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14. ABSTRACT

We have developed and implemented an automatic algorithm which produces a daily sea ice map combining multiple observations per day over high latitudes from MODIS/Aqua, MODIS/Terra and VIIRS/NPP as first proposed. Beyond what was proposed, we fuse the imagers with microwave data from AMSR-2/GCOM-W1 to create our Microwave/Imager Sea Ice Classifier (MISIC) daily product. In addition, the algorithm produces intermediate products for each imager pass including a three-feature high-resolution image viewable in false color

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Report Title

Final Report: Improved Characterization of Sea Ice with Combined NPP VIIRS and MODIS EOS: Focus on Leads and Polynyas

ABSTRACT

We have developed and implemented an automatic algorithm which produces a daily sea ice map combining multiple observations per day over high latitudes from MODIS/Aqua, MODIS/Terra and VIIRS/NPP as first proposed. Beyond what was proposed, we fuse the imagers with microwave data from AMSR-2/GCOM-W1 to create our Microwave/Imager Sea Ice Classifier (MISIC) daily product. In addition, the algorithm produces intermediate products for each imager pass including a three-feature high-resolution image viewable in false color image facilitating visual discrimination ice and water even when partially obscured by thin clouds while still revealing leads and polynyas. The algorithm produces a per-pass fused imager-microwave product for discrimination between ocean surface type even beneath clouds. All these products were designed to provide better guidance for NIC interactive products. Code implementing MISIC and regional Beaufort, Chukchi and Ross Sea results have been delivered to NIC for evaluation. As proposed we developed, a web-based monitoring system for MISIC products, as well as providing other currently available ice extent products for comparison. We have submitted a paper for publication along with a thorough evaluation of MISIC. In the project provided training and experience to PhD, Masters and undergraduate students.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

I. Gladkova, G. Bonev, M. Grossberg, P. Romanov, S. Helfrich, Integrated approach to automated sea ice mapping using multi-platform observations, Living Planets Symposium, Prague, May 2016

I. Gladkova, G. Bonev, M. Grossberg, P. Romanov, S. Helfrich, Integrated approach using multi-platform sensors for enhanced high resolution daily ice cover product, SPIE Optical Engineering and Applications, Earth Observing Systems XXI, San Diego, August, 2016

Number of Presentations: 2.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

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(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Book

TOTAL:

Received Book Chapter

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Fazlul Shahriar	0.80	
George Bonev	0.80	
FTE Equivalent:	**1.60**	
Total Number:	**2**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Michael Grossberg	0.10	
Irina Gladkova	0.15	
Peter Romanov	0.10	
FTE Equivalent:	**0.35**	
Total Number:	**3**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED	Discipline
David Leonard	0.20	Computer and Computational Sciences
Calvin Chu	0.80	Computer and Computational Sciences
FTE Equivalent:	**1.00**	
Total Number:	**2**	

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NAME

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Names of personnel receiving PHDs

NAME

Total Number:

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

See attachment

Technology Transfer

Code implementing Microwave/Imager Sea Ice Classifier (MISIC) algorithm has been delivered to National Ice Center (NIC) for evaluation.

Final Report: Improved Characterization of Sea Ice with Combined NPP VIIRS and MODIS EOS

1. Foreword

We have developed and implemented an automatic algorithm which produces a daily sea ice map combining multiple observations per day over high latitudes from MODIS/Aqua, MODIS/Terra and VIIRS/NPP as first proposed. Beyond what was proposed, we fuse the imagers with microwave data from AMSR-2/GCOM-W1 to create our Microwave/ Imager Sea Ice Classifier (MISIC) daily product. The algorithm is suitable for real-time processing and produces a high spatial resolution sea ice product that provides spatially continuous (cloud gap free) characterization of the ice extent and the ice edge at maximum possible spatial resolution.

