PAPER • OPEN ACCESS

Characteristics of mesoscale eddies of Arctic marginal seas: results of numerical modeling

To cite this article: Gennady Platov and Elena Golubeva 2020 IOP Conf. Ser.: Earth Environ. Sci. 611 012009

View the article online for updates and enhancements.

You may also like

- Effects of mesoscale eddies on the spatial coherence of a middle range sound field in deep water Fei Gao, , Fang-Hua Xu et al.
- Mesoscale eddies and their dispersive environmental impacts in the Persian Gulf Amin Raeisi, Abbasali Bidokhti, Seyed Mohammad Jafar Nazemosadat et al.
- Influence of warm eddies on sound propagation in the Gulf of Mexico Yao Xiao, , Zhenglin Li et al.





DISCOVER how sustainability intersects with electrochemistry & solid state science research



This content was downloaded from IP address 3.144.104.29 on 06/05/2024 at 20:26

Characteristics of mesoscale eddies of Arctic marginal seas: results of numerical modeling

Gennady Platov and Elena Golubeva

Institute of Computational Mathematics and Mathematical Geophysics SB RAS, 630090, Lavrentiev prospekt 6, Novosibirsk, Russia

E-mail: platov.g@gmail.com, e.golubeva.nsk@gmail.com

Abstract. A simple method is proposed for identifying mesoscale eddies in the results of numerical modeling. The method uses extrema in distributions of the sea level elevation as eddy markers. By using the method, we analyze statistics of mesoscale eddies resulting from SibPOM numerical simulations in the Eurasian sector of the Arctic marginal seas. The results of using this method show that the number of cyclonic eddies slightly exceeds the number of anticyclonic eddies, but the excess is only 2-3%. Also, we demonstrate that a significant number of eddies arise under the ice cover. The number of such eddies increases significantly in winter. This fact indicates that the convection caused by salt rejection during freezing plays an essential role in their formation. The numerical modeling results confirm the phenomenon of active eddy generation in the ice edge zone. Besides, the results show that in the near-edge zone, a more significant number of eddies are formed from the icy side adjacent to the edge, and not from the ice-free side. The periods of seawater freezing and ice melting, accompanied by corresponding displacements in the ice edge, produce eddies different in nature. The number of eddies in the marginal ice zone has two seasonal maxima corresponding to these two periods.

1. Introduction

Mesoscale eddies are formed, as a rule, in the frontal zones [14], due to baroclinic and barotropic instabilities of mean flows [15, 16], in regions of active vertical mixing and cascading [17, 18] in close connection with atmospheric variations. For example, [3] found that subtropical gyre potential energy variations are associated with the North Atlantic Oscillation (NAO). It could contribute to a 25% increase in eddy kinetic energy (EKE) near the Gulf Stream extension. In the Arctic, the edge zone of ice is also a place of active eddy generation [8].

Eddies play a significant role in the cross-frontal exchange and influence the along-front advection intensity [1]. A single eddy may carry trillions of tons of water and dozens of terajoules of heat [11]. Regions of strong currents are sources of mesoscale eddies responsible for the crossfrontal exchange. [4] derived the cross-front eddy heat flux as a result of a density change across the front and the along front velocity. Using the example of the North Atlantic current, [2] emphasized the role of eddies in compensating for the asymmetry of heat fluxes at the fronts.

Taking into account the role of mesoscale eddies in numerical models, even at the parameterization level, leads to significant improvements in the simulation of the global temperature distribution, the poleward and surface heat fluxes, and the locations of deep-water formation [5]. High-resolution ocean models containing an explicit representation of mesoscale eddies and realistic boundary currents, can be used to simulate AMOC (Atlantic meridional

Content from this work may be used under the terms of the Creative Commons Attribution 3.0 licence. Any further distribution of this work must maintain attribution to the author(s) and the title of the work, journal citation and DOI. Published under licence by IOP Publishing Ltd 1 overturning circulation) pathways [6] which are in close agreement with observations. These models also exhibit AMOC variability, which cannot be simulated at low resolutions.

