  | 0.65                   | 0.32                   |
| June        | 0.82                   | 0.82                  | 0.83                   | 0.52                   |
| July        | 0.81                   | 0.89                  | 0.85                   | 0.72                   |
| August      | 0.91                   | 0.89                  | 0.85                   | 0.7                   |
| September   | 0.94                   | 0.95                  | 0.89                   | 0.37                   |
| October     | 0.93                   | 0.90                  | 0.87                   | 0.77                   |
| November    | 0.89                   | 0.91                  | 0.69                   | 0.79                   |
| December    | 0.93                   | 0.94                  | 0.86                   | 0.73                   |
| Year        | 0.94                   | 0.91                  | 0.83                   | 0.64                   |

As seen from table 1, interannual variations in monthly means of SSH obtained from ICDC reanalysis exhibit significant statistical correlation with the actual monitoring data for all months. Similar results have been achieved for other seas as well. Systematic and absolute discrepancies between the reanalysis results and the tide gauge data have been found unsubstantial. Hence, a conclusion was made that the specified reanalysis could be used as an appropriate data source for this study.

By use of the reanalysis data, time series of SSH and SST of sufficient length were formed for all parts of the seas in question. Linear trends in these series were identified using the least square method and properly compensated for.

The correlation analysis and t-test were then applied to estimate the statistical significance of relationship between interannual variations in SSH and interannual variations in SST (we will further refer to it as ‘SSH-SST correlation’) for each month of the investigated period. 95% confidence level was picked as a threshold for determining the statistical significance of the correlation [18]. Situations in different parts of the seas in question were analyzed.

To estimate MSL rise rates for a particular sea area in a particular month, we analyzed trendline angular coefficients (TLAC) of the time series formed for 1979–2017 period. TLAC values were derived by use of the least square method. The statistical significance of MSL rise rate values obtained in such a way was estimated using the set of statistical parameters used for determination of the TLAC values.
It was taken into account that the accuracy of a TLAC estimate of a time series depends on the ratio of this estimate’s mean to its standard deviation (t-statistic). It also depends on the ratio of the mean square of the values (F) described by the regression to the mean square of their deviations from the regression line. The values of F follow the Fisher-Snedecor distribution (F-distribution). After the values of t and F were found for each trend, then, by applying t- and F-distributions, the statistical significance level of the trend estimate could be found. The TLAC estimates were considered significant, if SSH-SST correlation was established with at least 95% confidence.

The results of the correlation analysis were then presented on contour maps of the corresponding seas using the Delaunay triangulation method [20].

3. Results and analysis
SSH-SST correlation was estimated for each water area 13x13 km in size for all months and all seas adjacent to Russia’s coasts. Distributions of CC-values were plotted on contour maps.

![Figure 1](image_url)

**Figure 1.** SSH-SST correlation coefficient distributions in January for the seas: a) Black Sea, b) Baltic Sea, c) Sea of Japan, d) Sea of Okhotsk.
The results for the Black and the Baltic seas, as well as the seas of Japan and Okhotsk, obtained for January and July are presented below as an illustration. Figure 1 shows SSH-SST correlation in January.

As follows from figure 1a, a strong positive SSH-SST correlation is present all through the Black Sea except for a few areas situated in its northwestern part. The CC values are quite high in the near-coastal areas, the peak (>0.7) being attained in the center of the Western cyclonic gyre.

As seen in figure 1b, the specified correlation in the Baltic Sea is also strong. The CC values are distributed almost uniformly all over the sea area including its coastal parts, the exception being the Gulf of Finland. The highest CC values reach 0.74.

Figure 1c shows that in the Sea of Japan the SSH-SST correlation is strong and positive only in its central and southern parts. These areas are located off the west coast of Honshu and Hokkaido islands (on the path of the warm Tsushima current) and in the central part of the cyclonic vortex formed by the Liman and North Korea currents. The highest CC values reach 0.84. Similar features are observed in numerous areas of the Pacific Ocean located to the southeast of the mentioned islands.

The overall picture for the Sea of Okhotsk is presented in figure 1d. During winter months, much of its surface is covered in ice [12], which also is the case for some parts of the Baltic Sea. However, very few parts of the Sea of Okhotsk exhibit significant SSH-SST correlation. Some positive correlation has been found near the southwestern coasts of Kamchatka, in the Shantar Sea and the Sakhalin Gulf, and off the northeastern coasts of Sakhalin Island. A few areas demonstrating negative correlation have also been identified.

