24 July 2015

Addressing the revisions recommended by the Reviewer #1 (author's response are in **bold**):

Anonymous Referee #1

Received and published: 26 April 2015

GENERAL COMMENTS The authors present a method to create a blended high resolution sea ice concentration product from AMSR2 and MASIE/IMS and model results from US Navy's sea ice forecasting system (in hindcast mode) that assimilates this newly developed blending concentration data. This newly blended data includes information of human analysis, and has a very high horizontal resolution of 4km, and hence are well suitable for using in the forecasting model of the Arctic Ocean with the high horizontal resolution. Comparing with the independent NIC data, the new assimilation decreases the predicted sea ice edge error significantly. In recent years, US Navy updated its operational system from PIPS to ACNFS. This paper describes their latest advances over an earlier sea ice concentration data assimilation used in their operational system. This manuscript is well written, and the results are clearly presented. Although the paper is quite technical, I think the focus on improving high resolution sea ice edge forecast using this innovatively high resolution sea ice concentration data justifies publication in TC.

However, some points should be addressed before publication: 1) In the Introduction, the US Navy's forecasting system is described in too many details.

> **The system information has been moved from the introduction to section 2 (renamed to "System descriptions, data and methods").**

But for a scientific publication, it would be also helpful to add some overview of the advances of the sea ice data assimilation in the current scientific community.

> **While such a discussion could be useful, we think that including this information is not pertinent and too tangential to the scope of this paper.**

At present, there are already a lot of sea ice data assimilation method and related research, e.g., nudging, OI, 3D-Var and EnKF, why you still use this simple approach of weighting technique? Is this method particularly suitable for your operational use?

> **Text was added in the manuscript (section 2.4) describing the assimilation technique in more detail. It's a 2 step process: 1) reading in ice concentration observations (AMSR2/blended product) into NCODA (3DVAR) that produces an ice analysis, and 2) which then gets read into CICE where the concentration is blended with the model ice concentration along the ice edge. This simple methodology has been used in the past forecast systems and is continued here.**
>
> **We will soon be developing a more advanced technique for assimilating the IMS sea ice mask (along with new data sources, i.e. VIIRS) within NCODA. During this time, the blending that is currently implemented within CICE will be moved into NCODA. Adjustments to other ice variables will also be investigated in this work.**

Further, I would suggest the authors to re-organize the structure of the paper, e.g., to move the description of the forecasting system from the “introduction” to the “data and methods”.

Done.

2) In Part 2 and Figure 5, you show that the blended concentration varies from 70% to 100%, and there are no concentration values below 70%. Is this a reasonable approach? Could this method introduce additional errors to the model? E.g., it seems not realistic that the concentration data within the sea ice edge are as high as 70% in the blended data, but you fuse this information into your model.

The second to the last paragraph of Section 2.4 now addresses this topic. We tested other values, and more sophisticated schemes, but settled on 70% as the overall best approach.

3) In Part 3, more details of assimilation method is strongly required in the MS. Do you update the ice thickness and water temperature during the initialization? Is this initialization introduces inconsistency to your model physics?

More details on the assimilation were added in section 2.4. It is a well-known disadvantage of 3D-VAR that it always introduces an unbalanced state. However we have not seen any large consequences from this even though we are using direct insertion of the analyzed ice concentration. The other prognostic fields are updated based on the new ice concentration. SST is only adjusted when switching between ice free and ice covered or visa versa.

4) In Part 3, you show the substantial improvements in the sea ice edge area, but besides this, sea ice concentration and ice thickness are also very important information for the forecasting use. So how about the sea ice concentration change in the sea ice edge area? Can you also compare your results with some other sea ice concentration data set, for example, NSIDC, OSISAF, ESA CCI or ice analyze charts from Canada. It would be also interesting to investigate the effect on the sea ice thickness. Can the new assimilation further improve the ice thickness forecast over the earlier approach? I notice that you had done such comparison in Posey et al. (2010),so in this MS, I would suggest you also do such comparison with in-situ observations ,especially in the sea ice edge area. If you cannot show the improvements in the sea ice concentration and thickness, I would suggest you change the title of the MS to show the limit of this data assimilation study, e.g., Improving the Arctic sea ice edge forecasts by assimilating high resolution sea ice concentration data into the US NAVY’s ice forecast systems.

We agree that further testing could be done to show the improvements of other forecast fields such as ice concentration and ice thickness but for this paper we focused on the improvements of the ice edge error, which is of importance to the Navy. Because of this, as suggested, we changed the title of the paper.

