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Eddy generation and variability of the marginal ice zone in the Fram Strait according to satellite radar measurements

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Abstract. Based on analysis of spaceborne synthetic aperture data (SAR), acquired in summer of 2007 over Fram Strait and around Svalbard, we investigate spatial and temporal variability of the ice edge and generation of eddies in the marginal ice zone. During the season, the ice-water boundary nonuniformly moves along its entire length with the overall width of the ice edge displacement ranging from 30 to 220 km. The ice edge movement is often accompanied by generation of eddies and filaments peaking in August. Analysis of the data serves to find out over 2000 distinct MIZ eddies with a clear dominance of cyclones (78%). In July the detected eddies are predominantly formed along the ice edge, in August most of them are generated inside the MIZ, while in September their numbers along the ice edge and within the MIZ are similar. Larger eddies (10-20 km in diameter) are found over deep Fram Strait and the Greenland Sea shelf, while smaller eddies (~5 km) are observed in coastal regions around Svalbard.

1. Introduction

The marginal ice zone (MIZ) is the transition region from open ocean to dense ice cover with typically considered values of sea ice concentrations between 20% and 80%. This is an area of active atmosphere-ice-ocean interactions that determine the spatial orientation of the ice-water boundary.

The ice cover area changes significantly throughout the year, decreasing in the summer season and significantly increasing in winter. The area within which the ice field boundary moves is distinguished by significant wind variability and sharp gradients of thermohaline characteristics in the surface ocean layer. When the wind blows from ice-covered regions toward open water, there is a significant reduction in sea ice concentration inside MIZ, and the ice field displaces towards open water where it is subject to accelerated melting and various instabilities leading to formation of eddies of various sign. For winds directed from open water toward ice, individual ice floes are displaced toward the main ice cover, collide and split into smaller ice floes. The latter also stimulates melting and freshening of the under-ice layer and sharpening of density gradients [1], favoring the eddy formation in the MIZ that could be effectively observed from space [2-3].

2. Data and Methods

In this work we used spaceborne SAR observations made by Envisat Advanced SAR (ASAR) instrument in Wide Swath Mode (spatial resolution 150 m) from June to September 2007. Altogether 294 ASAR images were processed for the ocean region in Fram Strait and around Svalbard, i.e., between 75°- 82°N and 13°W - 30°E. Satellite data were used both for ice edge detection and identification of the MIZ eddies together with their coordinates, diameters and vorticity sign, similar to



what was done in [2]. The ice edge was defined as the boundary between the marginal ice zone and the open water.

3. Spatial variability of the marginal ice zone

Spatial orientation of the MIZ is one of the key parameters illustrating the complex interplay between ocean currents, wind, vertical heat fluxes and ice formation/melting processes. Analysis of the satellite data in Fram Strait and around Svalbard from June to September 2007 has shown that the ice edge is subject to strong deformation, and its movement is not homogeneous along its boundary (figure 1). The highest seasonal changes in the MIZ boundary location (up to 220 km northward) were observed in the regions north of Svalbard and south of 78° N.

To the north of Svalbard, the ice edge is moving not only in the northern, but also in the eastern direction. In September 2007, the region north of Svalbard became completely ice-free and the ice edge shifted to 82° N.

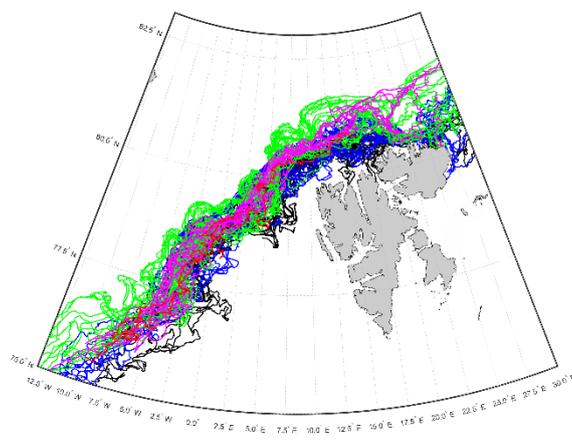


Figure 1. Spatial variability of sea ice edge in Fram Strait and north of Svalbard in June – September 2007. Colors mark the ice edge boundary: black – in June, blue – July, green – August, magenta – September.

