

1 **Improving Arctic sea ice edge forecasts by assimilating**
2 **high horizontal resolution sea ice concentration data into**
3 **the U.S. Navy's ice forecast systems**

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5 **P.G. Posey¹, E.J. Metzger¹, A.J. Wallcraft¹, D.A. Hebert¹, R.A. Allard¹, O.M.**
6 **Smedstad², M.W. Phelps³, F. Fetterer⁴, J.S. Stewart⁵, W.N. Meier⁶ and S.R.**
7 **Helfrich⁷**

8
9 [1]{Naval Research Laboratory, Stennis Space Center, MS }

10 [2]{Vencore Services and Solutions, Inc., Stennis Space Center, MS }

11 [3]{Jacobs Technology Inc., Stennis Space Center, MS }

12 [4]{National Snow and Ice Data Center, Boulder, CO }

13 [5]{J. Scott Stewart of Exploratory Thinking, Longmont, CO }

14 [6]{NASA Goddard Space Flight Center, Greenbelt, MD }

15 [7]{U.S. National Ice Center, Suitland, MD }

16 Correspondence to: P.G. Posey (pamela.posey@nrlssc.navy.mil)

17
18 **Abstract**

19 This study presents the improvement in ice edge error within the U.S. Navy's operational sea
20 ice forecast systems gained by assimilating high horizontal resolution satellite-derived ice
21 concentration products. Since the late 1980's, the ice forecast systems have assimilated near
22 real-time sea ice concentration derived from the Defense Meteorological Satellite Program
23 (DMSP) Special Sensor Microwave/Imager (SSMI and then SSMIS). The resolution of the
24 satellite-derived product was approximately the same as the previous operational ice forecast
25 system (25 km). As the sea ice forecast model resolution increased over time, the need for
26 higher horizontal resolution observational data grew. In 2013, a new Navy sea ice forecast
27 system (Arctic Cap Nowcast/Forecast System - ACNFS) went into operations with a
28 horizontal resolution of ~3.5 km at the North Pole. A method of blending ice concentration
29 observations from the Advanced Microwave Scanning Radiometer (AMSR2) along with a sea
30 ice mask produced by the National Ice Center (NIC) has been developed resulting in an ice

1 concentration product with very high spatial resolution. In this study, ACNFS was initialized
2 with this newly developed high resolution blended ice concentration product. The daily ice
3 edge locations from model hindcast simulations were compared against independent observed
4 ice edge locations. ACNFS initialized using the high resolution blended ice concentration
5 data product decreased predicted ice edge location error compared to the operational system
6 that only assimilated SSMIS data. A second evaluation assimilating the new blended sea ice
7 concentration product into the pre-operational Navy Global Ocean Forecast System 3.1 also
8 showed a substantial improvement in ice edge location over a system using the SSMIS sea ice
9 concentration product alone. This paper describes the technique used to create the blended
10 sea ice concentration product and the significant improvements in ice edge forecasting in both
11 of the Navy's sea ice forecasting systems.

12

13 **1 Introduction**

14 Knowing the ice edge location is extremely important for safe navigation and effective
15 execution of the U.S. Navy's daily operational missions (U.S. Department of Navy, 2014).
16 Since comprehensive records began with the satellite era in 1979, summer Arctic sea ice
17 extent has trended downward with a new record minimum of 3.41 Mkm² occurring in
18 September 2012 (NSIDC 2012). This 2012 record low in sea ice extent, followed by an
19 increase in extent during 2013 and 2014, indicate high year-to-year variability in the ice cover
20 and also in the spatial distribution of the ice (i.e., where open water forms) (Perovich et al.,
21 2014). In this rapidly changing Arctic environment (Meier et al., 2014), it is likely that Arctic
22 shipping will increase over the next decade. This, in turn, will demand an increase in U.S.
23 military presence in the Arctic. As the U.S. military presence increases in this region, it is
24 imperative to provide as accurate a sea ice forecast as possible.

25

26 Currently, the Navy uses two systems to predict ice conditions: the Arctic Cap
27 Nowcast/Forecast System (ACNFS) for the Northern Hemisphere as well as the Global Ocean
28 Forecast System (GOFS 3.1). Prior to 2 February 2015, the ice concentration fields from both
29 ACNFS and GOFS 3.1 had been updated with satellite-derived ice concentrations at a gridded
30 resolution of approximately 25 km using the U.S. Defense Meteorological Satellite Program
31 (DMSP) Special Sensor Microwave Imager/Sounder data (SSMIS). SSMIS has higher spatial
32 resolution (12.5 km gridded) for high frequency (85-91 GHz) channels. However, most

1 algorithms require the lower resolution channels, limiting the gridded resolution to 25 km,
2 with the effective resolution dependent on the frequency of each channel used in the
3 algorithm. During 2012, a 10 km satellite-derived ice concentration product from Advanced
4 Microwave Scanning Radiometer (AMSR2) on the Japan Aerospace Exploration Agency
5 (JAXA) Global Change Observation Mission – Water (GCOM-W) platform became
6 available. This higher horizontal resolution sea ice information derived from satellite
7 observations was critically needed for existing high resolution ice models. Also, during 2012
8 the National Oceanic and Atmospheric Administration (NOAA) National Ice Center (NIC)
9 recommended that a greater effort be undertaken to assimilate analyzed data that they produce
10 as well as other satellite sources into the Navy’s models in order to improve the forecasted ice
11 edge location, especially during the summer season.

12
13 Recently, investigators at the National Snow and Ice Data Center (NSIDC), National
14 Atmospheric and Space Administration (NASA), NIC, and Naval Research Laboratory
15 (NRL), developed a gridded ice concentration product that uses the daily observations from
16 the Interactive Multisensor Snow and Ice Mapping System (IMS) (Helfrich et al., 2007;
17 National Ice Center, 2008) as well as data from the new higher resolution AMSR2 passive
18 microwave sensor. The resolution of this blended data product is 4 km; much closer to the
19 resolution of Navy ice forecasting systems than the SSMIS data. This study examines the
20 impact on ice edge forecasts of assimilating this new, high resolution blended data into both
21 ACNFS and GOFS 3.1.

22 23 **2 System descriptions, data and methods**

24 **2.1 System descriptions**

25 Currently, the Navy uses ACNFS to predict conditions in all ice-covered areas poleward of
26 40°N, with a grid resolution of approximately 3.5 km at the North Pole (Fig. 1). ACNFS
27 graphical products are publically available from www7320.nrlssc.navy.mil/hycomARC. In
28 September 2014, GOFS 3.1 was transitioned to the Naval Oceanographic Office
29 (NAVOCEANO), and is presently in the final operational testing phase. When GOFS 3.1
30 becomes operational, it will replace ACNFS and provide a global sea ice prediction capability
31 including both the Arctic and the Antarctic. ACNFS and GOFS 3.1 are based on the HYbrid

1 Coordinate Ocean Model (HYCOM) (Metzger et al., 2015) coupled to the Los Alamos
2 National Laboratory Community Ice Code (CICE) version 4.0 (Hunke and Lipscomb, 2008).
3 Data assimilation is provided by the Navy Coupled Ocean Data Assimilation (NCODA)
4 system (Cummings and Smedstad, 2014).

5

6 Data assimilation is essential for accurate ice/ocean predictions for many reasons. For
7 example, many ocean phenomena are due to nonlinear processes (e.g., flow instabilities) and
8 thus are not a deterministic response to atmospheric forcing. Errors in the atmospheric
9 forcing, limitations in numerical algorithms and coarse grid resolution can reduce the
10 accuracy of the model's products. NCODA, a 3-D variational analysis (3DVAR), generates
11 both the ocean and ice analyses based on yesterday's 24-hr forecast along with available
12 observations. The ocean analysis variables include temperature, salinity, geopotential and the
13 vector velocity components that are all analyzed simultaneously and provide corrections to
14 the next model forecast in a sequential incremental update. The ice concentration analysis
15 assimilates SSMIS and provides an ice concentration field that is directly inserted into the ice
16 model. One major drawback in using SSMIS is its low spatial resolution of 25 km, which is
17 much coarser than the near pole 3.5 km resolution of both ACNFS and GOFS 3.1.