As is also seen from figure 1d, a positive SSH-SST correlation is also present in the Pacific Ocean and the Bering Sea. It is found predominantly on the eastern periphery of the Kuril Current.

Distributions of the CC-values through the same four seas in July are shown in figure 2.

Figure 2a illustrates the situation in the Black Sea. Areas exhibiting significant correlation are scarce. They are located mostly at the southern coasts of the sea’s western part and in the Bosphorus.

The Baltic Sea, as shown in figure 2b, exhibits no significant positive SSH-SST correlation whatsoever (even in the coastal areas). On the contrary, the opposite correlation is quite common throughout the sea, the exception, as is the case for January, being the Gulf of Finland.

The Sea of Japan, as seen in figure 2c, mostly shows no significant positive correlation either. Few areas that do so are located directly off the west coast of Honshu Island. Areas exhibiting similar correlation are also found in the Pacific Ocean, to the southeast of the mentioned island.

As follows from figure 2d, the areas of the Sea of Okhotsk that feature significant positive correlation are much more widespread in July. They are located in the central part of the sea, off the northeast coast of Sakhalin Island and in the Bering Sea (to the east of Kamchatka and the Kuril Islands).

Having investigated seasonal variations in CC distributions in the Black, Baltic, Japan and Bering seas, we have established that the distribution patterns observed in other winter months are quite similar to those observed in January. Likewise, the CC distribution features in July are similar to those obtained for other summer months. The greatest extent of the sea areas exhibiting significant positive correlation between monthly means of SSH and SST for the indicated seas falls on January, February and March, whereas the smallest extent is detected in June and July. This finding is in agreement with the ideas of seasonal variations in depths of the lower boundaries of the seas’ mixed layers [21].

The Sea of Okhotsk, in contrast, features a reverse annual variation in total extent of the areas with significant positive SSH-SST correlation, with minimums falling on January–February and maximums being attained in August–September. This fact supports the conclusions made in [12] on the anomalous level regime of the sea, which, unlike other Far Eastern seas, brings the sea level to its peak in winter. The specified level anomaly is most likely due to the prevalence of strong cold northerly winds blowing over the sea in winter periods. Being the feature of the Bering Sea as well, these winds emerge as a result of interaction between the Asian (Siberian) anticyclone and the Aleutian Low. They can increase flows of the currents transporting waters of the Kuril Current into the Sea of Okhotsk.
through the straits in the northern part of the Kuril Chain. This mechanism drives a sea level rise in most parts of the sea and, probably, weakens the correlation between variations in SSH and SST.

In summer, the climate of the Sea of Okhotsk is governed by the North Pacific High and prevailing southerly winds. Since these winds are mostly light (unless there is a cyclonic interference), the inflow of cold Pacific waters via the above-mentioned straits drops, while the outflow intensifies [12].

Figure 2. SSH-SST correlation coefficient distributions in July for the seas:
   a) Black Sea, b) Baltic Sea, c) Sea of Japan, d) Sea of Okhotsk.
In the Bering Sea, the areas featuring significant positive SSH-SST correlation are present throughout the year. They are located off the eastern coast of the Kamchatka Peninsula, as well as east of the Kuril Current region and north of the Near Islands and the Amchitka Pass. Their extent tends to peak during spring–summer periods. In summer months, the correlation is also evident in some areas of the central part of the sea, on the paths of the warm Pacific waters inflow.

For many shallow-water areas of the Sea of Azov, no significant relationships between sea levels and surface temperatures have been detected in any months. However, the thermal factor has never been a driver of sea-level changes in this sea. The major role here is played by surge effects, which can easily flood flat low-lying coasts of Rostov Oblast and Krasnodar Krai. Considering occurring variations in wind patterns due to global warming and possible intensification of surges, these regions are quite vulnerable to even short-term sea-level rises.

A significant positive SSH-SST correlation has been established in winter months in most parts of the Arctic seas adjacent to Russia’s coasts, the exceptions being the southern and eastern coasts of the White Sea (including the Throat), the western coasts of the Yamal Peninsula (the Kara Sea) and the southern coast of the Laptev Sea. In summer, the areas with positive SSH-SST correlation shrink in number and size dramatically, the remaining few being found off the coasts of the Barents Sea.

In the next section of the research, we revealed the coastal areas exhibiting highest MSL rise rates. A rise rate was considered significant if it exceeded 1.5 mm/year.

At first, non-arctic seas (the Baltic, Azov, Black, Japan, Okhotsk and Bering Seas) were investigated. Interestingly, all the seas except for the Baltic have shown no significant MSL rise (less than 1.5 mm/year).