SPECIFIC COMMENTS:

1) Page 2349, line 4, “difference” should be “different”

Done.

2) Page 2350, line 12, (29 vs. 45 km, a “)” is missed.

Done.

3) Page 2362, the color bar in Figure 5 is not clear. Please redraw this figure.

We re-made both figures 4 and 5 to ensure both plots and legends are more readable.

24 July 2015

Addressing the revisions recommended by the Reviewer #2 (author's response are in **bold**):

Anonymous Referee #2
This paper introduces an interesting approach to blending observations from different sources and resolutions to initialize coupled sea ice-ocean forecast models. The improvements made to ice edge forecasts is impressive and it would be good to see ongoing improvements of this magnitude.

The paper could be improved/made more useful by providing additional information about the observation data handling,

> **Section 2.2 describes the passive microwave data sources. These ice concentration products are simply used as gridded input into NCODA. In section 2.4 these ice concentration products are used as gridded input to NCODA. In section 3.2 we briefly describe the real time data handling.**

the assimilation methodology

> **Text was added in the manuscript (section 2.4) describing the assimilation technique in more detail. It's a 2 step process: 1) reading in ice concentration observations (AMSR2/blended product) into NCODA (3DVAR) that produces an ice analysis, and 2) which then gets read into CICE where the concentration is blended with the model ice concentration along the ice edge. This simple methodology has been used in the past forecast systems and is continued here.**
>
> **We will soon be developing a more advanced technique for assimilating the IMS sea ice mask (along with new data sources, i.e. VIIRS) within NCODA. During this time, the blending that is currently implemented within CICE will be moved into NCODA. Adjustments to other ice variables will also be investigated in this work.**

and the ice edge verification.

> **The ice edge verification is described in the second paragraph in section 3.1.**

A clear understanding of these would allow the reader to better understand the results presented.

In addition, the term resolution is used rather loosely to describe the various observations and greater rigour is advised.

> **Text has been added in the second paragraph in the Introduction to more precisely describe the resolution of the satellite data. In addition, text has been added in the second paragraph of section 2.2 to discuss the resolution of SSMIS, AMSR-E and AMSR2.**

Lastly, the results are presented without significant discussion about the sources of error or how these might be overcome in future.

The issues with passive microwave data are described in section 2.2. This is the reason we added IMS/MASIE into the assimilation scheme. This paper focused on ice edge error and, unfortunately, there are no uncertainty estimates of the independent NIC ice edge at this time.

P 2 L 20 and 21: numbers or references should be provided to clarify 'high year-to-year variability' and 'rapidly changing Arctic environment'

References have been added in paragraph 1 in the Introduction.

P 3 L 10: the term 'determined' is vague and should be replaced by observed or analyzed as appropriate –

Changed 'determined' to 'analyzed' in the last paragraph of section 2.1.

P 3 L 24: the resolution of SSMIS is frequency dependent so it would be helpful to indicate which channel has a resolution of 25 km and this should be relevant to the sensor's use for this application –

This has been addressed in the 2nd paragraph of the introduction.

P 3 L 28: the IMS acronym and reference should be indicated here and not repeated on page 5 lines 21-22

This specific text has been re-arranged and we have taken care to properly define all acronyms.

P 4 L 1: 'into the both' should be 'into both'

Done.

P 4 L 17-19: higher gridding resolution is not equivalent to higher resolution observations. The ice concentration retrieval algorithm that is being used should be identified and the resolution of the channels used should be provided

Text has been added in the second paragraph in the Introduction to more precisely describe the resolution of the satellite data. In addition, text has been added in the second paragraph of section 2.2 to discuss the resolution of SSMIS, AMSR-E and AMSR2.

P 5 L 6-7: it would be helpful to identify the 'human-analysis-based product' here

Identified this product as MASIE/IMS in the last paragraph of section 2.2.

P 5 L 21: insert ’using’ before the Interactive

This sentence has been reworded.

P 5 L 22: should indicate the valid time of the IMS product or indicate if it is a daily average product. This has significance to the later results.

A statement has been added concerning the valid time of the IMS product.

P 5 L 25: insert satellite before imagery

Done

P 5 L 26-27: suggest removing the remainder of the sentence beginning with ’with a 40% ..’

This has been removed.

P 6 L 12: should indicate the source of the AMSR2 ice product

AMSR2 website information has been added in the first paragraph of section 2.4.

