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Enhancing calculation of thin sea ice growth

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ABSTRACT

The goal of the present study is to develop, generate, and integrate into operational practice a new model of ice growth. The development of this Sea Ice Growth Model for Arctic (SIGMA), a description of the theoretical foundation, the model advantages and analysis of its results are considered in the paper.

The enhanced model includes two principal modifications. Surface temperature of snow on ice is defined as internal model parameter maintaining rigorous consistency between processes of atmosphere-ice thermodynamic interaction and ice growth. The snow depth on ice is naturally defined as a function of a local snowfall rate and linearly depends on time rather than ice thickness.

The model was initially outlined in the Visible Infrared Radiometer Suite (VIIRS) Sea Ice Characterization Algorithm Theoretical Basis Document (Appel et al., 2005) that included two different approaches to retrieve sea ice age: reflectance analysis for daytime and derivation of ice thickness using energy balance for nighttime. Only the latter method is considered in this paper.

The improved account for the influence of surface temperature and snow depth increases the reliability of ice thickness calculations and is used to develop an analytical Snow Depth/Ice Thickness Look up table suitable to the VIIRS observations as well as to other instruments.

The applicability of SIGMA to retrieve ice thickness from the VIIRS satellite observations and the comparison of its results with the One-dimensional Thermodynamic Ice Model (OTIM) are also considered. The comparison of the two models demonstrating the difference between their assessments of heat fluxes and radical distinction between the influences of snow depth uncertainty on errors of ice thickness calculations is of great significance to further improve the retrieval of ice thickness from satellite observations.

1. Introduction

The data on ice thickness are important for various studies and applications: from process modeling through general circulation models to climate change as well as for operational support of navigation and other practical commercial and military activities in Polar Regions with sea ice.

The heat budget in the Arctic is significantly affected by the presence of sea ice and by its annual cycle of growth and decay. Sea ice considerably inhibits the vertical flux of latent and sensible heat from ocean to the atmosphere and reflects a large fraction of the incident solar radiation. The insulating properties of sea ice are strongly dependent on its thickness, which is directly correlated to ice age. Thicker ice tends to be colder in the wintertime (Yu and Rothrock, 1996) when there is a thermal contrast between water and sea ice surface. This allows for thickness derivation from surface temperature (Lindsay and Rothrock, 1993; Massom and Comiso, 1994).

These studies have incorporated albedo and temperature data from the Advanced Very High Resolution Radiometer (AVHRR) into an energy balance model to derive ice thickness with a reported accuracy of 50%. Following that it became common-place to declare that the unreliable information on snow depth on ice is a major obstacle to estimate ice thickness. Because of such conclusions, the development of the methodology to calculate ice thickness was almost suspended and the theoretical description of ice growth practically was not improved after the works of Doronin (1971).

A current trend in the development of remote sensing also needs an improved theoretical description of sea ice evolution making the emphasis on using physically based models replacing empirical statistical relationships. The Sea Ice Growth Model for Arctic (SIGMA) described in this paper was proposed for the algorithm (Appel et al., 2005) to retrieve sea ice cover state using the Visible Infrared Radiometer Suite (VIIRS). This instrument important for numerous cryosphere applications of remote sensing,

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however the SIGMA model is applicable to other instruments without modifications.

One of the VIIRS products, Sea Ice Characterization, includes ice concentration and ice age types for the following classification: Ice Free, New/Young, and Other Ice. The retrieval of sea ice age is based on two algorithms: a reflectance method for the daytime and an energy balance approach for the nighttime.

The latter algorithm presenting a good example of using an analytical model describing the influence of physical processes on sea ice growth is considered in Section 2 of this paper providing a background of the model. The application of the model to the VIIRS instrument to generate the estimates of sea ice thickness, sensitivity studies, thickness calculations and validation of the SIGMA performance are included in Section 3. Conclusions are given in Section 4.

