

# **Suomi-NPP VIIRS Sea Ice Cover Algorithm Theoretical Basis Document (ATBD)**

Science Principal Investigator: Dr. Mark Tschudi

Correspondence e-mail address: [mark.tschudi@colorado.edu](mailto:mark.tschudi@colorado.edu)

Prepared by Mark Tschudi, George Riggs, and Dorothy Hall

Version 1.0

23 February 2017

## Table of Contents

1.0	Introduction.....	3
1.1	Science/Applications Rationale for the Product.....	3
1.2	Intended user community .....	4
2.0	Algorithm Description .....	5
2.1	Technical Background and Heritage .....	5
2.2	VIIRS Sea Ice Cover Algorithm Description.....	5
2.2.1	Algorithm Limitations .....	7
2.2.2	Algorithm Flow .....	8
2.3	Product Description.....	10
3.0	Product Inputs .....	10
3.1	Spectral Bands.....	11
3.2	Masks, Thresholds and Ancillary Data .....	11
4.0	Product Accuracy/Uncertainty.....	11
4.1	Uncertainty Estimate .....	12
4.2	Validation Approach .....	12
5.0	Data Format .....	13
5.1	Format .....	13
5.2	QA Metadata .....	13
6.0	Product Publications .....	13
7.0	References.....	13

## 1.0 Introduction

The NASA VIIRS Sea Ice Cover Product (Figure 1) provides daily coverage of Arctic and Antarctic sea ice in areas of clear sky. This product is VIIRS image quality (375m), and therefore provides a more detailed view of the sea ice cover than satellite-based passive microwave sensors. It is limited in areas of persistent cloud cover, but the additional level of detail can be useful in sea ice energy balance studies, navigation, and studies of marine productivity. The VIIRS Sea Ice Cover Product is a follow-on to the MODIS/Terra and MODIS/Aqua Sea Ice Extent products, available at the National Snow and Ice Data Center [Hall and Riggs, 2015].

The VIIRS sea ice cover algorithm identifies sea ice by its reflectance characteristics in the visible and near IR and its sharp contrast to open water. The darkness of polar winters will be a limiting factor in the temporal coverage of the product. Cloud cover in the central Arctic Basin will also be a limiting factor in mid-summer [e.g. Liu *et al.*, 2014], especially in the daily maps. Sea ice will be mapped during the spring, summer and autumn, when the greatest changes are taking place in the extent and movement of sea ice. During the summer daylight time there will be several S-NPP overpasses to use for mapping sea ice cover.

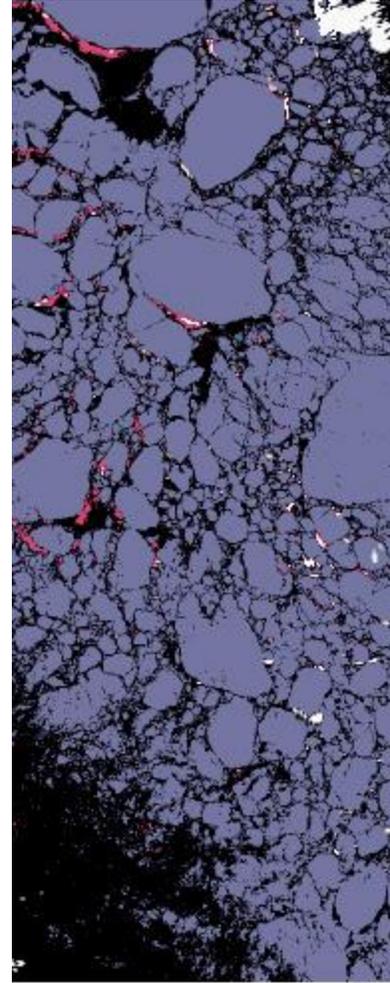


Figure 1: NASA VIIRS Sea Ice Cover in the Beaufort Sea, April 7, 2015.

### 1.1 Science/Applications Rationale for the Product

The Arctic sea ice environment is rapidly changing [Meier *et al.*, 2014]. The decline in Arctic sea ice extent, particularly evident in the western Arctic, is one of the better-known and more striking examples of this change [e.g., Comiso and Nishio, 2008; Stroeve *et al.*, 2012; 2011]. Areal coverage of Arctic sea ice is decreasing at a significant rate over the modern (since 1979) satellite record and appears to have accelerated over the past decade [e.g., Cavalieri *et al.*, 2012; Comiso and Nishio, 2008], particularly during summer, with record low minimum extents in the past several years [e.g., Parkinson and Comiso, 2013]. For September, the time of minimum extent, the sea ice extent has been decreasing by 13%/year, with the lowest 9 extents witnessed during the last 9 years (Figure 2). Recent satellite data have also indicated that older [Maslanik *et al.*, 2011; 2007] and thicker [e.g., Kurtz *et al.*, 2011] sea ice has also been steadily decreasing.