P 6 L 15: the term ’modeled forecast’ seems redundant –

Done

P 7 L 16-26: further details on the assimilation methodology would be helpful such as whether the ocean is adjusted according to the initial ice concentration, how the ice thickness is specified and how the weighting works.

More details on the assimilation methodology were added in section 2.4.

P 7 L 19: ’near the ice edge’ refers to the model ice edge?

This text has been removed from the manuscript.

P 7 L 25-26: what is the NCODA ice analysis and is there a reference**?**

This text has been removed from the manuscript. The NCODA reference is Cummings and Smedstad (2014) which is indicated in the first paragraph of section 2.1.

P 8 L 1: why is such a short forecast period used? It would be more instructive to see how the forecast error changes with forecast duration.

The results discussed in the paper were from a hindcast that stepped forward a single day at a time. Longer forecasts were not performed. In the GOFS 3.1 Validation Test Report (Metzger et al, 2015), ice edge error as a function of forecast length (out to 5 days) was examined. Ice edge error growth as a function of forecast length in GOFS 3.1 was small. Average ice edge error at the 12-hr forecast was 32.6 km and 36.6 km at the 132 hr forecasts. This 4 km difference is approximately equivalent to a single model grid point.

P 8 L 3: is there a reference for the NIC ice edge product?

There is no reference for the ASCII ice edge location.

How is the ice edge defined?

Text has been added in the first paragraph of section 3.1 that defines the NIC ice edge as the 10% isoline.

What is its valid time and is it an analyzed edge or a nowcast edge**?**

Text has been added in the first paragraph of section 3.1 that defines the valid time at 00Z and we also indicate that it is an analyzed product.

P 8 L 6: what is meant by ’conservative edge location’?

This statement has been reworded.

P 8 L 8: what is meant by ’buffer’?

This sentence has been reworded.

P 8 L 10-11: it seems odd that the NIC ice edge product and NIC IMS product use different data sources and that they are independent

The two NIC products are derived using different data sources and define different ice edges. While some of the data sources are the same, the NIC has maintained that these two products are independent.

The daily ice edge product is used to warn navigators and others in arctic sea where ice exists or is likely to form at any concentration. The daily ice edge product edge is always outboard of the IMS/MASIE edge. The NIC's weekly ice charts and ice edge products have marine transportation interest as primary users, while the IMS product is designed primarily for modelers.

P 8 L 19: ’observed’ should be replaced with analyzed or nowcast

Done.

P 8 L 23: how sensitive is the choice of a 5% threshold and is this consistent with the verifying data? It has been indicated that the model is never initialized with ice concentrations between 0 and 70%

> **Previous research has shown that using the 5% isoline produced lower ice edge error than using isolines of higher concentration, thus we continue to use this value. Sensitivity studies were not performed varying this threshold.**

P 8 L 23-25: more detail and a reference would be helpful here. For instance, how closely spaced are the 'NIC observed points' and is this consistent along the edge?

> **There is no reference for the NIC ice edge ASCII product. We added text in the first paragraph of section 3.1 to indicate the data sources used to produce this product. As indicated in the inset of figure 6, the spacing varies along the NIC ice edge.**

How are potential problems related to shore leads and patchy ice dealt with?

> **This was not considered in this study.**

Are the results the same if you measure the distance from the model edge to the NIC ice edge?

> **This is how we determine the ice edge errors.**

P 8 L 25: the results for the 6 regions are never discussed.

> **These results are not discussed in the text but are shown in the tables for completeness.**

P 8 L 30 and onward: while these improvements are impressive, the actual error seems incredibly large especially for a 6 hour forecast. To better understand this error, it would be helpful to quantify the error or difference in the IMS and the NIC ice edge.

> **Quantifying the error between the IMS and NIC ice edges has not been determined by the NIC, but they have plans to do so in the future.**

Presumably the difference between this and the reported errors are due to the model adjusting to the imposed ice field, i.e. melting ice or forming ice according to its internal SST/upper ocean heat content.

Also, is it possible to quantify whether the model under or overestimates the ice extent?

> **This is work in progress.**

P 9 L 5-10: it would be helpful to include this information in a table.

A new table (now Table 2) has been added to show seasonal errors.

P 9 L 20-25: it would be helpful to provide more and clearer detail here

This text has been re-worded in the first paragraph section 3.2.

