

Submesoscale Eddy Structures and Frontal Dynamics in the Barents Sea

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Complex analysis of spatial and temporal variability of surface manifestations of the submesoscale eddies in the Barents Sea is carried out based on generalization of a large amount of satellite SAR-images of ENVISAT ASAR obtained in course of the warm periods in 2007 and 2011. The relationship between the eddy structures and the frontal dynamics is also quantitatively evaluated. It is found that the submesoscale eddies represent a widespread phenomenon in the sea. They are most often observed to the northwest off the Franz Josef Land, near the eastern coast of the Western Spitsbergen, between the Franz Josef Land and the Novaya Zemlya, in the southwestern part of the sea and near the Kanin Nos peninsula. But their absolute maximum is recorded to the northeast off the Rybachy Peninsula. In both years the eddy activity peak falls on July. Though the diameters of the eddies under study vary from 0.2 to 25 km, those with the diameters 2–4 km (~ 45%) and of a cyclonic rotation type (~ 80%) are the most numerous. Being analyzed, the sea surface temperature data permit to reveal significant mesoscale and synoptic dynamics of the frontal zones and the associated frontal boundaries throughout the entire sea in course of the whole warm season. Comparison of the eddy locations with variability of the fronts' positions for each month (based on the data of 2007) shows that the submesoscale structures are often recorded within these regions (up to 50%). The period of the highest eddy activity in July coincides with that of the strongest synoptic and mesoscale dynamics of the fronts.

Keywords: submesoscale eddy, satellite radar image, sea surface temperature, thermal frontal zone, Polar front, Marginal ice or Arctic front, the Barents Sea.

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Introduction. The Barents Sea is located in polar regions, characterized by harsh climatic conditions. Its greater part (except for the southwestern one) is covered by ice during the winter. This is because oceanographic conditions are formed by currents under the heat advection effect [1]. The interaction of comparatively warm Atlantic waters and cold waters of the Arctic Ocean occurs in the Barents Sea. It determines the formation of the Polar frontal zone in the central part of the sea and the Marginal Ice frontal zone in its northern part [2–4]. The structures and characteristics of the frontal zones and fronts in them are different according to the data of different authors [2, 5–8]. There is no detailed description of the mesoscale and synoptic dynamics of these frontal zones and fronts in the literature. Descrip-

tions of frontal zones in the water area of the entire Barents Sea are generally based on the generalization of the data of long-term hydrological observations and illustrate their average position, but not the mesoscale dynamics during the ice-free period [2, 7, 9].

Meanders and eddies can be formed due to instability along the fronts. The existence of mesoscale eddy structures in the Polar frontal zone on the border with the Norwegian Sea was noted in [10, 11]. In the works [2, 12] eddies with a diameter ranging from one to tens of kilometers are mentioned. Such eddies are revealed during the polygon surveys in the northwestern Barents Sea and in the region of the Great (Perseus) Bank. Satellite data also permitted to record anticyclonic and cyclonic meanders near the Polar frontal zone [13] and submesoscale eddies in the entire water area [14]. So far, however, there has been no specialized research of the features of the spatial variability of the characteristics of small (submesoscale) eddies in the sea area for several years. In addition, there are no evaluations of the relationship between frontal dynamics and the features of the formation of small eddies, which can significantly affect the processes of vertical and horizontal exchange in the water area of the sea. The present study is aimed to describe the intraseasonal and interannual features of the manifestations of submesoscale eddies and to compare them with the variability of the position of fronts during the warm season in the Barents Sea.

Materials and methods. To detect small (submesoscale) eddy structures in the Barents Sea 1203 and 838 satellite SAR-images of *ENVISAT ASAR* respectively in June – October 2007 and 2011 in the C-band and *WSM* (swath width is 400 kilometers, a spatial resolution – 150 m) and *IMP* (100 km and 25 m, respectively) shooting modes. The choice of 2007 and 2011 years is due to the fact that in these years the minimum ice area in the sea area was observed [15]. On average, the coverage of the Barents Sea was 120 images SAR mages, while in 2011 its southeastern part was not practically covered by SAR images. So, in the both years the maximum coverage (over 200 images) fell within the northern part of the sea. According to this data, the variability of the position, diameters and the rotation type of the eddy structures was evaluated.

