

SAR Measurement of Sea Ice Parameters: Sea Ice Session Overview Paper

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ABSTRACT

The SAR sea ice community consists of operational users, radar and computer engineers who perform sensor verification and algorithm development, and climate scientists who want to use changes in sea ice characteristics to quantify climate change. The SAR sensors on board the RADARSAT and Envisat satellite systems are providing the sea ice community with several gigabytes/day in data. Algorithms have been created and validated to automatically locate the ice edge. The RADARSAT geophysical processor system has produced a multiyear record of arctic sea ice motion, sea ice deformation, and new ice formation. Uncertainties still exist in totally automated sea ice classification particularly for the new ice, young ice, and first year ice categories. The multi-frequency and multi-polarization SAR data obtainable from a combination of Envisat, RADARSAT 2, and ALOS (and other SAR sensors) can potentially be used to aid in differentiating the thin ice types.

1. INTRODUCTION

Sea ice mapping has been significantly improved during the last decade by the introduction of high-resolution synthetic aperture radar (SAR). Operational sea ice monitoring as performed by the United States National Ice Center (NIC), Canadian Ice Service (CIS), and various commercial and government ice centers in Finland, Sweden, Denmark, Norway, Germany, and Russia requires daily information about ice edge, ice concentration (fractional area coverage), ice type (new ice, young ice, first year, multi-year), ice thickness, ice deformations (ridges) and ice dynamics (drift). Additionally, the various ice centers require information on lake and river ice as well as iceberg locations. Operational sea ice monitoring has traditionally been based on NOAA AVHRR visual and thermal infrared radiometer and SSM/I passive microwave data. With the advent of all-weather wide-swath SAR data from RADARSAT-1 and Envisat, ice monitoring can be performed with higher resolution and better quality.

In addition to providing sea ice information for operational activities such as ship routing, military operations, offshore oil and gas drilling, and fishing

fleet support, SAR data can also play a significant role in polar and climate change monitoring. High-resolution SAR can potentially provide velocity fields, convergence/divergence fields, ice volume fluxes, vertical heat fluxes, brine rejection from the freezing ice, and onset of the melt season, all parameters that are very important in respect to understanding the response of sea ice to climate change.

In this overview paper we summarize both the operational and climate change research uses of SAR for sea ice parameter detection. The uncertainties and future direction for research in respect to extraction of SAR derived sea ice parameters is also presented.

Five focused technical papers provide additional details to the summary statements provided in this overview paper. Three papers (see Table 1) address operational uses of SAR, one addresses automated detection of the sea ice edge from SAR data, while the remaining paper discusses the use of SAR sea ice data starting with the Seasat SAR for studying climate change in the polar region as well as the algorithms used in those studies. In addition to the listed papers, the reader is referred to a paper entitled "Ocean Observer Study: A Proposed National Asset to Augment the Future U.S. Operational Satellite System." This paper [1] suggests a SAR instrument be added to the present suite of sensors that are being flown on NPOESS.

2. OPERATIONAL USE OF SAR TO MONITOR SEA ICE, ICEBERGS, LAKE AND RIVER ICE

The Canadian Ice Service (CIS), the U.S. National Ice Center (NIC), and various European countries utilize SAR as an integral part of their ice forecast efforts. The first three technical papers listed in Table 1 summarize the operational use including issues pertaining to requirements, SAR data requests, data capture, near-real-time processing, ice parameter extraction from the SAR data, and integration of the information into a focused data product.

The summary of the Canadian Ice Service ("Operational Use of SAR at the Canadian Ice Service: Present Operations and a Look to the Future," by Dean Flett) is a comprehensive paper that captures the

Table 1. Focused papers that address the use of SAR for sea ice detection

Title	Author(s)	Subject
Operational Use of SAR at the Canadian Ice Service: Present Operations and a Look to the Future	Dean G. Flett	Operational sea ice monitoring
Routine Production of SAR-Derived Ice and Ocean Products in the United States	William Pichel Pablo Clemente-Colón Cheryl Bertoia Michael Van Woert Chris Wackerman Frank Monaldo Donald Thompson Karen Friedman Xiaofeng Li	Operational sea ice monitoring
Sea Ice Mapping using Envisat ASAR Wideswath Images	Stein Sandven Kjell Kloster Helge Tayen Tommy S. Andreassen Harvey Goodman Kim Partington	Operational sea ice monitoring (ship routing)
Automated Location of Ice Regions in RADARSAT SAR Imagery	Chris Wackerman William Pichel Pablo Clement-Colón	Automated ice edge algorithm
Sea Ice Investigation from Seasat to Present, with Emphasis on Ice Motion: A Brief Review and A Look Ahead	Ben Holt Ron Kwok	Use of SAR for polar climate change studies (justification and algorithms)

requirements, procedures and methodology used to produce the required ice charts. A discussion on the role the new multi-frequency and polarization SAR satellite sensor in improving the ice products is also presented.

