

An improved sea ice detection algorithm using MODIS: application as a new European sea ice extent indicator

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General comments

The authors have developed open water – sea ice classification algorithm for the MODIS imagery denoted as IceMap500. This algorithm is further development of previous IceMap250 algorithm (Gignac et al. 2017). The IceMap500 has some novel properties compared to the operational MODIS MOD29 sea ice product algorithm: conducting open water detection over areas where visibility is sufficient – even through clouds (this feature was in the IceMap250); these areas may have been masked as clouds in the MOD35 cloudmask product, and correcting deficiencies originating from the MOD35 cloudmask, e.g. from snow/ice background flag derived from the NSIDC's Near-real-time Ice and Snow Extent (NISE) product at 25 km pixel size and used in the production of the cloudmask. The accuracy of the IceMap500 algorithm was validated with manual classification of pixels randomly selected from 32 sea ice maps. The average accuracy was very good, 95.96 %, and the average kappa coefficient was 0.853.

The IceMap500 algorithm was applied to Terra and Aqua MODIS L1B/L2 swath datasets acquired in March and Sep 2000-2019 over the northern European Seas, and the resulting open water – sea ice maps are compiled to monthly sea ice extent (SIE) maps. These monthly SIE maps are used to investigate SIE trends. No significant trends were observed for the Baltic Sea, but the European Arctic seas showed clear negative trends both in March and September, which is in agreement with many previous sea ice trend studies.

I think the most interesting and important part of the study is the new IceMap500 algorithm, which seems to be very good in the open water – sea ice classification, and to perform better than the MOD29 product (although this was not explicitly discussed in the paper). It would be very interesting to see figures related to different phases of the IceMap500 algorithm shown in Figure 3. I don't quite understand why a new MODIS monthly SIE extent map is needed; there are already microwave radiometer data based products available, e.g. NSIDC sea ice index used as comparison data in the paper – what new information the MODIS monthly SIE map gives us? It delineates the sea ice edge in finer resolution than the radiometer product, but does the resolution improvement mean much in monthly scale? In this time scale there is a lot averaging of the ice edge position due to the sea ice movement. The authors should explain why the new MODIS monthly SIE map is possibly needed, and how it is better than the existing products.

For the Baltic Sea a monthly SIE map does not make much sense as it is a highly averaged map due to sea ice movement in a small sea. The Baltic Sea Ice Services and many studies uses a maximum SIE during a single day within the ice season. I think you should drop the Baltic Sea SIE study with monthly data.

You should review in more details what kind of sea ice detection algorithms and products there are for the optical imagery, what are their deficiencies, what kind of sea ice trend studies have been conducted with them, and what kind of improvements you are targeting with the IceMap500? As the previous IceMap250 algorithm is a basis for your new algorithm you could describe it in more details in Section 2.3. You could also discuss applicability of the IceMap500 to other sensors, like VIIRS and Sentinel-3 SLSTR, possible usage of the IceMap500 maps in various applications, like ice charting, ship navigation, validation of SAR based products, and some topics for further development of the IceMap500.

In addition, you could study what is the typical minimum sea ice concentration for a pixel that it is still detected as sea ice by the IceMap500. I think this can be conducted using typical open water and sea ice signatures. Further, is bare new ice typically detected as sea ice or not? What TOA reflectances and TB values it should have to be detected as sea ice? This relates to detection of polynyas with thin ice as sea ice, and not as open water class. The effect of melt ponds would be also interesting, but I guess more difficult to quantify.

Instead of the SIE trend study, which I think do not give much information compared to previous studies, you could focus more on the capability of the IceMap500 applied on the swath data, and on daily aggregated scale, and comparison to existing product, like MOD29. Anyways, you should compare your SIE trends results (numbers) to previous studies, especially to the most recent ones, now it seems that latest studies you referred are from 2014, see e.g.

Matthews, J.L.; Peng, G.; Meier, W.N.; Brown, O. Sensitivity of Arctic Sea Ice Extent to Sea Ice Concentration Threshold Choice and Its Implication to Ice Coverage Decadal Trends and Statistical Projections. *Remote Sens.* **2020**, *12*, 807. <https://doi.org/10.3390/rs12050807>

Chen Ping, Zhao Jinping. 2017. Variation of sea ice extent in different regions of the Arctic Ocean. *Acta Oceanologica Sinica*, 36(8): 9–19, doi: 10.1007/s13131-016-0886-x

Comiso, J. C., W. N. Meier, and R. Gersten (2017), Variability and trends in the Arctic Sea ice cover: Results from different techniques, *J. Geophys. Res. Oceans*, 122, 6883–6900, doi:10.1002/2017JC012768.

