Study of fast ice in the Pechora and Kara Sea coastal region
Plan for work in AMETHYST project
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by
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1. Introduction

Fast ice forms during autumn freeze-up in the bays and along the coast. The nilas and young coastal ice is the initial form of fast ice. Fast ice form in the shallow areas with indented coastline. Near the strait coasts fast ice is characterized with lesser width. Maximum development of fast ice is observed in shallow waters, with depth up to 20-25 m. At steep coastlines with deeper waters, the fast ice belt is narrow or absent. The fast ice of the arctic seas are formed in the autumn. Sometimes fast ice can persist during the summer and become two-year or multi-year fast ice. In regions of Franz Josef Land, Spitsbergen, and the East Siberian Sea, two-year old fast ice may be found.

In the north-eastern part of the Kara Sea the fast ice covers vast areas, forming a continous area over hundreds of km wide, stretching from Belyi Island via Nordenskjold archipelago to the Severnaya Zemlya coast. During summer break-up it disintegrate into single ice floes, forming the base of Severozemelsky ice massif (Kupetsky, 1970). Fast ice also forms in several Severnaya Zemlya straits; the Vilkitski Strait, the Shokalski Strait, and the Red Army Strait.

In the southwestern part of the Kara Sea the fast ice forms in the end of December and its external boundary is limited by the 10-15 m isobath (Borodachev, 1998). At the coast near Amderma fast ice is often fractured. In some years the stable fast ice is not observed here at all in the winter season. Near the Yamal coast the fracturing of fast ice occurs rarely and only in the period of early ice formation (Bondarev et al., 1995). During winter a narrow stripe of fast ice, also covering the bays, forms along the eastern coast of Novaya Zemlya.

Polynyas are open areas along the coasts (shore polynya) or between the fast ice along the coast and the drifting ice (flaw polynya). If it recurs in the same position every year, it is called recurring polynya. These are often created by strong offshore winds. As the ice is blown away from the coast, open water is exposed and refrozen, so that these polynyas provide a source of ice production (Martin et al., 1992). Polynyas may be covered with new ice, nilas, or young ice, and/or they contain brash ice (WMO Sea Ice Nomenclature, 1970), and are important for heat transfer in winter (Andreas and Cash, 1999). Around the Kara Gate and along the Yamal Peninsula are areas where polynyas are found during winter and they are also important for navigation in the winter (Proshutinsky, 1999).