A complementary paper describing NOAA's ("Routine Production of SAR-Derived Ice and Ocean Products in the United States," by Pichel et al.) current use of and development of SAR applications to support its mission, provides a summary of algorithms used to produce wind field, vessel detection, SAR image, and ice/land mask products. Center geophysical requirements and the future vision for NIC are also presented.

The last paper in this group ("Sea Ice Mapping Using Envisat ASAR Wideswath Images," by Sandven et al.) describes a commercial pilot monitoring program referred to as ICEMON which has a program goal to develop and demonstrate an integrated monitoring service for sea ice and related atmospheric and ocean processes in high latitude regions. Examples of ICEMON products collected near Svalbard using Envisat wideswath images are discussed.

A typical standard daily ice product, created in this case by CIS, is shown in Fig. 1. The charts present the total ice concentration and the partial concentration, stage of development (ice type), and floe size for the three thickest ice categories in each polygon area.

Special features such as icebergs and heavily ridged ice are also shown when and where appropriate. A product such as the one shown in the figure is not created solely from the SAR data, but rather is created by integrating analysis of the SAR data with other remote sensing data such as, NOAA AVHRR visible and infrared data as well as SSM/I (passive microwave data), and other data sources. In some cases satellite altimeter and scatterometer data are also used. The merging of the various satellite data is done manually by trained ice image analysts. They utilize computers to register and overlay the data to assist the interpretation. The output is a digital product registered to Earth coordinates.

Figs. 2 and 3 are typical SAR images of sea ice that are analyzed by expert interpreters. Fig. 2 is an Envisat C-band (HH) image collected on 8 February 2004, in the Gulf of St. Lawrence, in the vicinity of Prince Edward Island, while Fig. 3 is a RADARSAT C-band (HH) image from 5 February of Lancaster Sound. The land masses on each image are outlined in red. The ice edge on the Gulf of St. Lawrence image is visible at the top of the figure, while Lancaster Sound is totally ice covered.

The three papers all discuss the positive attributes of SAR (i.e. all weather, day or night, and fine resolution), but at the same time indicate that fully automated algorithms for ice typing are still not reliable enough for operational ice charting in support