18

19 ACNFS has undergone validation by NRL (Posey et al., 2010), and declared operational
20 (September 2013) and runs daily at NAVOCEANO. GOFS 3.1 was transitioned to
21 NAVOCEANO on 26 September 2014 (Metzger et al., 2015) and is undergoing the final
22 operational testing by NAVOCEANO and the NIC. This new ice forecast system is expected
23 to be declared operational in summer/fall 2015. The NIC presently uses ACNFS output and
24 in the near future (once declared operational) will use GOFS 3.1 output to improve the
25 accuracy and resolution of the analyzed ice edge location.

26

27 **2.2 Passive Microwave**

28 Several methods have been developed to estimate sea ice concentration from passive
29 microwave brightness temperatures, generally via empirically derived algorithms based on
30 differences or ratios between the passive signatures of ice and open water at different

1 microwave frequencies and polarizations (e.g. Comiso and Nishio (2008); Markus and
2 Cavalieri (2000)). Since 1979, these algorithms have been applied to a series of multi-
3 channel microwave radiometers such as the SSMIS.

4

5 The AMSR on the NASA Earth Observing System (EOS) Aqua platform (AMSR-E) operated
6 from 2002 until the sensor ceased normal operations in October 2011. A follow-on sensor,
7 AMSR2, was launched in May 2012 on the JAXA GCOM-W platform. The AMSR2 sensor
8 has a much higher spatial resolution (instantaneous field of view, IFOV) than SSMIS and
9 slightly higher than AMSR-E. For example, at the 19 GHz channels, SSMIS has an IFOV of
10 approximately 70 km x 45 km, AMSR-E is 27 km x 16 km, and AMSR2 is 24 km x 16 km
11 (Kunkee et al., 2008; Imaoka et al., 2010). The higher spatial resolution of these new
12 instruments allows for a higher gridded resolution sea ice concentration product (12.5 km for
13 AMSR-E and 10 km for AMSR2 vs. 25 km for SSMIS).

14

15 Problems associated with the interpretation of sea ice signatures in passive microwave data
16 during summer months have been well documented (e.g., Cavalieri et al., 1990, Gloersen et
17 al., 1978, Campbell et al., 1980). Summer sea ice concentrations are more uncertain than
18 winter concentrations because of the presence of moist snow, wet ice surfaces, and melt
19 ponds. By confusing water atop sea ice with open ocean, passive microwave products tend to
20 underestimate the ice concentration within the pack ice, and may not detect ice at all in some
21 cases, even when ice is present in concentrations considerably greater than 15%. Broad
22 expanses of ice at relatively low concentration often make up the marginal ice zone (MIZ),
23 and passive microwave products often place the ice edge farther poleward than in actuality,
24 resulting in an underestimation of Arctic-wide ice extent relative to more accurate methods
25 used in human-derived analyses.

26

27 The magnitude of this underestimation of sea ice extent can be seen in Fig. 2 during the time
28 period of 25 July – 28 August 2012. Sea ice extent from passive microwave data (Fetterer et
29 al., 2002) is approximately 1 Mkm² less on 13 August 2014 than that obtained from the
30 Multisensor Analyzed Sea Ice Extent (MASIE) product. See section 2.3 for more information
31 on IMS/MASIE. The difference between the two extent products gradually decreases by the

1 end of August 2012. Differences can also occur in winter because passive microwave sensors
2 may fail to detect thin ice, although underestimation of ice extent in winter tends to be much
3 lower in magnitude than in summer. Some of these differences are due to the lower spatial
4 resolution of passive microwave imagery, with SSMIS sensor footprints on the order of 40-70
5 km for some channels used in the sea ice algorithms. AMSR2 has much higher spatial
6 resolution than SSMIS, but sensor footprints (on the order of 10-20 km) are still much larger
7 than the IMS resolution. It should be noted also that the IMS/MASIE product has limitations
8 as well. Analysts at the NIC use source data for IMS that can vary in quantity and quality
9 depending on, for example, the satellite coverage. This may cause inconsistency over time
10 (Meier et al., 2015) and some subjectivity will be imposed on the product due to the use of
11 human analysis. For example, occasional large jumps in total extent from one day to the next
12 were discovered; these were likely the result of limited SAR or visible/infrared data and/or
13 limited human resources for analysis.

14 **2.3 Interactive Multisensor Snow and Ice Mapping System (IMS) and** 15 **Multisensor Analyzed Sea Ice Extent (MASIE)**

16 The IMS is an operational ice analysis produced by the NIC daily and valid at 00Z. IMS is an
17 ice and snow mask product where sea ice is indicated when ice concentration is estimated to
18 be greater than 40% and open water where ice concentration is estimated to be less than 40%.
19 Human analysis of all available satellite imagery including visible/infrared (VIS/IR),
20 synthetic aperture radar (SAR), scatterometer, and passive microwave yields a daily map of
21 sea ice extent at 4 km spatial resolution. The IMS documentation (NIC, 2008) lists 28
22 potential sources for snow and ice information. Most, but not all, of these sources are from
23 satellite sensors. The MASIE product documentation (NIC and NDISC, 2010) has additional
24 information on how IMS fields are produced. The IMS ice fields are repackaged into several
25 user-friendly formats to create the MASIE product available to the public from the NSIDC
26 (NIC and NSIDC, 2010). Figure 3 is a sample of a daily MASIE product.

27

28 The IMS/MASIE ice map for any particular day is partially the product of subjective
29 interpretation and is not exactly reproducible. However; each daily IMS/MASIE ice extent
30 fields are produced according to fixed standards and quantified as areal coverage with set

1 metrics. This contrasts with the operational chart products, where the NIC analysts have more
2 flexibility with which to meet changing user needs.

3

4 We base our assertion that the IMS/MASIE product is a more reliable indicator of the
5 presence or absence of ice than AMSR2 data due to several factors. Primarily, the manual
6 analysis of numerous data sources is more dependable than a passive microwave
7 concentration product alone. There are also several situations when the passive microwave's
8 signature is identical to that of open water when sea ice is present (e.g., surface water on top
9 of ice during the summer, thin ice at any time of year) or to that of ice when ice is not present
10 (e.g. "weather effects" from presence of wind/aerosols and "land spillover" from the field of
11 view being partly over land and partly over open water). In addition, NIC analysts have
12 access to data sources that are of higher resolution than AMSR2. These factors lend a higher
13 quality to the IMS/MASIE product.

14

15 Meier et al. (2015), compare passive microwave-derived ice extent with ice extent from
16 IMS/MAISE annually and seasonally. While the magnitude of differences varied from day to
17 day, in general a pattern was found in which IMS/MASIE derived ice extent was larger than
18 that from passive microwave through most of the year, but with two distinct periods – in late
19 spring (May, June) during melt onset, and late summer (late September, October) during
20 freeze-up. These are both periods of rapid transition in surface properties that passive
21 microwave sensors are sensitive to, and likely contributes to these discrepancies. As noted
22 above, some instances were found of unrealistic large changes in IMS/MASIE ice extent over
23 just a day, highlighting the potential inconsistency in the human-based data fusion and
24 analysis. These large changes are likely a result of limited satellite imagery due to satellite
25 coverage (SAR) or clouds (visible/infrared), and/or resources available for the manual
26 analysis.