P 9 L 19-23: it's not immediately clear why the results found by including SSMIS are identical to those without it. In fact it's not clear how the SSMIS and AMSR2 ice concentrations are used in combination

NCODA can accept multiple data sources, but since AMSR2 has a much higher resolution it will dominate. We think the main reason why the results are similar, is due to the IMS assimilation. IMS will dominate what is going on close to the ice edge.

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

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Deleted: : Arctic Cap Nowcast/Forecast System (ACNFS) and the Global Ocean Forecast System (GOFS 3.1)

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Abstract

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

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

1 Introduction

Knowing the ice edge location is extremely important for safe navigation and effective execution of the U.S. Navy's daily operational missions (U.S. Department of Navy, 2014). Since comprehensive records began with the satellite era in 1979, summer Arctic sea ice extent has trended downward with a new record minimum of 3.41 Mkm^2 occurring in September 2012 (NSIDC 2012). This 2012 record low in sea ice extent, followed by an increase in extent during 2013 and 2014, indicate high year-to-year variability in the ice cover and also in the spatial distribution of the ice (i.e., where open water forms) (Perovich et al., 2014). In this rapidly changing Arctic environment (Meier et al., 2014), it is likely that Arctic shipping will increase over the next decade. This, in turn, will demand an increase in U.S. military presence in the Arctic. As the U.S. military presence increases in this region, it is imperative to provide as accurate a sea ice forecast as possible.

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

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Deleted: , with a grid resolution of approximately 3.5 km at the North Pole (Fig. 1). ACNFS graphical products are publically available from www7320.nrlssc.navy.mil/hycomARC. Recently, the Global Ocean Forecast System (GOFS) 3.1 has been transitioned to the Naval Oceanographic Office (NAVOCEANO), and is in the final operational testing phase. When GOFS 3.1 becomes operational, it will replace ACNFS and provide a global sea ice prediction capability including both the Arctic and the Antarctic.

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

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

2 System descriptions, data and methods

2.1 System descriptions

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

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

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

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

2.2 Passive Microwave

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

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¶
The National Oceanic and Atmospheric Administration (NOAA) National Ice Center (NIC) is charged with forecasting the location of sea ice in the Arctic. In addition to satellite imagery and other sources, the NIC presently uses ACNFS output and in the near future (once declared operational) will use the GOFS 3.1 output, to improve the accuracy and resolution of the analyzed determined and forecast ice edge location. ACNFS consists of coupled sea ice and ocean models that forecast sea ice conditions in all ice covered regions of only the northern hemisphere, whereas GOFS 3.1 covers both hemispheres. ACNFS and GOFS 3.1 are based on the HYbrid Coordinate Ocean Model (HYCOM) (Metzger et al., 2015) coupled to the Los Alamos National Laboratory Community Ice CodE (CICE) (Hunke and Lipscomb, 2008), and they employ the Navy Coupled Ocean Data Assimilation (NCODA) system (Cummings and Smedstad, 2014).¶

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

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

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

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

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

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

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

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

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The IMS sea ice extent fields upon which MASIE and the blended product are based upon are developed from a largely manual synthesis of information from numerous data sources. IMS documentation (NIC, 2008) lists 28 potential sources for snow and ice information. Most, but not all, of these sources are from satellite sensors. The MASIE product documentation (NIC and NDISC, 2010) has additional information on how IMS fields are produced.¶

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

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

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

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In this study, the MASIE product was used in an ACNFS hindcast from July 2012 – July 2013, while the IMS product was used in ACNFS and GOFS 3.1 hindcasts from June 2014 – August 2014. As stated above, these two products (MASIE and IMS) are identical in data values but differ in format and location of the data source; MASIE is delivered from the NSIDC, while IMS comes from the NIC.

2.4 Blended IMS/MASIE + AMSR2

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

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

- If model < NCODA analysis
  - Use model where NCODA analysis > 50%
  - Blend model and NCODA analysis for concentrations that fall within 25% < NCODA < 50%
  - Use NCODA analysis where NCODA analysis < 25%
- If model > NCODA analysis
  - Use model where model > 30%
  - Blend model and NCODA analysis for concentration that fall within 15% < model < 30%

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- Use NCODA analysis for model < 15%

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

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

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

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

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

Deleted: In the short term study (described in section 3.2), AMSR2 in swath format was read into the NCODA module thatto produced an ice analysis and then masked using the MASIE/IMS 4 km product. This modified ice analysis was then read into the CICE model. The blending rules listed below were used in developing both of the analyses whether the MASIE/IMS was applied before or after NCODA. The second technique of masking the NCODA analysis after NCODA is the way that the operational modelsystems uses this new data product.