The situation in the Baltic Sea differs dramatically. Distributions of MSL rise rates in January and July are illustrated in figure 3. In other winter and summer months the picture is similar.

As seen from figure 3, in summer, the MSL rise rates exceeding 5 mm/year are present in almost all parts of the Baltic Sea coast belonging to Leningrad and Kaliningrad Oblasts of Russia, as well as Lithuania, Latvia, Estonia and Finland. The highest rise rates in January and July have been established at the coasts of the Gulf of Finland.

In the next step, the situation at the arctic coasts of Russia washed by the Barents, White, Kara, Laptev, East Siberian and Chukchi seas was addressed. The highest MSL rise rates (up to 5.5 mm/year) have been revealed in the eastern part of the East Siberian Sea coast and throughout the coast of the Chukchi Sea. On the coasts of the Yenisei and Ob gulfs, as well as the Taimyr Peninsula, MSL rise rates reach 3–3.5 mm/year. The rate values at other coastal sections of the Russian Arctic are also significant throughout the year, however the above mentioned values are not reached.

Taken together, we can see that in 1979–2017 period the greatest rise rates were at the coasts of the Baltic (up to 5 mm/year), East Siberian and Chukchi Sea (both up to 5.5 mm/year).

It is important to bear in mind that the rate of shoreline inland movement depends not only on the MSL rise rate at the corresponding coast, but also on the rate of vertical movement of the underlying earth’s crust. Hence, to identify the coastal areas being threatened by potential inundation in the modern period, we had to account for both the MSL rise rates and the vertical crustal movement (VCM) rates in order to obtain SSH change rates relative to the surfaces of the corresponding land areas.

As follows from [22], the parts of the southern coast of the Gulf of Finland belonging to Leningrad Oblast are subject to marine regression with the VCM rate of 2 mm/year. Hence, the resulting sea-level rise of the Baltic Sea in this region equals to 2–3 mm/year.

The Baltic coasts belonging to Kaliningrad Oblast feature the opposite process – a marine transgression. Hence, the resulting sea rise rate relative to the land is 6–7 mm/year.

The coast of the East Siberian Sea also features a marine regression with a mean rate of 2–4 mm/year, hence no significant threats for its coasts are expected. On the contrary, no vertical crustal movements below the Chukchi Sea coasts have been detected, so the MSL rise rate relative to the land remains at 5.5 mm/year.
The highest VCM (transgression) rates in the modern period are detected on the eastern coast of the Yenisei Gulf (a part of the Kara Sea), as well as on eastern and western coasts of the Taimyr Peninsula (14 and 10 mm/year respectively). Therefore, considering the MSL rise rate estimates, the resulting rise rates relative to the land reach 17 and 13 mm/year respectively.

Since among all Russia’s threatened seacoasts featuring highest rates of shoreline inland movement, the most populated and economically developed are the ones located in Kaliningrad and Rostov Oblasts and Krasnodar Krai, it appears timely to already start planning flood protection measures in these regions.

4. Discussion
Overall, the results of this study are in agreement with the modern insights on the aftermath of global climate changes. Our findings demonstrate that increasing sea-surface temperatures caused by the climate warming will not always lead to a sea-level rise. This is particularly the case for Russia’s seacoasts. A number of sea sectors washing Russia’s coasts have been found to be void of any correlation between MSL rise rates and thermal variations of their surface layers in any months.
whatever. Among them are parts of the Sea of Azov, Sea of Japan and Sea of Okhotsk (except for the western coasts of Kamchatka and northeastern coasts of Sakhalin Island), as well as the eastern part of the Gulf of Finland located in the direct vicinity of Saint-Petersburg.

However, based on the findings, we can see that some areas already require attention and await countermeasures against the progressing sea advance. Coastal sea-level rise is obviously a slow process. Hence, the effects of the potential remedial actions as well as the correctness of their choice may not be obvious in any near future. They may well appear to be erroneous as MSL variations are hard to predict on time-scales of several decades. Therefore, quick decisions resulting in large-scale construction operations on the threatened coasts do not seem feasible at the moment due to a great level of uncertainty.

Under the current circumstances, the most logical way to respond seems to be: i) the acceptance of the fact that the problem is real and will most likely aggravate in future; ii) the adoption of a long-term strategy aimed at flood protection of particular seacoasts. The strategy has to be flexible and capable of quick adaption to the changing conditions and new emerging trends of sea-level variations.