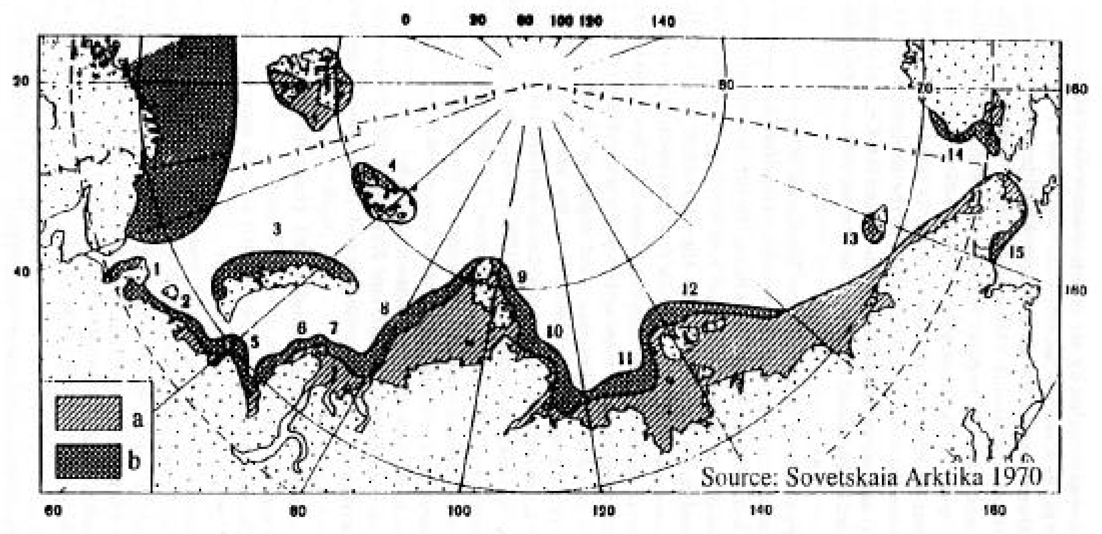


Figure 1. Map of fast ice (a) and polynyas (b) in the Russian Arctic. The main polynyas are named as follows: 1 Cheshskaya, 2 Pechorskaya, 5 Amderminskaya, 6 Yamalskaya, and 7 Ob'-Eniseyskaya. (From Proshutinsky *et al*., 1999.)

The surface of fast ice varies from level to rather rough. Its salinity depends on the area. Near the mouths of Ob, Yenisey, and other rivers it is less than in other regions. Radar signatures depend mainly on surface roughness and therefore one of the tasks could be retrieval of surface roughness from calibrated ERS-SAR images. In coastal areas of 1.5–2 m depth, fast ice can be frozen to the sea bottom and its SAR signature could be quite different from floating fast ice. This phenomenon could also be studied from calibrated SAR images. The boundary between these parts of fast ice are often characterized by occurrence of tidal ice cracks. Probably small motions and displacements of fast ice can be studied by INSAR.

The fast ice boundary can be determined from analysis of successive SAR images and probably by using radar interferometry. Influence of the fast ice on ice drift velocity near its boundary can be studied using successive SAR images. In several places shore ice ride-up can take place. Such areas should be evident with high brightness due to high surface roughness and therefore could be identified from SAR images. In some cases areas with shore ice ride-up could reach tens of meters or even more. By using high-resolution SAR it would be possible to estimate widths and areas of such zones. Near the mouths of Ob and Yenisey we can investigate the dependence between fast ice distribution (boundary) and river outflow (if the data on river outflow will be available).

The processes of fast ice destruction could also be investigated by analysis of series of SAR images. Probably in the very early stage of destruction radar interferometry data could be used to determine the start of this process. Later, this process could be investigated by means of determining ice drift vectors from successive SAR images. Near the mouths of Siberian rivers flooding of fast ice with river water take place after spring break-up. SAR signatures of such areas should be quite different from unflooded fast ice areas and therefore this phenomenon could be investigated with SAR images.

One of the interesting results of fast ice investigations could be determination of fast ice boundary and width in different parts of the Kara Sea. Physical explanation of the dependence of fast ice boundary on the meteorological conditions, river outflow, bottom bathymetry, and some other factors will be quite valuable. For example, the dependence of fast ice distribution in the eastern Kara Sea on winds in the fall have been investigated in previous research.

