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ICE MOTION AND ICE AREA FLUX IN THE FRAM STRAIT AT 79-81N

USING SAR AND PASSIVE MICROWAVE FOR AUG.2004 –JULY 2015.

by

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REPORT

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SUMMARY

In the present ongoing study, measurements of profiles of : 1) ice displacement by Envisat Radarsat-2 and Sentinel-1 wide-swath SAR images and 2) ice concentration by DMSP SSMI, SSMIS, AMSR-E and AMSR-2 are made in consecutive time intervals, generally each of 3 days duration. The resulting ice area flux across 79N (the "Fram Strait flux-gate") is computed for each time interval. They are then added to get longer period (monthly and yearly) area flux values. The average yearly ice area flux for 10 years between Aug.2004 and July 2015 has been computed to be 0.94 million square km. The ice-yearly flux has increased markedly during the first years, from 0.67 million square km in 2004-05 to a maximum of 1.17 in 2011-12. From Aug.2012 measurements are also made at a gate near 81N.

APPROVAL	
Kjell Kloster *Author*	Stein Sandven, Director.

swath width. Since July 2015, Sentinel-1 Extra Wide (EW) images from the Copernicus web portal are also used, having very good coverage with 420km swath.

A demonstration on the use of the ASAR WS mode for 3-daily mapping of the ice motion in the Fram Strait at 79N was started within the ICEMON project in 2003 (http://www.icemon.org). This line was chosen because many anchored buoys measuring the ice and water properties are situated here. Regular ice mapping continued within the SatHav project for NRS in 2005 and DAMOCLES in 2007.

Fig.1 ASAR image in October 2003 with 4 days ice displacements (white arrows).
The black lines mark ice concentration of 20%, 50% and 80% from SSMI data.

During the first years, scenes were based on advance ordering from ESA, using only descending passes. Later it was found convenient to base the scenes on those available in the ESA rolling archive and also ascending passes were used. With the use of passes in both directions, the scene overlap pattern is more complicated but more scenes are available. In Fig.1 is shown an example of the images used with a few selected ice motion arrows shown and ice concentration lines overlaid.

The capability of current satellites for this work had been investigated earlier, using both Radarsat-1 ScanSAR scenes obtained from Alaska SAR Facility (ASF) archive (Kloster, Jun.2003) and Envisat ASAR obtained from KSAT in near-real-time (Kloster, Nov.2003). The ASF archive data had 5 -7 days between the scenes, while the KSAT real-time data was obtained with 3 days time interval. Prior to measuring ice displacement, each SAR image was gridded, greytone-adjusted including range-normalization of backscatter, and printed to a fixed scale with optimal contrast. Ice displacement vectors were then measured by manual inspection of similar ice features on the pair of hardcopies. It was found that the same ice features were quite easy to recognize in the cold season with up to 3-5 days scene separation, but increasingly difficult with longer separation intervals and also during summer melt. The amount of ice deformation that takes place between the pair of scenes has a large effect, thus near to the ice edge and in the shear zone at the fast ice the features are generally too small and change too rapidly to allow certain recognition. The summer images are significantly more difficult to analyze due to thinner and more unstable ice with smaller floes and also often large backscatter changes following the changing temperatures around zero degC. Reliable measurements were possible with overlapping scenes every 3 -6 days in most seasons, but a scene separation of 1 -2 days were sometime necessary for reliable ice feature recognition, especially in summer.

In favorable situations, most of the ice in the overlapping area of each scene pair generally can be provided with accurate displacement vectors with a suitable spacing, less than about 50km. Following interpolation, the vectors can be outputted on a chosen grid, overlaid as arrows on one of the images, or listed along a line in a separate (ascii) file. Within the current project, it was decided to concentrate on vectors that cross latitude 79N ("gate B" as opposed to the shortest distance across the Strait at 80 -81N, called "gate A"), and to compute the southward ice area flux across this latitude line as the main product.

To compute ice area flux, ice area concentration is also required. Ice concentration maps are available from daily wide-area coverage passive microwave brightness temperature data using selected ice-algorithms. These maps were until May 2008 obtained from the SSMI sensor onboard the DMSP satellite F13 using the NORSEX-85H algorithm developed at NERSC. Thereafter, maps computed by the Bremen University "Artist Sea ice Algorithm" (ASI) using data from the AMSR-E sensor onboard the Aqua satellite (available at http://iup.physik.uni-bremen.de:8084/amsr/amsre.html) were used. This instrument had improved resolution compared to SSMI. After AMSR failed in October 2011, SSMIS data from the Bremen University was used until Oct.2013 when AMSR-2 data with resolution similar to AMSR-E became available. The reason for using passive microwave for ice concentration is that these data are considered to give more reliable ice concentration values at low spatial resolution than those measured by SAR. However, at the ice edge SAR is sometime used as an extra check on the passive microwave concentrations, mainly due to its much higher spatial resolution (about 500m versus 10km).