The algorithm first extracts maximum information on the sea ice cover from imaging instruments VIIRS and MODIS, including regions covered by thin, semitransparent clouds. This ability to identify ice cover underneath thin clouds, which is usually masked out by traditional cloud detection algorithms, allows for expansion of the effective coverage of the sea ice maps and thus more accurate and detailed delineation of the ice edge. In the next step of our algorithm, the labels obtained from individual imager overpass observations are supplemented by the microwave measurements, resulting in 5 intermediate classes: sea ice, ice-free water, ice under thick clouds, water under thick clouds and an undetermined class where there is insufficient information. For example, grid cells under cloud near the ice edge, can not be precisely determined by the lower resolution microwave ice concentration product. The confidently labeled grid cells serve as a training set for a Linear Discriminant Analysis (LDA) classifier in an experimentally derived feature space constructed from reflective, shortwave IR and thermal bands centered around 0.46*nm*, 0.64*nm*, 0.86*nm*, 1.24*nm*, 1.6*nm*, 11*nm* and 12*nm* from the imager instrument as well as polarization and gradient ratios of 18 and 36 GHz radiometer channels of the microwave instrument. The microwave data makes it possible to classify grid cells under thick clouds that cannot be classified using the imager input alone. Although this particular step of the algorithm relies on the classification involving microwave data and therefore results in a somewhat degraded effective spatial resolution of the ice extent, these grid cells have a special "microwave" tag and weighted less in the last step of the algorithm which combines the labels from the individual overpasses in an optimal way into daily ice extent product, resulting in the enhanced, high resolution, gap free ice extent product.

Code, implementing MISIC and regional Beaufort, Chukchi and Ross Sea results have been delivered to National Ice Center (NIC) for evaluation. As proposed we developed, a web-based monitoring system for MISIC products, as well as providing other currently available ice extent products for comparison. We have submitted a paper for publication along with a thorough evaluation of MISIC. In the project provided training and experience to PhD, Masters and undergraduate students.

2. Statement of the problem studied

Sea ice cover is both an important indicator and a critical factor in Earth's climate and weather system. The overall distribution of sea ice in the Arctic and Antarctic regions has a significant impact on water management, transportation, weather forecasting, and climate change studies. It affects atmosphere-ocean energy exchange by modulating the physical and optical properties of the ocean surface [1]. The character and distribution of sea ice affects the thermohaline structure and the fresh water balance of the ocean. Thus in understanding both ocean and atmosphere it is critical to monitor ice cover distribution, seasonal variability and long-term trends. These trends in the polar region may be studied through parameters such as the position of the sea ice front, total ice extent, ice concentration and thickness [2-7]. These parameters are widely viewed as major indicators of climate variability and change. In addition to their use for understanding and monitoring the climate, sea ice extent and concentration are key inputs to numerical weather prediction (NWP) models operated by National Centers for Environmental Prediction (NCEP) of NOAA National Weather Service (NWS).

Despite several currently available automated satellite-based ice cover datasets, analysts at National Ice Center (NIC) tend to rely on original satellite imagery from optical, passive microwave and active microwave sensors in their daily interactive analysis. This is primarily due to the fact that different instruments have different strengths and weaknesses with respect to ice retrievals and there is no automated algorithm compatible with interactive sea ice analysis that integrates the observations from instruments of various types, which fully preserves the complementary information available from each instrument type.

Given the limitations of optical and microwave instruments, developing ice products that integrate sensors is an important area of open research [8]. Currently the most widely used multisensor ice product is produced by the Interactive Multisensor Snow and Ice Mapping System (IMS) operated by the National Ice Center (NIC) [9 - 11]. IMS is operated by trained analysts who produce a daily digital product utilizing Geographic Information System technology and incorporating a variety of, and an ongoing expansion of, technological capabilities as well as sources of information. IMS produces estimates of snow and sea ice extent across the globe every day, regardless of the presence of clouds. This is possible primarily for two reasons. First, analysts supplement visible and near infrared imagery with many other sources of information such as passive microwave and active radar data. Second, because IMS analysts use a temporal sequence of images over recent days, they can integrate of information from both spatial and temporal perspectives. Thus, a key feature of the IMS product is that human judgment as to which data sources are most reliable in different conditions and regions, and as to the final evaluation of where sea ice is, remains an integral part of the process, and one of the strengths of the IMS product. However, manual sea ice mapping drawn by humans, is a subjective, labor intensive and time consuming procedure, that is not easily scalable as satellite resolution increases. Automated algorithm would unequivocally facilitate the work of human ice analysts and would result in more accurate ice products including ice extent, edge and type.

We have developed an algorithm that, first extracts maximum information on the sea ice cover (including observations made over semitransparent clouds) from matching the classification results obtained from optical and microwave observations independently and then fuses these results in an optimal way. Heterogeneous observations from optical and microwave sensors are combined to produce an enhanced high resolution, gap free daily ice extent product. Unlike approaches which simply use courser resolution microwave when clouds are present, our algorithm extracts surface information through thin and moderate clouds preserving information available in high resolution optical imagers whenever possible.