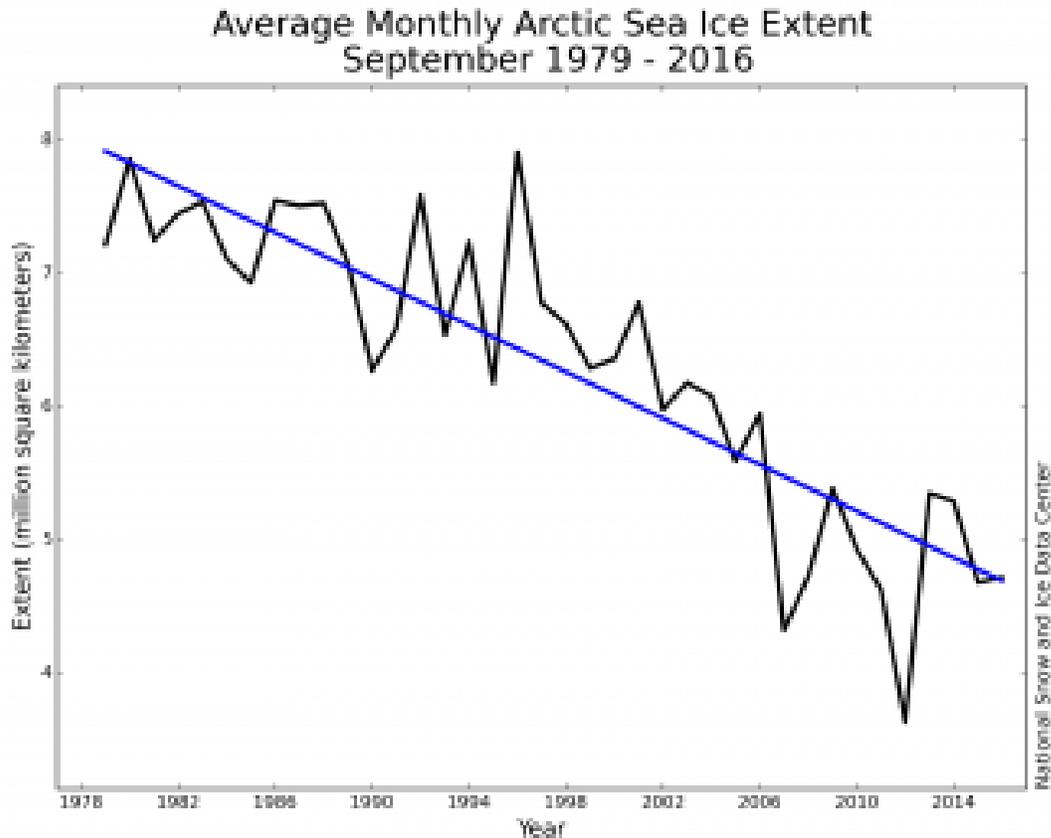


Figure 2. Monthly September ice extent for 1979 to 2016 shows a decline of 13.3% per decade.

The primary contribution of the VIIRS sea ice algorithm to the study and monitoring of sea ice will be the ability of VIIRS data to provide ice information at high spatial resolution (375m) to augment the data provided by passive- and active-microwave sensors.

Detecting sea ice using visible imagery has limitations, mainly due to cloud cover. Repeated overpasses of a satellite over transient clouds can reduce this issue, but area with persistent cloud cover cannot be observed. For this reason, we have chosen to call the NASA VIIRS sea ice product “Sea Ice Cover,” as opposed to “Sea Ice Extent,” as “extent” is a passive-microwave product that will map the entire sea ice area, since clouds mostly do not interfere with the surface-emitted passive microwave signal.

## 1.2 Intended user community

The VIIRS Sea Ice Cover product provides a data record of the areal coverage of sea ice, under clear skies, poleward of 50°N and 50°S latitude throughout the year, during daytime periods. Users of sea ice cover products include the U. S. National/Naval Ice Center (NIC), Naval Research Laboratory, and the Alaska Ice Desk of the National Weather Service, and various university and government researchers. The sea ice cover algorithm and data products will extend the Earth Observing System (EOS) sea ice extent data product record.

## 2.0 Algorithm Description

The NASA VIIRS Sea Ice Cover algorithm identifies sea ice by its reflectance characteristics in the visible and near IR and its sharp contrast to open water. The sea ice mapping algorithm employs the Normalized Difference Snow Index (NDSI) to determine if a pixel over the ocean is covered by sea ice. The usefulness of the NDSI is based on the fact that snow and ice are considerably more reflective in the visible than in the short-wave IR part of the spectrum, and the reflectance of most clouds remains high in the short-wave IR, while the reflectance of snow and ice are low.