From the two datasets: a) the SAR derived ice displacement vectors, and b) the passive microwave ice concentration maps, the ice-area-flux crossing 79N southward in square km over the given time interval is then computed. Time interval length can vary from 1 day and upward depending on the availability of overlapping SAR scenes, 3 days is the most frequent interval used, it is a near-repeat period of the SAR carrying satellites orbiting at about 700km above Earth.

2. Ordering and processing of SAR scenes.

2.1 Envisat data.

Before Envisat failed in April 2012, ASAR data in the format of N1-files were used. Until July 2005, descending scenes spaced 3 days apart (occasionally 1 or 4 days) were ordered from the European Space Agency (ESA), within the deadline of 15 days before acquisition set by this institution (for satellite programming reasons). All scenes were in WS-mode and with HH-polarization, as the horizontal polarization generally has better contrast between ice and water than the vertical. From Feb. to Apr. 2004 all orders were made under EAO (Envisat Announcement of Opportunity) project no.303, named "Arctic Ocean System - Global Environment". Thereafter, orders were mainly made under the ESA Cat.1 project no. 2363 named “ICEMON”.
Reception of ordered scenes on CD in ESA-format by mail was somewhat irregular. A total of about 160 scenes were ordered, of these 15 did not arrive for various reasons, resulting in some longer intervals than the standard 3 days. A few of the scenes were reported not available from ESA.

Starting in August 2005, the ESA Rolling Archive (at http://oa-ks.eo.esa.int) was the main source of data. In the beginning, ordering also on the Cat.1 project was made. But after some months, this was found not to be necessary, since ESA made the WSM data in this area available on the ESA Archive as a regular service.

For processing, the scenes have been averaged from 75 m/pixel to 300m/pixel. Since the HH-backscatter from ice varies by about 5 dB in cross-range due to the incidence angle variation from 18° to 43°, a normalization-to-midrange function is applied in range. Note that water backscatter is not normalized by this function, so windy water will generally be much brighter in near-range than in far-range. Images were fitted with gridlines, either based on the coordinates in the header data or using shorelines, and printed to hardcopy with a fixed scale and with optimum contrast for selecting suitable ice features. Since fall 2006, the quick-look images of 500 m/pixel in the SAR archive at NERSC (at http://sat.nersc.no/archive) containing copies of data from the ESA archive has been used as a shortcut instead of processing from 75 m/pixel data in the ESA archive.

Manual analysis of the displacement of recognizable ice features are made using pairs of printed and gridded images. A WSM image averaged to 300m/pixel spatial resolution has approx. 150 looks radiometric resolution, corresponding to a speckle noise well below 0.3dB. The thermal-noise-equivalent sigma0 (NESZ or noise-floor) is less than approx. -23dB. These noise values are generally good for recognizing a sufficient number of persistent ice features in the two images.

It is very important to use good contrast images. Accurate calibration to sigma-zero is available from ESA, but this is not necessary for the present work. Some saturation in windy water due to the 8 bits coding may be seen in near-range, but with no serious effects. In the cold season, scenes are displayed and copied with white equal to ESA pixel-values of approx. 1700, corresponding to a 31° incidence sigma-zero (midrange backscatter coefficient) of value -6.5dB. For images in the warm season, this maximum (white) sigma-zero has to be lowered to about -12dB, corresponding to the reduced backscatter from wet ice. To achieve optimal greytone contrast in the images as well as for display and print, the image processing software “XV” is used.

Gridding to about 2km accuracy can be made using the "gopgrid" program developed at NERSC by Torill Hamre. It uses the known satellite orbit and instrument parameters in addition to one reference point, generally one given in the image header data (e.g. center of first scanline) or a ground reference point seen in the image. However, a shoreline overlay map is often used as a quicker method and also for a check of gridding accuracy. Until summer 2010 the quick-looks in the NERSC archive had no grid information and required a shoreline overlay map to be used. Thereafter, these images have been fitted with gridlines from the information in the N1-files. The adjustment of greytones/contrast is limited for images in the NERSC-archive, with only two options of greytone range in dB available.

