ENVISAT ASAR MONITORING OF POLYNYA PROCESSES AND SEA ICE PRODUCTION IN THE LAPTEV SEA

Christian Haas(1), Wolfgang Dierking(1), Thomas Busche(1), Jens Hoelemann(1)

(1)Alfred Wegener Institute, Bussestrasse 24, D-27570 Bremerhaven, Germany
Email: chaas@awi-bremerhaven.de

ABSTRACT

The Laptev Sea is one of the main source regions of sea ice in the Arctic Ocean. Most ice forms in winter in a prominent, quasi-permanent flaw lead or polynya (region of open water), separating landfast from drifting sea ice. In winter 2003/2004 we have deployed two seafloor moorings in the polynya, equipped with sensors to continuously observe ice, water, and sediment properties. In parallel, ENVISAT ASAR Wide Swath Mode (WSM) and high resolution Image Product (IMP) and Alternating Polarization Product (APP) scenes have been ordered to monitor sea ice processes and ice formation throughout the winter. Here we present a preliminary assessment of SAR and weather data. Numerous different features and ice formation and break-up processes characteristic for different stages of polynya and fast ice development are qualitatively identified and discussed. These affect both ice production and water mass modification as well as sediment inclusion and transport in the Laptev Sea.

1. INTRODUCTION

Sensible heat polynyas are regions of open water or thin ice where offshore winds remove sea ice downwind on the lee-side of a coast. As open water is repeatedly exposed to the cold air during winter, these polynyas are regions of extensive ice formation, and have thus major impacts on convection and water mass modification [1]. If the water is shallow, convection can eventually reach the seafloor, with major implication for sedimentation and sediment redistribution and incorporation into sea ice. The Laptev Sea is one of the most prominent recurring polynyas on the vast, shallow Siberian shelve, where major fractions of ice in the Transpolar Drift originate. In recognition of its importance, the polynya has been the subject of several Russian-German research projects in the framework of studies of the "Laptev Sea System" project [2]. In winter 2003/04, two seafloor observatories have been moored in the shallow water of the polynya. These profile salinity, temperature, and currents in the water column and observe ice thickness and drift. ENVISAT SAR imagery will provide complementary information on ice properties and processes at the surface to complete a most comprehensive data set. The immense value of combined SAR imagery and ice thickness data for polynya studies has been demonstrated by [3], who were able to validate a model of polynya width, and to quantify ice production.

Due to the remoteness of the Laptev Sea from any SAR receiving station, SAR images of the Laptev Sea have not been acquired with ERS. Reference [4] studied fast ice properties and processes in front of the Lena Delta and their interaction with river water by means of HH-polarized Radarsat ScanSAR Wide-B imagery. They already pointed out the heterogeneity of the fast ice zone.

However, the present study is the first SAR investigation of processes in the Laptev Sea polynya itself. As the Lena Delta is also mapped on most Wide Swath images, VV-polarization data are available to complement results obtained in [4]. Results will be used to quantify ice production, water mass conversion, and sediment accumulation and redistribution in the polynya, as well as to validate sea ice models and develop new algorithms for sea ice type classification in this region of the Arctic Ocean.

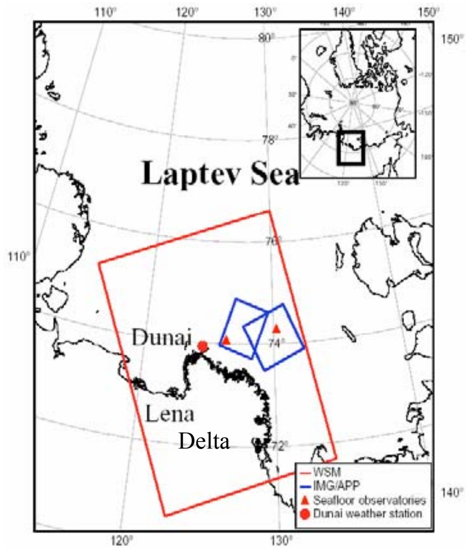

Fig. 1: Map of the southern Laptev Sea showing typical frames of WSM (red) and IMP/APP (blue) images. Red markers show positions of seafloor observatories and weather station.