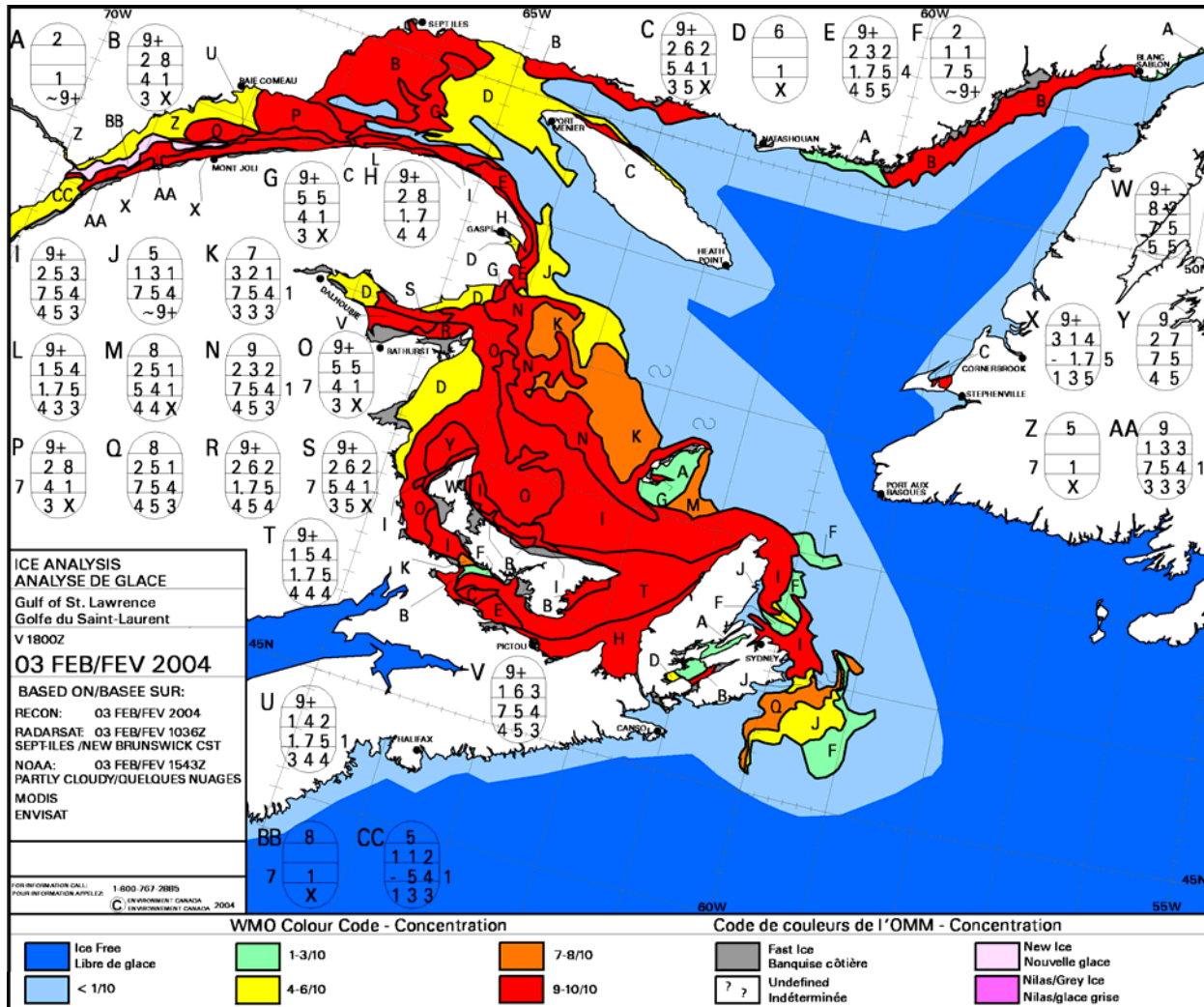


Fig. 1. Standard Daily Ice Analysis Chart

of navigation. Thus data analysis and chart production is done entirely by the expert ice analysts and forecasters using machine assisted manual interpretation techniques.

The first task of the operational sea ice forecasters is the identification of the boundary between ice and water or the ice edge. The ability to discriminate open water from sea ice is a function of the operating frequency and polarization of the SAR, the incidence angle, as well as the surface wind speed over the ocean and the resultant contrast between the ice and water backscatter [2-5]. High winds at the ice edge imaged at steep incidence angle can create ambiguities with respect to differentiating ice from water. Single channel (polarization) SARs, such as ERS-1/2 and RADARSAT-1, have experienced difficulties in these situations [6]. However, with the advent of polarization diverse or multiple-polarization satellite SAR, such as Envisat ASAR, there is great potential to realize improvements in ice versus water

differentiation. Open water backscatter from cross-polarization data (i.e. HV and VH), even under wind-roughened conditions, is much reduced. Selective use of the co-polarization channels (i.e. HH or VV) as a function of incidence angle can also reduce the ice/water ambiguity [3]. Also, the future availability of fully polarimetric as well as additional frequency sensors (e.g. ALOS PalSAR, TerraSAR X and L) offers potential improvements. The multi-frequency and polarization data also offer the potential to discriminate iceberg from the surrounding sea as well as thinner ice types. The disadvantage to the use of polarimetric data for use in operational ice monitoring is the reduced swath [5].

3. POLAR AND ENVIRONMENTAL CLIMATE STUDIES USING SAR

Sea ice plays a key role in the Earth's climate and has long been postulated to be a primary candidate as an indication of global warming [8]. As reported by Holt

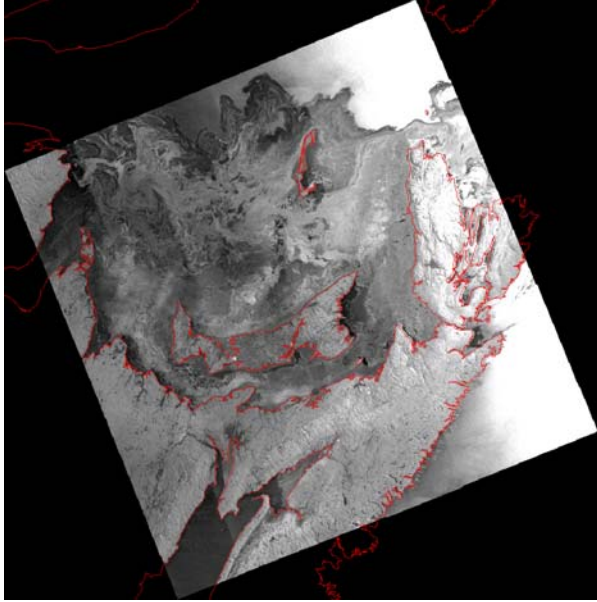


Fig. 2. Envisat SAR image showing sea ice in Gulf of St. Lawrence, collected on 8 February 2004. The ice edge is the dark boundary at the top of the image. (©ESA 2004; Data processed by Canada Centre for Remote Sensing)