To obtain an idea of the position of the fronts, the sea surface temperature and gradient fields were used. The fields were calculated from the daily sea surface temperature – of the *GHRSSST* product (*Global Foundation Sea Surface Temperature Analysis*) *Level 4 OSTIA* (*Operational Sea Surface Temperature and Sea Ice Analysis*) with 0.05° resolution by latitude and longitude from June to October 2007 and 2011. Based on this data, the averaged (monthly and decadal) fields of temperature and its gradient were calculated, according to which the positions of frontal zones and fronts were determined. In accordance to three mean meridional sections along 20° , 35° and 50°E for the frontal zones their mean width, maximum and average gradients were estimated. To compare the obtained data on fronts and eddy structures, composite maps were monthly constructed. They combined the position of the eddies and the ten-day position of fronts and frontal sections. Maps were constructed for the June – September 2007 period.

Submesoscale eddy structures. In the Barents Sea, eddy structures have been recorded almost within the entire sea area (Fig. 1). Single eddies and eddy structures of various forms: spiral, fungous and chain-like were detected. 2,934 in all small eddy structures were found, among which structures with a cyclonic type (*Cn*) – 2383 pcs (81%) predominated. The highest frequency of occurrence of eddies was monitored in the following regions: the northwest of the Franz Josef Land, near the West Spitsbergen eastern coast, the southwestern part of the sea (in the area of the Atlantic water entrance), the central part of the strait between the Franz Josef Land and the Novaya Zemlya, in the Kanin Nos area. Here, the eddies were observed even more often than in every tenth shot. The highest occurrence (more often than in every third image, that is, 33% of the images per considered grid unit) was noted in the area north-north-east of Rybachy Peninsula, where 14 eddies per 1,000 km² were registered. Spatial distribution of the eddy structure dimensions showed that on average large eddies (over 7–8 km) were detected in the Atlantic water propagation area (the southwestern part of the sea). Eddies with sizes less than 2 km were recorded mainly to the northeast of the Spitsbergen, as well as between the Franz Josef Land and the Novaya Zemlya. Eddies with a diameter of ~2–4 km were most often observed, both among the cyclonic and anticyclonic (*Ac*) ones, with an average value of 3.6 km, mode and median of 2.8 and 2 km, respectively.

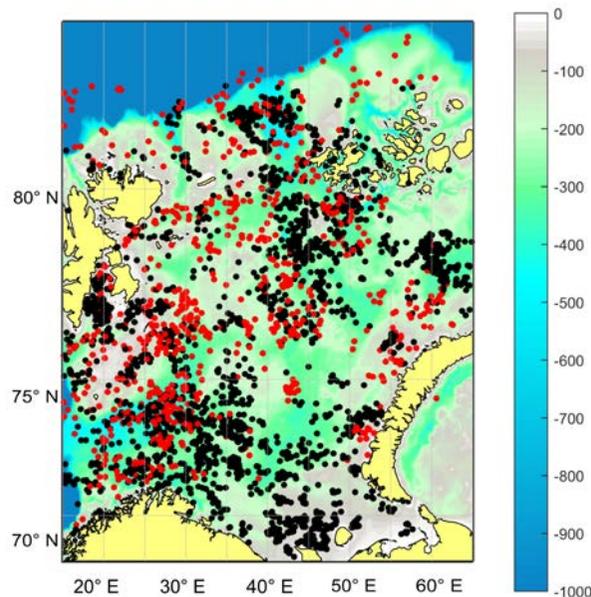


Fig. 1. Spatial distribution of the locations of the small eddy centers in 2007 (black circles) and 2011 (red circles). Depth scale is in meters

An analysis of the intra-seasonal distribution of eddy structures in the Barents Sea showed (Tab. 1) that from June to July their number increased and from July to October decreased by 4.5 times. The peak of the eddy activity was in July and equaled to 854 eddies per month. However, the maximum of anticyclonic eddies was observed in August, although it slightly differed from the July figure (by 9 eddies).

