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A physical algorithm to measure sea ice concentration from passive microwave remote sensing data

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Abstract

A conceptually new algorithm of sea ice concentration retrieval in polar regions from satellite microwave radiometry data is discussed. The algorithm design favorably contrasts with that of known modern algorithms. Its design is based on a physical emission model of the “sea surface – sea ice – snow cover – atmosphere” system. No tie-points are used in the algorithm. All the calculation expressions are derived from theoretical modeling. The design of the algorithm minimizes the impact of atmospheric variability on sea ice concentration retrieval. Beside estimating sea ice concentration, the algorithm makes it possible to indicate ice areas with melting snow and melt ponds. The algorithm is simple to use, no complicated or time consuming calculations are involved.

Keywords: Microwave radiometry; Sea ice; Melting snow

1. Introduction

Vast areas occupied by sea ice and its seasonal variability are in the focus of serious scientific studies. They have gained importance in recent decades as climate change has become a major global social and political issue. Since the polar regions are hard to reach and meteorological stations there are rather scarce, remote sensing techniques to investigate sea ice are in high demand. Active and passive instruments operating in microwave range on board Earth satellites make measurements regardless of the time of the day or cloudiness. Passive remote sensing instruments are the most adequate ones in terms of temporal (sensing duration and recurrence) and spatial (swath width and overlap) coverage (Carsey, 1992; Comiso, 2009; Massom and Lubin, 2006; Rees, 2006; Teleti and Luis, 2013).

Nevertheless, for various reasons, the techniques employed today to retrieve ice cover characteristics from passive microwave remote sensing data give significant errors (Agnew and Howell, 2003; Andersen et al., 2007; Carsey, 1992; Cavalieri et al., 1995; Comiso and Kwok, 1996; Fetterer and Untersteiner, 1998; Ivanova et al., 2014, 2015; Meier, 2005).

Analysis of ice concentration retrieval by various algorithms, intercomparison of the results, comparison of the results with optical and radar observations, as well as visual observations from ships show that errors of the algorithms currently in use reach 10% (Andersen et al., 2007;

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Meier et al., 2001; Meier, 2005; Spreen et al., 2008). In periods of summer melt and autumn freeze-up the errors rise dramatically, sometimes up to 50% (Agnew and Howell, 2003; Andersen et al., 2007; Ivanova et al., 2014; Knuth and Ackley, 2006; Meier et al., 2001; Spreen et al., 2008). The majority of authors note the following reasons for the errors in ice concentration retrieval by the algorithms from satellite microwave radiometry data:

- inability to separate emission from more than two ice types (see, for example, Teleti and Luis, 2013);
- seasonal variability of sea ice and snow emissivity (Agnew and Howell, 2003; Ivanova et al., 2015; Knuth and Ackley, 2006; Spreen et al., 2008);
- non-seasonal regional variability of snow and ice surface emissivity (Agnew and Howell, 2003; Ivanova et al., 2015; Knuth and Ackley, 2006; Spreen et al., 2008);
- surface effects, such as surface roughness, snow cover, melting snow, and melt ponds (Andersen et al., 2007; Hewison et al., 2002; Knuth and Ackley, 2006);
- weather effects, such as precipitation (rain, snow, snowstorm, etc.) (Andersen et al., 2006, 2007; Cho and Nishiura, 2010).