Julienne Stroeve and Dirk Notz, “Changing state of Arctic sea ice across all seasons,” 2018 *Environ. Res. Lett.* 13 103001

Your study area covers the northernmost European sea regions defined following the European Union’s Marine Strategy Framework Directive (MSFD) with addition of 400 km buffer, as shown in Figure 1. This leads to the Kara sea being included only partially, and the northern border not following any latitude limit or natural geographical borders. I think it would be better to follow many previous sea ice studies in the definition of your study area: e.g. Greenland, Barents and Kara Seas, see NSIDC region mask (https://nsidc.org/data/polar-stereo/tools_masks.html#region_masks). This way your SIE trend results could be better compared with previous studies.

In general, I think your IceMap500 algorithm has been developed and validated properly, and it makes important addition to the tools used in the sea ice remote sensing with the optical imagery. It should be of high interest to the sea ice remote sensing community. However, there are some details missing which I point out below in specific comments. Currently, I don’t clearly see value of the MODIS monthly SIE product and its usage in the SIE trend studies. I think the paper needs improvement in this issue and more detailed comparison to previous studies, or even dropping it and focusing more on the IceMap500 algorithm and usage of the swath/daily SIE product.

Specific comments

Abstract

“Aiming at the creation of an improved European sea ice extent indicator, the IceMap250 algorithm has been reworked...”

Likely a reader does not have at this point any clue what is the IceMap250 algorithm. Add at least reference if that is allowed in TC.

“...systematically achieving accuracies above 90 %.”

You could mention how this accuracy figure was determined.

1 Introduction

line 18: “The Arctic sea ice cover has been changing rapidly over the last decades, with its overall extent declining steadily since the first satellite observations in the late 1970s (Serreze et al., 2007; Comiso et al., 2008; Cavalieri and Parkinson, 2012; Massonnet et al., 2012; Meier et al., 2014)”

You should add some newer studies as reference.

l 21: “Moreover, sea ice thickness has decreased as much as 65 % in the period extending from 1975 to 2012 (Lindsay and Schwejger, 2015).”

More recent studies here:

Kwok, “Arctic sea ice thickness, volume, and multiyear ice coverage: losses and coupled variability (1958–2018)”, *Environ. Res. Lett.* 13 (2018) 105005

Liu et al., “Multidecadal Arctic sea ice thickness and volume derived from ice age,” *The Cryosphere*, 14, 1325–1345, 2020.

You could also write about observed decrease of multiyear ice.

l. 32: “Several sea ice variables are continuously obtained and distributed by institutions such as the EUMETSAT Ocean and Sea Ice Satellite Application Facility (OSI-SAF) or the National Snow and Ice Data Center (NSIDC), commonly at resolutions between 10 km and 25 km.”

Add references to the products.

l. 43: “as happens with MODIS sea ice products MOD29 and MYD29.”

Explain what are these MODIS products; what they contain, and add references to product algorithm and to products.

2 Materials and Methods

You should present in this section the NSIDC’s Sea Ice Index data which you use later in Section 3.3; how it is calculated, resolutions, accuracy figures, how it is processed to match your data, etc., with references.

l. 57: “This work focuses on the European regional seas established by the MSFD.”

Any reference for this?

In Section 2.2 add references to MODIS instrument, datasets and dataset algorithms, e.g. to:

l. 79: “It acquires data in 36 spectral bands, ranging from the visible spectrum to the thermal infrared. Spatial resolution at nadir varies from 250 80 m (bands 1 and 2) to 500 m (bands 3-7) and 1 km (bands 8-36).”

l. 85: “consisting of MODIS Terra level 1B Top-of-Atmosphere (TOA) radiance products MOD02HKM, MOD021KM, and the MOD35_L2 cloud mask.”

Spell out acronyms, like SWIR, in Table 1.

l. 89: “Although TOA data does not reflect the physical properties of sea ice and water, it avoids extensive processing due to atmospheric correction”

I don’t understand this; how come the TOA reflectance does not depend on the physical properties of sea ice and water?