2. DATA

For the period between October 2003 (freeze-up) and June 2004 we have ordered one or two ASAR Wide Swath Mode (WSM) and two Image Mode and Alternating Polarization (IMP/APP) images per week to cover the locations of our seafloor observatories. Both, images from ascending and descending orbits were acquired. Fig. 1 shows the typical coverage of SAR frames obtained once or twice per week. Unfortunately, only 60% of ordered WSM images and 30% of IMP/APP images were delivered so far (August 2004), and many of the scheduled IMP and APP scenes could not be acquired due to a lack of satellite ground-station visibility and communication capabilities in this remote area.
Images have been geocoded to the UTM projection. For presentation in this paper, they were not calibrated but enhanced using a Nyquist contrast enhancement to support their visual interpretation.
Interpretation of SAR images is also supported by operational wind, air temperature, and sea level pressure data obtained at a weather station on Dunai Island north of the Lena Delta, 50 and 180 km away from the seafloor observatories, respectively (Fig. 1). These data were provided by the Arctic and Antarctic Research Institute (AARI) in St. Petersburg, Russia, and are presented in Fig. 2. 3-hourly wind vectors have been averaged to represent daily means. Unfortunately, so far (August 2004) these data are only available until May 1, 2004.

3. RESULTS AND DISCUSSION

3.1 Temporal evolution of fast ice and the polynya derived from WSM images

Fig. 2 shows that air temperatures dropped below 0°C in the beginning of October 2003, and continued to decrease to temperatures below -30°C in the second half of November. Temperatures remained between -20°C and -40°C throughout the winter and rose only slowly in April 2004. Due to heat stored in the water column on the shallow shelf, freeze-up occurred only in the last third of October. The SAR image of June 2, 2004 (Fig. 3) indicates that melt has not fully started by early June, as backscatter differences in the fast ice zone are still visible and not obscured by wet snow possibly attenuating the radar waves.
Wind vectors reveal two main wind regimes (not shown here): A histogram of wind directions peaks at 90° (easterly winds). These prevailed in the second half of winter after January. The wind histogram has another mode between 180° and 230°, more characteristic for the early winter between October and January.
A SAR image of November 21 shows that a fast ice cover has established on the southern shelf (Fig. 3a). However, note that the fast ice is quite inhomogeneous, with a mixture of older first year ice and refrozen leads in between [4]. North of the Lena Delta, banded structures point towards some periods of ice production in the region of our westerly mooring in a small, recurrent polynya (see below).

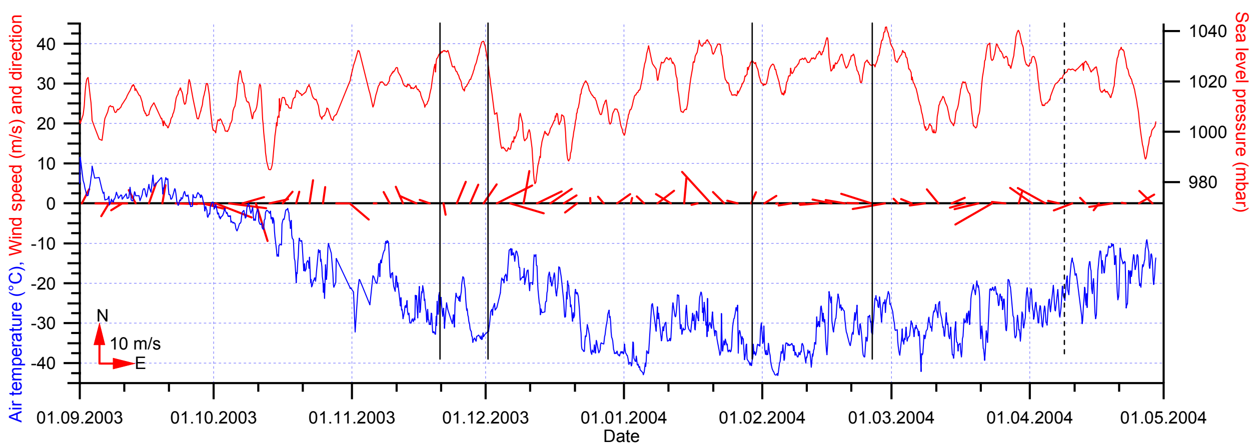

Fig. 2: Weather data obtained at Dunai Met Station until May 2004 (Courtesy Arctic and Antarctic Research Institute AARI, Russia; Location see map in Fig. 1). Daily wind vectors point to the direction of air flow. Black vertical bars show times of SAR data acquisition (cf. Fig. 3 and 4).