3. Summary of the most important results

We have developed and evaluated an automated algorithm, MISIC capable of using imager and microwave data from multiple instruments (MODIS, VIIRS, and AMSER-2) to estimate sea ice cover. The most distinctive feature of our approach is that we can use high-resolution imager data partially obscured by (thin) clouds to do open water versus sea ice classification. No other algorithm has this capability. When thin clouds are present, the MISIC single-pass enhanced product can combine the high resolution surface features only partially obscured by clouds, with the most recent microwave data, to produce the best current estimate the sea ice on the surface. When the surface is covered by thick clouds, the algorithm fills the missing data using cloud penetrating microwave data, at the cost of lower resolution. We have also shown that by combining the single-pass enhanced automated ice mask into a daily product increase the resolution over microwave where surface features were visible, potentially through thin clouds, at some point during the day. Beyond direct use of the automated product these products can provide important guides since they quickly summarize many information sources and can thus to accelerate the creation of expert derived interactive products. We have been evaluating the MISIC product since the summer of 2015. Results of these evaluations are presented in the next section.

3.1 Granule based Evaluation

A representative case is shown in Figure 1 depicting a scene from August 6th, 2015 off the east coast of Greenland. In Figure 1(a) the MISIC three-value feature space is shown in false color created from MODIS (Terra) at 13:40 UTC. In this image, ice (appearing in red in the false color composition) is dominating the scene. A thicker patch of cloud, shown in green, is visible in the center left with thin cloud over ice in yellow, and over water in cyan. The corresponding MODIS RGB-color image is shown in Figure 1(b), and from a Landsat 8 image from the same day at 14:13 UTC in Figure 1(c). In the RGB images (both Landsat and MODIS) clouds are present but the details of the surface ice and water are readily apparent. The MISIC granule product, shown in Figure 1(d), captures these high-resolution features through the thin clouds resolving the thicker part of the cloud with the help of supplementary microwave data. In contrast, both the MODIS IceMap (MOD26) product, and even the Landsat product, shown in Figure 1(b,c) respectively, are largely obscured by aggressive cloud masks. Where those products indicate ice or water, we see that the MODIS product lacks much of the detail visible in both the MISIC product and the Landsat image, particularly center bottom where MODIS misclassifies mixed water and ice as cloud.