### 2.1 Technical Background and Heritage

Sea ice *concentration*, which measures the fractional area of sea ice covered in each pixel of observations, has been measured using satellite-based passive microwave radiometers since the late-1970's. Passive microwave emission is largely unaffected by clouds, although their resolution ( typically 12 - 25 km) is lower than what is produced using visible sensors, such as the 500m resolution for MODIS. The most recent sea ice concentration product is produced from the AMSR-E satellite passive microwave sensor, and available in 12.5 km resolution [Cavalieri *et al.*, 2014].

Arctic sea ice *cover*, which we define as the sea ice viewed by visible sensors, was mapped using visible and thermal IR band data from the MODIS Airborne Simulator [Riggs *et al.*, 1999]. Sea ice extent and the generalized type of sea ice were identified based on reflective characteristics using a grouped criteria technique. The resulting sea ice cover maps were consistent with visual interpretation and with sea ice extent and type information reported in prior studies of the region. This technique was later used with MODIS data by Hall *et al.* [2001] to produce the MODIS/Terra and MODIS/Aqua Sea Ice Extent products (MOD29), available at NSIDC [e.g. Hall *et al.*, 2015].

The VIIRS Sea Ice Cover algorithm is an update of the MODIS Sea Ice Extent algorithm, replacing MODIS spectral bands with VIIRS bands. The VIIRS Sea Ice Cover product will utilize the improved technology and spatial resolution of visible imagery bands for VIIRS (375m, compared to 1km for MODIS).

### 2.2 VIIRS Sea Ice Cover Algorithm Description

Similar to the MODIS Sea Ice Extent algorithm by Hall *et al.* [2001], the VIIRS Sea Ice Cover algorithm utilizes two visible bands for mapping sea ice. Based on previous observations [Riggs *et al.*, 1999], sea ice is identified as ocean areas poleward of 50°N and 50°S that are much more reflective than ocean waters.

The basis of the NASA VIIRS Sea Ice Cover algorithm is the use of the Normalized Difference Snow Index (NDSI) to separate sea ice from open water. Sea ice has a strong visible reflectance and strong short-wave IR absorbing characteristics, in contrast to open water.

Additionally, some snow/cloud discrimination is accomplished using the NDSI. The VIIRS Sea Ice Cover algorithm computes the NDSI for each pixel with:

$$\text{NDSI} = (\text{I1 band} - \text{I3 band}) / (\text{I1 band} + \text{I3 band}) \quad (1)$$

The VIIRS I1 and I3 bands are image quality (resolution = 375m) and centered at 0.64  $\mu\text{m}$  and 1.61  $\mu\text{m}$ , respectively.

Figure 3 illustrates the variability in spectral albedo of different sea ice types, as well as the spectral coverage of VIIRS bands I1 and I3, the bands used for the NDSI algorithm. Open water was not measured for this set, but *Pegau and Paulson* [2001] measured a “flat” (i.e. across the visible/IR spectrum) reflectance over ocean water in leads of 0.666. These data are utilized to produce an NDSI and visible band thresholds for identifying sea ice. For example, using (1) and noting the central wavelengths for VIIRS band 1 (640nm) and 3 (1610nm), the NDSI for dry snow-covered ice is:

$$\text{NDSI (dry snow)} = (\text{I1} - \text{I3}) / (\text{I1} + \text{I3}) = (0.948 - 0.148) / (0.948 + 0.148) = 0.73 \quad (2)$$

Similarly, the NDSIs for all sea ice types in Figure 3, along with open water, are computed using (1):

<b>Sea Ice Type</b>	<b>I1 Reflectance</b>	<b>NDSI</b>
Dry snow	0.948	0.730
Melting snow	0.757	0.946
Bare white ice	0.722	0.951
Dirty bare ice	0.433	0.924
Deep blue melt pond	0.167	0.645
Blue – green melt pond	0.196	0.661
Dark pond	0.134	0.558
Ocean water	0.666	0.000

From these NDSI measurements, it follows that sea ice can be identified using the following criteria: if the  $\text{NDSI} \geq 0.4$  and the visible reflectance (VIIRS I1 band) is greater than 0.11, then the pixel contains sea ice. This threshold has been successfully used in the MODIS sea ice extent NDSI algorithm [*Hall et al.*, 2001].