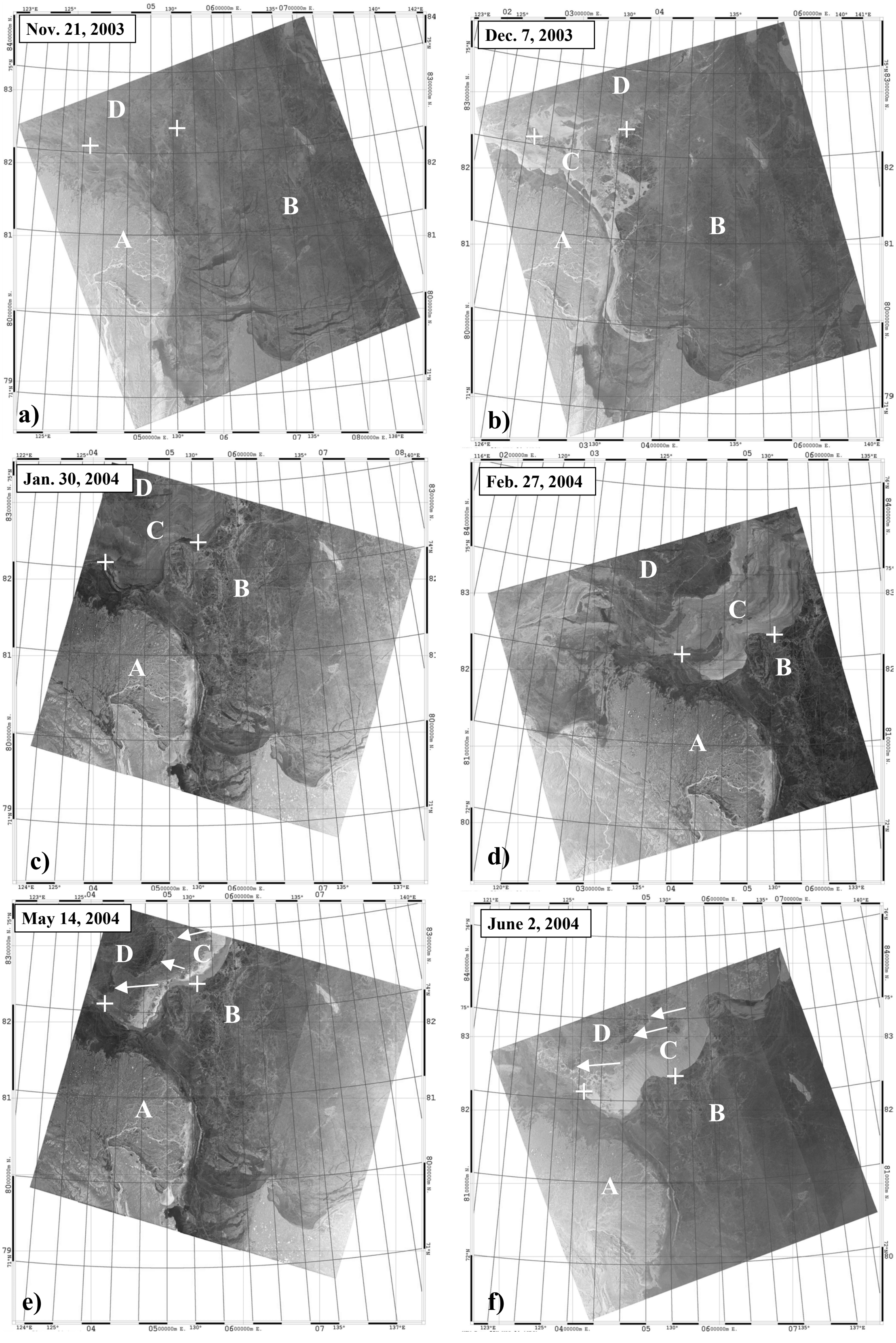

Fig. 3: Time series of ASAR-VV WSM images between Nov. 2003 and June 2004. Cf. Fig. 2 for weather conditions. White crosses indicate location of seafloor observatories. (A) Lena Delta; (B) Fast ice; (C) Polynya; (D) Drift ice. Arrows in (e) and (f) point to identical ice floes visible in both images.