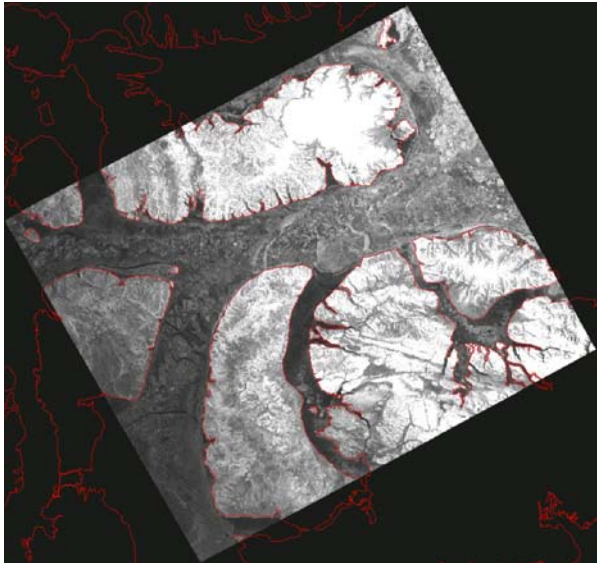


Fig. 3. RADARSAT image of sea ice collected on 5 February 2004 off Lancaster Sound. The Sound is most likely 100% ice covered with the darker areas being newer smooth ice. The brighter returns represent ice that is thicker and more deformed. (© CSA 2004; Data processed by RADARSAT International)

and Kwok (“Sea Ice Investigations from Seasat to Present, with an Emphasis on Ice Motion: A Brief Review and A Look Ahead”), sea ice acts to reduce the flux of heat from the comparatively warm ocean to the

colder atmosphere. When open water appears as the ice cover diverges and deforms, the heat flux increases tenfold, whereas it rapidly decreases again as new ice forms and thickens. As sea ice forms, salt is released from the water crystallization process to form brine, which drains from the ice into the ocean. Rapid ice growth can generate dense upper ocean water that mixes downward into the ocean column, thus being a source for convective overturning and eventually, deep water formation. The relatively salt-free sea ice (3-8 parts for thousand) then advects generally equatorward, thus supplying freshwater to other parts of the ocean for vertical mixing.

Sea ice also contributes significantly to the Earth’s albedo. Sea ice has a large albedo and reduces significantly during the summer melt. Albedo is sharply reduced when summer melt takes place with absorption of shortwave radiation increasing with the presence of liquid water, particularly within surface melt ponds on multiyear ice floe. Multiyear ice is sea ice that has survived one summer melt. Most of the brine has drained into the ocean. Multiyear ice in the arctic is typically 3-5 meters thick. The thinning of multiyear ice and percent of multiyear ice to the total ice cover are issues of concern, and climate models do predict a gradual retreat of Arctic sea ice volume and extent leading to ice free summer conditions by 2070 [9].

Recent observations strongly indicate significant climate changes in the Arctic are taking place. The arctic sea ice cover was found to have thinned by over 40% between 1958-1997, as measured by upward looking submarine sonar [10-11]. The Arctic ice cover has decreased in both the maximum and minimum extent and the length of the melt season appears to be increasing.

Recent climate changes, starting with the 1989 shift in the arctic oscillation (AO) have strongly affected the ice cover, circulation, and export of water from the arctic. It appears likely that polynya (open water or leads) activity in the Arctic and their possible role in halocline variability may be directly coupled to atmospheric circulation [12-14]. Synoptic, systematic high resolution SAR observation of the sea ice, and polynya formation would be a valuable tool to better understanding this complex system. To generate the synoptic observation of sea ice coverage in the Arctic, the RADARSAT Geophysical Processor System was established.

The RADARSAT Geophysical Processor System (RGPS) is designed to carry out semi-automatic tracking of the sea ice within single channel SAR images. Only the winter freezing months from

November to April are examined in order to avoid uncertainties induced by episodic melting-freezing events during spring and summer that can mask the sea ice texture/feature recognition. The texture or sea ice feature tracking is therefore effective, and one can observe when changes in area occur and thus keep track of the age of the corresponding newly formed ice areas. In addition, characteristics of the multiyear ice (MY) field can be determined. Currently the SAR image database contains approximately five years of RADARSAT data (approximately 15,000 scenes) of the Arctic Ocean (3-day repeat within US/Canadian Arctic mask; 6-day outside this mask), and systematic and regular RGPS analyses of three years of the data (1996-1999) are available.