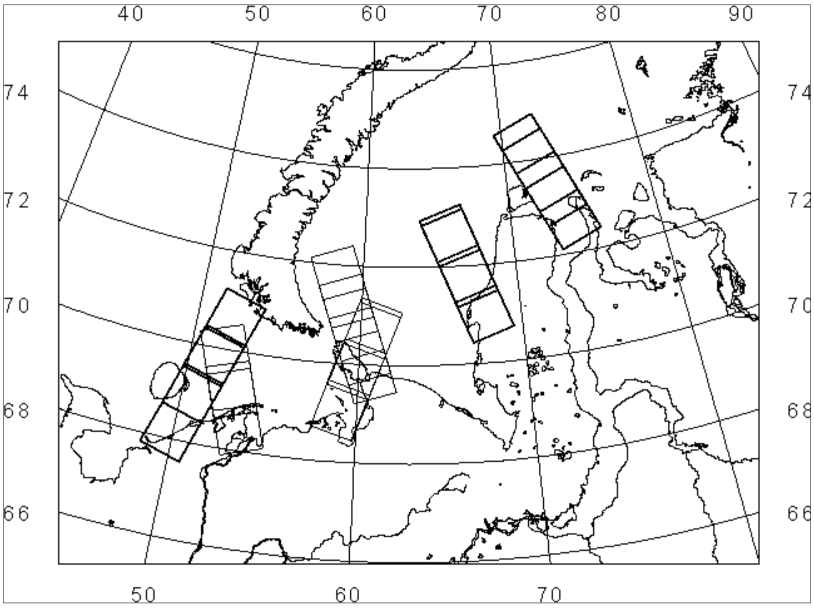


Figure 2. In the NERSC database for March 1994 are 137 ERS-1 SAR images for the Kara and Pechora Sea area. The good coverage and many near-coincident scenes are due to the satellite's 3 day repeat 'Ice orbit' in January-March 1994. This makes it possible to compute ice displacement at different locations throughout the month.

2. Outline of coastal sea ice study by satellite SAR images

At NERSC, an archive of nearly 5000 scenes from 1992 to date exists. Of these, over 50% are in the Pechora and Kara Sea. Many of these show fast ice in the areas of interest, both in the formation phase and the destruction phase. Also the flaw polynya, as well as recurring polynyas and various leads associated with the fast ice can be mapped. The development of these features both intra- and inter-anually can be studied. The coverage in space and time is variable, but the coverage is especially good between the autumn of 1993 and the spring of 1998 along the Nothern Sea Route in connection with the ICEWATCH program (Johannessen et al., 2000).

In addition to the feature-mapping using geographically corrected images, a study of the backscatter of the features, its dependence on various parameters and its changes with time, can be made using sigma-zero calibrated images. For PRI the accuracy is better than about ±0.3dB using the calibration procedure developed by ESA (Meadows, 1998), while for for LRI the accuracy it is about ±1dB (TSS, Tromsø, personal comm.).

Two successive ERS-1 SAR images were the same ice field is present can be used for computation of ice displacement vectors. The number and quality of the displacement vectors depend on spatial coverage, and on the stability of ice features, which alter the probability of recognition. Large individual ice floes give best probability, while features in first year ice tend to change quickly as the wind varies. It is therefore often more difficult to estimate ice motion in first-year ice than in multi-year ice.

Most images used have time interval of a period of three days. An automatic algorithm for estimation of ice displacement by correlation of two images is used (Sandven et al., 1991). The displacement vectors from the automatic algorithm are filtered by a correlation threshold. They are also quality-controlled by comparing them to manually derived vectors.

Examples of sea ice displacement vectors overlaid the images from the period 3 to 18 March 1994 are shown in Fig. 3. This image series shows the development of the polynya near Vaygach Island during the first half of March 1994.

Fast ice formation can be studied by analysis of series of successive images, covering the area under study from the beginning of freeze-up to stable winter conditions. To illustrate the formation of fast ice during the freezing period and its variability through the winter season, a time series of SAR images from the Varandey coast in the eastern Pechora Sea is shown in Fig. 4. In November and December during the initial freezing the fast ice has not formed a stable pattern. From January to March the same fast ice patterns can be found. After formation of the stable fast ice it is possible to study changes of radar signatures during winter as a function of ice thickness and snow depth from ERS SAR PRI images.

Examples of ice drift analysis from SAR images are shown in Fig. 3. Where the mean ice displacements over the 3 days intervals are: 3-6 March: 5.5 cm/s, 6-9 March: 12.6 cm/s, 9-12 March: 3.0 cm/s, 12-15 March: 4.4 cm/s, 15-18 March: 5.6 cm/s.