27

28 In this study, the MASIE product was used in an ACNFS hindcast from July 2012 – July
29 2013, while the IMS product was used in ACNFS and GOFS 3.1 hindcasts from June 2014 –
30 August 2014. As stated above, these two products (MASIE and IMS) are identical in data

1 values but differ in format and location of the data source; MASIE is delivered from the
2 NSIDC, while IMS comes from the NIC.

3 **2.4 Blended IMS/MASIE + AMSR2**

4 Posey et al. (2011) showed improved ice edge results when assimilating high resolution
5 AMSR-E ice concentration field into the ACNFS. Follow on testing provided additional
6 motivation to develop a concentration product that improves upon the use of passive
7 microwave concentration alone by capitalizing on the manual analysis and multiple data
8 sources that make the IMS/MASIE product. In 2012 AMSR2 ice concentration became
9 available in real-time (<https://gcom-w1.jaxa.jp/auth.html>), and, along with the IMS/MASIE
10 product, could be evaluated for daily initialization in order to improve the forecasted ice edge
11 location, especially during the summer season. Both data products (AMSR2 and
12 IMS/MASIE) are available (within 24 hours) for assimilation in daily operational forecasting
13 applications.

14

15 In the initial yearlong study (described in section 3.1), a gridded AMSR2 and MASIE blended
16 product was generated on a 4 km grid and input into NCODA to produce an ice analysis that
17 was then read into CICE. On restart, CICE directly inserts the NCODA analysis of ice
18 concentration and adjusts other fields (e.g., volume and energy of melting for both ice and
19 snow) for consistency. However, in ACNFS, we only use the NCODA ice concentration
20 analysis “near” the ice edge as follows:

- 21 • If model \leq NCODA analysis
 - 22 ○ Use model where NCODA analysis $> 50\%$
 - 23 ○ Blend model and NCODA analysis for concentrations that fall within $25\% <$
24 NCODA $< 50\%$
 - 25 ○ Use NCODA analysis where NCODA analysis $< 25\%$
- 26 • If model $>$ NCODA analysis
 - 27 ○ Use model where model $> 30\%$
 - 28 ○ Blend model and NCODA analysis for concentration that fall within $15\% <$
29 model $< 30\%$

1 ○ Use NCODA analysis for model < 15%.

2 CICE adjusts its water temperature based on the addition or removal of ice. If ice is added to
3 an initially ice free grid cell, the ocean temperature is cooled to prevent the ice from
4 immediately melting. Conversely, if ice is removed from a grid cell that had ice, the ocean
5 temperature is warmed to prevent the model from immediately forming ice.

6

7 The blended product converts ice extent into concentration using the following rules:

- 8 • If IMS/MASIE has no ice and AMSR2 has an ice concentration value, set the
9 ice concentration to 0%
- 10 • If IMS/MASIE indicates ice and AMSR2 has <70% ice concentration for that
11 grid cell, make the ice concentration 70%
- 12 • If IMS/MASIE indicates ice and AMSR2 has an ice concentration value >70%
13 for that grid cell, then use the AMSR2 ice concentration value

14 The IMS/MASIE ice mask has a 40% ice concentration threshold, meaning the actual
15 concentration within each ice cell falls somewhere between 40% and 100%, based on an
16 analyst's subjective estimation. The mid-point, 70%, is used as a reasonable minimum ice
17 concentration value in the blended product. We tested other values, and more sophisticated
18 schemes, but settled on 70% as the overall best approach. Figure 4 shows how ice extent
19 from IMS/MASIE differs from that seen by AMSR2 for representative days in the winter
20 (left) and summer (right) days. While both IMS/MASIE and AMSR2 show ice over most of
21 the Arctic, discrepancies are seen near the ice edge; in most cases IMS/MASIE indicates ice
22 where AMSR2 does not. In winter this is likely due to thin ice that falls below the threshold
23 of detectability by passive microwave sensors. In summer the cause is likely a combination
24 of thin, small ice floes of ice, and surface melt. However, there are some regions where
25 AMSR2 indicates ice but IMS/MASIE does not. This may be due to timing differences of the
26 source imagery (i.e., sub-daily change in the ice cover), spatial resolution limitations of
27 AMSR2, or limitations in the IMS/MASIE analysis.

28

29 Figure 5 shows the final blended AMSR2 and IMS/MASIE ice concentration product during
30 the winter (15 March 2014) and summer (15 September 2014) days of Fig. 4. The magenta
31 "MASIE only" areas of Fig. 4 are assigned a value of 70% (dark blue) in the blended ice

1 concentration product while the green “AMSR only” areas are assigned a value of 0%. There
2 are no ice concentration values between 0% and 70% in the blended product. The
3 homogenous expanses of ice at 70% are more noticeable in the summer when the passive
4 microwave underestimates the extent of ice over large areas. Also note, that the AMSR2
5 “land spillover” effect of false detection that can occur along coasts is mitigated by the
6 IMS/MASIE ice mask product. Some of the areas shown in green in Fig. 4 can be attributed
7 to land spillover.

8

9 **3 Assimilation study and results**

10 **3.1 ACNFS assimilating AMSR2 ice concentration and MASIE ice mask**

11 For this study, ACNFS assimilated three different sources of sea ice concentration for the
12 time period July 2012 through July 2013: 1) SSMIS only, 2) AMSR2 only and 3) blended
13 AMSR2 + MASIE. All three products used the same assimilation methodology to update the
14 initial ACNFS fields. The 6-hour forecast ice edge derived from ACNFS hindcasts of sea ice
15 concentration assimilating the three different products was compared to the independent ice
16 edge obtained from the NIC valid 00Z. The NIC analyzed ice edge product is generated
17 daily by an ice analyst for the full Arctic region using a variety of satellite sources (visible
18 images, infrared, scatterometer, SAR and passive microwave data) and defines the ice edge as
19 areas of < 10% sea ice concentration. In this product (Fig. 6 – black dots), the presence of
20 any known ice is used to determine an edge location as this product is used for navigational
21 purposes to avoid nearly all ice hazards. The location of the ice edge can shift based on the
22 resolution of the data sources. The IMS product (Fig. 6 – blue contour) is also generated by
23 an ice analyst, but it is generated as a gridded field that may provide more spatial detail at
24 smaller scales. The NIC ice edge product and IMS product are independently derived and
25 typically apply differing data sources. Although the NIC ice edge is one of the products
26 examined during the IMS ice analysis, the criteria for the IMS ice extent is different than the
27 NIC ice edge; the NIC ice edge can only provide an ice limit, whereas IMS provides a 4 km
28 estimate of areas with >40% ice cover. Over the last 10 years, the NIC ice edge has been
29 used for model ice edge validation, and will continue as part of this study since the NIC ice
30 edge is not assimilated into ACNFS or GOFS 3.1.

31

1 The daily mean distances between the independent daily analyzed NIC ice edge and derived
2 model ice edges from all ACNFS hindcasts were compared during the 13-month time period.
3 Model ice edge locations are defined as those grid points that exceed a certain threshold value
4 for ice concentration and that also have a neighboring point that falls below that value. In this
5 case a threshold of 5% was used to determine the model ice edge. The distances between each
6 NIC observed point and the nearest model-derived ice edge location were then calculated,
7 from which a daily mean was computed for each model day. Six analysis regions in the Arctic
8 were compared (Fig. 7). Table 1 contains the regional mean distance difference (km) between
9 the NIC ice edge and ACNFS assimilating SSMIS, AMSR2 only, and the blended AMSR2 +
10 MASIE. The last row is the percent improvement in ACNFS assimilating the new products
11 for the entire Arctic. During this 13-month time period, the mean distance between the
12 ACNFS ice edge using the SSMIS as initialization and the NIC ice edge was 45 km for the
13 full Arctic domain, compared to 32 km for the ACNFS ice edge initialized using AMSR2.
14 This is a 29% reduction in error by assimilating the higher resolution AMSR2 ice
15 concentration compared to using SSMIS alone. ACNFS assimilating the blended (AMSR2 +
16 MASIE) product showed a larger reduction in overall mean ice edge errors by 36% compared
17 to ACNFS assimilating SSMIS alone (29 km vs. 45 km). The slightly higher error for
18 AMSR2 only assimilation could result from anomalous concentration values along the coastal
19 boundaries (shown in Fig. 4). With the addition of the MASIE product, the AMSR2 coastal
20 spillovers are reduced as shown in the ice edge errors (32 km to 29 km for the full Arctic
21 domain).