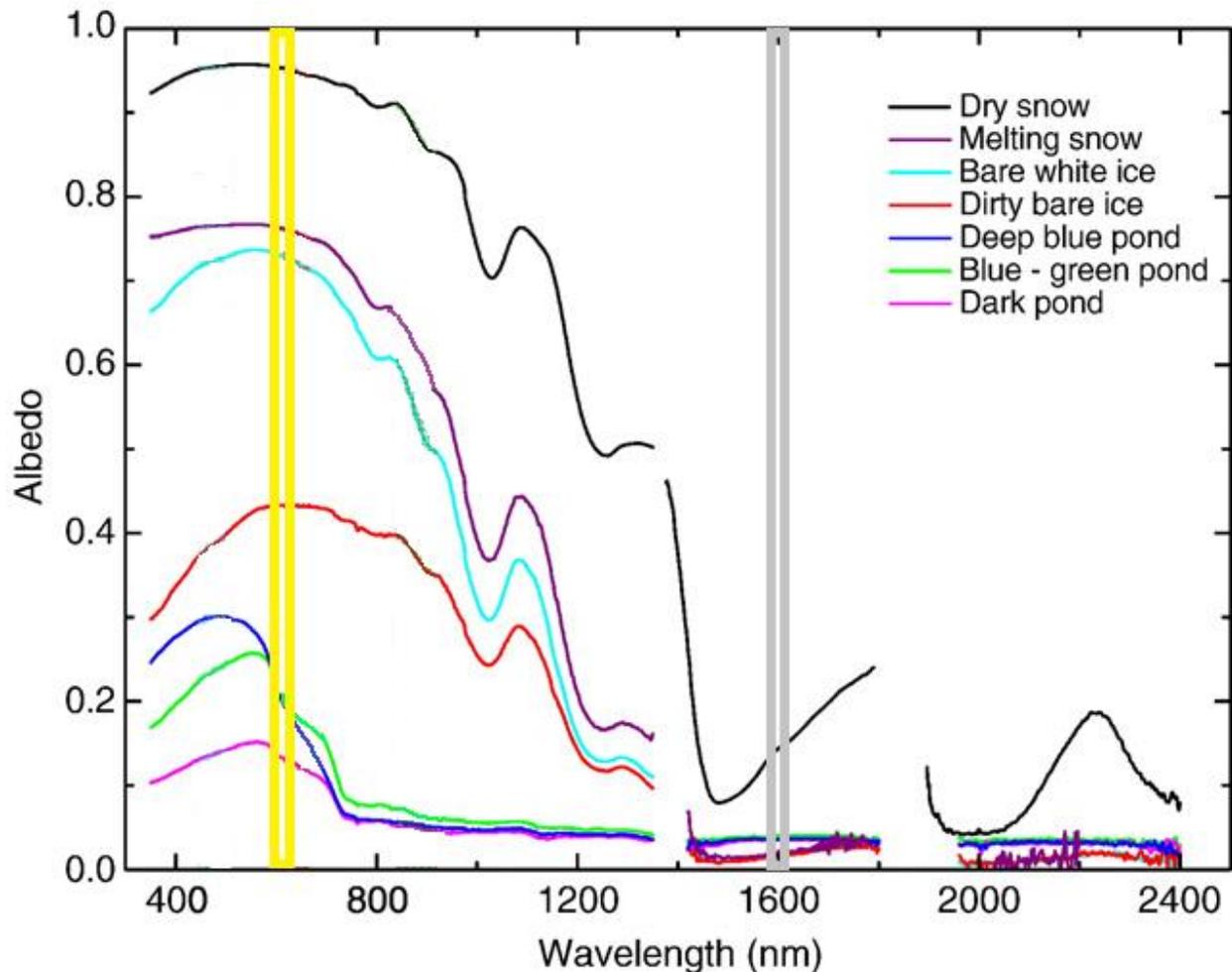


Figure 3: Spectral reflectance of surface feature types measured by D. Perovich (CRREL) near Barrow, Alaska, June 2004. VIIRS spectral coverage for VIIRS bands 1 (yellow, the color for this wavelength) and 3 (in grey) are shown by the vertical boxes. Edited from Tschudi et al., 2008.

### 2.2.1 Algorithm Limitations

The MODIS sea ice algorithm identifies sea ice by its reflectance characteristics in the visible and near IR and its sharp contrast to open water. The darkness of polar winters will be a limiting factor in the use of visible channels.

The major caveat with the Sea Ice Cover algorithm is that it is applicable only to clear-sky conditions. Inadequate cloud masking, by either an overly conservative cloud mask or cloud/ice confusion that results in ice being flagged as cloud, may result in significant error in estimating the presence of sea ice. The presence of cloud will be especially limiting in the daily maps.

In the VIIRS Sea Ice Cover product, screening for clouds is accomplished by applying the VIIRS Cloud Mask (VCM) data product [Godin, 2013]. The VCM Cloud Detection Results & Confidence Indicator flag is used to mask cloud and cloud contamination from pixels. If that flag is set to “confident cloudy” or “probably cloudy,” then the pixel is labeled as cloud obscured