Strong and persistent southerly winds between November 21 and December 7 lead to a partial breakup of the fast ice and northward advection of ice. Large areas of open water with a wind-roughened surface are visible all around the Lena Delta (Fig. 3b). This event shows that a stable fast ice cover did not develop before the middle of December. Such midwinter fast ice break-up events are likely to have major impacts on the sea-ice entrainment and transport of sediments from the shallow shelf waters into the Arctic pack ice, as was also reported by [5] for the East Siberian Sea.
The SAR image of January 30 (Fig. 3c) shows that the fast ice cover is finally fully developed, but that the earlier break-up events have left it very inhomogeneous. The fast ice edge in the North closely follows the seafloor bathymetry, roughly representing the 20 m depth contour. It should be noted that the fast ice cover is supported by shallow banks where the ice is actually grounded. The most prominent bank can be seen by an elliptical structure southwest of our eastern mooring. There, the ice was already immobile when the surrounding ice still drifted northward around it. Off the fast ice edge, a large banded sea ice zone indicates continued ice production in the polynya and northward transport, consistent with southerly winds. However, low backscatter and the texture in the polynya together with very low air temperatures of around -30°C point to the presence of smooth, dark nilas and the absence of any larger areas of open water.
On February 27, the SAR image is typical for most of the midwinter data (Fig. 3d), with persistent easterly winds (Fig. 2). A bright, banded zone of new ice formed in the polynya can be seen, each band indicative of different stages of development and ice thicknesses. Over our western mooring, some darker, older ice broken off the fast ice is incorporated into the brighter new ice. In fact, this is probably due to the existence of a larger open water polynya along the fast ice edge also visible in AMSR-E and MODIS imagery, allowing the development of waves and swell to break up the adjacent marginal fast ice. Bright new ice signatures might be due to frost flowers or rafted and deformed nilas and young ice. In contrast, older ice further north is probably snow covered, and backscatter could be reduced due to flooding or brine wicking into the snow, or due to a lack of small- and large scale deformation.
The situation in the polynya hardly changes until early April (Fig. 4), with persistent ice formation and export due to easterly winds. It should be noted that there is mostly very little open water, which might not be surprising given the generally very low air temperatures and moderate wind speeds.
Our data set is still very discontinuous in May and June. On May 14, appearance of the polynya region is quite different (Fig. 3e). There is not so much banding visible any more, and single ice floes can be outlined in the polynya. While the very bright features most likely represent open water, sequences of images showed some deformation events when the new ice was pressed against the fast ice edge under northerly winds. This leads to strongly deformed ice with a rough surface, responsible for bright SAR signatures as well (see also Fig. 4).
After May 20 (not shown here), a large polynya opened with mostly open water. The June 2 SAR image shows that there is no banding visible any more, and instead the polynya region is very heterogeneous with ice floes of different surface characteristics (Fig. 3f). Note that some of the dark, northernmost ice is still identical to the ice visible in the May 14 image (Arrows in Fig. 3e&f). On the open water, wind streaks are visible which might be related to large scale Langmuir circulation. Comparison with our mooring data will reveal if these events can penetrate through the pycnocline and can affect processes at the seafloor or if they only modify the surface mixed layer [2].

3.2 VV and HH dual-polarization

To obtain the highest possible spatial information as well as more quantitative data on ice conditions above our seafloor moorings, we ordered IMP and APP data over those two locations every three to four days. In addition to backscatter variations visible in single polarization data, VV and HH dual polarization imagery reveals additional information on the occurrence of open water and ice surface roughness.
Fig. 4 shows an example of VV- and HH-Pol images obtained on April 2, 2004, and the resulting difference image. Again, both VV and HH images reveal the typical banded appearance of the new ice generated in the polynya, with darker, probably snow covered ice in the North. There is a very bright band between the banded zone and the darker ice close to the fast ice edge. This has been generated during a deformation event a few days earlier when winds came from northerly directions. The ice adjacent to the fast ice edge appears very dark, except for a very narrow band of high backscatter. Except for this bright band, open water seems not to be occurring in the image.
The polarization difference image reveals no major differences between any of the small scale structures close to the fast ice edge, except for the very narrow bright band, which is also bright on the difference image. This points to the occurrence of open water in this narrow band. However, the signatures of the remaining thin ice are very similar at VV and HH polarization, pointing to a rough surface. Further investigations are required once all images have been retrieved to enable tracking of some features and observation of their temporal development.