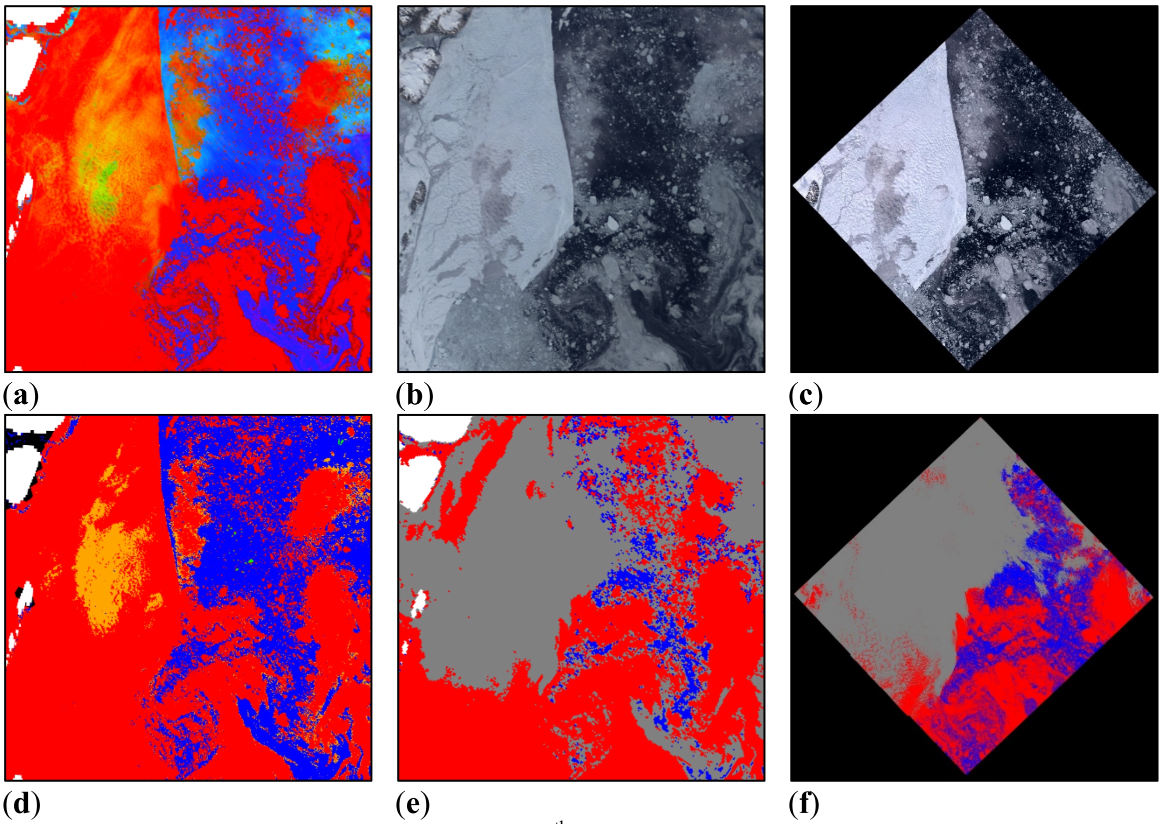
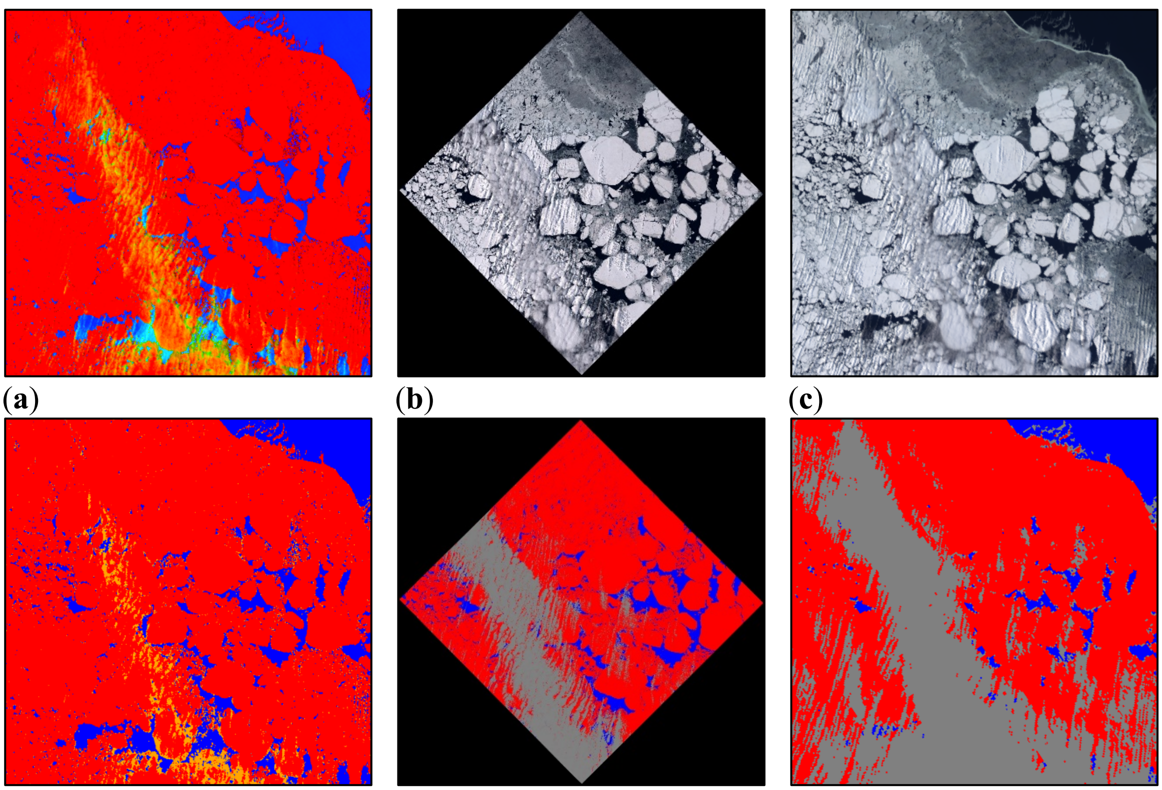


Figure 1. All images obtained from August 6th, 2015 in the Greenland Sea. (a) MODIS (Terra) based Features at 13:40 UTC; (b) MODIS RGB; (c) Landsat 8 RGB at 14:13 UTC; (d) MISIC overpass labels; (e) MODIS IceMap (MOD29) labels; (f) Landsat 8 Quality Assessment Band labels.