22

23 Table 2 shows the seasonal sea ice location errors initialized from SSMIS, AMSR2 and the
24 blended product were also examined for the same time period. During the winter time period
25 (January – April), ice edge locations for the Arctic region were similar assimilating the
26 different data products (29 km using SSMIS only, 22 km using AMSR2 only and 20 km using
27 the blended product). During the summer melt season (June – September), the errors were
28 larger (75 km using SSMIS only, 55 km using AMSR2 only and 33 km using the blended
29 product). The reduction in ice edge error locations are greater during the summer period
30 (August-September) as shown in Fig. 8 for the Bering/Chukchi/Beaufort Sea region.
31 Assimilating the blended product into the ACNFS, especially during the summer,

1 significantly reduced the ice edge errors and therefore improve the accuracy of the model ice
2 edge location.

3 **3.2 ACNFS and GOFS 3.1 assimilating AMSR2 ice concentration and IMS ice** 4 **mask**

5 In order for the operational ACNFS and GOFS 3.1 to assimilate the AMSR2 and IMS data
6 sources, these two products must be available daily in real-time at NAVOCEANO. Since
7 October 2014, NAVOCEANO has successfully implemented these real-time sources into the
8 daily data stream. In the second hindcast study, rather than assimilating a blended AMSR2 +
9 IMS gridded product as was done previously, AMSR2 ice concentration swath data and IMS
10 were implemented separately. The initial data assimilation step was based on AMSR2 and
11 SSMIS swath data and the model's 24-hr forecast from the previous day as background for
12 input into NCODA. The resulting gridded ice concentration analysis is then blended, using
13 the same technique as described in section 2.4, with the IMS (interpolated to the model grid)
14 to form the ice concentration field assimilated into CICE. ACNFS uses the direct insertion
15 only near the ice edge scheme described previously. GOFS 3.1 uses a similar scheme near the
16 ice edge but in addition it uses the analysis + 10% if the model is above this value and
17 analysis - 10% if the model is below this value.

18

19 An additional ACNFS hindcast and an original GOFS 3.1 hindcast were performed to test the
20 accuracy of assimilating the real-time NAVOCEANO data feed. These ACNFS and GOFS
21 3.1 hindcasts were integrated from June 1 – August 31, 2014 using the real-time
22 NAVOCEANO feed. As in the earlier test, the same ice edge error analysis was performed.
23 Two additional ACNFS simulations were run assimilating 1) AMSR2 + SSMIS and 2)
24 AMSR2 + SSMIS with IMS. These last 2 hindcasts measure the effect of keeping the current
25 coarser SSMIS as an assimilation data source. The assimilation study for GOFS 3.1 included
26 assimilating 1) AMSR2 with IMS and 2) AMSR2 + SSMIS with IMS. All results are shown
27 in Table 3. The regional results are tabulated for completeness, but the discussion below
28 focuses on the full Arctic domain.

29

30 During this 3 month time period, the mean ice edge distance between the ACNFS ice edge
31 using the SSMIS as initialization and the NIC ice edge was 61 km for the full Arctic,

1 compared to 44 km for the ACNFS ice edge initialized using the AMSR2. This results in a
2 28% reduction in error by assimilating the higher resolution AMSR2 ice concentration as
3 compared to the SSMIS alone. Assimilating both AMSR2 and SSMIS ice concentrations into
4 ACNFS lowered the mean ice edge error compared to assimilating SSMIS alone (on average
5 61 km to 46 km), an overall improvement of 25%. The largest reduction in mean ice edge
6 error occurred when the IMS blending technique was assimilated into ACNFS for both
7 AMSR2 and SSMIS. This resulted in a 56% reduction in ice edge error (on average, 61 km to
8 27 km). Similar to ACNFS, GOFS 3.1 had significant improvement in ice edge location for
9 the entire Arctic (64 km vs. 25 km, 62%) assimilating both the AMSR2 and SSMIS along
10 with the IMS ice concentration products over SSMIS alone.

11

12 In the operational ACNFS and GOFS 3.1 jobstreams, both SSMIS and AMSR2 data are
13 received in swath format and could intermittently have missing data. Because the ice edge
14 errors are nearly identical for ACNFS (27 km) and GOFS 3.1 (25 km) between 1) AMSR2
15 and IMS and 2) AMSR2+SSMIS and IMS, assimilating both AMSR2 and SSMIS data
16 sources into ACNFS and GOFS 3.1 will be beneficial if either source has missing data.

17

18 **4 Conclusions and future plans**

19 Previously, both ACNFS and GOFS 3.1 only assimilated near real time sea ice concentration
20 derived from SSMIS. SSMIS ice concentration data are available daily and are used to update
21 the initial ice concentration analysis field only near the model ice edge. As the model
22 resolution has increased, the need for higher resolution observational fields has become very
23 important. A method of blending ice concentration observations from AMSR2 and
24 IMS/MASIE has been developed resulting in an ice concentration field with a very high
25 spatial resolution of 4 km. In this study, the blended AMSR2/IMS product was interpolated to
26 the ACNFS and GOFS 3.1 grids (3.5 km resolution near the pole) and assimilated to create
27 the initial conditions for each ACNFS and GOFS 3.1 model run. Once assimilated, sea ice
28 concentration forecasts were compared to the model runs initialized from the coarser
29 resolution SSMIS data. The ACNFS initialization study was performed for two periods: 1)
30 July 2012 - July 2013 and 2) June – August 2014, while the GOFS 3.1 initialization study was
31 performed during the latter period only. The daily mean ice edge location distance difference
32 between the NIC ice edge location and the ice edge obtained from ACNFS and GOFS 3.1

1 initialized using both SSMIS and AMSR + IMS/MASIE data sets was calculated. Daily
2 analyses of the ice edge location in both studies indicated that ACNFS and GOFS 3.1
3 initialized using the both AMSR2 and SSMIS + IMS/MASIE data sets have substantially
4 lower ice edge errors than the ACNFS and GOFS 3.1 initialized using the coarser SSMIS
5 data. ACNFS initialized using the blended AMSR2 + IMS/MASIE product improves the
6 ACNFS predicted ice edge location by 56%, while GOFS 3.1 showed an improvement of
7 62%.

8

9 The blended technique described in this paper is the initial methodology for implementing the
10 IMS/MASIE and AMSR2 data products into the operational ice forecast systems. Research is
11 currently underway to develop improved methods to assimilate these new data sources along
12 with other products (i.e., VIIRS ice concentration) that will adjust the ice and ocean fields
13 within the NCODA framework.

14

15 This analysis has shown that assimilating a higher horizontal resolution, blended AMSR2 +
16 IMS/MASIE ice concentration product yields a more accurate ice edge forecast. While
17 including the SSMIS ice concentration field (AMSR2 + SSMIS along with IMS/MASIE) did
18 not reduce the ice edge error in ACNFS or GOFS 3.1, it could prove to be beneficial if
19 AMSR2 data becomes unavailable. For operational forecasting, the current SSMIS ice
20 concentration real-time data source will still be utilized in addition to the AMSR2 ice
21 concentration and the IMS ice mask for daily use. On 02 February 2015, these two new data
22 sources (AMSR2 and IMS) were added to the operational ACNFS and the pre-operational
23 GOFS 3.1 jobstreams.