2. Methodology to calculate ice thickness

2.1. VIIRS instrument

The Visible/Infrared Imager/Radiometer Suite (VIIRS) onboard the Suomi National Polar-orbiting Partnership (Suomi NPP) platform launched in October 2011 is a 22-channel scanning radiometer instrument providing observations in the wavelength range from the visible to infrared (Hillger et al., 2013). It was developed to combine the advantages of three previously existing sensors: the Operational Linescan System (OLS)—the visible/infrared scanner with a Low-Level Light Sensor (LLLS) capable of detecting visible radiation at night, the Advanced Very High Resolution Radiometer (AVHRR)—the visible/infrared sensor of low operational and production cost, and the Moderate Resolution Imaging Spectroradiometer (MODIS) serving as a standard of high accuracy for a wide range of satellite-based environmental measurements. Nominal VIIRS spatial resolution at nadir is 375 m for five imagery (I) resolution spectral bands and 750 m for sixteen moderate (M) resolution spectral bands. The Day-Night Band (DNB) has a 750 m spatial resolution across full scan (Lee et al., 2006). Because of a novel scanning and aggregation scheme, VIIRS observations are characterized by a pixel growth factor of only two both along a track and along a scan giving the opportunity of getting imagery globally at 750 m resolution (Hutchison and Cracknell, 2006)—much finer than 2.4 km for similar MODIS bands-at a wider swath (3000 km) than MODIS (2320 km). VIIRS offers moderate resolution observations with the spectral coverage from 412 nm to 12 μm providing continuity and enhanced quality of measurements in comparison with the Advanced Very High Resolution Radiometer (AVHRR) and the Moderate Resolution Imaging Spectroradiometer (MODIS).

2.2. VIIRS sea ice products

On the whole, VIIRS contributes to 23 Environmental Data Records (EDRs) and is the principal source of information for 18 EDRs. The measurements provided by the VIIRS instrument are used to generate sea ice information along with a large number of other products beginning from January 2012. Sea Ice Characterization is one of the required VIIRS EDR products, as stated in the Level 1 Requirements Supplement of the Joint Polar Satellite System (JPSS) Program (JPSS Program, 2014). The content of the Sea Ice Characterization EDR includes ice concentration and an ice age class.

The determination of ice age corresponds to the actual age of the ice that happens to be at a particular location-a Lagrangian description of sea ice type redistribution. It is not intended to mean the time interval that has passed since ice first formed at that spot. Surface properties cannot be observed through cloud cover by Visible/Infrared (VIS/IR) sensors. The VIIRS sea ice retrieval needs to achieve the performance specifications. According to the JPSS Program requirements, sea ice age must be classified on the basis of the VIIRS observations as New/Young or Other Ice over ice-covered regions of the global ocean at a horizontal cell size of 1 km under clear (non-cloudy) conditions with a 70% probability of correct typing. The goal for the future is to distinguish between New/Young and Other Ice with a 90% probability of correct typing after additional research and development.

2.3. Ice age

The changes in ice thickness are revealed in the changes of ice types traditionally characterized by the stage of ice development. The stage of development (ice age) and ice thickness represent different sides of the same thermodynamic process—ice growth—but their meaning is different. Variability in ice thickness, to a great degree, depends upon location, climatic conditions, and seasons. Changes in influencing factors lead to a different rate of ice growth and quite different ice thickness achieved for the same period of time after ice formation.

The stage of ice development included in the international system of sea ice symbols (Sea Ice Nomenclature, 2014) is routinely used in ice charts. It is a standard and most common parameter describing the formation and growth of sea ice cover (Table 1).

The changes in the stage of ice development (thickness) are closely associated with the changes in ice color (albedo). On the whole, ice reflectance is correlated with ice thickness varying during the seasonal cycle. The wide range in reflectance of growing ice of various types and thickness is a well-established characteristic of sea ice (Grenfell and Maykut, 1977; Grenfell and Perovich, 1984).

The correlation of snow depth with the stage of ice development contributes to the characteristic reflectance signature of varying ice thickness. Essentially sea ice color is a primary identifier of the stage of sea ice development. Therefore observations on ice reflective properties are useful to determine ice type as well as its thickness to a large degree of accuracy, though the relationship between ice thickness and color could be considered reliable only for growing ice thinner than 0.5 m.

However, during a great part of the seasonal cycle, if sea ice surface is not illuminated by sunlight, the infrared observations are the only available VIIRS information to classify ice type and calculate ice thickness in the case when there are thermal contrasts between water and the ice surface. Our approach based on the model of sea ice growth described in the paper separates New/Young ice from Other Ice for a horizontal cell by a thickness threshold of 0.3 m.

2.4. Ice surface temperature

Ice thickness is the main factor regulating the vertical heat flux through ice under specified atmospheric conditions. Ice surface temperature is determined by the processes of vertical heat exchange and is a distinctive indicator of ice thickness. Given the same atmospheric conditions, New/Young ice will have a higher surface temperature than thicker sea ice because surface temperature is defined by processes of the thermodynamic interaction between the atmosphere and the underlying surface (Groves and Stringer, 1991; Massom and Comiso, 1994).

Changes in sea ice surface temperature are governed by the influence of vertical heat fluxes of different origin. The intensity of turbulent exchange of heat between the atmosphere and the underlying ice surface as well as the surface balance of longwave radiation directly depend on ice surface temperature. The vertical heat flux through ice cover is an explicit function of the vertical