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Initial Evaluation of MODIS Sea Ice Observations

GEORGE RIGGS,[1] DOROTHY K. HALL[2], AND JEFFREY R. KEY[3]

ABSTRACT

Sea ice data products generated with data from the National Aeronautics and Space Administration (NASA) Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra spacecraft have been produced since 24 February 2000. Algorithms generate products that contain data on sea ice extent and ice surface temperature determined with visible and thermal data. Sea ice extent is determined by visible reflectance characteristics and ice surface temperature is estimated with a split-window technique. Analyses have revealed that sea ice extent and ice surface temperature in the products are in reasonable agreement with independent sources. Analyses have also identified errors occurring in the sea ice algorithm. Discerning clouds from sea ice is a significant problem in daytime imagery; however, changes in cloud detection may alleviate much of the problem. The algorithms are briefly described; findings of early analysis and current state of the sea ice data products are presented.

Key words: sea ice, ice surface temperature, MODIS, remote sensing

INTRODUCTION

The National Aeronautics and Space Administration (NASA) Terra spacecraft was successfully launched on 18 December 1999 from Vandenberg AFB, California. Terra is one of a series of satellites in NASA's Earth Observing System (EOS). The goal of the EOS is to provide data from a series of satellites specially designed for long-term comprehensive study of the Earth. The Moderate Resolution Imaging Spectroradiometer (MODIS) on board Terra is an imaging spectroradiometer designed for observation of the Earth's land, oceans and atmosphere in the visible and infrared regions of the spectrum. MODIS has 36 bands over the spectrum from 0.41-14.39 μm and ranging from 0.25 – 1.0 km in spatial resolution. The MODIS design and Terra orbit result in multiple image acquisitions over the polar regions every day, both day and night, that allow for study of the cryosphere. Sea ice data products generated from MODIS can provide daily information on sea ice extent and ice surface temperature. MODIS began to acquire data on 24 February 2000. The MODIS sea ice products are produced in the MODIS Adaptive Processing System (MODAPS) at NASA Goddard Space Flight Center (GSFC). MODIS sea ice products are then transferred to the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado, where they are archived and distributed. Sea ice data products have been publicly available since 24 January 2001. The MODIS sea ice products and algorithms are a sequence of products from a level-2 swath of data (5 minutes of MODIS data) to a level-3 global gridded projection. The focus

[1]Science Systems & Applications Inc., NASA, GSFC, Code 974, Greenbelt, Maryland 20771; E-mail; griggs@ltpmail.gsfc.nasa.gov
[2]NASA, GSFC, Code 974, Greenbelt, Maryland 20771 USA; E-mail; dhall@glacier.gsfc.nasa.gov
[3]NOAA/NESDIS, 1225 West Dayton Street, Madison, Wisconsin 53706 USA; E-mail; jkey@ssec.wisc.edu

of this paper is on description and analyses of the level-2 swath product where sea ice extent and ice surface temperature are estimated. Algorithms for the level-3 products are essentially compositing algorithms that result in a daily view of sea ice mapped in a polar projection.

BACKGROUND

The primary purpose of the MODIS sea ice algorithm (level-2) is to map sea ice extent. The sea ice algorithm consists of two parts; detection of sea ice by visible reflectance characteristics and estimation of ice surface temperature (IST) using a split-window technique (Key et.al., 1997). Estimated IST is calculated for day and night emissive data. Sets of coefficients for the Northern and Southern Hemispheres and temperature ranges have been derived for use in the IST calculation. Clouds are identified using data from the MODIS cloud mask data product. Analysis of the cloud mask data and algorithm is an integral part of sea ice analysis as it is critical to determine the presence of clouds. A grouped criteria methodology is employed to identify sea ice on a per pixel basis. The rationale for using the grouped criteria methodology is that the criteria are robust, can be easily modified or changed and can be dynamically linked with geographic or seasonal parameters affecting identification of sea ice, and is amenable to enhancements derived from future studies and independent validation.

The assumption is made that sea ice is snow covered and that snow dominates the reflectance characteristics. Based on that assumption the MODIS snow-mapping techniques (Hall et al., 1995; Riggs et al., 1996) are applied to detect sea ice. The main criterion is the normalized difference snow index (NDSI). The NDSI is used to detect the high reflectance of snow at visible wavelengths, and the low reflectance at approximately 1.6 μm: NDSI = (visible reflectance - near-infrared reflectance) / (visible reflectance + near-infrared reflectance). NDSI is calculated with MODIS bands 4 and 6; NDSI = (band 4 – band 6)/(band 4 + band 6). The second criterion is visible reflectance, where snow has a high reflectance and water has a very low reflectance. The purpose of this criterion is to separate water, which has high NDSI values similar to snow (Hall et al., 1995; Riggs et al., 1996), from snow-covered sea ice. If only the NDSI criterion was used, water would be confused with snow-covered sea ice. Sea ice is identified where NDSI ≥ 0.4 and visible reflectance > 0.11 in MODIS band 2 (0.86 μm).