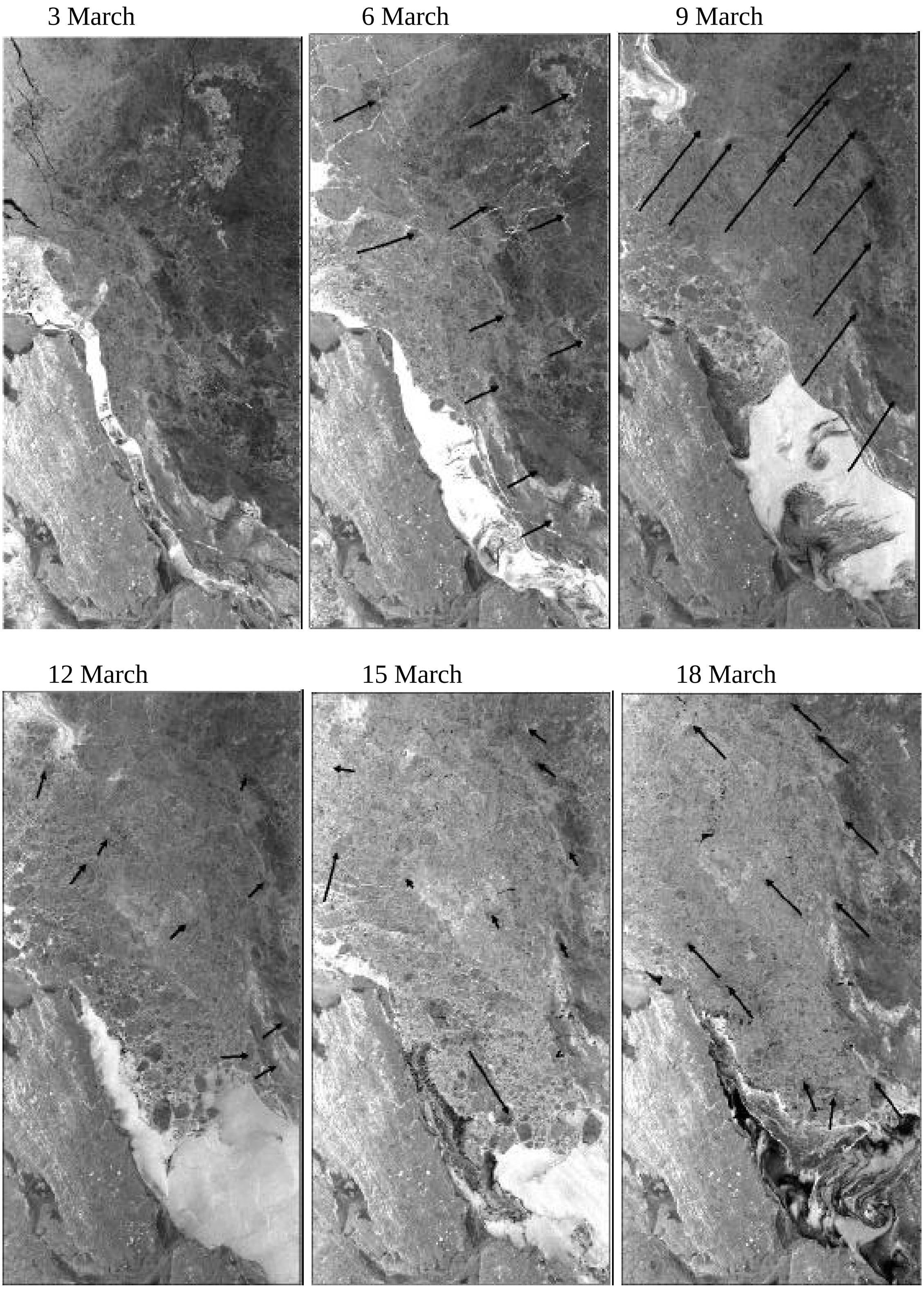
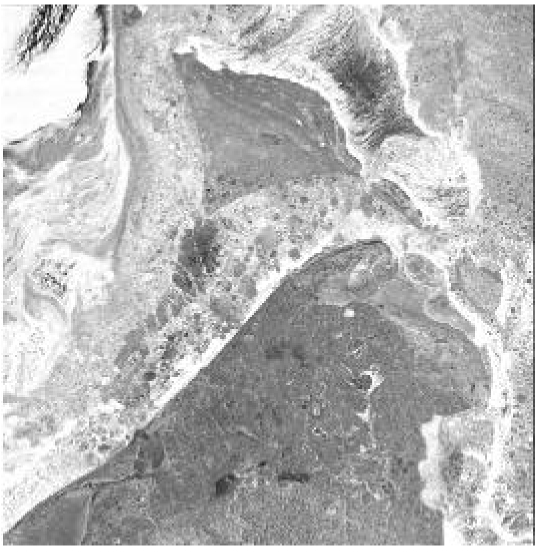
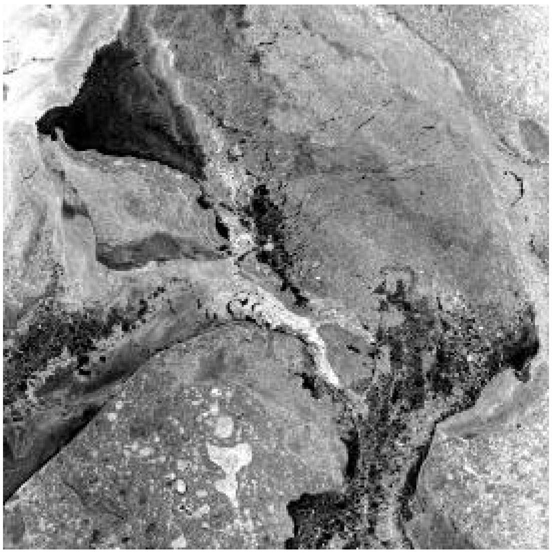