The number of generated eddies and their physical properties are key parameters to evaluate the integral effect of eddies on the variability of the large-scale ocean circulation. Analysis of satellite radar images of Envisat ASAR for the summer-autumn period of 2007 and 2011 [8] showed that 64% of the total number of eddies are cyclonic, and the range of observed eddy diameters was from 1 to 50 km, but about 80% of all eddies had diameters less than 10 km. According to the results of [10], cyclonic eddies are also twice more frequent compared to anticyclonic eddies at the surface. It is distinct from the dominating anticyclonic eddies observed at depth by in situ moorings [12] and ice-tethered profilers [13]. An intrahalocline eddy observed on the Chukchi slope in [9] was also anticyclonic.

2. Numerical models, data, and experimental conditions

In our study, we will use a nested model system described in some previous works (see, for example, [19, 18]). The system includes the Siberian Coupled Ice and Ocean Model (SibCIOM) as a large-scale model of the Arctic and North Atlantic and the Siberian clone of the Princeton Ocean Model (SibPOM) tuned for several Arctic marginal seas: the Barents Sea, the Kara Sea, the Laptev Sea, the East Siberian Sea, and the Chukchi Sea with a horizontal resolution of about 2-3 km.

In the numerical experiment, we used data on the state of the lower atmosphere from the CORE-II [20] reanalysis as a forcing of the SibCIOM model in 1948–2010. The run of regional SibPOM models was started in September 2006 and finished in October 2008. When nested, SibPOM uses the large-scale model temperature and salinity distributions as the "climatic" state, and the stream function and horizontal velocity components as fluid boundary conditions. In this variant of the experiments, feedbacks (the influence of regional processes on large-scale ones) were not taken into account.

3. Mesoscale eddy recognition method

To recognize eddy formations, we used a selection of solitary minima and maxima in the field of surface elevation, treating them as cyclonic and anticyclonic eddies, respectively. For each 2D output of sea surface elevation, we construct a field with a uniform one-kilometer resolution using bilinear interpolation. Then, averaging the resulting field over squares of 3×3 or 4×4 grid nodes, etc., we can identify a set of solitary minima and maxima. We consider as a maximum at point (i, j) in case the value at this point satisfies the following expressions in both coordinate directions:

$$\begin{cases} \eta_{i,j} - \frac{\eta_{i-1,j} + \eta_{i+1,j}}{2} > \alpha |\eta_{i-1,j} - \eta_{i+1,j}| \\ \eta_{i,j} - \frac{\eta_{i,j-1} + \eta_{i,j+1}}{2} > \alpha |\eta_{i,j-1} - \eta_{i,j+1}|, \end{cases}$$
(1)

where $\eta_{i,j}$ is the surface elevation matrix obtained as a result of averaging over the corresponding square, and α is the tuning coefficient, which after a series of tests we chose equal to 0.5. If, for example, the value at the point (i, j), when averaged over 4×4 km squares, satisfies the conditions (1) while the values at all eight neighboring points do not satisfy this condition, then we consider that the point (i, j) contains an anticyclonic eddy of 4 km scale. The identification of cyclonic eddies is carried out similarly.

According to [8], the observed eddy diameters range from 1 to 50 km. The horizontal resolution of the model is 2-3 km; therefore, it makes no sense to identify eddies of 1-2 km. To identify larger eddies, we used squares with sides of 3, 5, 7, 10, 14, 20, 28, 40, and 56 km.

The energy of eddy formations can be estimated by taking the integral value of the eddy kinetic energy

$$EKE = \frac{\rho_0}{2} \int_{\Omega_{i,j}} \int_{-H}^{\eta_{i,j}} \left(\overline{u'u'} + \overline{v'v'} \right) dz \, d\Omega, \tag{2}$$

IOP Publishing

where the integral is taken over $\Omega_{i,j}$ - a corresponding vicinity of the point (i, j) and from the bottom z = -H to the surface $z = \eta_{i,j}$. In this case, during the model run it is necessary to store not only the time-average values of the horizontal velocity components \overline{u} and \overline{v} , but also their squares $\overline{u^2}$ and $\overline{v^2}$, so that, using the well-known statistical expression, from the results of numerical simulation it would be possible to calculate

$$\left(\overline{u'u'} + \overline{v'v'}\right) = \left(\overline{u^2} + \overline{v^2}\right) - \left(\overline{u^2} + \overline{v^2}\right).$$
(3)