Figure 1 depicts well that the minimal shift of the ice edge is observed at 79° N, 2° E. This location is known for the existence of quasi-stationary cyclonic eddy formed over the Molloy Deep, where two branches of the West Spitsbergen Current (WSC) carrying relatively warm and saline water of Atlantic origin recirculate over its south and north flanks [4, 5, 6].

The character of the ice edge deformation and spatial shift in June (figure 2(a)) illustrates the overall pattern of the Atlantic water (AW) pathways in the studied region. One can clearly see that the ice edge is shifted westward under the influence of warm recirculation branches of the WSC. Well-developed filaments directed eastward, i.e., toward open water regions, are found between these two recirculation branches. The overall ice edge configuration shows an eddy pattern over the Molloy Deep. During June 2007, the eastern ice edge boundary located north of Svalbard shifted from Cape Verlegenhuken (16° E) to Cape Platen (23° E), i.e., by 135 km.

South of 76° N, many mushroom-like eddies are encountered near the ice edge. They propagate from southwest to northeast, i.e., against the main ice drift direction (to the southwest) that may be caused by southerly winds. By the end of June, disturbances on the ice-water boundary decay, the ice edge becomes more stable, compacted and leveled under the influence of prolonged moderate easterly winds.

In the first decade of July, a change in the wind direction to the north led to a strong thinning of the ice edge and its displacement to the south in the northern part of the area, which, with the subsequent turn of the wind in the second decade, contributed to the emergence of numerous eddies along the ice edge (figure 2(b)).

As a result, in July the ice edge north of 79.5° N practically retained its extreme northern position with a displacement range of more than 80 km. South of 79.5° N, its retreat continued, and fluctuations in the position of the ice boundary reached almost 200 km. The minimum width of the displacement zone in July took place at 76.4° N, 4.5° W (45 km) and 79.8° N, 3.75° E. (66 km) (figure 2(b)).