Figure 3. Ice displacement near Vaygach Island from ERS-1 SAR images. Original Data © ESA/TSS 1994. Image Processing NERSC.

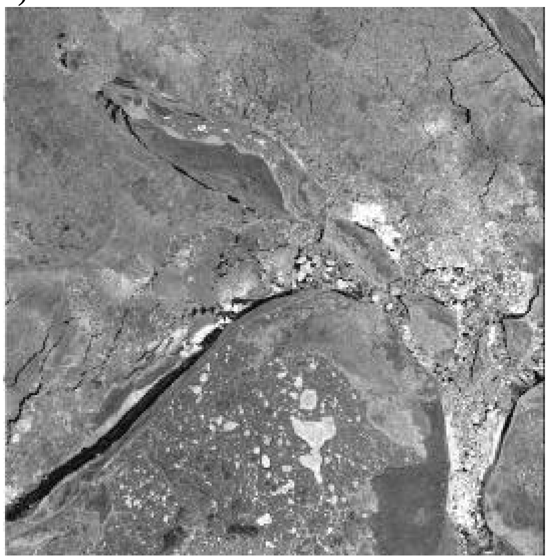


a)



b)

c)



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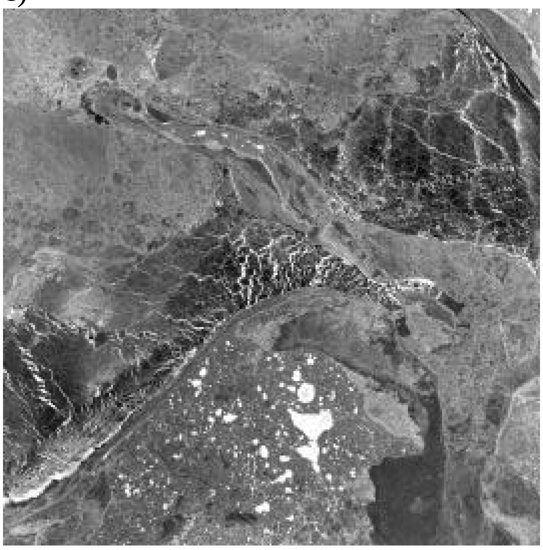

e)

Figure 4. Fast ice signatures along the land boundaries in the Pechora Sea during a winter season. (a: 19.11.1993, b: 05.12.1993, c: 05.01.1994, d: 29.01.1994, e: 21.03.1994.) Original Data © ESA/TSS 1993/1994. Image Processing NERSC

3. Methods and data sets to be used in the project

ERS archive of LRI/PRI SAR
Extensive archive of ERS-1/2 SAR images (high and low resolution) covering coastal areas in the Pechora and Kara Sea. Best spatial and time coverage from 1993 to 1998.

