TECHNICAL MEMORANDUM

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Comparing Arctic winter sea-ice thickness from SMOS and ORAS5

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Abstract

In this report, Level 3 sea ice thickness observations from SMOS provided by the University of Hamburg (SMOSIce data) are compared to the ocean-sea ice analysis ORAS5. It is concluded that SMOS provides valuable and unique information on thin sea ice during winter. This is immediately relevant to numerical weather prediction, because thin ice in winter allows appreciable heating of the surface atmosphere by the relatively warm ocean underneath, with heat fluxes of the order of several tens of Wm-2. There is a promising match between SMOS and ORAS5 early in the freezing season (October-December), while later in winter, sea ice is consistently modelled thicker than observed. This seems to be mostly due to deficiencies of the model to simulate polynyas and fracture zones. However, there are regions where biases in the observational data seem to play a role. In the current data version 2, the uncertainties provided with the data set do not seem to characterise well the complex uncertainties of the retrieval model; future data versions will bring further refinements. The large and poorly characterised uncertainties make a direct use of SMOSIce data for model evaluation and data assimilation difficult. However, in order to exploit the unique observational information that SMOS provides about thin sea ice, an operational diagnostic monitoring facility has been implemented into ORAS5, so that statistics of departures between the observed and modelled sea ice state can be routinely monitored, and can help to quantify the impact of thin sea ice on operational ECMWF forecasts. In conclusion, it seems premature to consider assimilation of SMOS sea ice thickness, but it is recommended to use SMOSIce observations for the qualitative detection of thin ice during winter, until further improvements in sea ice model, data assimilation, and retrieval algorithms allow a more direct use of the SMOS sea ice thickness data.

1 Introduction

Sea ice has been observed by satellites since the late 1970s. The most useful observations for use in large-scale weather and climate models come from passive microwave radiance in the range between 7 and 90 GHz, with a continuous daily pan-Arctic coverage with 50km or better resolution. However, because of the very small penetration depth into ice at these frequencies, these observations only provide information about the fraction of an area covered by sea ice, not about the thickness of this sea ice. The thickness of ice is much harder to measure from space, and each of the existing three methods has severe limitations. Infrared emission measurements of the ice surface temperature only work for very thin ice without snow cover, and can only be used for cloud-free conditions. Laser and radar altimetry suffers from high measurement noise and narrow foot-prints, and has larger errors for thicknesses below 50cm. The third method, L-band microwave radiance measurements, for instance from the MIRAS instrument aboard the SMOS satellite (Mecklenburg et al., 2016), allows daily pan-Arctic coverage for ice thickness of up to 1m with about 30km spatial resolution. It requires however a complex radiative transfer model – calculated emissivities might be sensitive to assumptions and ancillary fields used.

This report investigates the properties of a level-3 sea ice thickness product provided by the University of Hamburg, and compares it with ECMWF ocean-sea ice simulations. Non-trivial model-observation departures are reported, which change with region, time of the year, and thickness range considered. Routine monitoring of the departures has been implemented at ECMWF, and this investigation is a step towards eventual assimilation of the data, although successful assimilation will require further improvements in the model and observation retrievals.

2 Model, data, and processing chain

2.1 SMOSIce sea ice thickness product

This report uses version 2.1 of the University of Hamburg L3C SMOS sea ice thickness, as available from http://icdc.zmaw.de/1/daten/cryosphere/l3c-smos-sit.html on a 12.5km polar stereographic grid. The methods to produce the data are documented in Kaleschke et al. (2012); Tian-Kunze et al. (2014), who also provide comparison to EM-bird measurements, infrared-derived, and modelled sea ice thickness.

It was initially planned to use version 3 of the data for this report, but several outstanding data issues were discovered, so that the official release of the data has been delayed until the winter season 2016/2017. These data will correct several known issues for version 2.1 (see later sections). They will also comprise a revised estimation of the uncertainty, and will also be based consistently on v620 of the L1C SMOS brightness temperatures (TB), which are on average 3K higher than the v505 brightness temperatures (Tian-Kunze, personal communication). The version 2.1 data uses v620 TB for the winter 2015/2016, and the v505 TB before that.