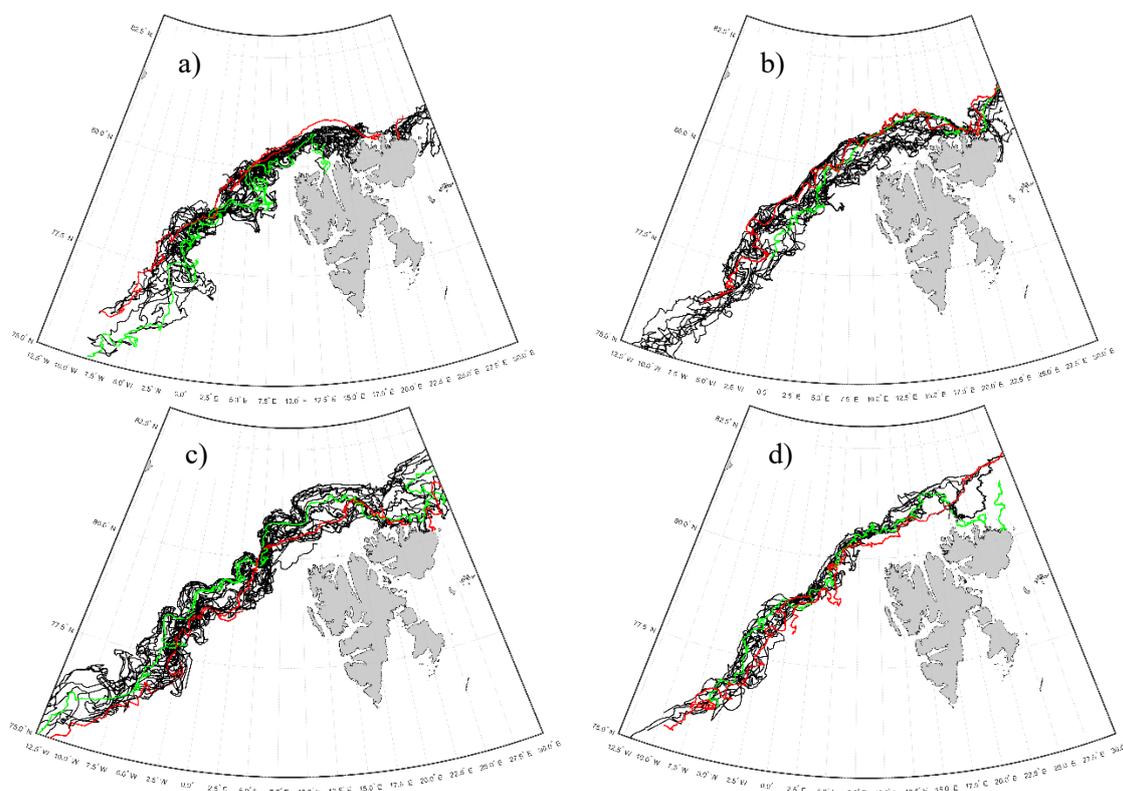


Figure 2. Same as in figure 1, but shown separately for every month:
(a) June, (b) July, (c) August, (d) September 2007.

The seasonal retreat of the ice distribution boundary, leading to an increase in the open water areas, occurred until the first days of August, after which the direction of the displacement was reversed (figure 2(c)). In early August, there was a pronounced undulating deformation of the ice edge, which was also noted in the previous months. The length of such wave-like motions, estimated from the distance between the crests, was 97 - 100 km. At the same time, the ice edge was significantly compacted due to southerly winds.

The region north of the Nordaustlandet Island (Svalbard archipelago) was completely ice-free in the first decade of August. But with northerly winds at the beginning of the third decade, the ice cover formed again close to the archipelago over shallow depths between 22.5° E and 27.4° E. In August, the ice edge displacement zone was about 135 km along its almost entire length with a minimum of 30 km at 79.9° N, 6.25° E (figure 2(c)).

In September, the largest displacements of the ice field boundary were noted in the southern part of the studied site, i.e., south of 79° N (figure 2(d)). The width of the ice displacement zone reached 90 km. North of 79° N, fluctuations of the ice edge occurred within 55 km. North of Svalbard, the ice edge retreat to the pole in September continued and amounted to more than 110 km. Ice "bulkhead" at 20° E completely disappeared by the end of the second decade of September 2007.

The displacement of the ice edge north of Svalbard is demonstrated in figure 3, which shows the variability of the distance between the ice field boundary and the three different points of the archipelago - the northern tip of the Amsterdam Island (79.78° N, 10.75° E), Cape Verlegenuken (80.06° N, 16.25° E) and Cape Platen (80.51° N, 22.79° E). As can be seen, the poleward retreat of the ice edge north of

Svalbard was interrupted twice during the summer period of 2007 - in the first decade of July and in the second decade of August. Yet, the ice cover formed again in the northeastern shelf of Svalbard.

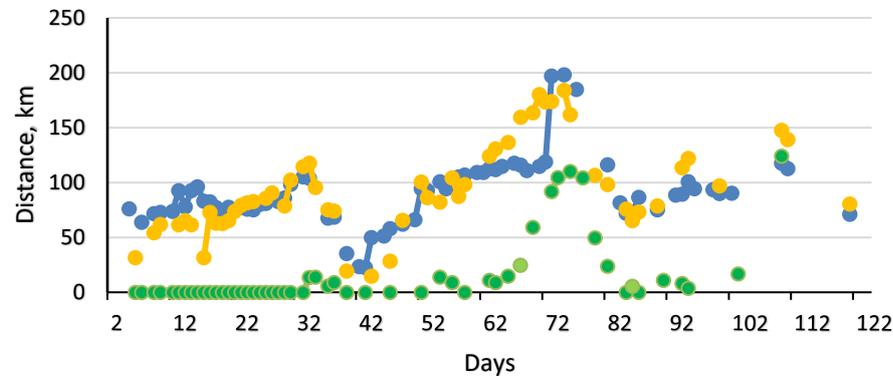


Figure 3. Distance (km) of the ice edge from selected points of the northern Svalbard: blue – from Amsterdam Island, yellow – from Cape Verlegenuken, green – from Cape Platen.