Table 1 shows the statistics of the August 6th, 2015 scene classification, along with 5 other representative cases. For all examples the classification of the IceMap and MISIC MODIS-based products are up-sampled to the Landsat 8 reference scene and resolution, and the Landsat quality band (which contains ice/water classification) is used as ground truth for cloud-clear pixels in all products. In all cases shown, the True Positive Rate (TPR) is superior for the IceMap product while the False Positive Rate (FPR) is superior in 5/6 cases for MISIC. This is mostly indicative of the IceMap product being more aggressive in the classification of ice. The over-all accuracy is approximately equal. The important thing to note here is the percent of pixels IceMap declares as cloud, which are now classified by the MISIC granule product, shown in the last column. Thus the MISIC product provides a high-resolution accurate classification comparable to the MODIS product, but is able to classify ice and water through thin cloud at high resolution, and thicker cloud with the aid of supplemental passive microwave.

Date	Product	TPR	FPR	ACC	Cov. Inc.
05/25	MISIC	0.945	0.026	0.961	67.380%
	IceMap	0.957	0.019	0.970	N/A
08/06	MISIC	0.896	0.353	0.828	86.725%
	IceMap	0.971	0.579	0.821	N/A
08/17	MISIC	0.899	0.197	0.871	75.484%
	IceMap	0.966	0.488	0.836	N/A
09/11	MISIC	0.822	0.121	0.834	56.937%
	IceMap	0.975	0.352	0.906	N/A
09/15	MISIC	0.886	0.011	0.962	90.954%
	IceMap	0.925	0.016	0.968	N/A
12/02	MISIC	0.987	0.351	0.955	89.481%
	IceMap	0.998	0.517	0.950	N/A

Table 1. Evaluation parameters and their values for 6 examples.

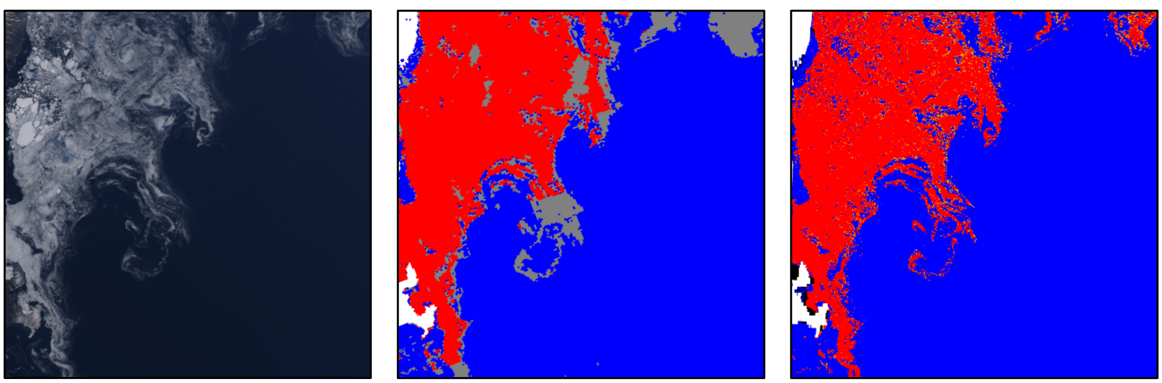


(a) **(b)** **(c)** **(d)** **(e)** **(f)**

Figure 2. Images in a,c,d, and f obtained from MODIS (Terra) on December 2nd, 2015 @ 18:45UTC. Images in b and e obtained from Landsat 8 at 19:18UTC. (a) MODIS based Features; (b) Landsat 8 RGB; (c) MODIS RGB; (d) MISIC granule labels; (e) Landsat 8 Quality Assessment Band labels; (f) MODIS IceMap (MOD29) labels.

The last example of Table 1, based on a MODIS (Terra) acquired on December 2nd, 2015 at 18:45 UTC, and Landsat 8 at 19:18 UTC, near the Ross Sea, is shown in Figure 2. Again Figure 2a shows the MISIC three value false color, clearly showing thin cloud running from the bottom to top through the left center of the image. The numerous ice floes are clearly identifiable as is obvious from the corresponding MODIS and Landsat 8 RGB images shown in Figure 2b, c. The MISIC granule product indicates the ice floes as well as the thin cloud, while the IceMap and Landsat 8 products block much of the central image with a cloud mask. A coded comparison of Landsat 8 with IceMap (Figure 3a), and MISIC granule product (Figure 3b) shows agreement on ice in red, water in blue and disagreement in green. While both pick up the floe details, again, the IceMap is much more aggressive in declaring ice as well as leaving thin cloud masked.