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

3 Assimilation study and results

3.1 ACNFS assimilating AMSR2 ice concentration and MASIE ice mask

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

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Deleted: Figure 5 shows the final blended AMSR2 and IMS/MASIE ice concentration product during the winter (15 March 2014) and summer (15 September 2014) days of Fig. 4. The magenta MASIE only areas of Fig. 4 are assigned a value of 70% (dark blue) in the blended ice concentration product. The homogenous expanses of ice at 70% are more noticeable in the summer when the passive microwave underestimates the extent of ice over large areas. Also to note, the AMSR2 coastal spillover (shown in green in Fig. 4) is mitigated by the IMS/MASIE ice mask product. There are no ice concentration values between 0 and 70% in the blended product. It should be noted that this example (shown in Fig. 5) shows an extreme case; however, in the average daily assimilative run, the differences between IMS/MASIE are not this extreme does typically does not have a sharp gradient between 0 and 70.

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<#>ACNFS and GOFS 3.1 previously assimilated near real-time sea ice concentration derived from SSMIS each day and generated a daily initialization ice concentration field, although the methodology is slightly different in each system. SSMIS-derived ice concentration is directly inserted into both ...

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

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

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

3.2 ACNFS and GOFS 3.1 assimilating AMSR2 ice concentration and IMS ice mask

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

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

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

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

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

4 Conclusions and future plans

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

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

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

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

Acknowledgments

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

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

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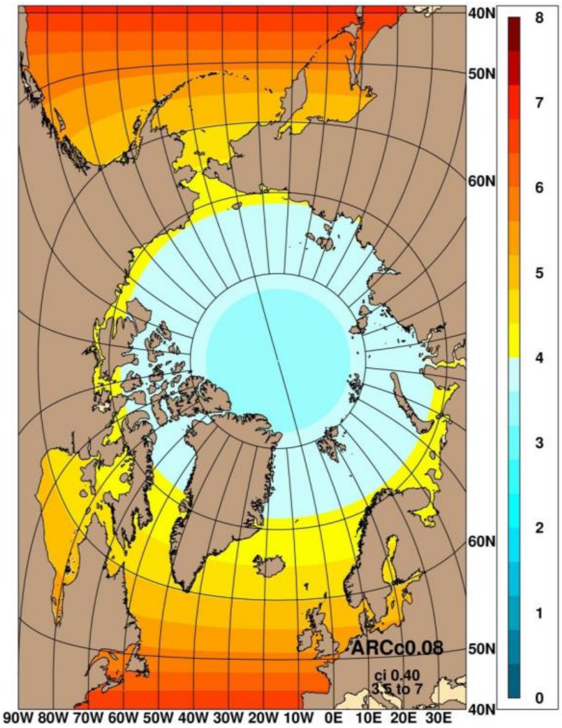

Figure 1. ACNFS and GOFS 3.1 model grid resolution (km) for the Arctic region.

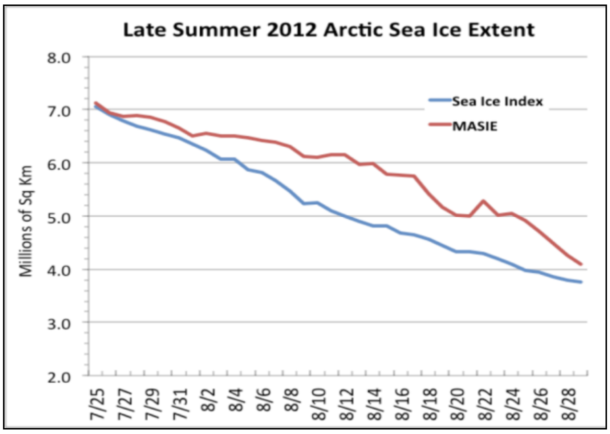

Figure 2. Arctic sea ice extent (Mkm^2) calculated using passive microwave data (blue) and the Multisensor Analyzed Sea Ice Extent (MASIE) product (red) for 25 July – 28 August 2012. The passive microwave data are from the SSMIS on board the DMSP F17 satellite.