4. Generation of eddies in the marginal ice zone

Processing of 294 Envisat ASAR images served to identify more than 2000 eddy signatures in the marginal ice zone of Fram Strait and around Svalbard. Here, the formation of eddies could be due to a multitude of possible reasons - barotropic and baroclinic instability of an ice edge jet along the MIZ, topographic generation and trapping, interaction of AW eddies advected to the ice edge with meltwater fronts, wind-induced Ekman pumping along the ice edge, or their combinations [4, 5, 7, 9].

The spatial distribution of all identified eddies is shown in figure 4, where cyclonic structures are marked in blue, and anticyclonic ones are in red. The size of the marker in figure 4 is proportional to the real diameter of the eddy. As it was obtained, cyclonic eddies were dominant over anticyclones (78% vs 22%). As figure 4 shows, the spatial distribution of eddy diameters is different depending on the region. The mean diameter of eddies north of Svalbard is about 5 km, which is much smaller than in Fram Strait or over the shelf regions of the Greenland Sea, where it is about 10-20 km. This may be explained by the wind shadowing effects of the archipelago and smaller Rossby radii over the shelf regions of Svalbard [10].

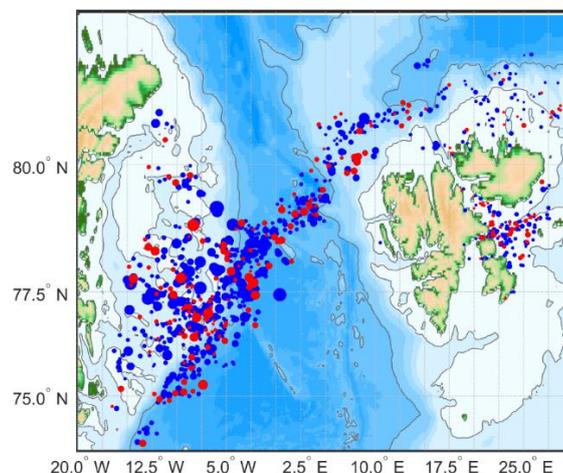


Figure 4. Spatial distribution of eddies detected in Envisat ASAR images over the marginal ice zone of Fram Strait and around Svalbard in July-September 2007.

In figure 5, the distribution of eddies observed per given summer month is combined with the initial and final positions of the ice boundary during particular month. In general, figure 5 demonstrates a good spatial correlation between the location of the ice edge boundary and the regions of eddy formation. One can clearly see that in July, the detected eddies prevail along the ice edge, while in August most of them are found inside the MIZ, i.e., over the Greenland Sea shelf northwest from the ice edge. In September, the number of eddies formed along the ice edge and within MIZ is nearly similar.

Eddies of larger diameters are mainly confined to the eastern shelf of the Greenland Sea with high number of eddies elongated along the shelf break. Most likely, the reason for their generation and development is the spread of the AW (the WSC recirculation branch at 78° N) following the topography features, which, in combination with wind action, leads to intense mixing and active eddy formation in the form of dipoles. Therefore, there is a high frequency of anticyclonic eddies in this area, while outside the shelf and marginal ice zones, the frequency of cyclonic eddies is usually much higher [2, 6, 8, 9]. Over the Molloy Basin, eddies of both signs of rotation are constantly generated at the periphery of the quasi-stationary gyre, and then are advected downstream by currents.