ERS INSAR SLCI pairs for interferometry
In the ERS-1/2 tandem period, 11 scene pairs between October 1995 and March 1996 have been acquired within the ESA AO3-417 project. In addition comes one 3-day ERS-1 repeat of 22–25 February 1994 over Franz Josef Land. Most scene pairs contain some areas with glaciers (on Novaya Zemlya, Severnay Zemlya and Franz Josef Land), but the majority also contain some areas of fast ice, see Fig. 5. A few pairs cover the Pechora Sea coast (Varanday) and the Bayadaskhara Guba coast, areas where fast ice and pack ice are imaged.

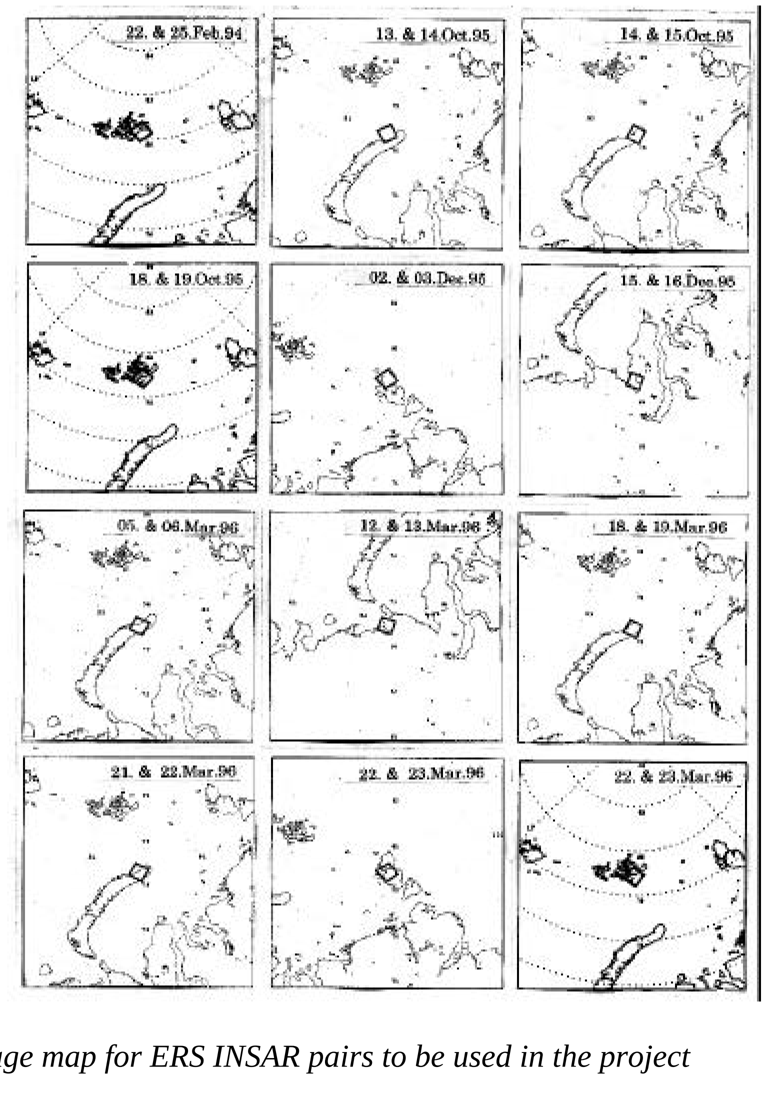

Figure 5. Coverage map for ERS INSAR pairs to be used in the project

RADARSAT data
The main improvement of RADARSAT data in ice monitoring is that high resolution SAR images are available over much larger areas, and with more frequently observation interval, than was possible with other satellite systems such as ERS-1/2. A few scenes of ScanSAR data in WeRA has already been acquired in 1998, but their resolution and temporal coverage is too coarse to to do very detailed fast ice studies. However, in an approved project for ice studies, a number of scenes from the Alaska SAR Facility archive is expected be available at