The first stage of the proposed strategy shall include construction of minimally required flood protection barriers in the areas where the inundation has already been confirmed. The characteristics of these barriers have to be adequate enough to withstand the sea advance and prevent potential damage to the affected territories, however with no excess of their properties (i.e. height, width, strength, etc.) at this stage. At the same time, their design has to allow for their possible reconstruction and strengthening, should it be required at some moment in the future.

In next stages, the already commissioned and operating protective systems in view of the newly discovered circumstances can be upgraded, widened or heightened or, if necessary, additional barriers can be constructed in other parts of the coast. This approach will allow to most effectively deal with the problem of funding as the need for money allotment will be based on real circumstances and be clear for the public.

The fastest advance of sea waters onto the land has been detected on the coasts of the Yenisei Gulf and the Taimyr Peninsula. However, these areas can hardly be considered a priority as they are very scarcely populated and poorly developed economically, hence no sense is seen in their protection. It seems logical to effect the prioritization using the next criteria:

- high level of economic development and infrastructure;
- high population;
- high ecological risks of potential inundation;
- certain geographical and geomorphological features, e.g. flat low-lying relief, shores of the abrasive, accumulative, or abrasion-accumulative type;
- significant mean sea-level rise rate exhibited in the current period;
- significant correlation between the MSL and a factor that can potentially lead to its rise.

Analyzing the areas identified in the current study, we assume that the most threatened are certain coasts of the Baltic Sea, belonging to Kaliningrad Oblast, which fully meet the above criteria. The coasts of the Sea of Azov (Rostov Oblast and Krasnodar Krai) have also to be closely monitored as, though not fully meeting the last two criteria, they are highly exposed to surge effects.

5. Summary and conclusion
The present study addressed several issues related to environmental management on Russia’s coasts in the context of continuing global warming and subsequent sea level rise. The attention to this problem was drawn due to the great extent of Russia’s coastline and high economic potential of certain coastal zones, inundation of which would be detrimental for the Russian economy and the population dwelling there. At the same time, up to this date few research data have been published on the subject. A systematic understanding of how global warming contributes to sea level rise in Russia’s seas and whether or not highly developed coastal zones may be threatened is still lacking.

The present study was primarily aimed at identification of statistical correlation between sea-surface temperatures, affected by global warming, and variations in sea topography that can possibly
lead to inundations. The second aim of this study was to reveal the areas exhibiting highest sea-level rise rates in the modern period. Finally, measures to deal with this situation were discussed.

The following conclusions can be drawn based on the findings:

The correlation between surface temperatures and sea levels is found in all seas except for the Sea of Okhotsk, being most obvious in winter-spring months.

In summer months, the correlation is statistically significant only in southern and eastern areas of the Baltic Sea, as well as on the Barents Sea coasts.

In 1979–2017 period, highest rates of sea-level rise (5 mm/year or more) have been detected in some coastal areas of the Baltic Sea, as well as the East Siberian and Chukchi seas.

Cumulative action of the warming-induced sea-level rise and neotectonic processes in the foreseeable future (2–3 decades) will increase risks of inundation of Russia’s seacoasts located at the Baltic, Kara, Laptev and Chukchi seas. The highest priority among the listed coasts should be given to the coastal areas of Kaliningrad Oblast, where flood protection strategy must already be taken into consideration. Special attention should also be paid to the coasts of Rostov Oblast and Krasnodar Krai due to expected intensification of surge effects in the Sea of Azov.

This study has provided some general insight into the scale of the problem. However, further systematic research into the trends of sea topography variations and the related risks for particular coastal areas is needed to estimate the scope of the required countermeasures.