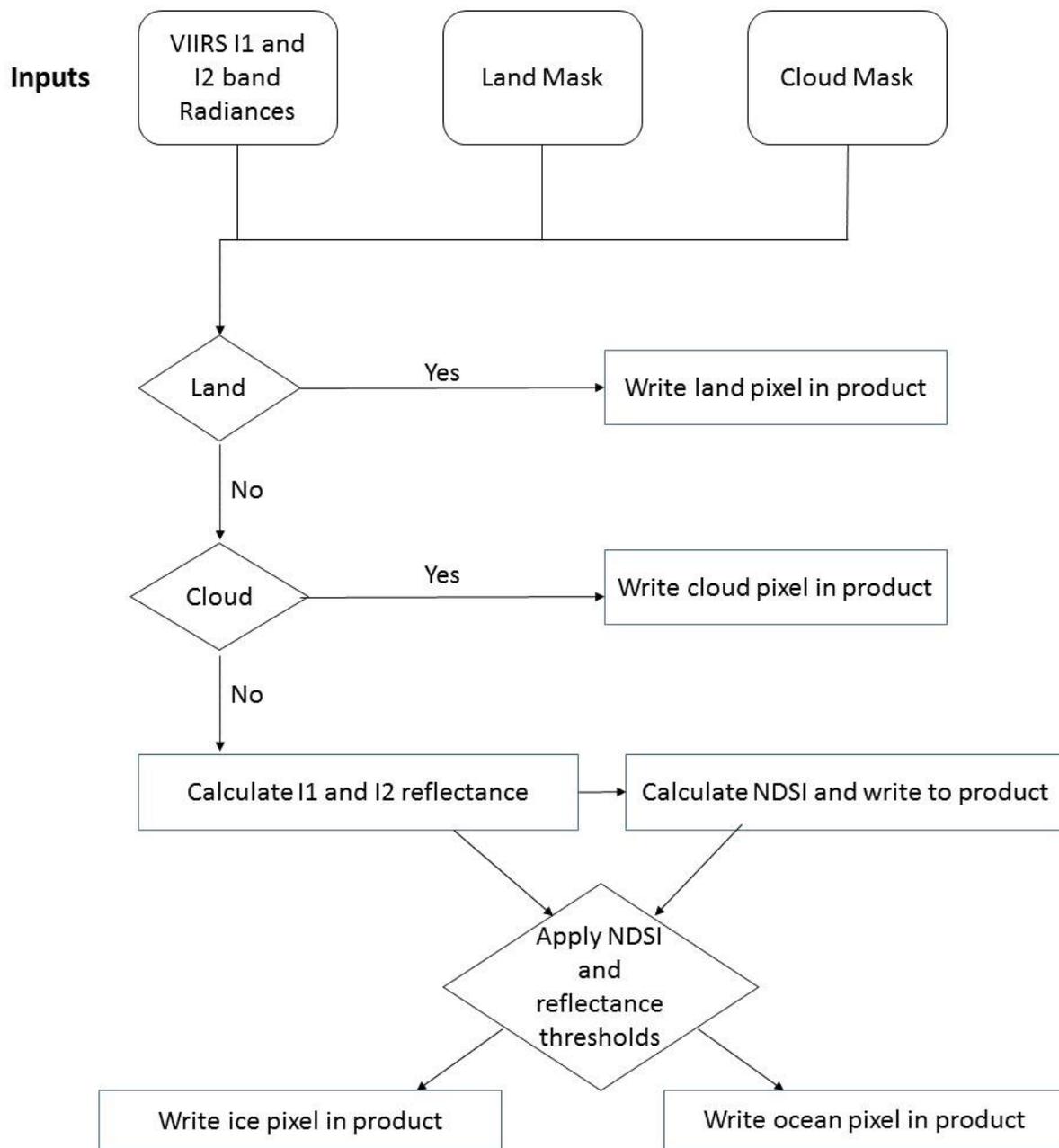
in the sea ice map, and Sea Ice Cover is not calculated. In daylight, the cloud mask has been cloud biased resulting in greater cloud coverage than may exist and identifies sea ice as cloud in many situations.

It is recognized that surface melting and melt ponds may affect the accuracy of the Sea Ice Cover calculation during the melt season. Melt pond reflectance is significantly lower than snow-covered sea ice [e.g. *Tschudi et al*, 2008]. The standard NDSI thresholds may need to be adjusted for these conditions, but more validation studies are required to assess how to adjust NDSI values for summer melt conditions.

### 2.2.2 Algorithm Flow

The general flow of the Sea Ice Cover algorithm is shown in Figure 3. The algorithm is run for all ocean pixels for VIIRS image-band swaths poleward of 50°N and 50°S latitude, without restrictions. The NASA VIIRS land/water mask is used to map the oceans. A land mask is then applied, and a Sea Ice Cover product is computed using (1) over all ocean pixels and stored. Next, the cloud mask (VCM) is applied, with a flag value assigned for all “confidently cloudy” or “probably cloudy” pixels. An “open ocean” mask is then applied for all pixels not identified as sea ice by (1), with a flag value assigned. This modified dataset is then stored in the record. For each pixel, quality flags (QFs) are stored a bit flag array. These QFs are the VCM cloud flag, and I1 and I3 band QFs, which are carried over from the VCM and the visible band input data, respectively. Other QFs produced are the day/night flag (day if solar zenith angle < 85°) and an overall QF, which is based on the values of the other QFs.