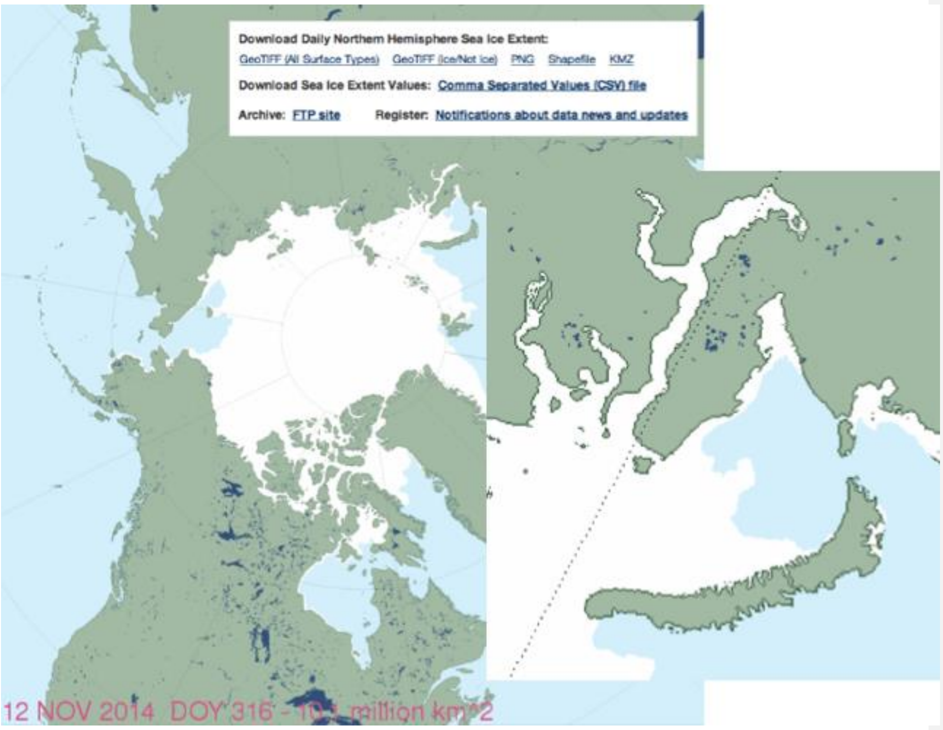

Figure 3. Sample MASIE product (with zoomed Kara Sea region inset on right) valid 12 November 2014. White indicates ice covered areas.

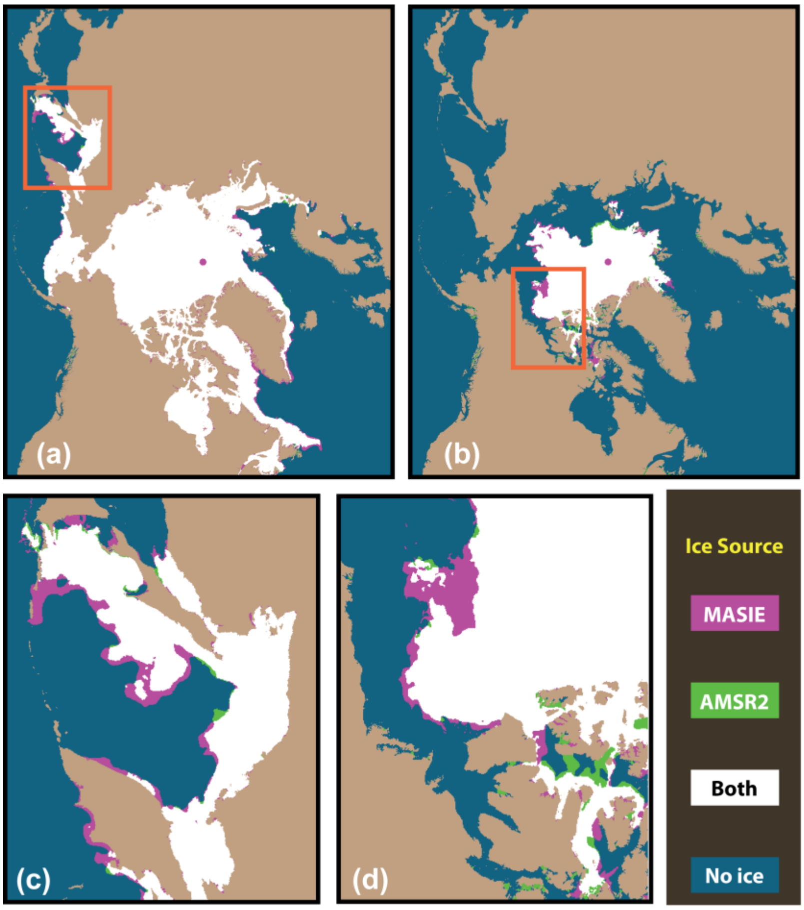

Figure 4. AMSR2 and IMS/MASIE ice extent differences during (a) 15 March 2014 - winter and (b) 15 September 2014 - summer. Magenta: IMS/MASIE shows ice where AMSR2 does not show ice greater than 15%. Green: AMSR2 shows ice where IMS/MASIE does not. White: Both indicate ice. Blue: Both indicate no ice.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