2.2 Radarsat data.

ScanSAR HH-polarization scenes have been used since April 2012 after Envisat failed. They were downloaded from the “flerbruker-arkiv” at Kongsberg Satellite Services A/S (at http://www.ksat.no), first as geotiff-format “quick-looks” with resolution 400m -600m/pixel on an equal-distance grid with straight lat. and long. lines. These had to be re-gridded to an approximate polar stereographic grid by the program “cimfix”. Since April 2013, images in strip-map format and near-conformal projection have been used. These are found in the high-resolution (50m/pixel) zip-format files. Images are greytone-normalized in range by processing at KSAT with the use of pre-defined lookup-tables, named “ice” and “mixed”. After unpacking, the images are greytone-adjusted to optimal contrast using the XV image processing package, they are then analyzed the same way as the Envisat images. Visible shorelines are used for defining the gridlines with sufficient accuracy (5km), this it is always possible since the swath is wider than for Envisat.

3. Analysis of ice displacement and computation of ice-area-flux.

Recognition of the sea ice features used for measuring displacements varies from very easy to difficult depending on the specific ice conditions and the time interval length. Most difficult are: 1) the ice edge region and also the shear zone region off the Greenland fast ice, which may have only small floes and large ice deformations, 2) image pairs with large time intervals, and 3) images in the ice melt season. In winter, the ice is stationary as fast ice out to 70 -140km from the Greenland coast. Outside is found a relatively narrow (10 -30km) shear zone followed by ice with a (generally) gradual increase in drift speed further eastward. For most image pairs, it is possible to find reliable displacements vectors in the scene-overlapping area with a spacing of about 30 - 50km, excluding the shear zone and the ice-edge zone where inter- and extrapolation is done.

In order to compute the Fram Strait ice area flux, the ice displacement profile is tabulated in 21 intervals (bins), each of one degree longitude with centers from 15W to 5E along 79N, using interpolation between the measured vectors nearest to this line. In the shear zone, linear interpolation from zero motion in the stable fast ice to the first measured motion vector is made. Near the ice edge, it is assumed that ice displacement to the east of the last measured vector is constant. When possible to check, this extrapolation of motion in the difficult ice edge region has been found to be correct – the ice speed does not seem to change significantly at the ice edge. Ice concentration is measured on the dates of the SAR images along the 79N profile, and the temporal mean ice concentration is computed from the values at the start date and the end date of the displacement interval.

The ice area-flux across the 79N line is then calculated from the displacement profile and the mean concentration profile. It is the integral in longitude (the sum of the 21 values) of the product of: 1) the mean ice concentration, 2) the ice displacement distance, 3) the negative cosine of the azimuth-angle of the displacement, and 4) the interval length of 21.3km. Positive flux value is southward, since the direction of ice motion in the Fram Strait most of the time is within ±30° of south (180° azimuth). In other words, the ice export from the Arctic Ocean across 79N (gate B) is as a rule measured in square km per 3 days. From this, the flux over longer period (month, year), as well as the mean daily value (sq.km/day) can be calculated. Also, studies of 3-day-mean ice motion (displacements) as function of longitude across the Strait can be made.

Table 1. Area flux across 79N in the Fram Strait (gate B).
Monthly values in 1000 sq.km. Adjusted to months a 30.5d starting from 01.Jan.

Ice-year	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Sum
2004 -2005	006	004	042	076	137	116	083	083	062	071	-006	-002	= 672
2005 -2006	007	065	087	096	039	065	111	128	076	049	031	011	= 765
2006 -2007	008	035	074	113	106	133	060	083	109	072	064	025	= 882
2007 -2008	017	070	118	138	107	134	097	129	116	086	013	020	=1 045
2008 -2009	020	025	097	163	100	092	118	132	116	028	031	041	= 963
2009 -2010	024	061	130	115	115	097	102	145	079	046	035	011	= 960
2010 -2011	001	030	104	081	146	131	072	169	120	083	061	062	=1 060
2011 -2012	025	019	099	107	159	095	151	115	129	142	064	064	=1 169
2012 -2013	035	049	130	107	095	111	134	144	151	068	028	029	=1 081
2013 -2014	018	001	081	145	106	048	122	109	119	066	039	027	= 881
2014 -2015	013	017	068	065	149	082	133	137	090	065	062	015	= 896
Month.avg.:	016	034	094	110	114	100	108	125	106	071	038	028	= 943

Computed monthly ice area flux values are summarized in Table 1. To compensate for varying month-lengths, measured values have been adjusted (by interpolation) to the dates corresponding to "standard month" interval of about 30.5 days starting from 01.Jan. In the last row is the monthly average flux. In early spring (March) the flux often has its highest value, possibly connected with most intense cyclonic activity. Summer values are low, partly due to less ice at 79N and partly to low cyclone activity.