2.2 ORAS5 sea-ice–ocean reanalysis

This report concerns itself with the comparison of SMOSIce sea ice thickness data with sea ice thickness simulated by the ECMWF ocean reanalysis system 5 (ORAS5). ORAS5 is a state estimate of the global ocean and sea ice from 1979 to today, and in the near future will be used to initialise the state of the ocean and sea ice for medium-range, monthly and seasonal predictions at ECMWF on an operational basis.

The NEMO ocean model version 3.4.1 (Madec, 2008) has been used for ORAS5 in a global configuration with a tripolar grid with a resolution of 1/4 degree at the equator. One of the poles of the grid is located on the Antarctic continent, and the other two are in Central Asia and North Canada. Horizontal resolution in northern high latitudes ranges from less than 5 km (Canadian Archipelago south of Victoria Island) to about 17 km (Bering Sea and Sea of Okhotsk). There are 75 vertical levels, with level spacing increasing from 1 m at the surface to 200 m in the deep ocean.

ORAS5 contains the dynamic-thermodynamic sea ice model LIM2 (Fichefet and Maqueda, 1997). The sea ice model is run with a viscous-plastic rheology and is coupled to the ocean model every three time steps. LIM2 has fractional ice cover, a single ice thickness category (Hibler III, 1979), and calculates vertical heat flux within the ice according to the three-layer Semtner scheme. Snow on sea ice is modelled, but melt ponds are not.

Forcing fields for ORAS5 are derived from the atmospheric reanalysis ERA-Interim (Dee et al., 2011) until the end of 2014, and from the operational ECMWF analysis from the beginning of 2015 on. Sea surface temperature is constrained to observational data by applying an additional surface heat flux of $200 \mathrm{Wm}^{-2}\mathrm{K}^{-1}$. The observational sea surface temperature data comes from HadISST2 until 2008, and from the OSTIA operational product from 2008 onwards. Assimilation of subsurface ocean temperature and salinity, of sea ice concentration and sea level anomalies is performed using the 3DVar-FGAT procedure. The length of the data assimilation window is 5 days.

Sea ice concentration (SIC) in ORAS5 is assimilated from the level-4 OSTIA product (Donlon et al., 2012). SIC in OSTIA is created by interpolating the OSI-SAF operational sea ice product (http://osisaf.met.no/p/ice) to a global regular grid with 1/20 degree resolution and filling in missing values. This report uses OSTIA SIC interpolated to the SMOSIce polar stereographic grid.

ORAS5 consists of five ensemble members which are obtained by perturbing forcing fields according according to uncertainties derived from inter-product differences, and by assimilating observations that were sampled in a slightly different way for each ensemble member.

For a full description of the immediate predecessor of ORAS5, see the documentation of ORAP5 in Zuo et al. (2015); Tietsche et al. (2015).

2.3 Technical implementation of SMOSIce monitoring

An observation operator has been implemented in the ECMWF system, which involves deriving the effective mean ice thickness from modelled ice concentration and in-situ ice thickness, and interpolating the model values to the observational grid points of the SMOSIce data product.

Since 1 January 2016, version 2.1 of the SMOSIce data from the Hamburg server has been integrated into the ECMWF data acquisition system ECPDS, and is automatically retrieved as soon as it becomes available. It is then used by the operational ORAS5 task to produce so-called feedback-files, in which the calculated analysis-observation departures are stored in observation space. These can be used for diagnostic monitoring, and are also the native format of NEMOVAR, the software at ECMWF which performs the ocean and sea ice data assimilation. Data structures that allow quality control of SMOSIce data are also in place. Hence, the first technical steps towards assimilation of SMOSIce data in the ECMWF system have been taken.