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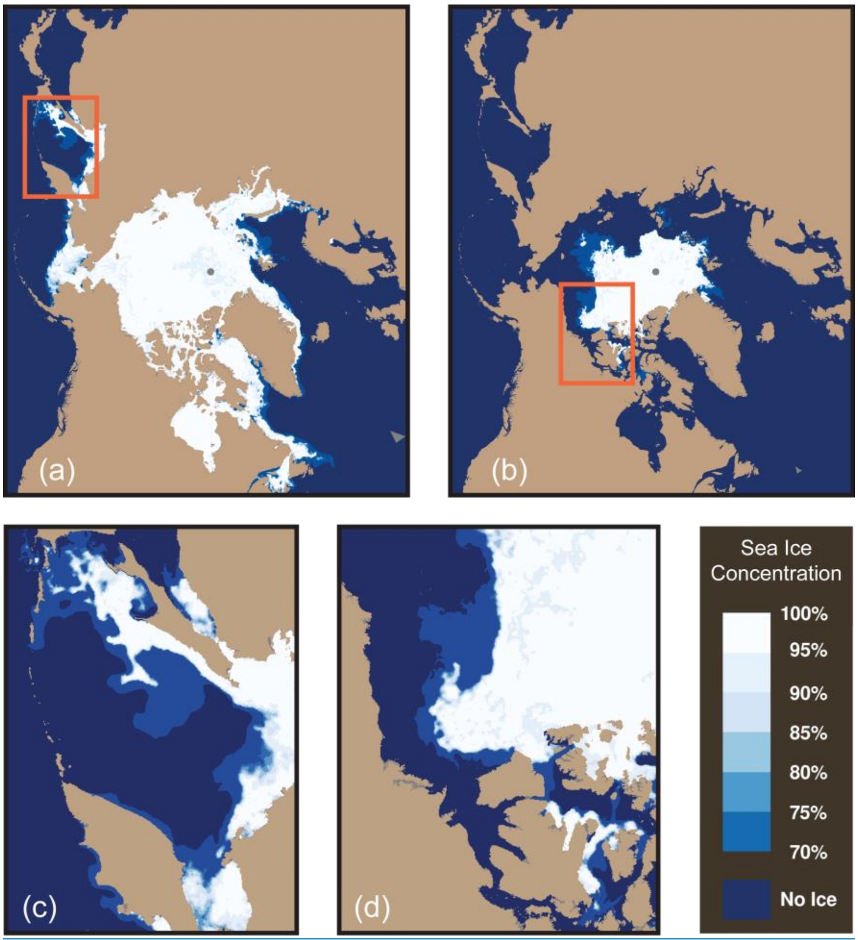

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Figure 5. AMSR2 and IMS/MASIE blended ice concentration (%) product for (a) 15 March 2014 – winter and (b) 15 September 2014 – summer. If IMS/MASIE and AMSR2 indicate ice, then the greatest of 70% or the AMSR2 ice concentration value is used. If IMS/MASIE 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).