4. Results and discussion

Table 1 shows the average monthly number of identified eddies in the seas of the Eurasian sector of the Arctic with a scale of at least 5 km. There were 19.43 thousand eddies on average in these seas, of which 10.19 thousand are cyclonic (52%). The absolute predominance of cyclonic eddies as a whole is justified by the cyclonic nature of water movement in these areas. If the jet has a cyclonic bend, then, provided the potential vorticity is preserved, the number of cyclonic vortices generated by this jet should be more generous. Seasonality is expressed in a greater number of eddies in winter (under the ice) with a maximum in March and a minimum in September. Seasonal fluctuations are approximately \pm 16% of the average annual amount.

This statistics is significantly different from the results of [11, 10, 8], obtained on analysis of space-borne observations. For example, in [8] it is stated that the largest number of registered eddies was in August and September, while the eddies of the cyclonic type of rotation are 64%; i.e., there are about two times more of them than the anticyclonic eddies. A possible reason for this discrepancy is, firstly, that the possibility of observing eddies is available only for ice-free water areas. Secondly, registration of anticyclonic eddies is visually more difficult, because they often reside in the subsurface layers [9].

Table 2 presents statistics for the Barents and Chukchi Seas for areas where, according to model calculations, the ice concentration was less than 15%. As can be seen in this case, the maximum number of identified eddies coincides with the time of maximum sea openness from ice, even in the Barents Sea, which is not entirely covered by ice. For the Chukchi Sea, the absence of eddies is noted throughout the winter solely because there is no surface sufficiently open from ice. We did not present calculations for other seas, which also confirm the conclusion that the maximum number of eddies in about September is not associated with an increase in the eddy activity during this period (or not only with it) but with the maximum ice-free area of the sea surface. Besides, a comparison of the results of Table 1 and Table 2 shows that a significant part of eddies resides under sea ice, where its concentration is higher than 15%. The share of subglacial eddies in the Barents Sea is about 32%, and in the Chukchi Sea it is 85%. Perhaps the main reason for such a high ratio in the Chukchi Sea is that this sea is under ice for a significant part of the year. However, even in the Barents Sea, these eddies account for about a third. The only mechanism of eddy formation, we believe, is convective instability during the freezing period. In March, the fraction of sub-ice eddies in the Barents Sea is 39% against 16%in September, and in the Chukchi Sea the comparison gives 100% against 41%. Nevertheless, even during ice melting, the fraction of sub-ice eddies is nonzero; therefore, other mechanisms need to be studied.

In paper [10], results showed that the marginal ice zone is one of the sources of mesoscale eddy formation. The reason is a jump in the flow of heat, moisture, and momentum at the ice boundary, which creates some semblance of a front. Moreover, the same front is also present in the atmosphere. Unfortunately, we cannot estimate the effect of the atmospheric

front within the framework of this formulation of the problem, since we had prescribed the lower atmosphere's characteristics, and the ice boundary in the reanalysis hardly coincides with the boundary obtained in our experiment. Nevertheless, we can assess the role of the boundary in the formation of mesoscale eddies.

Table 1. Average number of eddies (in thousands) with a scale of at least 5 km by months simultaneously existing in the marginal seas of the Eurasian sector of the Arctic, detected using the proposed procedure based on the results of numerical modeling in the period from September 2006 to September 2008: the first value corresponds to the number of cyclonic eddies, the second is the number of anticyclonic eddies. The first column contains the average annual number of cyclonic and anticyclonic eddies in each of the seas and in total.