Mis-identified clouds are a well-known and frequent problem in the IceMap product as can be seen in Figure 3 from derived stitched MODIS (Aqua) granules on September 15th, 2015 at 13:10 UTC and 13:15 UTC. From the RGB shown in Figure 3a it is clear that the swirl in the center is mixed ice, yet the IceMap declares it cloud while MISIC correctly identifies it.



(a) **(b)** **(c)**

Figure 3. Images derived from MODIS (Aqua) on September 15th, 2015 at 13:10UTC and 13:15UTC. (a) MODIS RGB; (b) MODIS IceMap labels; (c) MISIC granule labels.

3.2 Daily Product Evaluation

Overall validation of the daily product over a large region is challenging. There are very limited and sparse in-situ measurements. Even the notion of daily ground truth is difficult. In particular, it is possible for ice to move several kilometers over the course of a day, making clear-cut delineation of ice and water ill defined. Our claim is that our fully automated product should be consistent with the best semi-automated products available. These products include: the Interactive Multisensor Snow and Ice Mapping System (IMS) produced and hosted by the National Ice Center; the Daily Sea Ice Concentration Analyses product produced and hosted by the Marine Modeling & Analysis Branch (MMAB) of the National Centers for Environmental Protection (NCEP); the Global Sea Ice Concentration product produced and hosted by the Ocean and Sea Ice Centre at the EUMETSAT Network of Satellite Application Facilities (OSI SAF); and the Global

Daily Ice Edge product produced by the Canadian Meteorological Center (CMC) and distributed by the NASA Jet Propulsion Laboratory through the Physical Oceanography Distributed Active Archive Center (PODAAC).

We present the consistency of ice extent for the time series Oct. 1st-15th, 2015 corresponding to sea ice freeze-up time in the Beaufort Sea. The product comparison results are shown in Figure 4. The light gray line without dots represents ice extent according to NCEP microwave thresholded at .5 with the grey shading band showing ice extent corresponding to thresholds between .25 and .75. We see that most daily ice products including IMS, OSI SAF, CMC and the MISIC presented here, stay within this band. The NIC product follows the same shape but is much more aggressive in indicated ice due to its mission requirements. There is a consistent increase in the ice extent over time, as the sea freezes throughout October. We also see the products converging with the freeze up as the ice becomes less variable. Whereas, some of the other products tend to be more aggressive at indicating ice, MISIC has been developed to reveal high-resolution ice features which may account for its generally consistent lower estimate of ice extent. Still the MISIC daily prediction is able to automatically achieve an ice extent, consistent with microwave-based products, while maintaining the higher resolution, outperforming imager-based semi-manually created products.