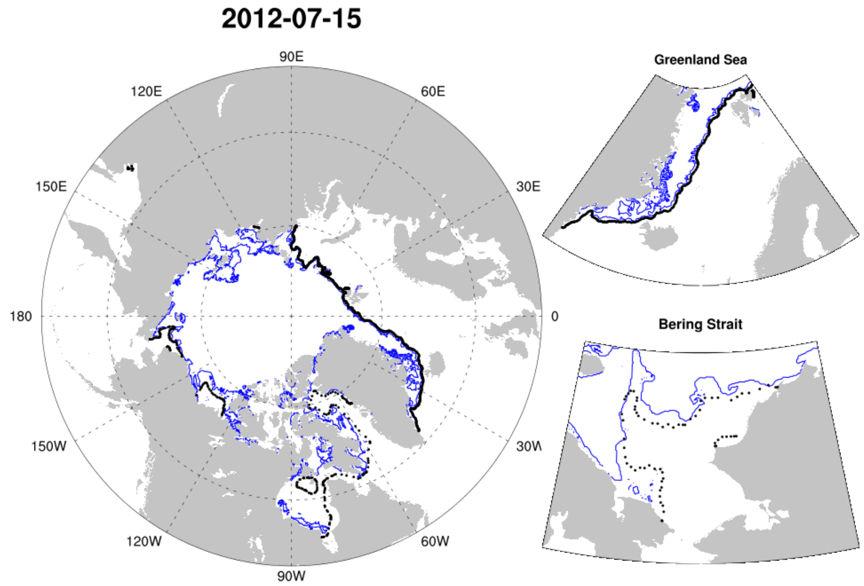

Figure 6. Ice edge location for 15 July 2012 from the NIC (black dots) and the IMS/MASIE (blue line) products for the full Arctic (left) and zoomed areas of the Greenland Sea (upper right) and the Bering Strait (lower right). The black dots represent the presence of any known ice and is used to determine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

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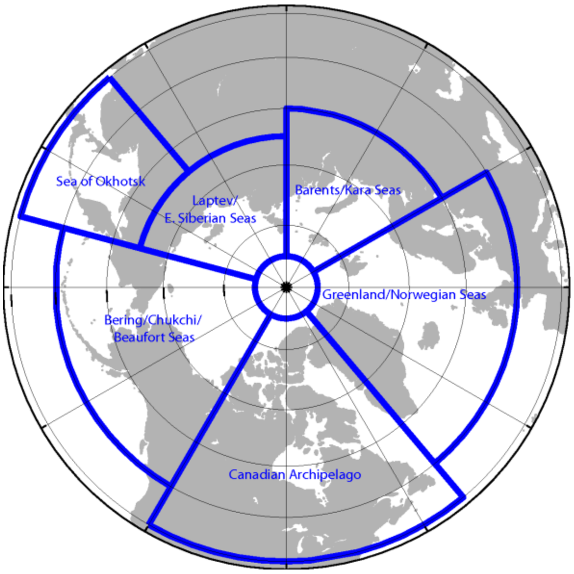

Figure 7. Analysis regions used for the NIC ice edge comparison shown in Table 1, 2 and 3.

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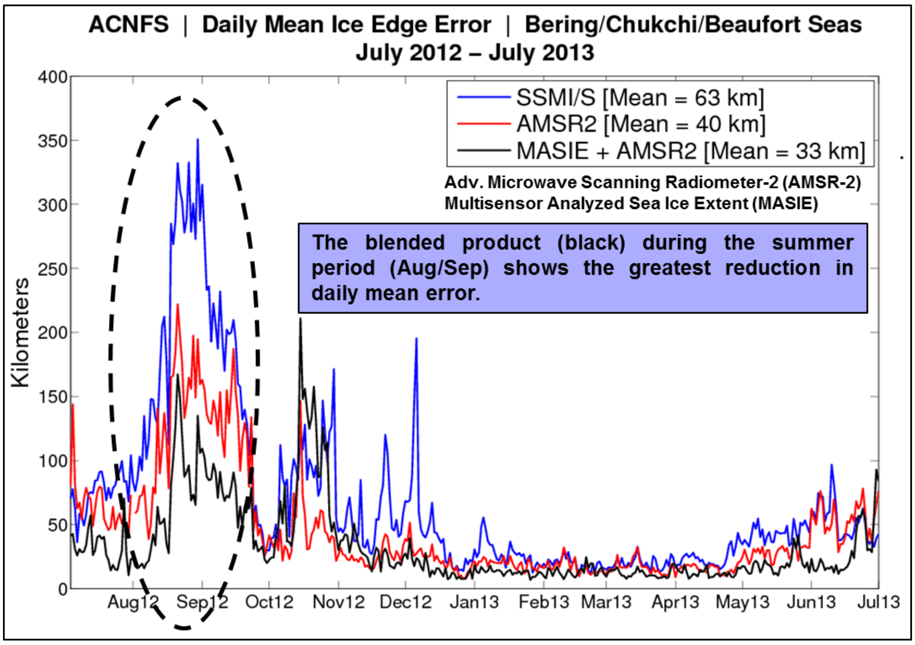

Figure 8. Daily mean error (km) for the Bering/Chukchi/Beaufort Seas versus time for ACNFS ice edge (define as the 5% ice concentration) against the independent ice edge analysis from the NIC over the validation period 1 July 2012 – 1 July 2013. The blue line is using SSMIS assimilation only, the red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