	1	2	3	4	5	6	7	8	9	10	11	12
Barents Sea 3 55/3 21	$3.8 \\ 3.6$	$\frac{3.8}{3.5}$	$3.9 \\ 3.6$	$\frac{3.8}{3.5}$	$\frac{3.8}{3.5}$	$\frac{3.5}{3.1}$	$\frac{3.3}{2.9}$	$\frac{3.1}{2.7}$	$\frac{3.1}{2.7}$	$3.4 \\ 3.0$	$\frac{3.6}{3.2}$	$\frac{3.8}{3.5}$
Kara Sea	1.9	2.1	2.1	2.2	2.1	1.9 1.7	1.7 1.4	1.6 1.4	1.5	1.5 1.4	1.7	1.8 1.7
Laptev Sea 1.32/1.12	1.0	1.5 1.5 1.3	1.5 1.5 1.3	1.0 1.4 1.2	1.3 1.1	1.3 1.0	1.1 1.1 0.9	1.1 1.1 0.9	1.0 1.1 0.9	1.1 1.3 1.1	1.3 1.5 1.3	1.5 1.3
East Siberian Sea 1.42/1.29	1.5	$1.6 \\ 1.5$	1.8 1.7	$1.8 \\ 1.6$	1.8 1.7	$1.7 \\ 1.6$	$1.3 \\ 1.2$	$\begin{array}{c} 1.1 \\ 0.9 \end{array}$	1.0 0.8	$\begin{array}{c} 1.1 \\ 1.0 \end{array}$	$1.3 \\ 1.2$	1.4 1.3
Chukchi Sea 2.07/1.99	$\begin{array}{c c} 2.4\\ 2.3 \end{array}$	$2.3 \\ 2.2$	$2.3 \\ 2.2$	$2.1 \\ 2.1$	$1.8 \\ 1.7$	$\begin{array}{c} 1.7\\ 1.7\end{array}$	$\begin{array}{c} 1.8\\ 1.6\end{array}$	$1.9 \\ 1.8$	$2.1 \\ 2.0$	$2.2 \\ 2.1$	$2.2 \\ 2.1$	$2.2 \\ 2.1$
Total 10.19/9.24	$\begin{vmatrix} 11.1 \\ 10.3 \end{vmatrix}$	$\begin{array}{c} 11.4 \\ 10.5 \end{array}$	$\begin{array}{c} 11.6\\ 10.6\end{array}$	$\begin{array}{c} 11.3\\ 10.3 \end{array}$	10.8 9.8	$\begin{array}{c} 10.1\\ 9.0\end{array}$	$9.2 \\ 8.1$	$8.7 \\ 7.6$	$8.5 \\ 7.6$	$\begin{array}{c} 9.5\\ 8.6\end{array}$	$\begin{array}{c} 10.2\\ 9.4 \end{array}$	$\begin{array}{c} 10.7\\ 9.9 \end{array}$

Table 2. Average number of eddies (in thousands) with a scale of at least 5 km by months simultaneously existing in the marginal seas with less than 15% ice cover in the Eurasian sector of the Arctic, detected using the proposed procedure based on the results of numerical modeling in the period from September 2006 to September 2008: the first value corresponds to the number of cyclonic eddies, the second is the number of anticyclonic eddies. The first column contains the average annual number of cyclonic and anticyclonic eddies in each of the seas and in total.

	1	2	3	4	5	6	7	8	9	10	11	12
Barents Sea $2.42/2.19$	$\begin{vmatrix} 2.6 \\ 2.4 \end{vmatrix}$	$2.3 \\ 2.1$	$2.4 \\ 2.2$	$2.1 \\ 2.0$	$2.2 \\ 2.0$	$2.0 \\ 1.8$	$2.3 \\ 2.0$	$2.4 \\ 2.1$	$\begin{array}{c} 2.6 \\ 2.3 \end{array}$	$2.7 \\ 2.4$	$2.7 \\ 2.4$	2.6 2.4
Chukchi Sea 0.38/0.36	$\begin{vmatrix} 0.0 \\ 0.0 \end{vmatrix}$	$0.0 \\ 0.0$	$0.0 \\ 0.0$	$0.0 \\ 0.0$	$0.0 \\ 0.0$	$\begin{array}{c} 0.03 \\ 0.03 \end{array}$	$\begin{array}{c} 0.4 \\ 0.4 \end{array}$	1.0 0.9	$1.2 \\ 1.2$	$1.3 \\ 1.2$	$\begin{array}{c} 0.6\\ 0.6\end{array}$	$0.03 \\ 0.03$