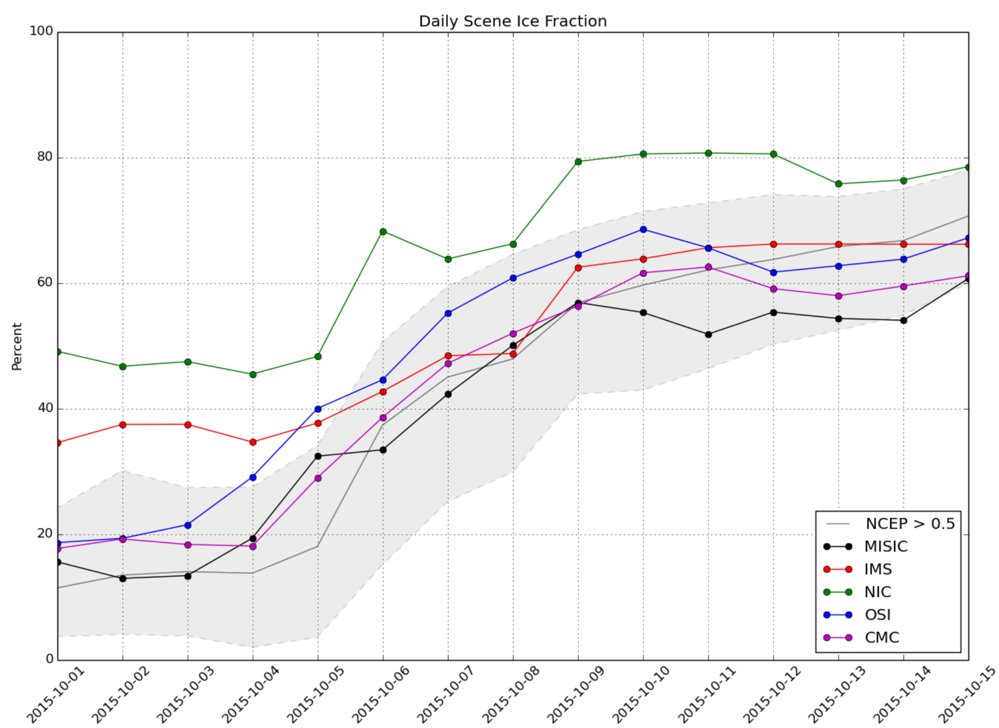


Figure 4. Daily product ice fraction comparison of different ice coverage products in the Beaufort Sea region from 10/1/2015-10/15/2015. MISIC aggregate ice fraction consistent with current operational products.

Imager based products such as IceMap have similar resolution to the MISIC product. Yet because IceMap uses an aggressive cloud mask, coverage is often limited by the frequent presence of clouds. For thin and even moderate clouds, the MISIC algorithm does not mask, but instead attempts to classify the surface through the clouds. This should be contrasted with methods that simply use microwave whenever any amount of cloud is present. By using any surface visible/infrared data available, MISIC is able to achieve higher resolution over partly cloud-occluded areas than achievable with microwave.

Figure 5 shows the same period in the Beaufort Sea region used in Figure 4. The area where a determination of ice vs water, using all the IceMap observation is indicated in Figure 5 as the blue bar. MISIC is able to also determine ice vs. water in those regions, while in addition MISIC classification using visible is able to discriminate ice and water though thin cloud at least once during the day shown in gray. Finally, the red portion shows the area where MISIC falls back to microwave to complete the classification. Note that over this period between 60% and 25% of the region was cloud obscured according to the MODIS cloud mask, but could still be identified using MISIC.

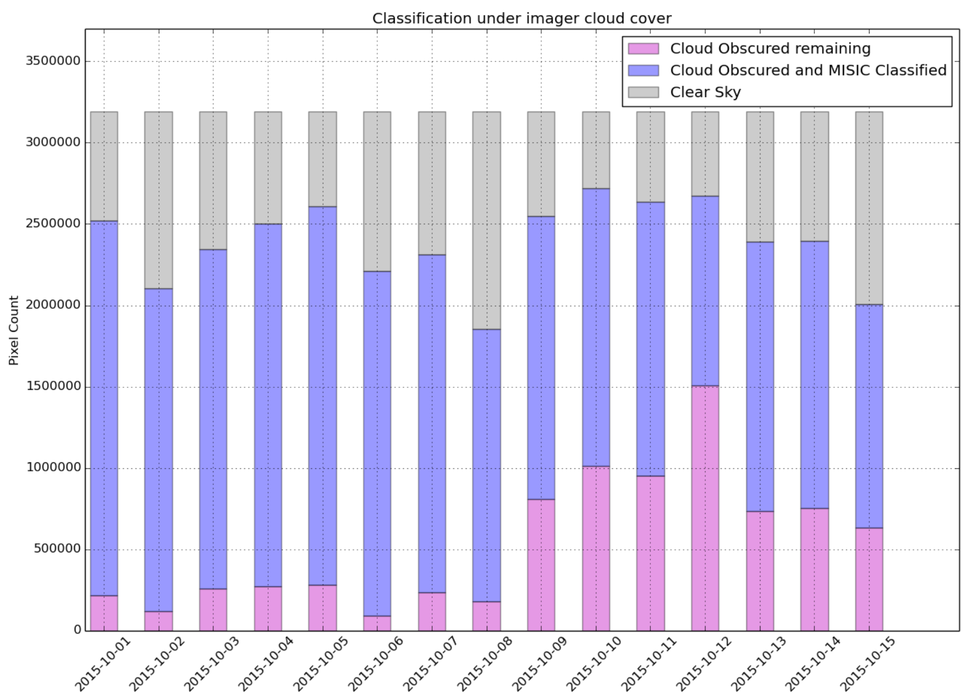


Figure 5. Daily product ice fraction comparison in the Beaufort Sea region from 10/1/2015-10/15/2015.