This algorithm flow is used so that the algorithm is applied under all conditions, allowing the user to examine the NDSI data before any masks or screens are applied, except the land mask. The NDSI data is then used to assign an “ice/no ice” value to each screened with the VCM, ocean/ice mask, and stored as a second dataset. For each pixel, QA bit flags are produced so users can determine if the result for a pixel is usable in their research or application.



*Figure 3: Suomi-NPP VIIRS Sea Ice Cover Algorithm Flow Chart.*

## 2.3 Product Description

The NASA VIIRS Level-2 Sea Ice Cover Product, with Earth Science Data Type name VPN29, will have the following data arrays: NDSI, Sea Ice Cover, and algorithm QA bit flags. Each data array has local attributes describing the data, and the product has global metadata to support archiving and use of the product. All arrays are produced for areas poleward of 50°N and 50°S.

### Sea Ice Cover

The Sea Ice Cover data array is the sea ice map generated by the algorithm, with clouds (VCM) overlaid by setting the sea ice cover to a flag value corresponding to the cloud mask. Sea Ice Cover is represented as a value of 100. If the array element is not sea ice, then it is either flagged as open water, cloud, or land. Figure 1 shows an example of the Sea Ice Cover array.

### Quality flag arrays

Quality flags from the VCM and the input VIIRS visible bands (I1 and I3) are stored in separate arrays.

### Basic Quality

A general quality flag is assigned, based on the VIIRS visible band flags, as well as whether the data was screened by the land mask or by the cloud mask (VCM). This is used to indicate quality ranging from best to poor, to provide a user with a convenient value for initial quality assessment of the data.

### Algorithm Bit flags (QFs)

Algorithm specific bit flags are set in this data array. Bit flags are set for day/night, land, and cloud/no cloud. The cloud bit is set to “cloud” if the VCM indicates the pixel is “confidently cloudy” or “probably cloudy.” Multiple bit flags may be set. Local attributes describing the data, i.e. each bit flag, are included for the data array.

## 3.0 Product Inputs

The following Earth Science Data Types (ESDT) and corresponding data arrays are used as input for production of the VNP29 Sea Ice Cover Product:

<b>ESDT</b>	<b>Data array names</b>	<b>Nominal spatial resolution</b>	<b>Descriptor</b>
NPP_VMAE_L1	BrightnessTemperature_I1	375 m	TOA
	QF1_VIIRSMBANDSDR_I1		Poor quality flag
	BrightnessTemperature_I3	375 m	TOA
	QF1_VIIRSMBANDSDR_I3		Poor quality flag
	SolarZenithAngle	750 m	Solar zenith angle
	SatelliteZenithAngle	750 m	Satellite zenith angle

NPP_CMIP_L2	QF1_VIIRSCMIP (bits 2-3)	750 m	Cloud mask confidence
	QF2_VIIRSCMIP (bits 0-2)	750 m	Land/water mask

Table 1. VIIRS data product inputs to VNP29\_L2 algorithm.

### 3.1 Spectral Bands

VIIRS image-quality bands are used as input. Input ESDTs and spectral bands are listed in Table 2.

ESDT	Data array	Wavelength	Nominal spatial resolution
VNP02IMG	Reflectance_I1	640 nm	375 m
	Reflectance_I3	1610 nm	375 m

Table 2. VIIRS spectral band inputs to VNP29\_L2 algorithm.

### 3.2 Masks, Thresholds and Ancillary Data

Several data screens, masks and thresholds are applied in the algorithm to mask clouds, flag uncertain sea ice detections, and set QA bit flags. Data screens and masks are created within the algorithm with data read from the VIIRS input data products. No ancillary data are used in the algorithm. Data screens and masks used are described next.

#### Land/Water Mask

The NASA VIIRS land/water mask is used to mask land and to identify inland water bodies. The VIIRS Sea Ice Cover algorithm does not currently perform ice detection in inland waters.

#### Cloud Mask

Discrimination of cloud from snow on sea ice is very challenging because some types of clouds and snow on sea ice can have very similar reflectance characteristics. The VCM cloud detection results & confidence indicator is used in the Sea Ice Cover algorithm to mask clouds. If the cloud confidence flag reports “confident cloudy” or “probably cloudy” for a pixel, the pixel is masked as cloud. If a pixel is “confidently clear” or “probably clear,” the pixel is processed.

The VCM is accurate in cloud detection in most situations; however there are some persistent cloud/sea ice confusion problems that may appear in the Sea Ice Cover product. Some discussion of uncertainty in cloud detection is presented in Sec. 4.0.

## 4.0 Product Accuracy/Uncertainty

Sea ice identification does not have many of the complicating factors of varying surface covers that affect mapping features on land, but there are complications that make sea ice mapping difficult. Because sea ice can vary in concentration from near zero to 100 percent, sea ice cover may not be detected within a scene, due to mixed-pixel effects. The

presence of melt ponds and leads in the summer months will also affect the detection of sea ice, and may cause the ice cover product to underestimate the coverage of ice in particular areas.