The RGPS products include:

- Sea ice motion dataset;
- Records of sea ice deformation, new ice formation areas and their ages covering the Arctic Ocean;
- Conversion of new ice age distribution into estimates of ice thickness distribution, (relevant and important to Cryosat sea ice thickness retrievals);
- Records of backscatter; and
- Multiyear ice fraction and timing of melt onset.

The availability of these regular fields to the scientific community has been welcomed and in particular has led to growing awareness of the complicated dynamic and thermo-dynamic behavior of the Arctic sea ice cover during winter. An offspring of this has, in turn, led to focused development and implementation of new sea ice rheology formulation in sea ice models. The RGPS Science Working Group meets every year to present, discuss, and obtain an overview of progress and development in science and application of the RGPS products [15-18].

Regular access to such sea ice products (see Fig. 4 for an example) should also gradually stimulate new interest in the climate research community, in particular as the data records exceed 10 years. In so doing one needs to define and recommend standard sea ice monitoring products that possibly blend and optimize high-resolution SAR images with coarser resolution active and passive microwave data. With the current rapid development of web mapping technology such information products, building on the RGPS products, should be easy to access and allow for user friendly browsing capabilities in space and time. The RGPS products could also support the IPY in 2007-08, encouraging hemispheric collaborative work. It would therefore be quite timely and desirable to also start discussion on collaboration and implementation of the RGPS at a European SAR receiving station/processing

center to ensure parallel and complementary information production of the European sector of the Arctic. In the context of the near future possible regular flow of wide-spread SAR imaging data issues to be considered (not exclusive) are thus:

- Establishment of systematic and continuous monitoring of the Arctic Ocean using SAR data from Envisat, RADARSAT-2, and (in the near future) ALOS;
- Implementation of RGPS in Europe and the division of the task of processing the Arctic Ocean SAR image data between Europe and North America;
- Optimizing the complementarity between RGPS products from imaging radar and sea ice thickness retrievals from Cryosat and ICESat; and
- Generation of Arctic scale sea ice products (synergy between SAR, altimeters and coarser resolution active – passive microwave sensors) for environmental and climate studies.

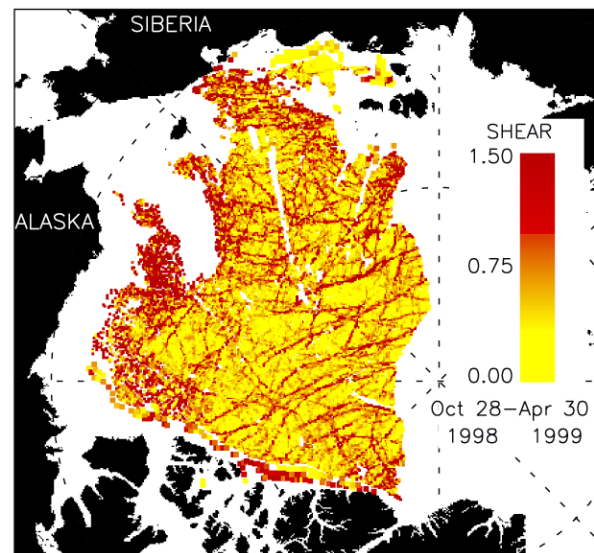


Fig. 4. This shows the net shear at each RGPS element (~10 km on a side) over the winter (end of October through April) as sampled by the small-scale kinematics observed in RADARSAT data.

At the margin of the sea ice cover (the edge), the abrupt transition to open water gives rise to unique processes including water mass formation, oceanic upwelling, wave propagation into the ice, eddy formation and atmospheric boundary layer processes [19]. The ice extent, the latitude of the ice edge as a function of longitude, is both of climatological and practical importance. Annual variation of sea ice extent is carefully observed as an early indication of greenhouse-induced climate change [20]. Monitoring

the ice extent and variability of the ice edge is important for practical reasons such as sea traffic, fisheries, offshore operations and other military marine activities in ice edge regions.

High resolution SAR data is the sensor of choice to study the marginal ice zone (MIZ). The present set of spaceborne scatterometers lack sufficient resolution to resolve subtle MIZ features. A detailed discussion on SAR detection of MIZ feature can be found in Synthetic Aperture Radar Marine User's Manual; Chapter 18. Processes at the Ice Edge – The Arctic [21].