References
[1] Church J A et al. 2013 Sea-level rise by 2100 Science 342 p 1445 Doi: 10.1126/science.342.6165.1445-a
[2] Kopp R E, Horton R M, Little C M, Mitrovica J X, Oppenheimer M, Rasmussen D J, Strauss B H and Tebaldi C 2014 Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earths Future 2 383–406 Doi: 10.1002/ef000239
[3] Bamber J L, Oppenheimer M, Kopp R E, Aspinall W P and Cooke R M 2019 Ice sheet contributions to future sea-level rise from structured expert judgment Proc. Natl. Acad. Sci. U.S.A. 116 (23) pp 11195–11200 doi: 10.1073/pnas.1817205116
[4] Jevrejeva S, Jackson L P, Riva R E, Grinsted A and Moore J C 2016 Coastal sea level rise with warming above 2°C. Proc. Natl. Acad. Sci. U.S.A. 113 pp 13342–13347 Doi:10.1073/pnas.1605312113
[5] Bamber J L and Aspinall W P 2013 An expert judgement assessment of future sea level risefrom the ice sheets. Nat. Clim. Chang. 3 pp 424–427 Doi: 10.1038/nclimate1778
[6] Oppenheimer M and Alley R B 2016 How high will the seas rise? Science 354 pp 1375–1377 (2016) Doi: 10.1126/science.9460
[7] Rasmussen D J, Bittermann K, Buchanan M K, Kulp S, Strauss B H, Kopp R E and Oppenheimer M 2018 Extreme sea level implications of 1.5 °C, 2.0 °C, and 2.5 °C temperature stabilization targets in the 21st and 22nd centuries. Environ. Res. Lett. 13 034040 Doi: 10.1088/1748-9326/aaac87
[8] Nicholls R J, Marinova N, Lowe J A, Brown S, Vellinga P, de Gussmão D, Hinkel J and Tol R SJ 2011 Sea-level rise and its possible impacts given a ‘beyond 4°C world’ in the twenty-firstcentury. Philos Trans A Math Phys Eng Sci 369 pp 161–181 Doi: 10.1098/rsta.2010.0291
[9] Nerem R S, Beckley D D, Fasullo J T, Hamlington B D, Masters D and Mitchum G T 2018Climate-change-driven accelerated sea-level rise detected in the altimeter era Proc. Natl. Acad. Sci. U.S.A. 115 (9) pp 2022–2025 doi: 10.1073/pnas.1717312115
[10] Ivanov V A and Shul’ga T Ya 2018 Numerical Analysis of Surge Phenomena, Currents, and Pollution Transport in the Sea of Azov Doklady Earth Sciences 479 (2) pp 543–546 doi.org/10.1134/S1028334X18040256
[11] Boy M, Roldin P, Swietlicki E, Kulmala M, et al. 2019 Interactions between the atmosphere, cryosphere, and ecosystems at northern high latitudes Atmospheric Chemistry and Physics 19 pp 2015–2061 doi: 10.5194/acp-19-2015-2019
[12] Belonenko T V, Koldunov V V, Staritsyn D K, Fuks V R and Shilov I O 2009 Izmenchivost’ urovnya Severo-zapadnoj chasti Tihogo okeana (Level variability of the Northwestern part of the Pacific Ocean) (Saint Petersburg: SMIO Press) p 309

[13] akharchuk Ye A 2008 Sinopticheskaya izmenchivost’ urovnya i techeniy v moryakh, omvayushchikh severo-zapadnoy i arkticheskoye poberezh'ya Rossii (Synoptic variability of the level and currents in the seas washing the northwestern and arctic coasts of Russia) (Saint Petersburg: Gidrometeoizdat) p 359

[14] Goryachkin Yu N, Zhukov A N, Lebedev N E, Sizov A A 2017 Quasi-Periodicity of the Black Sea Wind Spatial-Temporal Variability and its Relation with the North Atlantic Oscillation Phases Morskoy gidrofizicheskii zhurnal 5 (197) pp 47–55 doi: 10.22449/0233-75584-2017-5-47-55

[15] Integrated Climate Data Center. Ocean http://icdc.cen.uni-hamburg.de/1/daten/ocean (Accessed 01 July 2019)

[16] Zuo H, Alonso-Balmaseda M, de Boisseson E, Hirahara S, Chrust M and de Rosnay P 2017 A generic ensemble generation scheme for data assimilation and ocean analysis ECMWF Technical Memoranda 795 p 44 doi: 10.21957/cub7mq0i4

[17] AVISO+ Satellite Altimetry Data https://www.aviso.altimetry.fr/en/home.html (Accessed 01 July 2019)

[18] Unified State Ocean Information System http://data.oceaninfo.ru (Accessed 01 July 2019)

[19] Montgomery D C and Runger G C 2013 Applied Statistics and Probability for Engineers, 6th Edition (New York: Wiley) p 836

[20] Skvortsov A V 2002 Triangulyatsiya Delone i yeye primenenyiye (Delaunay triangulation and its application) (Tomsk: Izd-vo Tomskogo gosudarstvennogo universiteta) p 128

[21] Zuenko Yu I and Yurasov G I 1995 Water masses of the North-Western part of the Sea of Japan Russian Meteorology and Hydrology 8 pp 50–57

[22] Klochko A A, Romanovskaya M A, Grechushnikova M G et al. 2004 Natsional’nyy atlas Rossii. Priroda i ekologiya (National Atlas of Russia: Nature and Ecology) (Moscow: FGUP "GOSGISTSENR") 2 p 495