ENVIROMIS 2020	IOP Publishing
IOP Conf. Series: Earth and Environmental Science 611 (2020) 012009	doi:10.1088/1755-1315/611/1/012009

If we set the ice concentration isoline equal to 50% as the ice field's conditional boundary, we can estimate what fraction of the eddies is on the free surface side and the under-ice side. Table 3 shows that about 61% of eddies formed in the near-edge zone appeared on the side of concentrated ice. That is, there are about 1.5 times more such eddies. In general, the number of cyclonic eddies is somewhat larger than that of anticyclonic ones. However, the difference is not as significant as, for example, in [8], and the fraction of cyclonic eddies is about 51%. Also, the table shows two separate maxima. The first maximum corresponds to August and the second one to October. These two periods differ in that in August, the ice mostly melts, and, therefore, the ice boundary is also a source of freshened water on the ocean surface. In the second case, the formation of young ice, accompanied by salt rejection, prevails. Therefore, in the edge zone dense waters are formed, creating conditions for convection. However, the process continues throughout the wintertime since December, it is already wholly hidden from observation, and the edge zone is merely absent.

Table 3. Average number of eddies with a scale of at least 5 km by months (June-December) simultaneously existing in the area with ice cover of 10-50% and 50-80% in the Chukchi Sea resulting from numerical modeling in the period from September 2006 to September 2008.

	6	7	8	9	10	11	12
Ice cover is 10-50% 72/69	$\begin{array}{c} 10\\ 8 \end{array}$	$\begin{array}{c} 131 \\ 125 \end{array}$	207 191	$\begin{array}{c} 244 \\ 233 \end{array}$	82 83	128 121	$\begin{array}{c} 60 \\ 57 \end{array}$
Ice cover is 50-80% 114/109	$\begin{array}{c} 37\\ 30 \end{array}$	$\begin{array}{c} 223\\ 205 \end{array}$	$\begin{array}{c} 407\\ 384 \end{array}$	$\begin{array}{c} 374\\ 364 \end{array}$	48 48	142 141	$\begin{array}{c} 121 \\ 122 \end{array}$

Figure 1 shows some of the distributions of eddies over the five seas in August 2007. The animation based on such figures shows that most of the medium and large eddies are stationary, since they are trapped to the topographic features. The most mobile are mesoscale eddies on a scale of 3-10 km. The figure shows the most obvious trajectories of such eddies.

In the Barents Sea (Fig. 1a), this is the trajectory of the Norwegian and West Spitzbergen Currents along the Scandinavian coast and further towards Svalbard. Also, as noted in [18], under the conditions of cascading formation (sliding of dense shelf waters along the sloped bottom), eddies form and move along the right slopes of Bear Island Trough (Bjørnøyrenna), Franz-Victoria Trough, and along the northern coast of Novaya Zemlya. In the Kara Sea (Fig. 1b), cascading develops in the area of St. Anna Trough and Voronin Trough, which is accompanied by a series of mesoscale eddies generated in these areas and propagating towards the open ocean along the right slopes of the troughs. Besides, many eddies are formed in the area of the mouths of the Ob and Yenisei rivers at the front of fresh and salty waters and contain, respectively, either freshened river water or Arctic salty water. These eddies spread towards the adjacent shelf areas of the Kara Sea. We can also note a series of eddies arising in the Matochkin Shar Strait area and propagating along the southern coast of Novaya Zemlya. At the front of the river waters of the Lena, Olenek, and Khatanga Rivers and sea waters in the Laptev Sea (Fig. 1c), many mesoscale eddies are also formed, they propagate mainly in the northern direction towards the shelf-slope. Along the shelf-slope itself, we also note a series of eddies moving eastward. These eddies come from the St. Anna Trough and the Voronin Trough from the Kara Sea. Besides, some of them arise due to the baroclinic instability of the Atlantic water flow along the shelf-slope. Trapped by topography, these eddies propagate further along