The dynamics of the MIZ as imaged by SAR is illustrated in Fig. 5, an area of the Greenland Sea. Each SAR strip, which is 500-km long and 100-km wide, covers the same geographical area in the ice-edge region between 76°N to 80°N, and 8°W to 4°E. This series of annotated ERS-1 images and corresponding interpretation maps shows how the ice-edge location and features changed during the period from 13 to 16 January 1992. During this period, oceanographical investigations in the area were conducted from the R/V Håkon Mosby showing a number of shallow surface tongues of colder and fresher water associated with the ice tongues in Fig. 5 [22].

SAR images with 25-m resolution were the only data capable of providing accurate ice-edge location in a period of almost no daylight. SAR images transmitted to the ship in near-real-time were used to route the ship to positions near the edge of the ice. Without SAR imagery, the R/V Håkon Mosby would not have been able to operate close to the edge of the ice, as the wind conditions were variable and included storm events with wind speeds exceeding 25 m s^{-1} . During southeasterly winds, the ice edge was pushed towards the west. From 10 to 13 January, the wind began as northerly and then shifted to southerly, resulting in a more eastward location of the edge. On 16 January the effects of a north-northwest wind is made visible by ice streamers in the open ocean oriented parallel to the wind. Three days later, westerly winds produced an ice edge that is very diffuse. The rapid change in edge location and detailed ice features as characteristic of this area could only be observed from a time series of SAR images. The repeat period for the ERS SAR coverage was three days.

4. AUTOMATED SAR SEA ICE ALGORITHMS

As discussed in the operational monitoring section, the most important parameter to extract from the SAR data is the ice water boundary or ice edge. The Wackerman et al. paper on the “Automated Location of Ice Regions in RADARSAT SAR Imagery” summarizes the

NOAA/NESDIS Alaska SAR Demonstration Project. The demonstration project includes ship detection and wind vector determination. The ice edge algorithm (see Fig. 6 for an example) was used to remove ice from the data to improve the ship and wind vector performance. The sea ice classification algorithm is a supervised training algorithm that uses a series of hyperplanes to separate different classes in a n -dimensional feature space. The algorithm employs use of a combination of statistical measures and texture metrics drawn from the co-occurrence matrix to form the feature vector. The algorithm has been tested; less than 7% misclassification from the algorithm with almost no errors after applying spatial rules about the area imaged. This algorithm thus shows promise for creation of an automated procedure that can be used by the operational ice forecasters.

5. SUMMARY AND CONCLUDING REMARKS

The SAR sea ice community consists of operational users, radar and computer engineers who perform sensor validation and algorithm development, and climate scientists who want to use changes in sea ice characteristics to quantify climate change. Since the first SAR workshop held at Johns Hopkins in 1999, single channel SAR algorithms have been developed for first year and multiyear ice determination and ice feature tracking for ice dynamics.

The onset of RADARSAT provided the sea ice community with approximately 1 Gigabyte/day in data. Algorithms have been created and validated to automatically locate the ice edge. The RADARSAT geophysical processor system has produced a five-year record of arctic sea ice motion, records of sea ice deformation, new ice formation areas and their ages covering the Arctic ocean, conversion of new ice distribution into estimates of ice thickness distribution, radar backscatter records, multiyear ice fraction and timing of melt onset. Although these JPL products produced by the Geophysical Processor are exciting, not all of the products have been extensively validated and the algorithms have only been run on RADARSAT data. Calibration will be necessary before Envisat or ALOS data is routinely used.

Uncertainties exist in totally automated sea ice type classification particularly for the new ice, young ice and first year categories. This problem is exacerbated in the late spring and summer, when the snow covering sea ice becomes wet. The multi-frequency and multi-polarization SAR data obtainable from a combination of Envisat, RADARSAT 2, and ALOS (and other SAR sensors) can potentially be used to aid in differentiating the thin ice types. Typically the polarimetric data is narrow swath, versus the single frequency and