Clouds pose many of the same problems in mapping sea ice cover as they do when mapping other surface features, such as snow. Sea ice may move relatively rapidly and clouds may obscure this movement or make the movement of the sea ice appear incoherent when an 8-day time series, partially obscured by clouds, is compiled. Small ice floes, polynyas, and leads at subpixel resolution contribute error to identification and mapping of sea ice. Global error analysis is ongoing with other sources of data, e.g. passive-microwave and regional operational sea ice data products, to estimate error at regional and global scales in the post-launch time period.

#### 4.1 Uncertainty Estimate

The targeted uncertainty of the NASA Sea Ice Cover Product is 5%, i.e. 95% of the viewable surface should be correctly classified as either sea ice or open water. Some error in geolocation may be associated with projecting from latitude and longitude coordinates to this data set's EASE2-Grid Polar equal area projection. Geolocation error may be notable along coast lines, which may appear to shift from day to day between cells of the grid. Errors in sea ice detection are more probable in the summer, when melt ponds may be detected as open water, causing the algorithm to classify sea ice as open water. Similar errors may occur where sea ice is in low concentration in an EASE-2 grid cell.

#### 4.2 Validation Approach

Global and regional error analysis of the NASA VIIRS Sea Ice Cover product is accomplished via comparison with the product's predecessor, the MODIS sea Ice Extent Product [Hall and Riggs, 2015]. The VIIRS Sea Ice Cover Product was developed to achieve continuity with the MODIS product, with VIIRS being the follow-on instrument to MODIS. Other products for the VIIRS product inter-comparison include sea ice concentration products from passive microwave sensors: AMSR-E [Cavaieri et al., 2014] & SSM/I [Cavalieri et al., 1996].

To validate the product, the uncertainties and accuracy of the NASA VIIRS Sea Ice Cover product at the pixel level will be defined via comparisons with airborne observations from NASA's Operation IceBridge [Kurtz et al., 2013]. This ongoing campaign, over the Arctic in Spring and Antarctic in Fall, deploys an aircraft with several instruments, including a DMS digital camera [Dominguez, 2010], which will be useful for ice cover validation. Adjustments to the NASA VIIRS Sea Ice Cover NDSI algorithm thresholds may be made, based on results from these validations.

## 5.0 Data Format

Data products will be produced for 6-minute swaths, and daily in 1km and 4km EASE-grid formats.

### 5.1 Format

The Sea Ice Cover data will be stored as data sets with local attributes describing the data. The product will include metadata relevant to archive, data identification, provenance/processing history and data quality of the product.

### 5.2 QA Metadata

Metadata is written as global attributes that provide information on overall summary quality of the product, such as the percentage of good data processed in a swath. There will also be metadata attached to the datasets, indicating their specific quality.

## 6.0 Product Publications

Data products will be archived and distributed by NSIDC. A NASA VIIRS Sea Ice Cover data product user guide will be posted at the NSIDC DAAC. The User Guide and ATBD, along with a general description of the product, will be available at the NASA VIIRS Land Team website: <https://viirsland.gsfc.nasa.gov/index.html>.

## 7.0 References

- Cavalieri, D. J., T. Markus, and J. C. Comiso (2014), AMSR-E/Aqua Daily L3 12.5 km Brightness Temperature, Sea Ice Concentration, & Snow Depth Polar Grids, Version 3. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: [http://dx.doi.org/10.5067/AMSR-E/AE\\_SI12.003](http://dx.doi.org/10.5067/AMSR-E/AE_SI12.003).
- Cavalieri, D.J. and Parkinson, C.L. (2012), Arctic sea ice variability and trends, 1979–2010, *The Cryosphere*, 6, 881-889, doi:10.5194/tc-6-881-2012.
- Cavalieri, D. J., C. L. Parkinson, P. Gloersen, and H. J. Zwally (1996), updated yearly. Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data, Version 1. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: <http://dx.doi.org/10.5067/8GQ8LZQVL0VL>.
- Comiso, J.C., and F. Nishio (2008), Trends in the sea ice cover using enhanced and compatible AMSR-E, SSM/I, and SMMR data, *J. Geophys. Res.*, 113, C02S07, doi:10.1029/2007JC004257.
- Dominguez, Roseanne (2010), updated 2017. IceBridge DMS L0 Raw Imagery. Boulder, Colorado USA: NASA DAAC at the National Snow and Ice Data Center. <http://dx.doi.org/10.5067/UMFN22VHGGMH>.