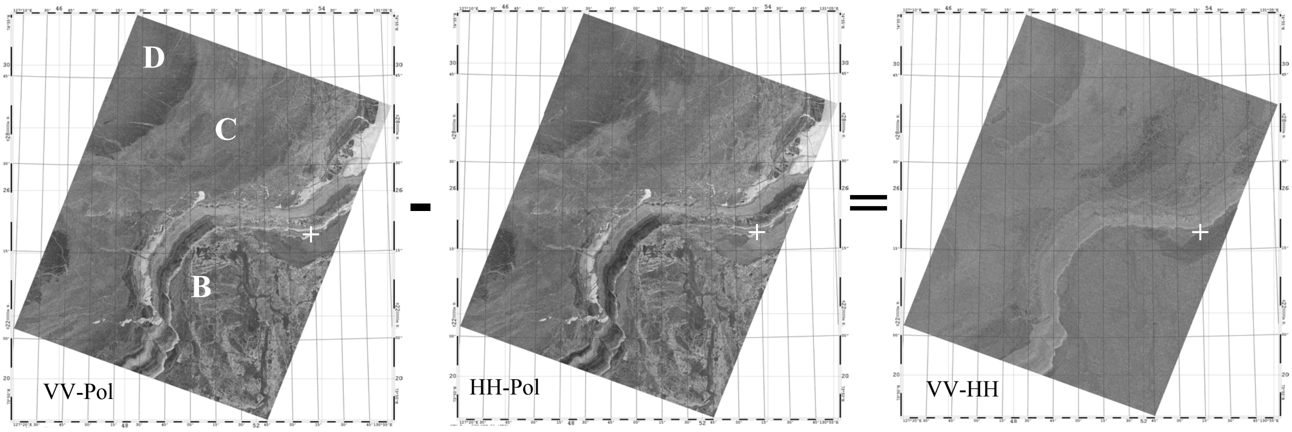

Fig. 4: ASAR APP-VV, -HH, and difference image of April 2 over easterly mooring (cf. Figs. 1&3). White crosses indicate location of seafloor observatories. (B) Bottom-fast ice; (C) Polynya; (D) Drift ice.

4. CONCLUSIONS AND OUTLOOK

We have presented a first assessment of ENVISAT WSM and IMP/APP SAR imagery obtained from the Laptev Sea throughout the sea ice season in 2003/2004. These provide detailed insights into ice formation and break-up processes and developmental stages of the fast ice zone, in the polynya, as well as in the drifting pack ice further north. These processes affect sediment entrainment and transport [5] as well as water mass modifications in the area of the Laptev Sea polynya [2]. Images show how rapidly ice conditions change in response to varying wind conditions, demonstrating the importance of a high temporal resolution in monitoring polynya processes. Our imagery also provides a wealth of information on other features like lake and near-shore fast ice, which is complementary to data from Radarsat SAR presented by [4]. Seafloor observatories will be recovered in mid September 2004. Afterwards, we will investigate the combined data set of water temperature, salinity, currents, and sea ice draft and drift, together with the SAR imagery [3]. Here, the high resolution IMP and APP data will be of particular importance in identifying ice conditions in the polynya. Interpretation of open water signatures will be supported by passive microwave (AMSR-E) and visible/near-infrared (MODIS/AVHRR) imagery. However, a complete analysis can only be performed after we have received the majority of SAR images, hopefully by the end of 2004.

5. ACKNOWLEDGEMENTS

SAR imagery was obtained from ESA through EO500: “Formation, Transport and Distribution of Sediment-laden Sea Ice in the Arctic Shelf Seas”. We thank Peter Schütte for help with image processing. Weather data was kindly provided by Arctic and Antarctic research Institute AARI, St. Petersburg, Russia. SAR studies are funded by Alfred Wegener Institutes MarcoPolI research program (POL 1&3).

6. REFERENCES

1. Morales Maqueda, M.A., A.J. Willmott, and N.R.T. Biggs, Polynya dynamics: A review of observations and modelling, *Rev. Geophys.*, 42, doi:2002RG000116, 2004.
2. Dmitrenko, I., J.A. Hoelemann, K. Tyshko, V. Churun, S. Kirilov, and H. Kassens, The Laptev Sea flaw polynya, Russian Arctic: effects on the mesoscale hydrography, *Ann. Glaciol*., 33, 373-376, 2001.
3. Drucker, R., S. Martin, R. Moritz, Observations of ice thickness and frazil ice in the St. Lawrence Island polynya from satellite imagery, upward looking sonar, and salinity/temperature moorings, *J. Geophys. Res.*, 108(C5), 3149, doi:10.1029/2001JC001213, 2003.
4. Eicken, H., I. Dmitrenko, K. Tyshko, A. Darovskikh, W. Dierking, U. Blahak, J. Groves, H. Kassens , Zonation of the Laptev Sea landfast ice cover and its importance in a frozen estuary, *Global Planet. Change*, in press.
5. Eicken, H., J. Kolatschek, J. Freitag, F. Lindemann, H. Kassens, and I. Dmitrenko, A key source area and constraints on entrainment for basin-scale transport by Arctic sea ice, *Geophys. Res. Lett.,* 27(13), 1919-1922, 2000.