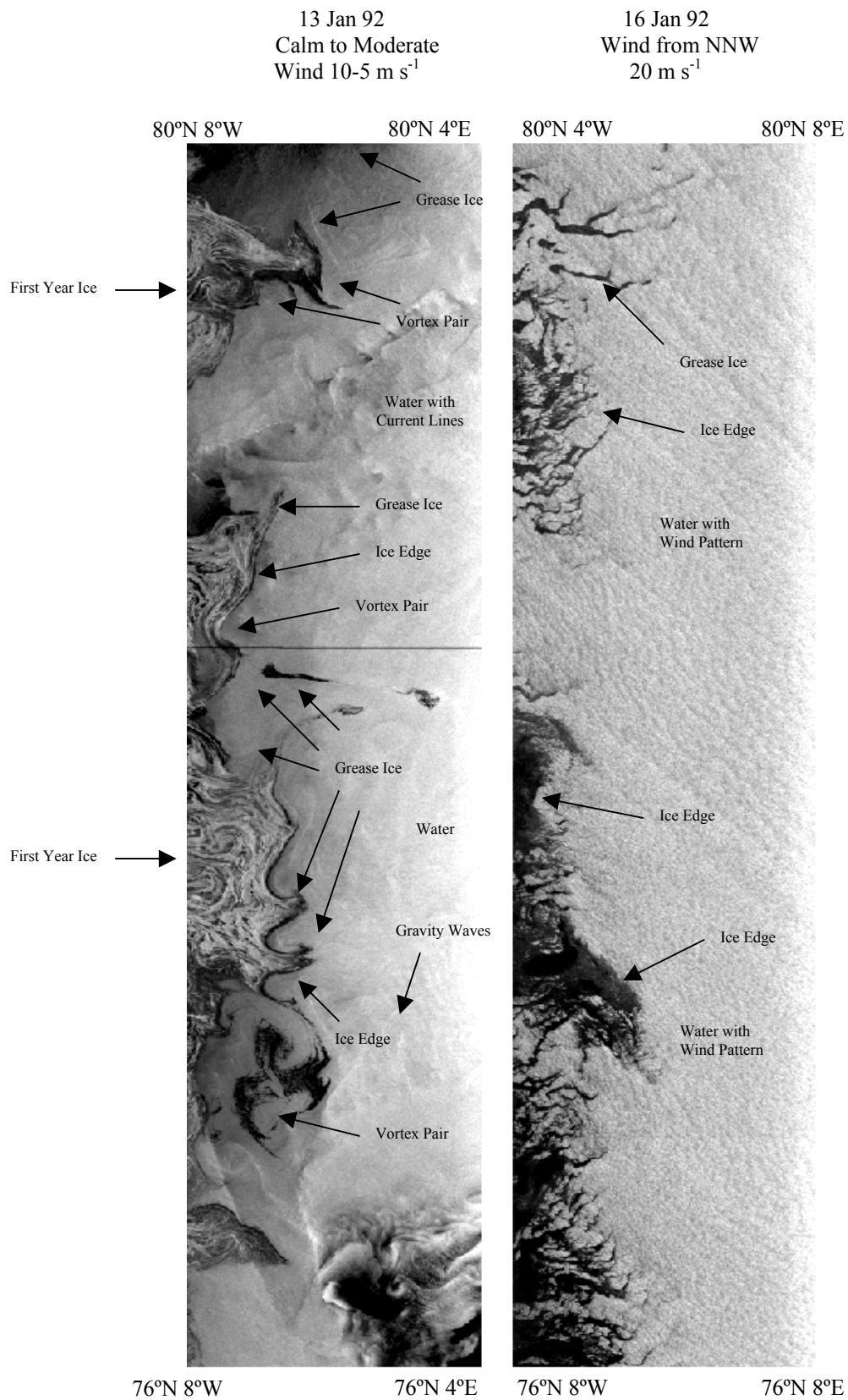


Fig. 5. ERS-1 SAR Example of rapid ice edge variability in the Greenland Sea – Fram Strait area as a result of strong off-ice winds. The ice edge is delineated on the SAR images. (From reference 21)