Describe in Section 2.2 how MODIS L1B and L2 swath datasets are georectified, i.e. gridded, to your study area shown in Figure 1. What projection is used, polar stereographic?

1. 102: “Threshold tests based on the Normalized Difference Snow and Ice Index 2 (NDSII-2)”

You could show here equation (3) for the NDSII-2.

You could mention that the Jenks natural breaks optimization is the same as k-means clustering applied to univariate data.

1. 103: “the TOA reflectance at 545-565 nm”

Give MODIS band number here.

1. 107: “When batch processing MODIS data it may be likely to run into scenes lacking either ocean water or sea ice and, consequently, the Jenks optimization splits pixels into both surface classes erroneously.”

Could you prevent this by using some kind of pre-classification data to open water vs. sea ice or using co-incident MOD29 product as priori information? If these show that there is only (mostly) one surface class in the image then the Jenks optimization split is not conducted for the threshold determination, but a threshold from a similar image (same time of year and similar location) is used?

1. 128: “summarized in the product’s user’s guide (Strabala, 2004).”

Add also references to MOD35 product algorithm.

1. 129: “Unobstructed FOV, selecting only pixels identified as confident clear.

Add that ‘confident clear’ means confidence > 0.99; from Ackerman et al. (2010).

Describe in the text how the downscaling in Figure 3 is conducted.

1. 139: “This mask is intended to identify areas where visibility is sufficient to perform a classification, for the sole goal of detecting open water.”

Se detection of open water is possible through thin clouds?

1. 143: “where μ and σ are the mean and standard deviation of $R(B20/B32)$,”

Are the mean and std swath calculated from the same swath data which is being classified with R?

1. 167: “Mid-range infrared has been selected instead of thermal infrared because the atmospheric correction is straightforward and may be affected by reflected solar radiation, making easier the exclusion of sun glint as a result of the temperature increase.”

But you are not conducting atmospheric correction of the MODIS data, so why you mention “the atmospheric correction is straightforward”?

1. 171: “refer, for instance, to global SST products by the NOAA”

Give reference to these SST products.

Section 2.3.3 MODI35 correction: I don’t quite follow how this works: you have the MOD35 map which has NISE artefacts or blocks. These blocks are marked as cloudy, so how you remove them with the MOD35 correction when the TOA data is not available; it is masked as cloudy? The correction only affects cloud-free areas close to the blocks? Please show here some example figures.

1. 216: “The synthesis maps are generated by calculating the sum of composite maps where ice = 1 and water = 0, and later normalizing the results according to the maximum number of coincident sea ice observations achieved.”

Give some statistics for the maximum number of coincident sea ice observations.

l. 225: “Finally, the euclidean distance from both sea ice and water is calculated, and is later used to fill NoData gaps by setting as sea ice those pixels closer to sea ice than to water,”

What is a typical area fraction of NoData gaps in a monthly map?

3 Results

The Results Section could have short introduction in the beginning of its content.

l. 240-242: What p-value limit you used here?

l. 244: “While the Baltic Sea trend line in Fig. 7 clearly shows a negative tendency,”

I don't think there is a clear trend by visual analysis; seems quite 'random' variation.

l. 267: “On the contrary, as due to the extensive sea ice cover March scenes are especially prone to almost lack water”

Looking your large study area in Figure I would assume you have always open water in so,e MODIS imagery, e.g. south of Svalbard. Or do you mean that there are many scenes with only sea ice? Please elaborate.

Table 5: How about giving the percentages with 0.1% accuracy? Same for the text. Three decimals for the kappa coefficient really needed?

It seems that Figure 9 is not discussed nor introduced in the text,

4 Discussion

l. 324: “According to EEA (2016), Baltic sea ice extent trends are affected by large interannual variability caused by the North Atlantic Oscillation that prevents them from being statistically significant.”

You could put here also Vihma and Haapala as reference. Also the Arctic Oscillation (AO) has a role here: the annual maximum ice extent generally decreases with increasing indices of AO and NAO.

The monthly March and September sea ice extent maps from 2000 to 2019 are available at <https://doi.org/10.5565/ddd.uab.cat/196007>.

What is the projection in the tiff-file maps? I did not find it in the readme file.