The mean monthly diameter of the eddies varies from 2.3 to 4.2 km. At the same time, from June to October, there is a tendency to its reduction. Almost in all the months, the mean monthly diameters of anticyclonic eddies were larger than those of cyclonic eddies, while the latter were recorded several times more frequently every month.

Table 1

Parameters of the eddies in the Barents Sea during the warm season, Ac denotes the anticyclonic eddies, Cn – the cyclonic ones and (Ac + Cn) – all the eddies

Month	Number of eddies, pcs			Mean diameter, km		
	<i>Ac</i>	<i>Cn</i>	<i>Ac + Cn</i>	<i>Ac</i>	<i>Cn</i>	<i>Ac + Cn</i>
June	116	563	679	4.7	4.2	4.2
July	156	698	854	5.9	3.7	4.1
August	167	549	716	3.4	3.3	3.3
September	87	411	498	2.4	2.4	2.4
October	25	162	187	2.9	2.2	2.3
Sum total for the season	551	2383	2934	4.2	3.4	3.5

2,187 and 747 eddy structures had been registered for 2007 and 2011, respectively (Tab. 2). As compared with 2007, there are fewer radar images for 2011, the coverage of images is more uneven: the northern part of the sea is mostly covered and the southeastern part of it is almost not covered. For this reason this part is not considered when comparing eddy areas. In 2011 the eddies are recorded northward than in 2007, due to the larger ice-free water region [15]. But on the whole, the situation of the eddy structure clusters is similar in the both years (as well as the regions with the highest occurrence, except for the southeastern part of the sea), and the general regularities within the season throughout the data array (Tab. 1) remain separately for each year (Tab. 2). About 90% of the small eddy structures were up to 6 km in size, which allows them to be classified as a submesoscale ones, with diameters ranging from 2 to 4 km prevailing in both years, from 20 to 30% of the eddies had size of up to 2 km, from 10 to 20% – 4 ... 6 km.

The generalization carried out shows that submesoscale eddies are a common phenomenon throughout the Barents Sea. It is interesting that some of their characteristics and patterns established by eddy manifestations on the Barents Sea surface were observed in other regions of the World Ocean. In particular, it concerns the predominance of cyclonic eddies over the amount of rotation of the eddies with anticyclonic rotation [16–19], although most of the Beaufort Sea detected small-scale eddies have anticyclonic rotation [20], which developed within the existing in summer anticyclonic circulation of the surface waters. Probably, a background cyclonic vorticity is a favorable condition for the dominance of cyclonic submesoscale eddies (in the Northern Hemisphere).

Table 2

Parameters of the eddies in the Barents Sea in 2007 and 2011, *Ac* denotes the anticyclonic eddies, *Cn* – the cyclonic ones and (*Ac* + *Cn*) is all the eddies

Month	Number of eddies, pcs			Mean (min – max) diameter, km		Mean diameter, km
	<i>Ac</i>	<i>Cn</i>	<i>Ac</i> + <i>Cn</i>	<i>Ac</i>	<i>Cn</i>	<i>Ac</i> + <i>Cn</i>
2007						
June	103	390	493	4.7 (0.3–17.1)	4 (0.3–15.6)	4.2
July	139	498	637	6 (0.2–21)	3,8 (0.2–25)	4.3
August	156	366	522	3.5 (1–18.3)	3,7(0.7–20.4)	3.6
September	83	279	362	2.4 (0.5–12.1)	2,2 (0.2–15.9)	2.2
October	25	148	173	2.9 (0.5–10.6)	2,2 (0.4–9.8)	2.3
Sum total	506	1681	2187	4.2 (0.2–21)	3,4 (0.2–25)	3.6
2011						
June	13	173	186	4,6 (1.6–10.3)	4.4 (1.6–12.9)	4.4
July	17	200	217	5.2 (1.9–14.5)	3.5 (0.9–15.6)	3.6
August	11	183	194	3.1 (1.7–6.4)	2.3 (1.2–5.4)	2.4
September	4	132	136	2.0 (1.5–2.6)	2.7 (1.0–9.9)	2.7
October		14	14		2.5(1.0–4.9)	2.5
Sum total	45	702	747	4.2 (1.6–14.5)	3.3 (0.9–15.6)	3.3