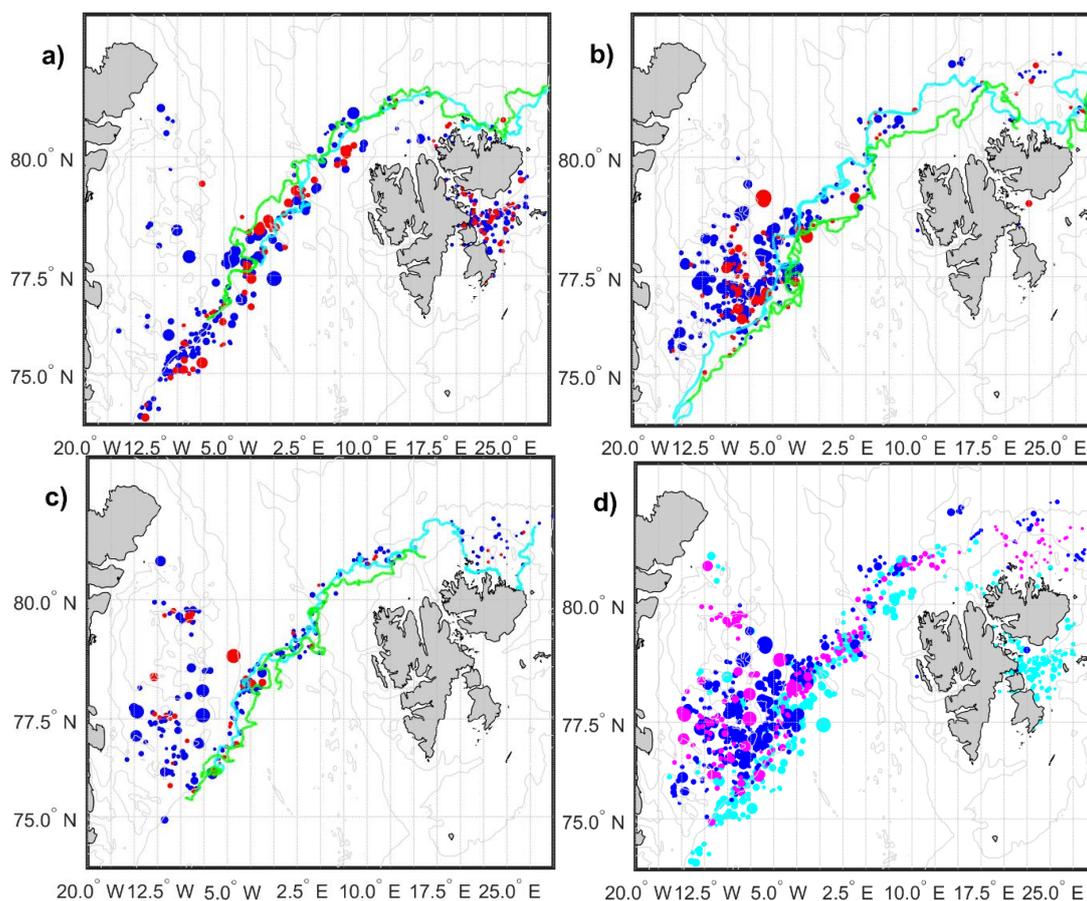


Figure 5. Locations of MIZ eddies and ice edge boundaries inferred from spaceborne SAR data for a) July, b) August, c) September, d) all three months. Cyan lines in a)-c) mark the position of MIZ in the beginning of particular month, while green ones stand for in the end of month. Different colors in d) mark eddies encountered in different months: cyan – in July, blue – in August, magenta – in September 2007.

The MIZ eddies observed in summer 2007 had a larger diameter in July and August (figure 5(a-b)). The ice edge at that time underwent significant deformation that resulted not only in active generation of eddies, but also in formation of well-developed ice filaments elongated towards the open water, as

is often reported in this region [3]. By the end of the summer season, the diameters of MIZ eddies became smaller, while the ice edge became leveled and compacted. In September, mixing processes on the eastern shelf of the Greenland Sea also weakened, having their peak in August.

Conclusions

Analysis of spaceborne SAR images over the marginal ice zone in Fram Strait and around Svalbard in summer 2007 allowed observing spatial and seasonal variability of the ice edge and the manifestation of a large number of eddies formed both at the ice edge and inside the MIZ.

The boundary of the ice edge has been found to move nonuniformly along its entire length. The seasonal retreat of the ice edge in Fram Strait occurred until early August. North of Svalbard, ice cover retreat and northward movement of ice-water boundary continued also in September. The overall width of the ice edge displacement during June-September 2007 ranged from 30 to 220 km.

For the study period, an intense process of eddy generation in the MIZ and along the ice edge has been documented. Altogether more than 2000 MIZ eddy signatures have been detected in July-September 2007 with cyclones having been detected more frequently. In July, the detected eddies prevailed along the ice edge, in August most of them were found inside the MIZ, while in September their number along the ice edge and within MIZ was similar. Larger eddies of 10-20 km in diameter were found over deep Fram Strait and the Greenland Sea shelf, while smaller eddies of ~5 km in diameter were found around Svalbard.

Acknowledgments

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