24

25 **Acknowledgments**

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27 computers at Stennis Space Center, Mississippi, using grants of computer time from the DoD
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29 Charles Perry, and Keith Willis for implementing the real-time feed of the AMSR2 and IMS
30 data sources at NAVOCEANO. Thanks also to Bruce Lunde (NAVOCEANO) for adding the
31 AMSR2 data source into the operational NCODA.

32

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1 Table 1. Regional mean distance differences (km) between the NIC ice edge and 6-hour
 2 ACNFS forecasts initialized from SSMIS, AMSR2 only and blended AMSR2 + MASIE.
 3 Analysis is done for time period July 2012 – July 2013. The bold numbers denote the
 4 smallest mean distance error between the assimilation test cases. The bottom row shows the
 5 total Arctic percent improvement from each ice forecasting system compared to using SSMIS
 6 assimilation alone.

Region	ACNFS w/ SSMIS	ACNFS w/ AMSR2 only	ACNFS w/blended AMSR2 + MASIE
GIN Seas	37 km	27 km	28 km
Barents/Kara Sea	28 km	22 km	20 km
Laptev Sea	66 km	49 km	46 km
Sea of Okhotsk	42 km	30 km	19 km
Bering/Chukchi/Beaufort Seas	63 km	40 km	33 km
Canadian Archipelago	53 km	37 km	39 km
Total Arctic	45 km	32 km	29 km
Percent improvement over SSMIS		29%	36%

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1 Table 2: Seasonal mean distance differences (km) between the NIC ice edge and 6-hour
 2 ACNFS forecasts initialized from various combinations of SSMIS, AMSR2 and IMS data for
 3 the time periods January-April and June – September. The bottom row shows the total Arctic
 4 percent improvement from each ice forecasting system compared to using SSMIS
 5 assimilation alone. The Laptev Sea is fully ice covered in the winter season and no ice edge
 6 analysis was performed.

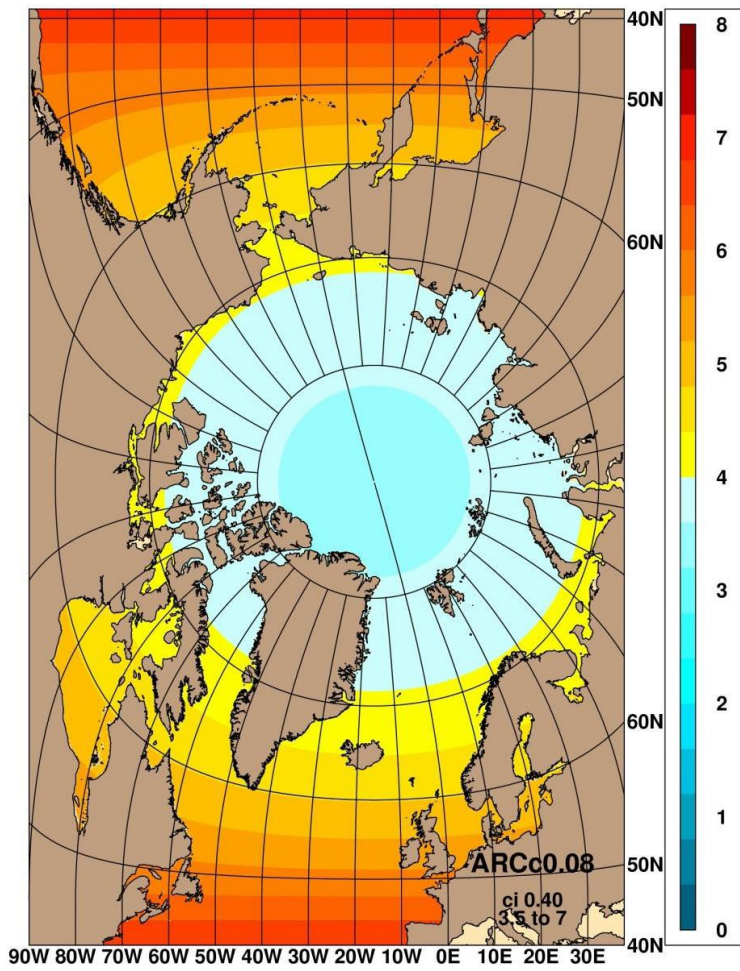
Region	January - April			June - September		
	ACNFS w/ SSMIS	ACNFS w/ AMSR2	ACNFS w/blended AMSR2 + MASIE	ACNFS w/ SSMIS	ACNFS w/ AMSR2	ACNFS w/blended AMSR2 + MASIE
GIN Sea	33	24	26	46	29	20
Barents/Kara Seas	16	14	13	37	29	19
Laptev Sea	-	-	-	94	78	43
Sea of Okhotsk	33	25	16	62	51	20
Bering/Chukchi/Beaufort	22	16	13	116	84	45
Canadian Archipelago	29	25	22	65	48	36
Total Arctic	29	22	20	75	55	33
Percent improvement over SSMIS	---	24%	32%	---	26%	55%

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1 Table 3: Regional mean distance differences (km) between the NIC ice edge and 6-hour
 2 ACNFS or 12-hour GOFS 3.1 forecasts initialized from various combinations of SSMIS,
 3 AMSR2 and IMS data for the time period June – August 2014. The bottom row shows the
 4 total Arctic percent improvement from each ice forecasting system compared to using SSMIS
 5 assimilation alone.

Region	ACNFS					GOFS 3.1		
	SSMIS	AMSR2	AMSR2 and IMS	AMSR2 + SSMIS	AMSR2 + SSMIS and IMS	SSMIS	AMSR2 and IMS	AMSR2 + SSMIS and IMS
GIN Sea	64	35	21	37	21	72	19	19
Barents/Kara Seas	45	31	24	31	24	47	22	22
Laptev Sea	49	41	25	43	25	59	24	24
Bering/Chukchi/Beaufort	54	38	24	40	24	57	22	22
Canadian Archipelago	74	60	35	63	35	83	31	31
Total Arctic	61	44	27	46	27	64	25	25
Percent improvement over SSMIS	---	28%	56%	25%	56%	---	62%	62%

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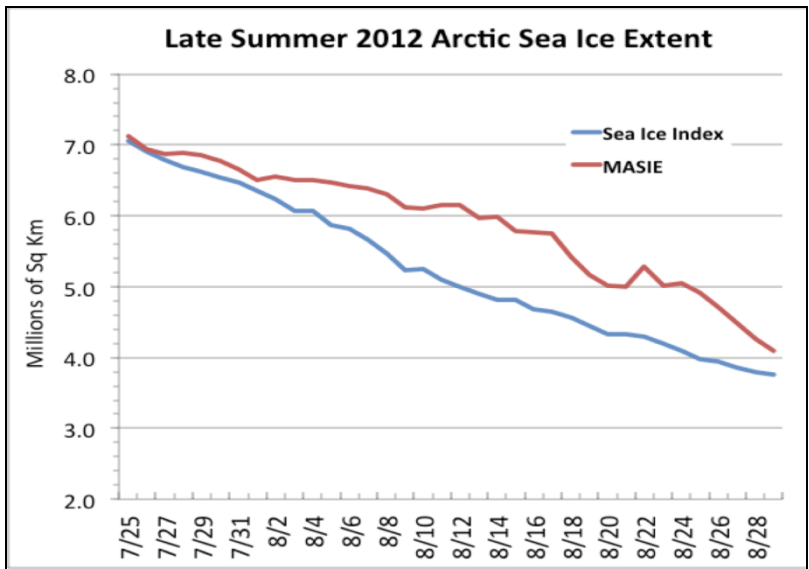


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3 Figure 1. ACNFS and GOFS 3.1 model grid resolution (km) for the Arctic region.