Ice surface temperature is estimated with a split-window technique. Split-window techniques allow for correction of atmospheric effects, primarily water vapor, and yield reasonably accurate sea surface temperature (SST) or ice surface temperature (IST) estimates. MODIS bands 31 and 32 centered at approximately 11.0 and 12.0 μm are used for estimation of surface temperature.

At level-2 the data products are in a latitude and longitude reference system that can be applied to every pixel in a swath. At level-3 the sea ice data from the level-2 products are mapped into the EASE-Grid polar projection (Brodzik, 2001). Only a single daily observation is retained from the multiple observations in the level-2 products for the day. The level-3 sea ice algorithm and product are not discussed in this paper, as the focus is on the level-2 sea ice algorithm and product.

METHODOLOGY

MODIS radiance data are converted to top-of-the-atmosphere reflectance or brightness temperatures using data in the files and equations in the MODIS L1B User's Guide (MCST, 2000). Top-of-the-atmosphere reflectance is calculated as

$$R_\lambda = I_\lambda / Io_\lambda * \cos(\theta)$$

where R_λ is reflectance at λ (μm)
I_λ is radiance measured in the channel (W m^{-2} sr^{-1} μm^{-1})
Io_λ is solar spectral irradiance (W m^{-2} μm^{-1})
θ is solar zenith angle.

Thermal band data are converted from radiance to brightness temperature by the inversion of Planck's equation (Gumley et al., 1994)

$$T = C_2 / \lambda * \ln[(C_1 / (\lambda^5 * R * 10^6)) + 1.0]$$

where T is brightness temperature in K
$C1 = 2*h*c^2 = 1.1910439 * 10^{-16}$ W m^{-2}
$C2 = (h*c)/k = 1.4387686 * 10^{-2}$ m K
λ is wavelength in m
R is Planck radiance in W m^{-2} sr^{-1} m^{-1}

The technique for estimating IST described in Key et al. (1997), which applied to the Advanced Very High Resolution Radiometer (AVHRR) and the Along-Track Scanning Radiometer (ATSR), was adapted for use with MODIS data. The algorithm uses MODIS channels 31and 32 centered at approximately 11.0 and 12.0 μm, respectively. Radiances in these bands are simulated for a wide range of Arctic and Antarctic conditions, employing thousands of atmospheric temperature and humidity profiles as well as directional spectral emissivities of snow in the simulations. A regression relationship between the ice surface (skin) temperature (IST) and the simulated brightness temperatures is then derived:

$$IST = a + bT_{11} + c(T_{11}-T12) + d[(T_{11}-T_{12})(\sec(\theta)-1)]$$

where T_{11} is brightness temperature 11.03 μm
T_{12} is brightness temperature 12.02 μm
θ is sensor scan angle
a,b,c,d are regression coefficients.

A different set of a, b, c, and d coefficients is used for each of three temperature ranges in the Northern and Southern Hemispheres separately.

RESULTS

The first ocean cruise validation of the sea ice product in the Ross and Amundsen Seas 14 February to 31 March 2000 found that the sea ice extent and estimated IST generally agreed with field measurements and observations (Li, 2000). Li (2000) collected data on: all-wave irradiance and albedo measurements, directional spectral radiance measurements, surface temperature and thermal infra-red thermal brightness temperature, air and ocean surface water temperatures, and hourly ice observations including ice concentration, ice type, floe size, floe surface, topography and snow. Li (2000) reported that MODIS ice extent and surface temperature products agree with field measurements and observations in general, and the ice edge with known surface temperature (-1.7°C) is an effective means of sea ice surface temperature calibration.

There have been no other validation cruises or studies, to date, to validate the MODIS sea ice algorithms and products in other areas or by other investigators. Analysis of the MODIS sea ice products depends largely on vicarious validation to estimate the accuracy of the products. Vicarious validation of estimated IST with the new sets of coefficients show that IST is within a reasonable range of expected ice surface temperature based on seasonal data and sea ice atlases. However, explicit validation studies to quantitatively determine the accuracy of the IST are needed.

DISCUSSION AND CONCLUSION

Analysis is ongoing to determine the accuracy of the MODIS level-2 sea extent and ice surface temperature (IST) at global and regional scales. For clear views of polar oceans, results from the algorithm appear to be reasonably accurate in that there is agreement with ice extent by visual analysis of MODIS data. Analysis of transition seasons, formation and ablation, has not been done in detail. Ablation may have the greatest effects because of melt ponds, exposed ice and increased water vapor in the atmosphere.