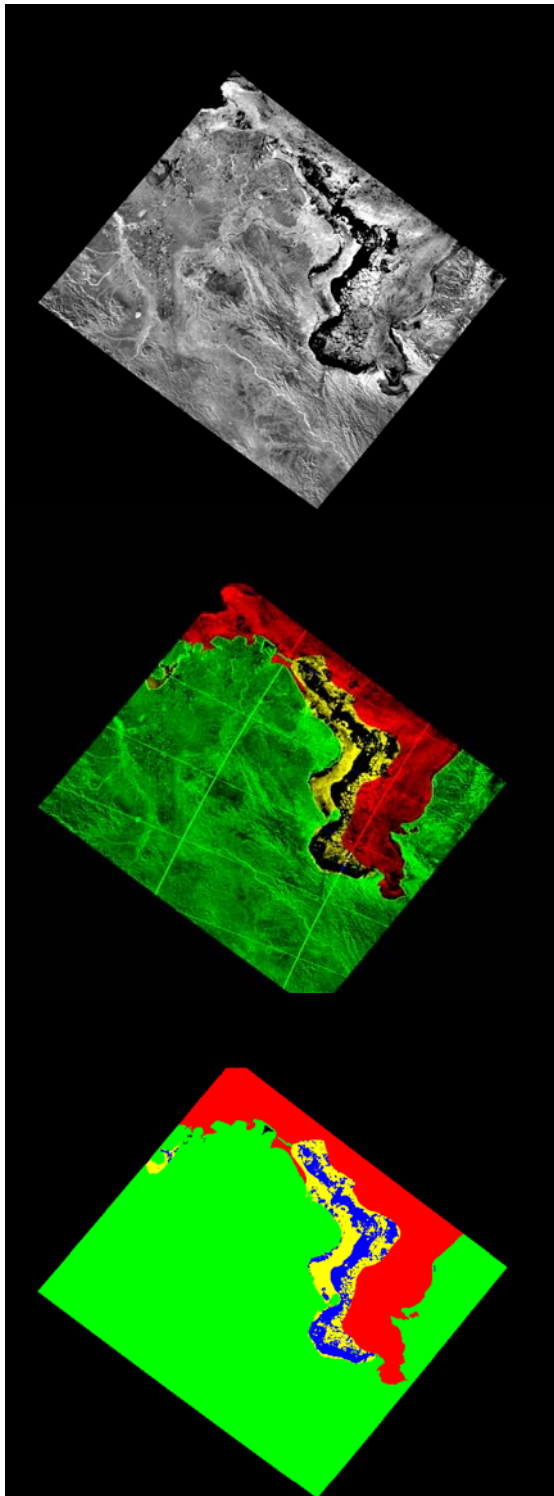


Fig. 6. Example of the ice classification results. Top image is the original SAR image, middle image is the classification map scaled by the SAR image, bottom image is the classification map. Red = solid ice, yellow = finger ice, blue = open water, green = land. (From Wackerman, *et al.*)

polarization wide swath data. Thus a nesting concept where the high-resolution polarimetric data is used to “truth” the wide swath data has been suggested.

Ice thickness is the fundamentally most important sea ice measurement. Sea ice thickness from SAR is presently inferred based on ice type. One approach discussed by Holt and Kwok is to measure freeboard, the portion of the ice cover above sea level (approximately 10% of the entire sea ice thickness). Fusion of SAR satellite data with altimetry holds the most immediate promise for accurate determination of thickness.

In summary, in the field of SAR sea ice mapping, a real user base exists, paying actual dollars to acquire the data. It is a mature operational tool, where manual interpretation techniques are utilized. The ice drift information obtainable from the high-resolution SAR is very useful. When fully validated, the additional use of SAR to obtain ice thickness distribution and ice volume changes (in combination with Cryosat and ICESat) will be very powerful operational, scientific research, and climate monitoring products.

Challenges remain in respect to fully exploiting SAR sea ice data. These challenges include:

- Most operational users largely rely on manual analysis;
- Little use of SAR data in models to date (e.g. ice drift assimilation); and
- Real operational benefits dependent on more reliable, volume access.

Opportunities exist to better integrate SAR in the operational and research communities. For example, the operational use of ice drift data (assuming SAR spatial and temporal sampling is adequate) into regional ice models is expected to emerge. Moreover, opportunities will soon exist to improve the SAR’s ability to discriminate the ice edge and thin ice types. These opportunities include:

- Use of wideswath multi-polarization data – ice/water and type ambiguity resolution. Fully polarimetric data for limited regions;
- Possible use of Envisat Global SAR monitoring mode at 1 km resolution;
- Near simultaneous X and L band data in a few years; and
- Along-track INSAR for regional information.

A key question for operational sea ice monitoring will center on assessing the potential advantages of fully polarimetric data against the disadvantage of reduced coverage. In addition, the impact of commercialization

of new SAR satellite missions and future data policies on the scientific and operational communities will need to be addressed

Envisat, RADARSAT-2, and several other SAR missions planned for launch in the next 1-5 years encompassing wide-swath, multi-frequency, polarization diverse, and polarimetric technology will be capable of providing both the operational and scientific communities with a wealth of data to meet their respective needs. Operational applications in support of ship routing and navigation, oil and gas offshore development, fishing fleet support, iceberg tracking, and support to submarine operations should be well served with a variety of robust data sources and options. So too should studies examining changes of sea ice extent and dynamics as a result of climate change. Although the Envisat, RADARSAT, and ALOS satellites provide a large amount of SAR data (RADARSAT early-morning and evening; Envisat late-morning and evening; ALOS similar to Envisat, but at L-band), a truly international program where the U.S. under NPOESS would fly a SAR at a time to complement these satellites is highly desirable.

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