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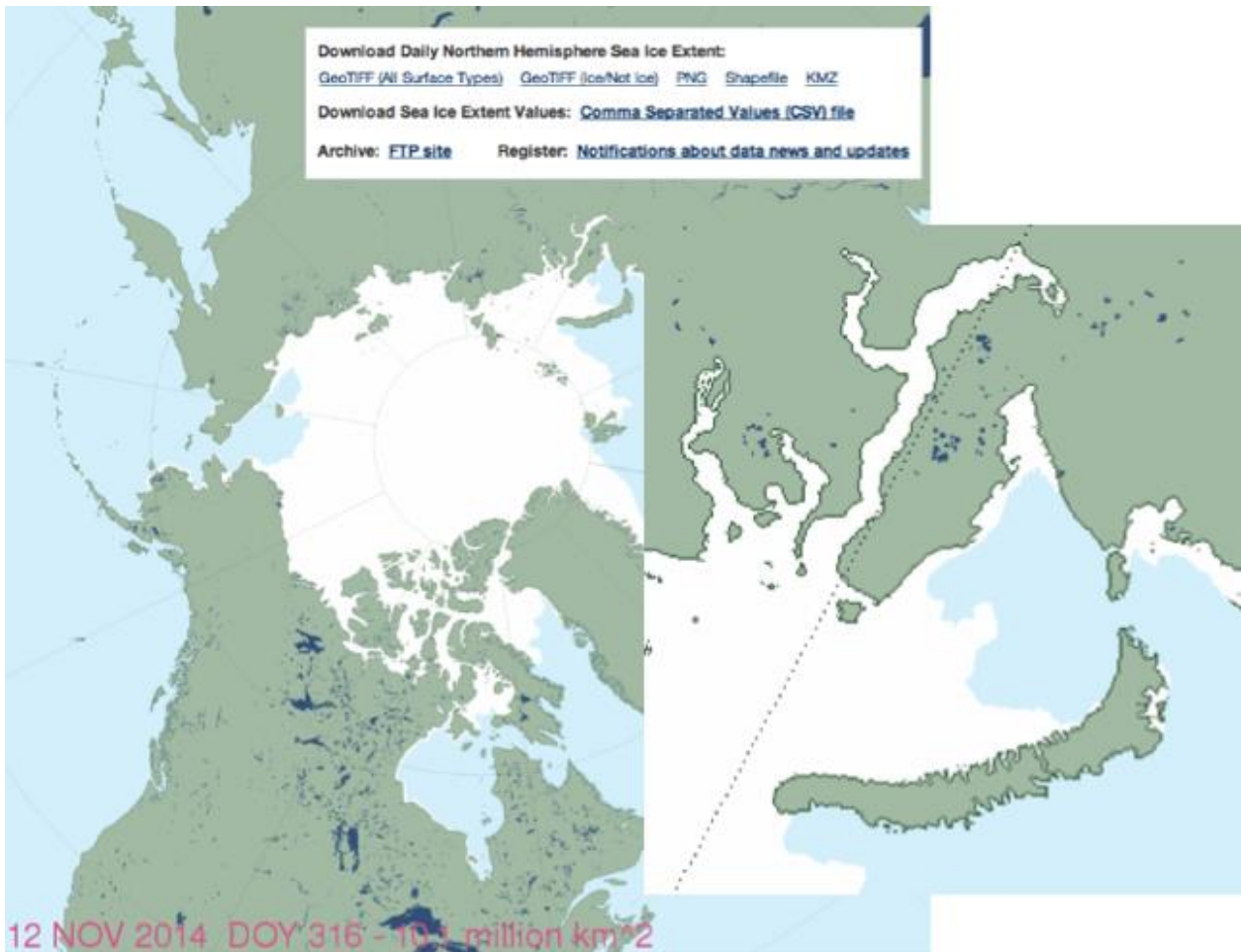


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3 Figure 2. Arctic sea ice extent (Mkm²) calculated using passive microwave data (blue) and the
 4 Multisensor Analyzed Sea Ice Extent (MASIE) product (red) for 25 July – 28 August 2012.
 5 The passive microwave data are from the SSMIS on board the DMSP F17 satellite.

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3 Figure 3. Sample MASIE product (with zoomed Kara Sea region inset on right) valid 12
4 November 2014. White indicates ice covered areas.