Figure 1. Eddies in marginal seas in August 2007: (a) Barents Sea, (b) Kara Sea, (c) Laptev Sea, (d) East Siberian Sea, (e) Chukchi Sea. Red circles correspond to cyclonic, and blue ones to anticyclonic eddies. The diameter of the circles corresponds to the characteristic size of the eddies. Arrows indicate the most obvious direction of eddy propagation as it is seen from corresponding animation (not presented).

the Lomonosov Ridge towards the open ocean. This trajectory can be seen in the figure (Fig. 1d) for the East Siberian Sea. On the opposite side, along the shelf slope, a series of eddies moves. They arise on the outskirts of the Beaufort Gyre. Some of the eddies appear in the shallow areas off the coast. They spread northward towards the shelf slope. An active source of eddy formation in the Chukchi Sea (Fig. 1e) is the branches of the current of the Pacific waters entering through the Bering Strait. Since these waters are less saline, there is a front where mesoscale eddies are formed and propagate towards the Beaufort Gyre, mainly along the coast of Alaska, but at the same time, a prominent part of them moves along the coast of Chukotka towards Wrangel Island. On the Beaufort Gyre's outskirts, we can also note a series of eddies propagating along the isobaths in a westerly direction.

Figure 2 demonstrates the normalized statistical distributions of eddies by their length scales, obtained from the results of modeling. It shows that large eddies have an enormous total kinetic energy, even though their number is 2-3 orders of magnitude less, and this is not because they have a large area. The eddy kinetic energy per unit area also grows with increase in eddy size and reaches a plateau when it becomes about 40 km in size.



Figure 2. Normalized statistical distributions of eddies by their length scales obtained from the results of modeling the five marginal Arctic seas of Eurasia - the Barents (red line), Kara (blue), Laptev (green), East Siberian (magenta), and Chukchi (cyan) Seas: (a) the number of eddies, (b) the eddy kinetic energy (EKE), (c) the eddy kinetic energy per unit area. Solid lines correspond to distributions of cyclonic eddies, and dashed lines to anticyclonic ones.

5. Conclusion

A simple method was proposed for identifying mesoscale eddies in the results of numerical modeling. The method uses extrema in the distributions of the sea level elevation as eddy markers. Using the method, we analyzed statistics of mesoscale eddies in marginal seas of the Eurasian sector of Arctic. The results of using this method show that the number of cyclonic eddies in this area slightly exceeds the number of anticyclonic eddies, but the excess is only 2-3%. Also, we have demonstrated that a significant number of eddies arise under the ice cover. The number of such eddies increases significantly in winter. This fact indicates that the convection caused by salt rejection during seawater freezing plays an essential role in their formation. The numerical modeling results confirm the phenomenon of active eddy generation in the ice edge zone. Besides, the results show that in the near-edge zone, a more significant number of eddies are formed from the icy side adjacent to the edge, and not from the ice-free side. The periods of water freezing and ice melting, accompanied by corresponding displacements in the ice edge, produce eddies different in nature. The number of eddies in the marginal ice zone has two seasonal maxima corresponding to these two periods.

Acknowledgments

This work was supported by the Russian Science Foundation under grant 19-17-00154. The SibCIOM and SibPOM models used in the study were created within the framework of the budget project 0315-2019-0004 for ICMMG SB RAS.

References

 Bashmachnikov I L, Kozlov I E, Petrenko L A, Glok N I and Wekerle C 2020 Eddies in the North Greenland Sea and Fram Strait from satellite altimetry, SAR and high-resolution model data J.