Additional monitoring of SMOSIce data on a workstation has been set up: a scheduled automatic task retrieves data once a day, and produces a range of diagnostic monitoring plots. Using this workstation monitoring, it is possible to detect and document the availability of data. It has been found that for the last winter season from 1 October 2015 to 16 April 2015, SMOSIce data arrived late for 36 out of 200 days, where "late" is defined as more than the 24h latency advertised. Most of these issues were related to server failures at the Hamburg site (Tian-Kunze, personal communication). From ECMWF point of view, late arrival of the data increases the likelihood that they will not be used at all in the operational tasks, and will be lost for near-realtime monitoring and data assimilation.

Flexible and in-depth analysis of the SMOSIce data alone, as well as in comparison with numerical experiments run at ECMWF has been realised by developing a Python-based software package that is based on the widely understood "feedback" file format of NEMO/NEMOVAR, used for instance for exchange of data in the GODAE community. This software package has been used to produce all plots in this report, and is now available for future investigations at ECMWF.

With the next operational release of the forecast model, ECMWF will start using a fully prognostic sea ice model in the operational medium-range and monthly ensembles. This means the initialisation and forecast monitoring of sea ice properties become ever more important. Along with sea ice concentration from conventional passive microwave sensors, and sea ice thickness from CryoSat, sea ice thickness from SMOSIce will be an essential observational ingredient.

3 Characterisation of analysis-observation departures

3.1 Pan-Arctic statistics

SMOSIce sea ice thickness data provides essential information about sea ice that is complementary to observation of sea ice concentration by higher-frequency passive microwave (PMW) channels. To illustrate that, Figure 1 (top row) shows the changing sea ice thickness during the freeze-up in Oct-Dec 2015 as observed by SMOS. Vast areas of newly-formed sea ice have high concentration above 90%. Widely used PMW algorithms cannot differentiate them well from the areas of older ice in the Central Arctic. But SMOS clearly detects that these areas have thicknesses of below 0.5m in contrast to the areas of older ice.

The bottom row of Figure 1 shows the corresponding model field of effective mean ice thickness in ORAS5. There is overall reasonable correspondence between areas of no ice/thin ice/thick ice, but the model clearly tends to simulate thicker ice on average. For instance, in November ORAS5 reproduces the location of the border between thick (old) and thin (new) ice. But, the thin ice areas are about 60cm as opposed to 30cm in SMOSIce. Part of the reason for this is the simplified representation of thin ice in ORAS5, which tends to drive sea ice thickness towards 60cm during the freeze-up (see Tietsche et al. (2014)).

As the freezing season progresses, the ice edge moves further south outside of the Arctic Basin, and previously formed thin ice in the Arctic Basin becomes thicker. Polynyas and fracture zones begin to form. Figure 2 shows SMOSIce and ORAS5 SIT fields for three consecutive months late in the 2015/2016 freezing season. There are extensive polynyas in the Beaufort and Laptev Seas visible in SMOSIce. ORAS5 has only a hint of the Beaufort Sea polynya, and misses the Laptev Sea polynyas completely. The extensive fracture zone in the Beaufort Sea detected by SMOSIce is not simulated by ORAS5. In the Barents and Kara Seas, ORAS5 simulates some thin ice, but it is still thicker than in SMOSIce. Finally, the Baffin Bay stands out as having extensive thin ice cover in SMOSIce, but thick ice in ORAS5. The well-known polynya at the northern end of Baffin Bay is captured both by SMOS and ORAS5.

For a more complete picture of the analysis-observation departures, collocated daily ice thicknesses are collected over the complete freeze-up period 15 October to 15 December 2015. This allows plotting the joint frequency distribution (JFD) of analysed and observed sea ice thickness.

Figure 3 (left) shows quite promising agreement between observed and analysed SIT. However, the overestimation of thickness by ORAS5, which was already visually apparent from the maps in Figure 1, is confirmed. For observed SIT between 0 and 0.5m, ORAS5 SIT is about 30cm higher. For higher observed SIT, the analysed SIT does not increase proportionally (slope in the JFD), so that there is quite good agreement in the range 0.5m-1m. Note that the distribution has wide tails in the analysed SIT. For instance, for 0.4m observed SIT, analysed SIT of up to 1.5m exist.