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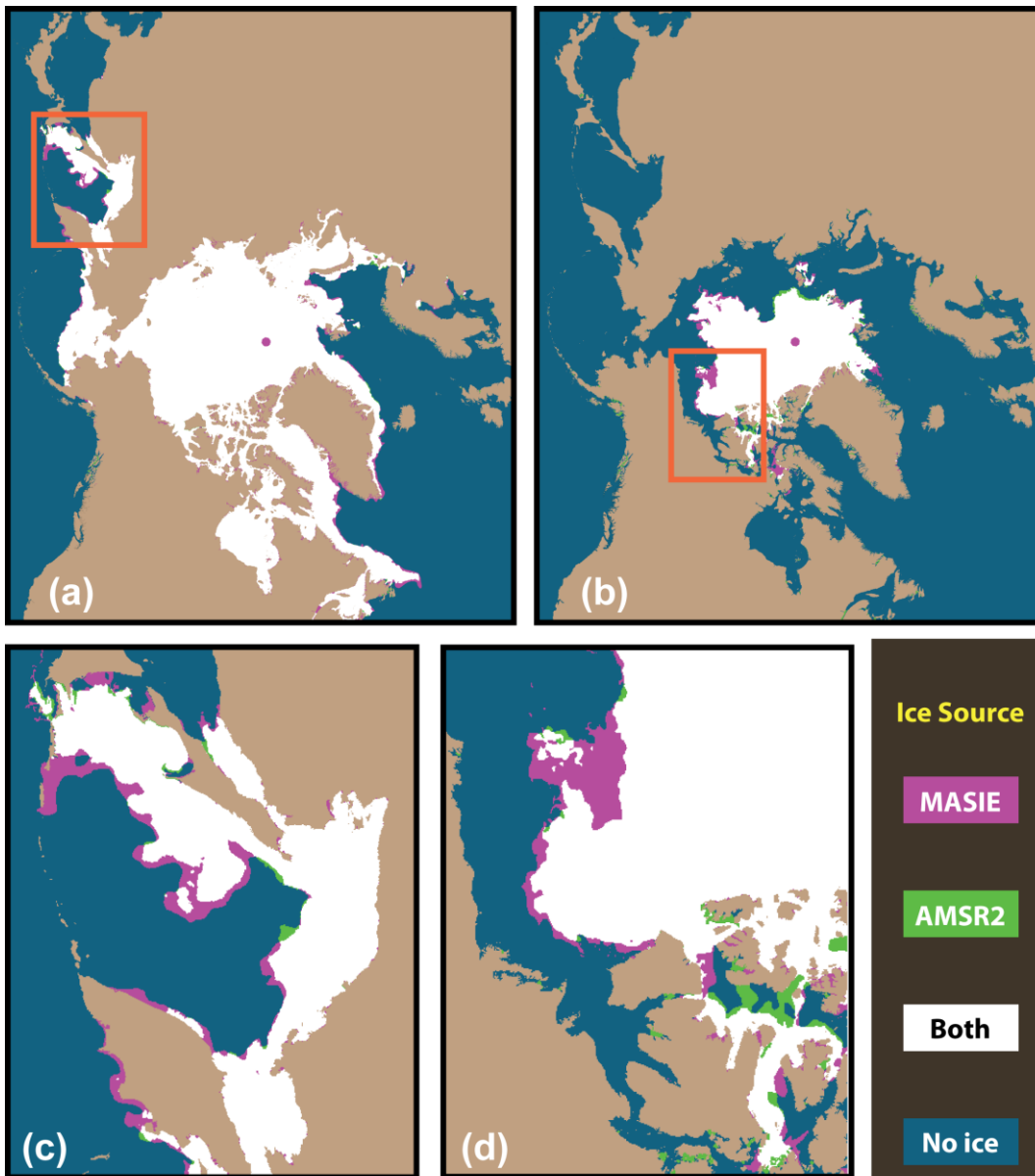
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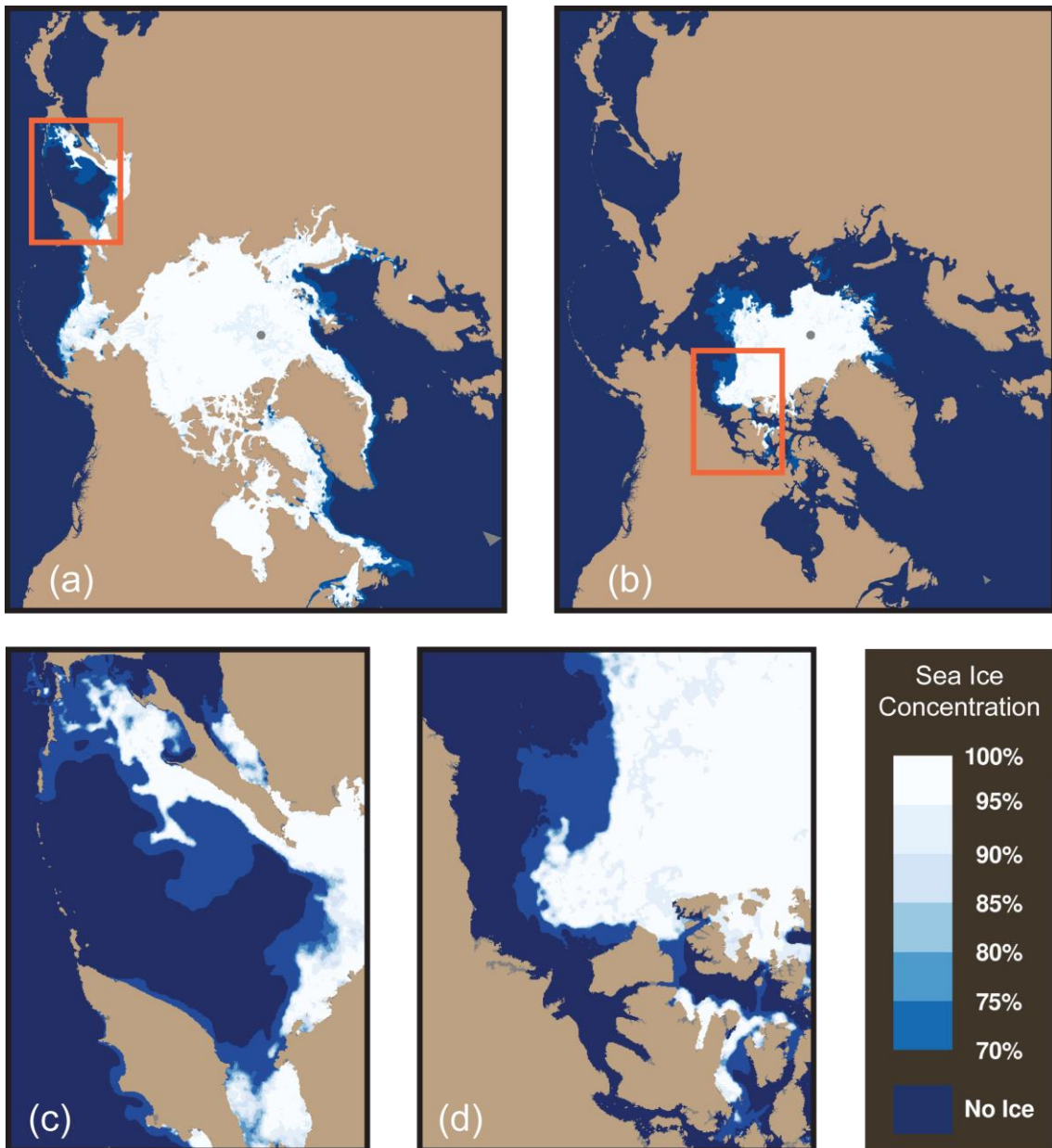
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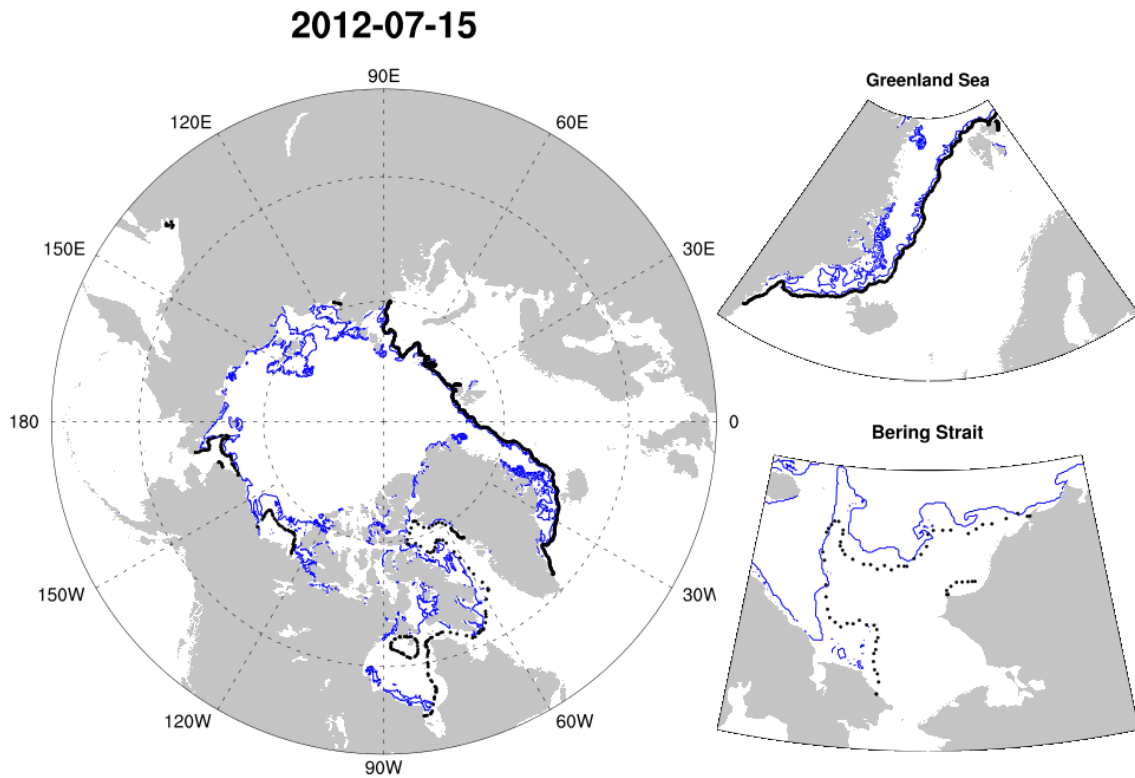
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3 Figure 4. AMSR2 and IMS/MASIE ice extent differences during (a) 15 March 2014 - winter
 4 and (b) 15 September 2014 - summer. Magenta: IMS/MASIE shows ice where AMSR2 does
 5 not show ice greater than 15%. Green: AMSR2 shows ice where IMS/MASIE does not.
 6 White: Both indicate ice. Blue: Both indicate no ice. A closer view of the Sea of Okhotsk
 7 region in winter (c) illustrates where the passive microwave data is failing to detect thin ice
 8 around the Kamchatka Peninsula and near the ice edge in the Sea of Okhotsk. The much
 9 smaller areas where AMSR2 sees ice and IMS/MAISE does not (shown in green), may be due
 10 to a mismatch in data acquisition time. The Beaufort Sea on this day in summer (d) has a
 11 large expanse of ice not detected by the AMSR2 data.