The standard length of the flux time interval is 3 days. It may vary somewhat depending on the scene availability, so both shorter and longer intervals occur. The ice motion is often very variable on a daily basis or less, thus the mean daily values may not be representative for the instantaneous ice speed/ice flux. The greatest 3-day-mean ice flux values found are close to 10 000 sq.km/day. This can be compared to the Radarsat ScanSAR results of 03.Nov.2001 -12.Jun.2002 which had 6 400 sq.km/day as the maximum value. Since the Radarsat data used longer time intervals (6 days), lower peak values are expected.

The mean daily ice flux value measured during spring 2004 in a period of 140 days was 2 700 sq.km/day . For the 144 days in the fall of the same year it was 1 700 sq.km/day. For comparison, ASAR in 23 days Oct.-Nov.2003 gave 2 700 sq.km/day, while Radarsat in the winter 2001 -02 period gave a mean value of 3 400 sq.km/day. From Table 1, the mean daily flux in a 10 year period from Aug.2004 is computed to be close to 2 600 sq.km/day. Since the average width of the Fram Strait pack ice (with near 100% ice) at 79N is about 220km, the overall mean ice speed is about 12 km/day (0.14 m/s). There are large variations between the mean speed in the winter months (about 0.2m/s) and in the summer months (about 0.07m/s).

4. Discussion of the accuracy of ice displacement and flux.

The accuracy of the measured ice displacement vectors depends on the co-registration accuracy of the two scenes. For each scene, coordinates are found by comparison with shorelines to be within about 2km of correct position. Each measured displacement vector is dependent on accurate co-registered coordinates for the two scenes and should then be within ±4km in accuracy. This is about 10% of the average 3-day displacement and considered to be sufficient for the present analysis. For scenes with visible and reliable coastlines (NE Greenland is problematic on some older maps!), an increase in the accuracy up to about 1km is possible if needed for special cases. Since this error can be assumed to be randomly distributed and not biased, the relative accuracy of added fluxes for longer time period will improve to considerably better than 10% accuracy.

Important is also the often sparse and uneven distribution of accurately measured displacement vectors. Interpolation may be necessary over distances up to hundred kilometers where no reliable vectors can be found. The error due to this can in extreme cases amount to several tens of km. A more detailed and time-consuming analysis using higher resolution images can increase the vector density, and thus decrease the interpolation distances. Another solution is to decrease the time interval between the pair of satellite scenes, by using all SAR partly-overlapping passes available or by using SAR from satellites simultaneous operating with Radatsat-2 (e.g. Terra_X SAR, Sentinel-1). At the moment, this will be time-consuming whithout much increase in accuracy and is therefore not used in the current project.

Drifting platforms with GPS positions that can be used to check the ice displacement are only sporadically found in the area. One of these was the vessel TARA that in 2007 drifted from 81.5N, 2W on 26.Nov. to 77.5N, 6W on 25.Dec. It has been used to check the accuracy of our SAR motion vectors along its track. The agreement was very good, with a difference of only 15km over a 450km long track, indicating about 3% displacement measurement error.

The accuracy of the ice concentration is about ±5% by the use of the passive microwave algorithms mentioned in the introduction, that is ±125 sq.km for a daily flux of 2500 sq.km. The southward displacement accuracy estimated above of ±4km over 3 days in the ice field between 12W and 4W (170km) results in a daily flux accuracy of ±230 sq.km. Total accuracy of the 3-day flux in this case is then about ±270 sq.km/day, or about ±10%. For flux over longer periods, the relative accuracy is expected to improve considerably (as the square-root of the number of 3-day values added together), to about ±3% accuracy for the monthly values in Table 1.

5. Comparison with other datasets.

Since the ice flux is generally minimum in the months of July and August (see Table 1), the ice-season from August one year to July the next year was chosen for definition of the "ice-year" for flux. Table 2 summarizes the values found in the present study:

Table 2. Ice area flux across 79N for ice-year periods.