In late winter, ORAS5 simulates much higher sea ice thicknesses than SMOSIce (Figure 3 right). Departures between 0.5m and 1m are common. This marked deterioration of analysis-observation match towards the end of the freezing season will be discussed in the following paragraphs. The vertical gaps visible in the frequency distributions are an artefact of the SMOSIce data processing (see Section 3.3.

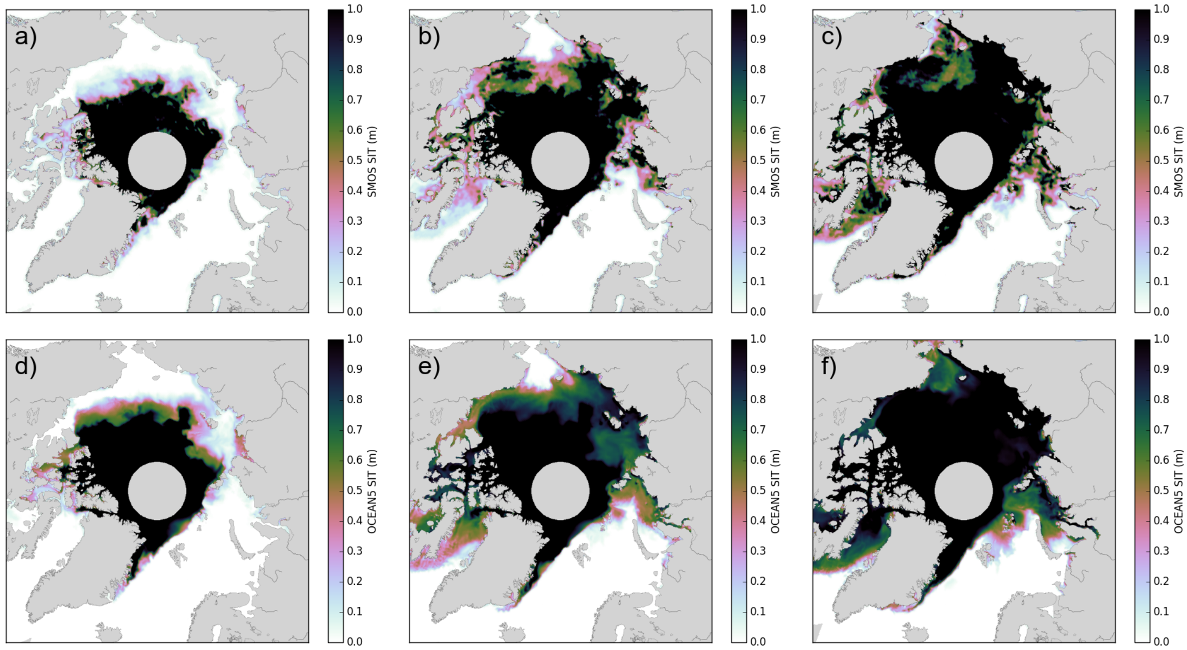

Figure 1: Thin sea ice during the freeze-up of 2015 as observed by SMOS (top row) and analysed by ORAS5 (bottom row). The dates are 15 October for (a)+(d), 15 November for (b)+(e), and 15 December for (c)+(f). There is reasonable correspondence between ORAS5 and SMOS regarding regions with thin sea ice, but ORAS5 overestimates thickness of thin sea ice.