Geophys. Res. Oceans 125 doi: 10.1029/2019JC015832

- [2] Dutkiewicz S, Rothstein L and Rossby T 2001 Pathways of cross-frontal exchange in the North Atlantic Current J. Geophys. Res. Oceans 106 26917–26928 doi: 10.1029/1999JC000089
- [3] Fratantoni D M 2001 North Atlantic surface circulation during the 1990's observed with satellitetracked drifters J. Geophys. Res. Oceans 106 22067–22093 doi: 10.1029/2000JC000730
- [4] Spall M A and Chapman D C 1998 On the efficiency of Baroclinic eddy heat transport across narrow fronts J. Phys. Oceanogr. 28(11) 2275–2287. doi: 10.1175/1520-0485(1998)028j2275:OTEOBE¿2.0.CO;2
- [5] Danabasoglu G, McWilliams J C and Gent P R 1994 The role of mesoscale tracer transports in the global ocean circulation Science 264(5162) 1123–1126. doi: 10.1126/science.264.5162.1123
- [6] Hirschi J J M et al. 2020 The Atlantic meridional overturning circulation in high resolution models J. Geophys. Res. Oceans 125 e2019JC015522 doi: 10.1029/2019JC015522
- [7] Luo D and Lu Y 2000 The influence of negative viscosity on wind-driven, barotropic ocean circulation in a subtropical basin J. Phys. Oceanogr. 30 916–932 doi: 10.1175/1520-0485(2000)030j0916:TIONVO¿2.0.CO;2
- [8] Artamonova A V, Kozlov I E and Zimin A V 2020 Characteristics of ocean eddies in the Beaufort and Chukchi Seas from spaceborne radar observations *Current Problems in Remote Sensing of the Earth from Space* 17 203–210 doi: 10.21046/2070-7401-2020-17-1-203-210
- [9] Fine E C, MacKinnon J A, Alford M H and Mickett J B 2018 Microstructure observations of turbulent heat fluxes in a warm-core Canada Basin eddy J. Phys. Oceanogr. 48 2397–2418 doi: 10.1175/JPO-D-18-0028.1.
- [10] Kozlov I E, Artamonova A V, Manucharyan G E and Kubryakov A A 2019 Eddies in the Western Arctic Ocean from spaceborne SAR observations over open ocean and marginal ice zones J. Geophys. Res. Oceans 124 doi: 10.1029/2019JC015113
- [11] Bashmachnikov I, Neves F, Calheiros T and Carton X 2015 Properties and pathways of Mediterranean water eddies in the Atlantic Progress in Oceanography 137 149–172 doi: 10.1016/j.pocean.2015.06.001
- [12] Zhao M, Timmermans M-L, Cole S, Krishfield R and Manucharyan G E 2018 Partitioning of kinetic energy in the Arctic Ocean's Beaufort Gyre J. Geophys. Res. Oceans 123 4806–4819 doi: 10.1029/2018JC014037
- [13] Timmermans M-L, Toole J, Proshutinsky A, Krishfield R and Plueddemann A 2008 Eddies in the Canada Basin, Arctic Ocean, observed from ice-tethered profilers J. Phys. Oceanogr. 38(1) 133–145 doi: 10.1175/2007JPO3782.1
- [14] Manucharyan G E and Timmermans M-L 2014 Generation and separation of mesoscale eddies from surface ocean fronts J. Phys. Oceanogr. 43(12), 2545–2562 doi: 10.1175/JPO-D-13-094.1
- [15] Manley T O and Hunkins K 1985 Mesoscale eddies of the Arctic Ocean J. Geophys. Res. Oceans 90 4911–4930 doi: 10.1029/JC090iC03p04911
- [16] Spall M, Pickart R, Fratantoni P and Plueddemann A 2008 Western Arctic shelfbreak eddies: Formation and transport J. Phys. Oceanogr. 38(8) 1644–1668 doi: 10.1175/2007JPO3829.1
- [17] Muench R D, Gunn J T, Whitledge T E, Schlosser P and Smethie W 2000 An Arctic Ocean cold core eddy J. Geophys. Res. Oceans 105 23997–24006 doi: 10.1029/2000JC000212
- [18] Platov G A and Golubeva E N 2019 Interaction of dense shelf waters of the Barents and Kara Seas with the eddy structures *Physical Oceanography* 26(6) 484–503 doi: 10.22449/1573-160X-2019-6-484-503
- [19] Platov G A 2011 Numerical Modeling of the Arctic Ocean Deepwater Formation: Part II. Results of Regional and Global Experiments Izvestiya, Atmospheric and Oceanic Physics 47(3) 377–392 doi: 10.1134/S0001433811020083
- [20] Large W G and Yeager S G 2009 The global climatology of an interannually varying air-sea flux data set *Climate Dynamics* 33(2-3) 341–364 doi: 10.1007/s00382-008-0441-3