Frontal zones. In the both years the Marginal Ice frontal zone was traced in the northern part of the sea to the west of the Spitsbergen and south of the Franz Josef Land, changing its position after the ice edge shift. At the same time, at the beginning and the end of the warm period in the western part of the sea, the Marginal and Polar frontal zones were located close to each other. For the period from June to October, the southernmost position of the Marginal Ice frontal zone was recorded in early June, the northernmost – in the middle of August. Its displacement for the season exceeded 450 km. The width of the Marginal Ice frontal zone, based on the data of three meridional sections, ranged from 44 to 122 km in 2007 (mean about 80 km) and in 2011 – from 44 to 139 km (mean 90 km). In the both years in the frontal zone, a stepped type of thermal structure predominated. The maximum gradient of sea surface temperature in 2007 was 0.07 °C/km, and in 2011 0.05 °C/km.

The Polar frontal zone was situated mainly in the central part of the sea and was oriented from west to east. Its width, according to the aforementioned sections, in 2007 varied from 44 to 206 km (the mean is value 130 km), and in 2011 – from 53 to 167 km (on average 120 km). The position of the Polar frontal zone in the western part of the sea was quasi-permanent, the maximum gradients of 0.05°C/km were also observed here. The greatest dynamics of the frontal zone and its front was recorded in the eastern part of the sea, where the gradients were much weaker than in the western part. Both in the Marginal and Polar frontal zones, in both years the stepped type of thermal structure was most often recorded.

Both fronts showed a significant temporal dynamics, which was reflected both in the decadal averaging interval and in the monthly one. It should be noted that the intensive dynamics of the fronts took place within the monthly intervals. Moreover,

comparing the monthly averages and the average decadal positions of the frontal lines (Fig. 2), it follows that in studying the intra-season frontal dynamics it is desirable to focus on to the decadal data, characterizing the significant mesoscale variability of the front position.

Analysis of composite maps showed that a quarter of all eddies were recorded inside and on the periphery of the frontal variability zone of for the entire period, while only 1% less eddy structures were detected in the Polar Front zone than in the Marginal one. In the areas of decadal variability of the fronts, eddies of small size (up to 4 km) with cyclonic rotation type prevailed. However, occasionally on the periphery of the frontal zones, large formations (over 8 km in diameter) with an anticyclonic rotation type were observed.

Maximum number of eddies in the variability area of the Marginal and Polar Fronts was registered in July 2007 (20 and 24% respectively of the total for the month). In the same month there was an eddy activity peak and the displacement of the decadal fronts was the highest (Fig. 2b). The aforementioned fact of the frequent manifestations of small eddies in the frontal zones, and in our case – in the variability zone of surface fronts, suggests the relationship of these eddies with the frontal activity. In June and August from 10 to 13% eddies per month inside and on the periphery of each of the zones was recorded, while in September, there were only 14% of the number of eddies in September in these two areas.

However, the formation of submesoscale eddies with a short lifetime cannot always be identified with any mechanism based on available satellite information, especially since these mechanisms can work in combination. Nevertheless, this comparison allows stating the submesoscale eddies to be more often manifested in the first half of summer, when the fronts are more dynamic and the seasonal heating of the upper layer has not reached its maximum yet.