Sea ice extent, determined by reflective characteristics in the level-2 sea ice algorithm, in the Bering Strait is shown in Figure 1 for 24 February 2001, 2345 UTC. Visual analyses of band combinations of MODIS radiance data indicate that the sea ice algorithm correctly detects the general extent of sea ice. Such comparative analyses also indicate that significant confusion occurs between sea ice and clouds. This is most problematic in regions of broken clouds and is therefore related to cloud type. Also apparent in the image are rectangular cloud patterns that are related to the processing paths and ancillary data that are used in the cloud mask algorithm.

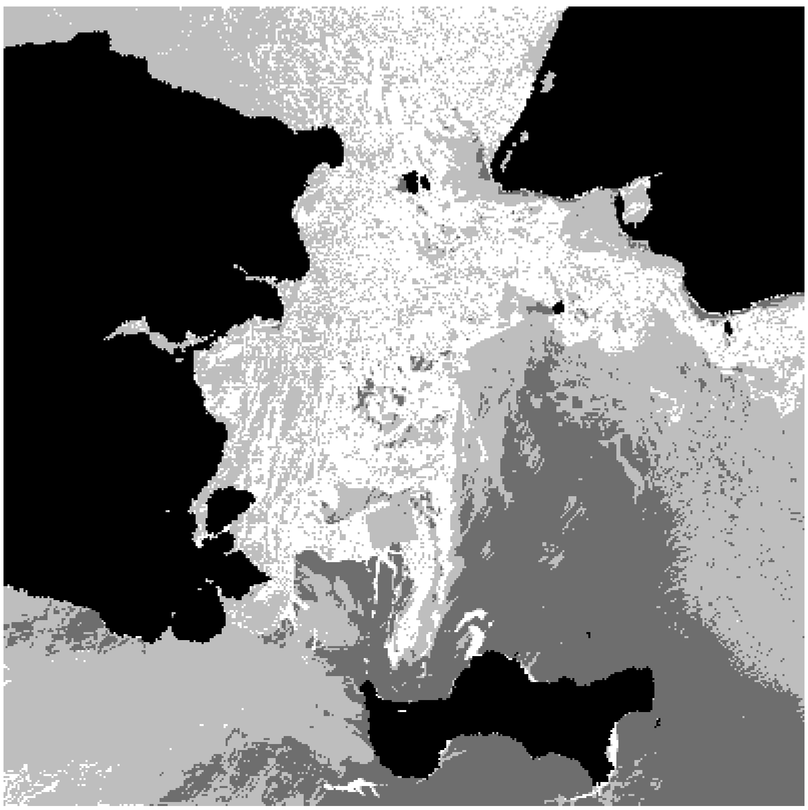

Figure 1. A subset (400 x 400 pixels) from MOD29 acquired 24 February 2001 at 2345 UTC showing sea ice by reflective features. Bering Strait is at top center and St. Lawrence Island is at bottom center. Shades of gray are; black-land, dark gray-ocean, light gray-clouds, white-sea ice.

Determination of clouds has posed some interesting challenges. Currently the summary cloud flag from the MODIS cloud mask product is used to identify cloud. The cloud mask is extremely conservative and identifies much more cloud in daytime images that there is by visible interpretation of the image. The processing path and tests for clouds within the cloud mask algorithm are determined in part by the surface being imaged. Open ocean is processed differently from ice covered ocean and ocean processing paths change poleward of 60° latitude. Analysis has shown that the appropriate processing path may be missed because of the initial determination of sea ice in the cloud mask algorithm. The inappropriate processing path leads to erroneous identification of sea ice as cloud a majority of the time. However, selective use of certain of the cloud tests in the cloud mask data alleviates this problem. During the nighttime the cloud mask tends to miss some types of cloud so that in the sea ice algorithm IST is calculated for those clouds. Collaboration with the MODIS cloud-masking group is underway to understand the sources of confusion in the cloud mask algorithm and data and to resolve them.

Level-3 sea ice products are the result of compositing and gridding the level-2 sea ice products into tiles of approximately 10° x 10° size in the EASE-Grid polar projection. The daily compositing tends to minimize cloud obscuration. (Images of the snow products are posted on the MODIS snow project web page, at the URL below, or browse images may linked to from the NSIDC web page.)

The MODIS sea ice data products are initially declared as provisional in quality. Provisional conveys that the products are free of gross errors and contain reasonable results that could be used only in qualitative ways. However the sea ice products are unvalidated; they are not scientifically reliable for quantitative studies. Vicarious validation investigations and independent validation studies are underway to provide quantitative accuracy of the products. Searching for errors in the algorithms and data products is a continuing activity. Archived MODIS sea ice data products, with caveats regarding the quality of the data products, are available from the NSIDC Data Active Archive Center (DAAC).

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URLs for Sources of Information:

MODIS snow project	snowmelt.gsfc.nasa.gov/MODIS_Snow/modis.html
NSIDC	nsidc.org/NASA/MODIS/
TERRA	terra.nasa.gov