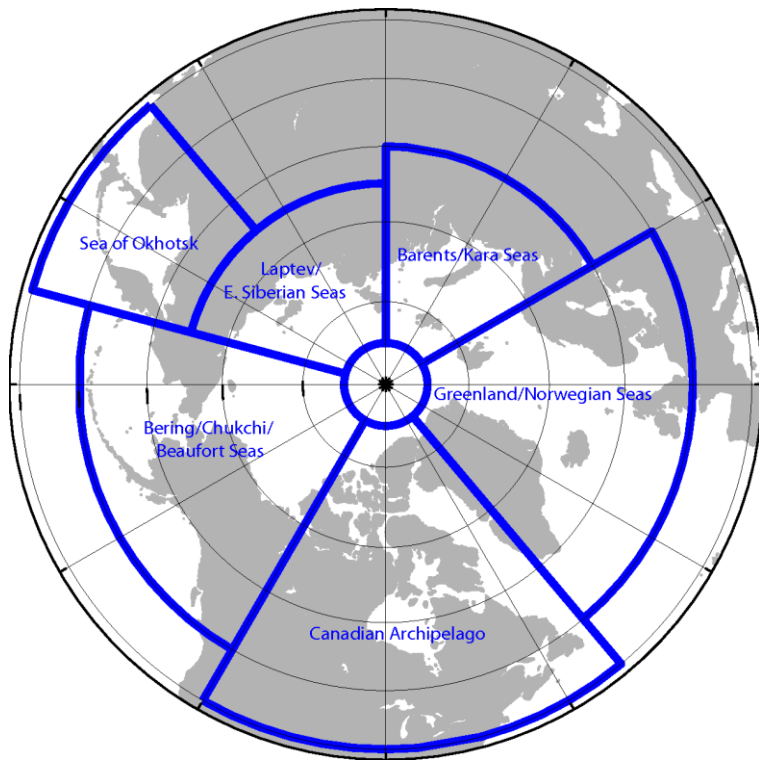


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Figure 5. AMSR2 and IMS/MASIE blended ice concentration (%) product for (a) 15 March 2014 – winter and (b) 15 September 2014 – summer. If IMS/MASIE and AMSR2 indicate ice, then the greatest of 70% or the AMSR2 ice concentration value is used. If IMS/MASIE indicates ice and AMSR2 has none, then 70% (light blue) is used as ice concentration value. The zoomed areas (c) and (d) can be compared with (c) and (d) in Fig. 4 to see the effect of filling with 70% in the blended product. Note the detail in the Beaufort Sea ice edge. A prototype version of the blended product is available from NSIDC (Fetterer et al, in preparation).



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 2 Figure 6. Ice edge location for 15 July 2012 from the NIC (black dots) and the IMS/MASIE
 3 (blue line) products for the full Arctic (left) and zoomed areas of the Greenland Sea (upper
 4 right) and the Bering Strait (lower right). The black dots represent the presence of any known
 5 ice and is used to determine a conservative edge location. The blue line represents a gridded
 6 field (4km with >40% concentration) that may provide more spatial detail at smaller scales.

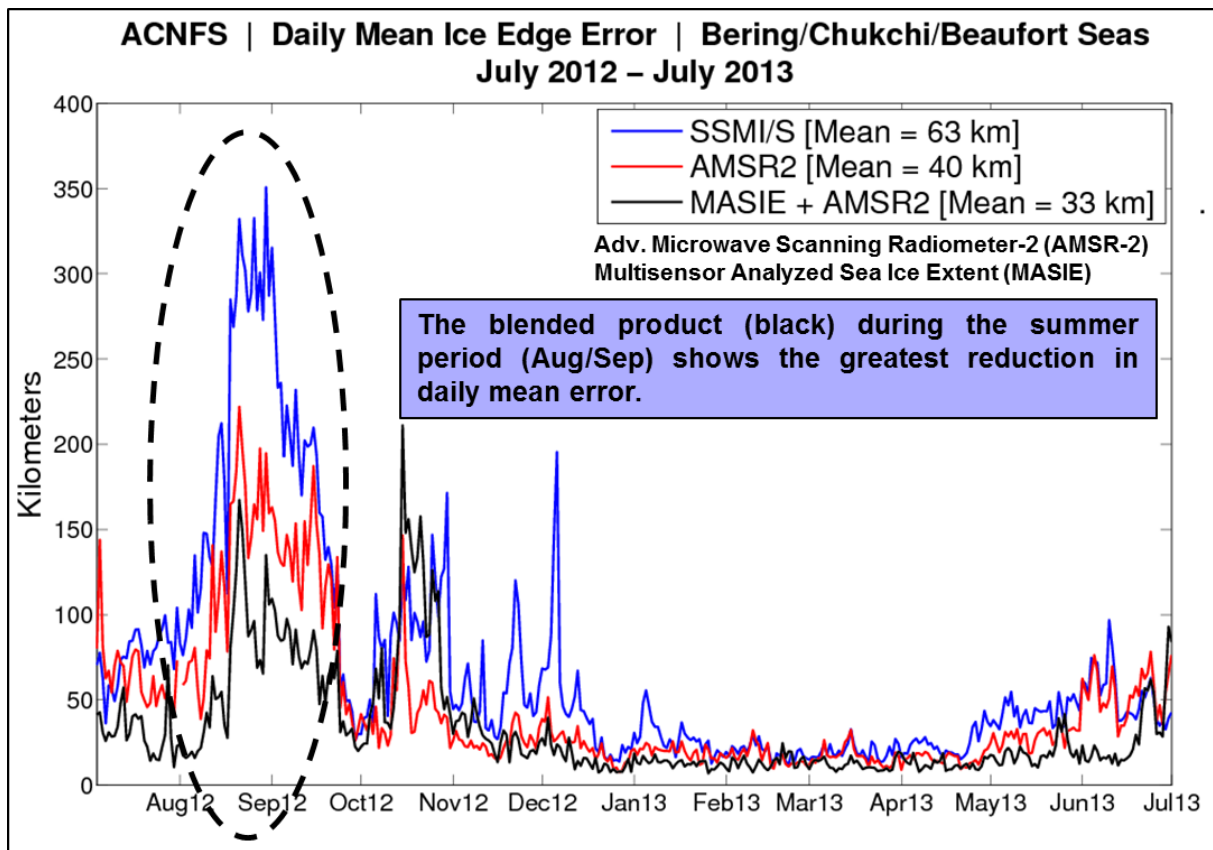


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3 Figure 7. Analysis regions used for the NIC ice edge comparison shown in Table 1, 2 and 3.

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3 Figure 8. Daily mean error (km) for the Bering/Chukchi/Beaufort Seas versus time for
 4 ACNFS ice edge (define as the 5% ice concentration) against the independent ice edge
 5 analysis from the NIC over the validation period 1 July 2012 – 1 July 2013. The blue line is
 6 using SSMIS assimilation only, the red line is using AMSR2 assimilation only, and the black
 7 line is using the blended AMSR2 + MASIE assimilation.