Dividing ice into types (multiyear, first-year, etc.) from satellite microwave radiometry data is an important, but practically unattainable goal. The solution is attempted based on the differences in frequency dependencies of emissivity or brightness temperature of different ice types. However, the dependencies were obtained by in-situ measurements (Spreen et al., 2008) for level and clean ice surface. The radiometer spots in those measurements were several meters in size (see, for example, Comiso et al., 1989). For satellite microwave radiometers, pixel size is over 10 km. Emissivity of such extended area is determined not only by the ice type, but also the surface roughness and snow cover. Theoretical estimates demonstrate that dry snow penetration depth at frequencies over 19 GHz is less than 40 cm (Tikhonov et al., 2013, 2014). Therefore, a layer of snow on ice will change considerably the brightness temperature difference between multiyear and first-year ice. Brightness temperature values retrieved from satellite data are significantly affected by surface roughness. These statements were proved by many experimental and theoretical studies (Agnew and Howell, 2003; Cavalieri and Comiso, 2000; Comiso et al., 1989; Hewison et al., 2002; Matzler, 2000; Powell et al., 2006). It is unclear how to select ice type if both multiyear and first-year ice types are present within a pixel area. Notice, that many currently used algorithms produce concentration of ice not specifying its type or age (NASA Team 2, Bootstrap, ARTIST Sea Ice). However, in some cases existing algorithms (e.g. NASA Team, NORSEXS, ECICE) allow reasonable distinguishing of various types of ice (Han and Lee, 2006; Shokr et al., 2008; Svendsen et al., 1983; Voss et al., 2003). Probably, this happens when the ice is flat and there is no snow cover.

Fixed values of emissivity, brightness or physical temperature of ice or open water surface, called tie-points, are widely used in the algorithms. This also leads to considerable errors in calculated ice concentration (Agnew and Howell, 2003; Andersen, 1998). The emissivity of ice, even if it is one-type ice, cannot always remain constant. It depends on surface temperature and climate conditions during formation. Ice emissivity is affected by its snow cover, whose thickness, structure and wetness vary depending on the season and region of formation. Sea ice emissivity is also conditioned by surface roughness that has regional and seasonal characteristics as well.

Elimination of errors in ice concentration retrieval essentially addresses two problems: better account for atmospheric properties and higher accuracy of tie-points determination (Andersen et al., 2006; Cavalieri and Comiso, 2000; Cho and Nishiura, 2010; Comiso, 1995; Ivanova et al., 2014; Kaleschke et al., 2001; Kern, 2004; Lovas et al., 1994; Meier et al., 2001; Pedersen, 1994; Spreen et al., 2008). Attempts in the first direction represent algorithms SEA LION (Kern, 2004), CalVal (Meier et al., 2001), NASA Team (Cho and Nishiura, 2010), NASA Team 2 (Cavalieri and Comiso, 2000), and ASI (Spreen et al., 2008) using various atmospheric models and methods to reduce atmospheric effects. The second problem is addressed by all algorithms since tie-points determination is the principal stage in ice concentration retrieval from microwave satellite data. In particular, it was suggested to introduce dynamical tie-points, that is to determine tie-points individually for different regions and seasons (Agnew and Howell, 2003; Andersen, 1998; Ivanova et al., 2015). Employing dynamical tie-points raises the accuracy of the algorithms (Agnew and Howell, 2003; Andersen, 1998; Ivanova et al., 2015). However, such approach also makes them more difficult to use as tie-point values vary depending on region and season. Consequently, the tie-points should be monitored continuously on regional and seasonal scales. The problem cannot be solved once and for all in conditions of gradual climate transformation. Ice and snow cover climatic formation conditions are changing, which affects surface emission properties as well. The examples are algorithms ASI and Bootstrap, whose tie-point values were modified as time passed (Comiso, 1995; Kaleschke et al., 2001).

In the paper, we discuss a possibility to develop a principally new class of algorithms to retrieve sea ice concentration from microwave satellite radiometry data. Such an algorithm is based solely on a model of emissivity of the "sea surface – sea ice – snow cover – atmosphere" system. It does not use tie-points. Input parameters are real physical and structural properties of sea ice and snow cover (temperature, density, wetness, etc.) of the Arctic and Antarctic, as well as climate characteristics (air temperature and humidity, atmospheric pressure, etc.) of the regions. The schematic of the algorithm is given in Section 2. Section 3 describes the use of satellite and ship observation data for validation of the algorithm. A