Aug.2004 – Jul.2005:	672 000	sq.km
Aug.2005 – Jul.2006:	765 000	“
Aug.2006 – Jul.2007:	882 000	“
Aug.2007 – Jul.2008:	1 045 000	“
Aug.2008 – Jul.2009:	963 000	“
Aug.2009 – Jul.2010:	960 000	“
Aug.2010 – Jul.2011:	1 060 000	“
Aug.2011 – Jul.2012:	1 169 000	“
Aug.2012 – Jul.2013:	1 081 000	“
Aug.2013 – Jul.2014:	881 000	“
Aug.2014 – Jul.2015:	896 000	“
Sum=	10 374 000	sq.km

Thus, over these 11 years the mean flux is 943 000 sq.km/year, or 2 580 sq.km/day.

Several authors have computed the ice exported across a given fluxgate in the Fram Strait, chosen either at 79N (gate B) or the “shortest line across” (gate A). Yearly values for 11 studies are compared in (Rothrock, Kwok and Groves 2000), based on various combinations of satellite ice data, buoy drift patterns and atmospheric pressure data, and also varying greatly in duration, from 2 month and up to 30 years. The mean yearly ice flux value of these 11 studies is close to one million sq.km. The variation between the various studies is large, ranging from 0.69 up to 1.28 million sq.km per year.

The study that compares most closely with our value for the first 2 years (Aug.2004 – Jul.2006) was made by analysis and ice tracking of AVHRR for 2 years in 1993 –94 (Martin and Wadhams 1996). Here, the mean annual ice flux across 79N was found to be 710 000 sq.km.

Our results starting in 2004 show a marked increase in the ice area flux during the first years (55% increase from 2004/05 to 2007/08). This is probably related to the large decrease in the total area of arctic summer ice that has been observed during the same time period, making the ice thinner and more easy to move (Smedsrud, Sorteberg and Kloster 2008), (Smedsrud, Sirevaag, Kloster, Sorteberg and Sandven 2011).

6. Iceflux over the shortest line Svalbard –Greenland near 81N.

Starting summer 2012, the use of Radarsat ScanSAR A and Sentinel EW images with better spatial coverage of the whole Fram Strait has enabled the ice area flux also to be easily measured over the shortest line across the Strait (also called "gate A") from 79.8N,10E to 81.4N,12W. The monthly values across this line are given in Table 3.

Table 3. Area flux over the shortest line across the Fram Strait neat 81N.
Monthly values in 1000 sq.km. Adjusted to months a 30.5d starting from 01.Jan.

Ice-year	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Sum
2012 -2013	055	084	104	094	095	094	099	139	155	044	025	044	= 1 032
2013 -2014	049	038	089	152	110	035	126	093	123	056	052	006	= 929
2014 -2015	022	055	086	059	156	086	144	132	098	072	071	026	= 1 007

Since the ice may change considerably moving between the two gates, either by freezing (in winter) or by melting (in summer), and also by forming ridges (increasing ice thickness), a close correspondence between the flux values at gate A near 81N and B at 79N is not expected. The correspondence between the yearly values at the two gates is about 5-10% in these 3 years. It indicates that measurements made at different gates can be compared within this error value. This is important, since different investigators may use different gates.

7. Demonstration products and further analysis.

In the present study, the ice area flux over consecutive 3-day-periods at 79N latitude in the Fram Strait has been calculated by manually finding displacement vectors using Envisat, Radarsat and Sentinel SAR images and combining with ice concentration from passive microwave maps. Starting each new ice-year on 01.Aug, the cumulative ice area flux at 79N is shown in Fig.2.

Other products which data from this study can be used for are e.g:

- mean monthly ice displacement profiles at 79N,
- individual 3-daily ASAR images with the ice motion vectors overlaid,
- comparison with geostrophic wind (Halvorsen 2014) and ocean currents in the Strait.

Data may be used in a more detailed spatial or temporal analysis of the ice motion. Some of the early ice maps and profile products are displayed on the web, at http://www.icemon.org.