NERSC in the near future. Here, fine resolution scenes can also be expected. The amount and coverage of these scenes are not yet clear.

Meteorological data from NCEP

Temperature and wind information from the global NCEP reanalyses data will be used together with the SAR data to investigate selected polynya and fast ice areas in the Pechora and Kara Sea region.

Analysis methods

Fastice is an important part of the WeRA coastline in the cold season, and its mapping along with other coastal features should be made over at least one ice season. The ice season starts with the formation in the fall, its development through the winter and spring including formation of stamukhi. Finally the fastice melts and moves away into opena water in the summer.

For the selected test sites of WeRA, the fastice is to be mapped and analysed through one winter season where we have the best data coverage. For this mapping, already available archived high-resolution SAR PRI and also INSAR imagery is used.

Aerial extent and development through the year will be identified from the SAR images by classification of areas of both fastice and polynya areas. Ice displacement in response to atmospheric forcing will be studied using the ice kinematics algorithm (Sandven et al., 1991). Classification of ice types will be performed to identify various stages in the formation of young and firstyear ice and process studies in the fast- and drifting ice will be carried out to describe the behaviour of this ice during a winter season (Sandven et al., 1999; Alexandrov et al., 2000).

The proposed work will be done with the following methods:

1) A number of fall, winter and spring PRI scenes 1993 –98 is selected from the current extensive archive at NERSC. One winter season, 1993 - 1994, with most optimal data coverage will be prioritized.
2) Additionally, about 10 tandem SLC scene pairs Oct.95 –Mar.96 with interesting areas of fast ice are also selected. Also a single ERS-1 SLC scene pair of FJL 22. –25-Feb.94 is selected.
3) Selected PRI scenes will be analysed using ER-MAPPER at NERSC. For each scene, wind-data from the NCEP database is obtained, to aid in the segmentation and subsequent analysis of ice dynamics and ice types.
4) For the selected areas, drawing of the outer boundary of the Fast-ice is made. This is based on inspection of the texture of backscatter in shallow-water areas (to depth of approx. 30 -40m) and outward from steep coastlines. Detection of the boundary as a Flaw-lead (in offshore wind) or as a Flaw (in onshore wind) is made where possible. Often, a grounded pressure ridge will mark the outer boundary of this ice.
5) Inspection is made for Tide-cracks, Ridges, Rubble-fields, Stamukhi, etc. These features are marked on the map with appropriate symbols.

The INSAR scenes are processed with appropriate software. Images are expected to show generally good correlation with clear fringes in the fast ice areas. In the areas with sufficient high correlation, the small fast ice movements due to tides and temperature change are computed and analysed. Using INSAR, very detailed analysis of the motion of fastice is possible, as shown in the Bay of Bothnia (Dammert et al., 1998).

The PRI based analysis and mapping is made with 30 m spatial resolution (12.5m pixels) in the selected areas within each scene. Since these images have low radiometric resolution (3-looks), filtering of the data (e.g. low-pass, Lee-filter) is made when found necessary. Fast ice studies will be made jointly by NERSC and NIERSC.

4. Ice terms (from WMO Sea-ice nomenclature 1970)

Fastice is sea-ice which forms and remains fast along the coast, attached to the shore, to an **ice-wall** (=seaward glacier margin not afloat), to an **ice-front** (= floating glacier-margin or ice-shelf), to shoals, or to grounded icebergs.