3.3 Product Monitoring System

Within his project we have developed the web-based monitoring system that allowed us to compare the performance of our proposed Multisensor Integrated Sea Ice Classifier (MISIC) product with the several independent operational daily products. The list of products incorporated into the system will include the Ice Edge product of NIC, IMS interactive snow/ice charts, NCEP sea ice concentration maps derived from satellite observations in the microwave, the sea ice product generated EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI SAF), Canadian Meteorological Center (CMC) ice map, ice concentration map derived from AMSR2 data by JAXA (Japan) as well as Radarsat and Sentinel imagery when available.

The system provides gridded images for a selected region of interest on a user specified date. For each satellite observation at the granule level, these images will include a true color RGB, our proposed false color and ice extent, and the current operational VIIRS ice fraction product with the ability to navigate between different overpasses. Figure 6 shows a prototype screen capture of our proposed monitoring system.

The system was developed using the Python scientific stack for the image generation. The frontend was developed using HTML5 technology (Javascript, CSS and HTML.) The frontend development uses the popular and well supported Zurb Foundation, as well as SASS. JSON is used for data serialization.

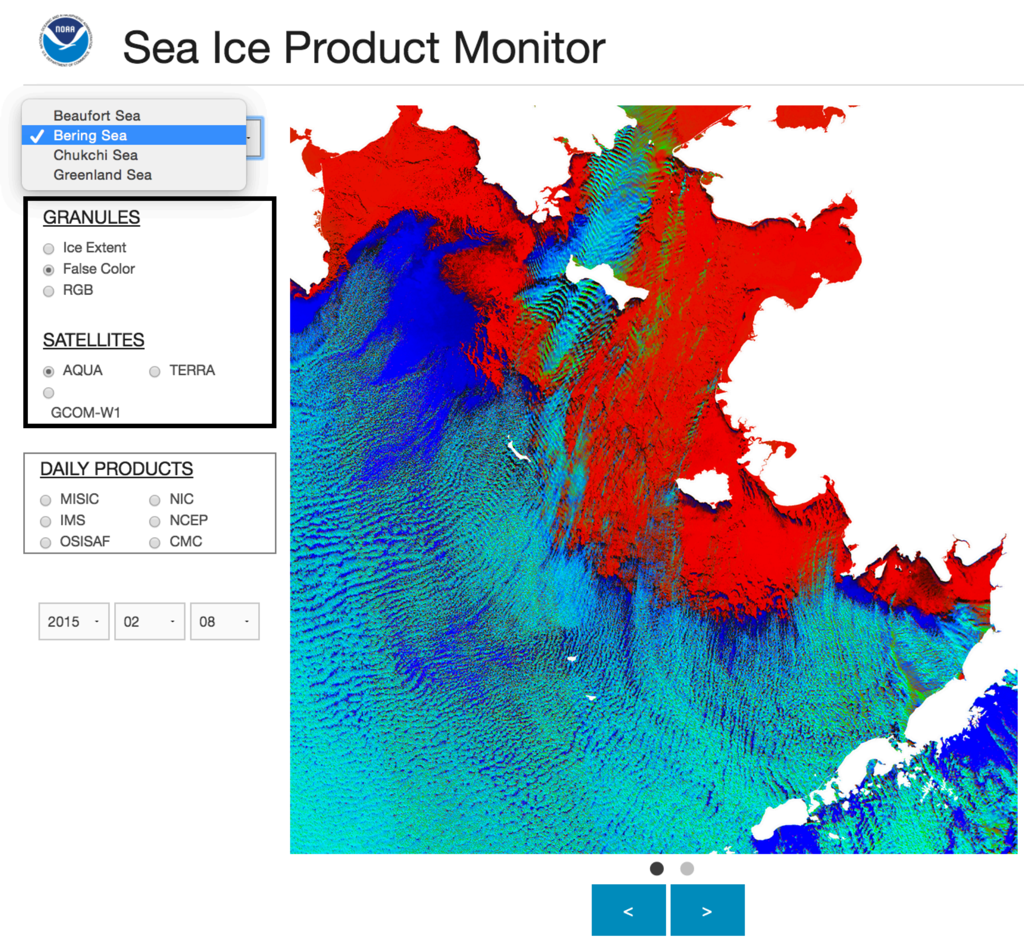


Figure 6: Screen capture of the current state of web-based monitoring system

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