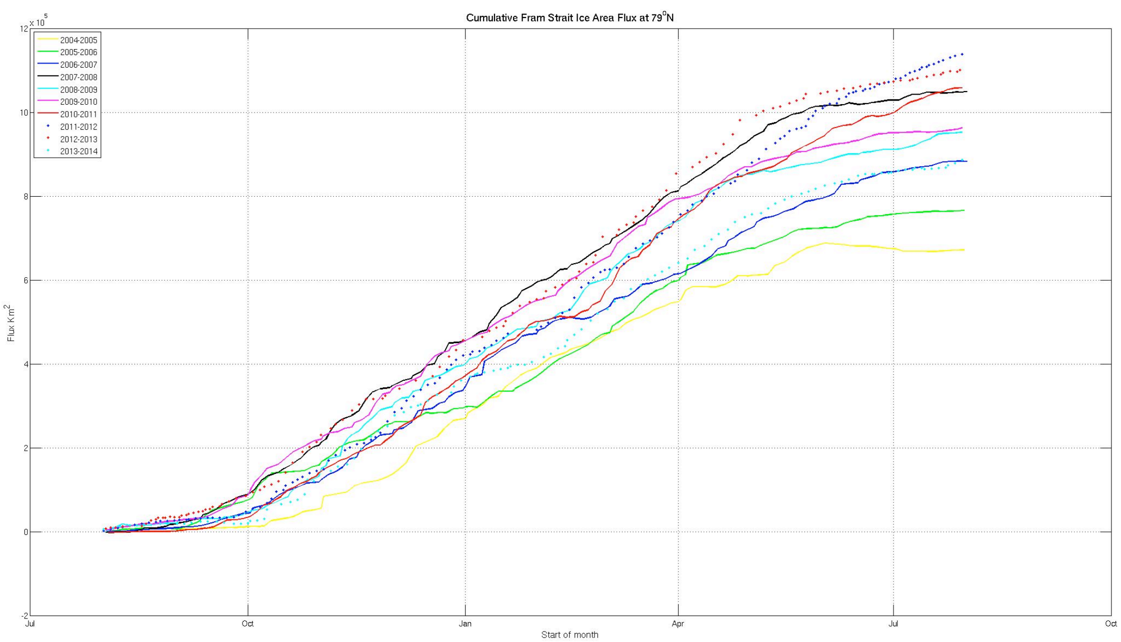

Fig. 2. Cumulative area flux at 79N for 10 ice-years.

Ice drift data from other sources in this region can be used for comparison and analysis, either for comparison with the SAR vectors, or possibly for filling-in where the SAR displacement vectors are sparse or missing. NOAA AVHRR images, Upward Looking Sonar (ULS) equipped with doppler velocity measurements, and drifting buoys are all data sources that can be considered. However, the first is severely limited by clouds /darkness, the second is spatially only point-measurements and available (at best) several years after measurement. Other satellite based ice displacement data sources to consider are low resolution microwave satellite imagery from the SSMI and SSMIS sensors on the DMSP satellites and from the AMSR-E and AMSR-2 instruments, and also low-resolution images from the Scatterometer sensor on the Quick-Scat satellite. These satellite images have very regular coverage (whole arctic each day), but with low spatial resolution of the order of 10km. They can be automatically processed by algorithms based on spatial maximum cross correlation (MCC) of the features in two successive images. The low resolution and also the frequent occurrence of missing data in dynamic ice regions will limit their use in the highly dynamic ice region of the Fram Strait, resulting in many time intervals without motion data over large areas. Measurement is often not possible at all in the summer ice (May –Sept.).

The ice volume flux is a better climate-related product than the ice area flux. It will therefore be of great interest to compute the volume flux using the area flux reported here together with profiles of the ice thickness across the Strait. Presently, passive microwave measured ice concentration can be used only as a very rough proxy of ice thickness (in effect it is a measure of ice/no ice with “ice” to be above some thin ice limiting thickness – not well defined). Also, using differences in the SAR backscatter value as a measure of ice types/thickness have large uncertainties in the dynamic ice regions found in the Fram Strait. As more reliable ice thickness data probably will become available in the future, especially from altimeter satellites, it is expected to be possible to estimate reliable values of the ice volume flux in cubic km per time unit. The ICESat satellite operating between 2003 and 2009, and also the CRYOSAT-II satellite that was launched in April 2010, both have the capability to measure ice or ice+snow freeboard. After proper compensation for the snow load and having good estimates of the ice density, the freeboard data can be used for calculation of the ice thickness. Some ice thickness data may also be obtained from upward-looking ice measuring sonar buoys (ULS), e.g. by those deployed near 79N, 5W by the Norwegian Polar Institute. Comparison of data from these buoys was one of the reasons to choose the 79N latitude as the line for making the flux measurements by satellites in the current report. However, a reliable thickness profile over the whole Strait cannot be made using only these buoys.

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