- Godin, N. (2013), JPSS VIIRS Cloud Mask Algorithm Theoretical Basis Document (ATBD), Rev E, 474-00033, 101 pp., NASA Goddard Space Flight Center, Greenbelt MD.
- Hall, D. K. and G. A. Riggs (2015). MODIS/Aqua Sea Ice Extent 5-Min L2 Swath 1km, Version 6. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: <http://dx.doi.org/10.5067/MODIS/MYD29.006>.
- Hall D.K., G.A.Riggs and V.V. Salomonson (2001), Algorithm Theoretical Basis Document (ATBD) for the MODIS Snow and Sea Ice-Mapping Algorithms. <http://modis-snow-ice.gsfc.nasa.gov/atbd.html>.
- Kurtz, N., M. S. Studinger, J. Harbeck, V. Onana, and D. Yi (2015). IceBridge L4 Sea Ice Freeboard, Snow Depth, and Thickness, Version 1. [Indicate subset used]. Boulder, Colorado USA. NASA National Snow and Ice Data Center Distributed Active Archive Center. doi: <http://dx.doi.org/10.5067/G519SHCKWQV6>.
- Kurtz, N., J. Richter-Menge, S. Farrell, M. Studinger, J. Paden, J. Sonntag, and J. Yungel (2013), IceBridge Airborne Survey Data Support Arctic Sea Ice Predictions, Eos Transactions American Geophysical Union, 94(4), 41-41, <http://dx.doi.org/10.1002/2013eo040001>.
- Kurtz, N.T., T. Markus, S.L. Farrell, D.L. Worthen (2011), Observations of recent Arctic sea ice thinning and its effect on ocean-atmosphere energy exchange and ice growth, J. Geophys. Res., 116, C04015, doi:10.1029/2010JC006235.
- Liu, Y., Key, J. R., Liu, Z., Wang, X., and Vavrus, S. J. (2012), A cloudier Arctic expected with diminishing sea ice, Geophys. Res. Lett., 39, L05705, doi:10.1029/2012gl051251.
- Maslanik, J., J. Stroeve, C. Fowler, and W. Emery (2011), Distribution and trends in Arctic sea ice age through spring 2011, Geophys. Res. Lett., 38, L13502, doi: 10.1029/2011gl047735.
- Maslanik, J.A., C. Fowler, J. Stroeve, S. Drobot, J. Zwally, D. Yi, and W. Emery (2007), A younger, thinner Arctic ice cover: Increased potential for rapid extensive sea-ice loss, Geophys. Res. Lett., VOL.34, L24501, doi:10.1029/2007GL032043.
- Meier, W.N., G. Hovelsrud, B. van Oort, J. Key, K. Kovacs, C. Michel, M. Granskog, S. Gerland, D. Perovich, A.P. Makshtas, and J. Reist, 2014. Arctic sea ice in transformation: A review of recent observed changes and impacts on biology and human activity, Rev. Geophys., 52(3), doi:10.1002/2013RG000431.
- Parkinson, C.L. and J.C. Comiso (2013), On the 2012 record low in Arctic sea ice cover: Combined impact of preconditioning and an August storm. Geophys. Res. Lett., 40, 1356-1361, doi: 10.1002/grl.50349.

- Pegau, W. S., & Paulson, C. A. (2001). The albedo of Arctic leads in summer. *Annals of Glaciology*, 33, 221–224.
- Perovich, D.K., B. Light, H. Eicken, K.F. Jones, K. Runciman, and S.V. Nghiem, (2007). Increasing solar heating of the Arctic Ocean and adjacent seas, 1979-2005: Attribution and role in the ice-albedo feedback. *Geophys. Res. Lett*, **34**, L19505, doi:10.1029/2007GL031480.
- Perovich, D. K., K. F. Jnes, B. Light, H. Eicken, T. Markus, J. Stroeve and R. Lindsay, (2011). Solar partitioning in a changing Arctic sea-ice cover. *Annals Glaciol.*, **52** (57), 192-196.
- Riggs, G. A., D. K. Hall, and S. A. Ackerman, (1999). Sea ice extent and classification with the Moderate Resolution Imaging Spectroradiometer Airborne Simulator (MAS). *Remote Sensing of Environment*, 68 (2): 152-163.
- Tschudi, M., G. Riggs, D. Hall, and M. and M. Román, (2016). Suomi-NPP VIIRS Ice Surface Temperature Algorithm Theoretical Basis Document (ATBD). NASA. Online at <https://viirsland.gsfc.nasa.gov/Products/CryoESDR.html>.
- Tschudi, M.A., J.A. Maslanik and D.K. Perovich, (2008). Derivation of melt pond coverage of Arctic sea ice using MODIS. *Rem. Sens. Env.*, 112, 2605-2614.
- Tucker, C.J., 1979: Red and photographic infrared linear combinations for monitoring vegetation, *Remote Sensing of Environment*, 8, pp 127-150.
- Tucker, C.J., 1986: Maximum normalized difference vegetation index images for sub-Saharan Africa for 1983-1985, *International Journal of Remote Sensing*, 7, pp 1383-1384.