Flaw is the separation between pack-ice and fast-ice in cases of shear between the ice-types. It is narrow, usually filled with chaotic ice pieces.

Flaw-lead is a wider zone between the pack-ice and fast-ice. It may contain brash-ice (=small ice pieces) or thin ice types. Non-linear openings are called Flaw-polynyas.

Tide-crack is a **fracture** (= rupture from deformation process), between an immovable **ice-foot** (= narrow coastal ice fringe not moved by tides) or ice-wall, and the movable fast-ice.

Ridge is ice forced upward by pressure in shape of long hills. In case of short hill it is called **hummock**. The **ice-keels** (= downward part) of the ridges or hummocks in fast-ice may often be grounded. An area with many smaller ridges or hummocks is called a **rubble-field**.

Stamukhi is the (Russian) name of the remains of a grounded ridge or hummock after the fast ice around has melted in late spring.

References

Alexandrov, V. Yu., S. Sandven, O. M. Johannessen, Ø. Dalen and L. H. Pettersson. Winter navigation in the Northern Sea Route. Polar Record, Vol. 36 (199), 333-342, 2000.

Andreas E. L. and Cash, B. A. (1999). “Convective heat transfer over wintertime leads and polynyas”, *Journal of Geophysical Research*, Vol. 104, No. C11, pp. 25721-25734.

Bondarev, V.N., N.V. Golovin, O.N. Mayorov, S.I. Rokos. (1995). Baydaratskaya Bay ice cover and necessity of its accounting during marine hydrotechnical construction – *In POAC’95*, August15-18, Murmansk, Vol. 3, pp.180-186.

Borodachev, V.E. (1998). Ldy Karskogo morya (Sea ice of the Kara Sea), Edited by V.A. Volkov, St. Petersburg, Gidrometeoizdat.

Dammert, P. B. G., Lepparanta, M., and Askne, J. (1998). “SAR interferometry over Baltic Sea ice”, *International Journal of Remote Sensing*, Vol. 19, No. 16, pp. 3019 –3037.

Johannessen, O. M., and others. (2000). “ICEWATCH: Real-Time Sea-Ice Monitoring in the Northern Sea Route (a Cooperative Earth Observation Project Between the Russian and the European Space Agencies)”, *Earth Observation and Remote Sensing*, Vol. 16, No. 2, pp. 269-281.

Kupetsky, V.N. (1970). The ice cover, In: Soviet Arctic (Seas and islands of the Arctic Ocean), Nauka, Moscow, pp. 200-214.

Martin, S. et al. (1992). “Microwave remote sensing of polynyas”, in Microwave Remote Sensing of Sea Ice, ed. F. D. Carsey, Geophysical Monograph 68, American Geophysical Union, Washington, pp. 73-104.

Meadows, P. J., Laur, H., Sanchez, J. I., and Schattler, B. (1998) “The ERS SAR performance”. *Proc. of CEOS SAR Workshop in February 1998*. ESA WPP-138.

Proshutinsky, A. Yu., Proshutinsky, T., and Weingartner, T. (1999). “I.5.8 Environmental Conditions Affecting Commercial Shipping on the Northern Sea Route”, *INSROP Working Paper No. 126*, ISBN 82-7613-296-0, 52 pp.

Sandven, S., Kloster, K., and Johannessen, O. M. (1991). SAR ice algorithms for ice edge, ice concentration and ice kinematics. *NERSC Technical Report No. 38*.

Sandven, S, O. M. Johannessen, Martin Miles, Lasse H. Pettersson and K. Kloster. Barents Sea seasonal ice zone features and processes from ERS-1 SAR. J. Geophys. Res. Vol. 104, No. C7, p. 15843 – 15857, July 15, 1999.

World Meteorological Organization. (1970). “WMO Sea-Ice Nomenclature”, Secretariat of the World Meteorological Organization Publication No. 259. Tp. 145, Geneva, Switzerland.