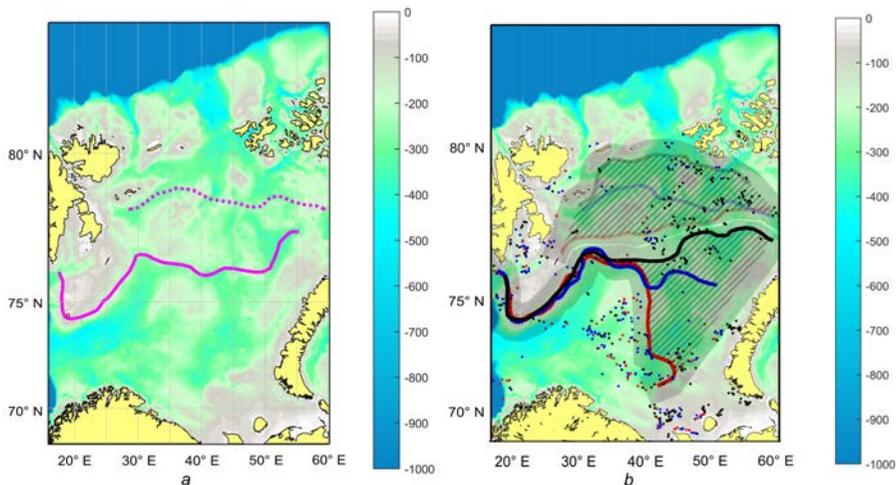


Fig. 2. Monthly average (a) and decadal (b) locations of the Marginal ice front (dashed line) and the Polar front (solid line) in July, 2007. Pink color denotes their monthly average positions, red – in the 1st decade, blue – in the 2nd decade and black – in the 3rd one. Slanting lines show the areas of variability of the fronts' decadal locations in July, 2007 and grey color – the 50 km zone close to the area of variability. Depth scale is in meters

Conclusion. Within the scope of the works on radar images for June – October 2007 and 2011 the following characteristics of small eddies were detected: the position of the center, the type of rotation and the diameter. The analysis of these characteristics made it possible to identify the intraseasonal and interannual features of the spatiotemporal variability of the parameters of small eddies, and their comparison with frontal dynamics made it possible to evaluate their relationship.

In total, about 3,000 small eddy structures were recorded in the Barents Sea, which were most often observed to the northwest off the Franz Josef Land, near the eastern coast of the Western Spitsbergen, between the Franz Josef Land and the Novaya Zemlya, in the southwestern part of the sea (in the area of entrance of the Atlantic waters) and near the Kanin Nos peninsula. But their absolute maximum is recorded to the northeast off the Rybachy Peninsula. In both years the eddy activity peak falls on July, when more than a quarter of the eddy structures was recorded on the whole, with eddies with the diameters 2–4 km and with a cyclonic rotation type prevailing. The mean parameters of the eddies from year to year and during the warm season totally persisted.

In both years, in the Barents Sea area, the position of the Marginal and Polar fronts was identified according to the processing results of the decadal and monthly averages of sea-surface temperature and its gradients. In addition, the mean widths for each frontal zone of the fronts identified were estimated. With a mean width of both frontal zones of about 100 km, the maximum width of the Marginal Ice frontal zone reached almost 140 km, and the one of the Polar – nearly 200 km. It was also revealed that the Marginal front during the warm period can shift over a distance of 450 km from June to the end of August – the beginning of September, and the Polar front is quasi-stationary in the western part of the sea and is dynamic in its eastern part. Thus, the decadal data was the best to reflect the synoptic variability.

Comparison of the eddy locations with variability of the fronts positions for each month (based on the data of 2007) shows that the submesoscale structures are often recorded within these regions (a quarter of the eddies of the season), at that the period of the highest eddy activity in July coincides with that of the strongest synoptic and mesoscale dynamics of the fronts.

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Aleksey V. Zimin – scientific supervision and checking of the results

Egor I. Svergun – radar data processing, building of the composite maps

Aleksandr A. Konik – sea surface temperature processing

All the authors have read and approved the final manuscript.

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