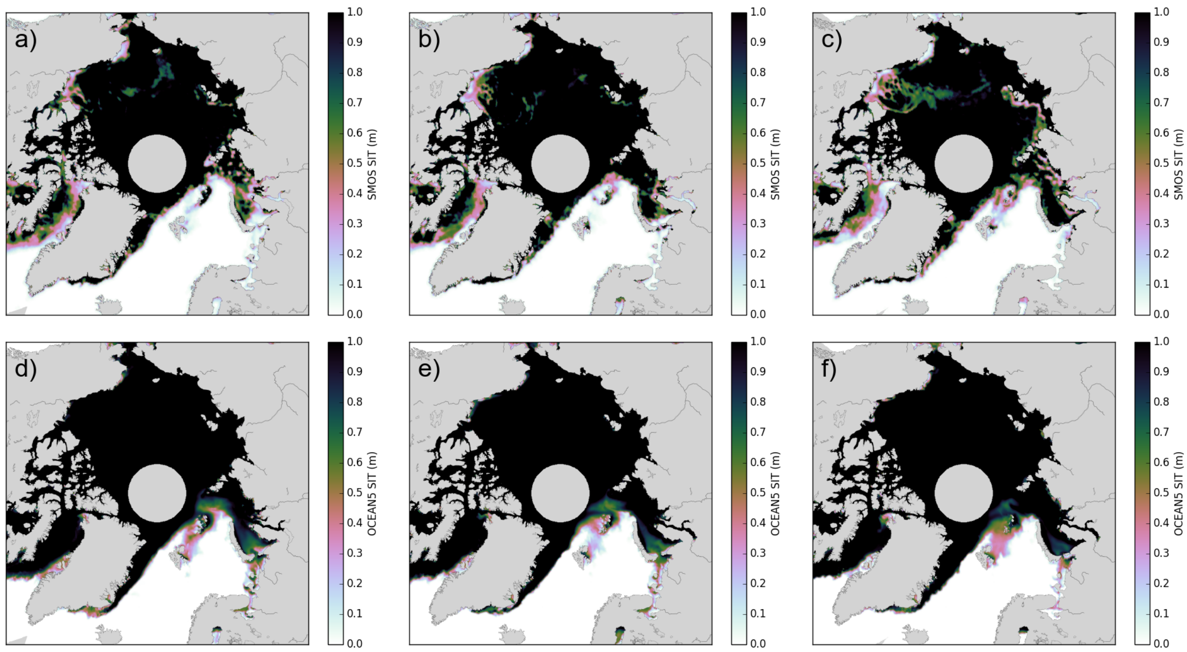

Figure 2: Thin sea ice late in the 2015/2016 freezing season as observed by SMOS (top row) and analysed by ORAS5 (bottom row). The dates are 10 February for (a)+(d), 10 March for (b)+(e), and 10 April for (c)+(f). Thin sea ice in polynyas and fracture zones is detected by SMOS, but not captured by ORAS.

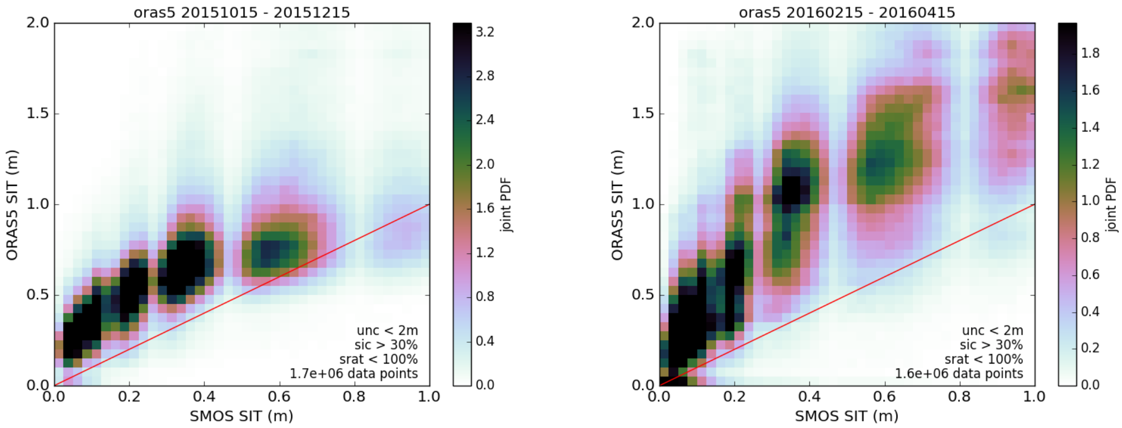

Figure 3: Joint frequencies of observed and analysed thin sea ice, (left) October to December 2015, (right) February to April 2016. ORAS5 agrees reasonably well with SMOS early in the freezing season, but has much larger ice thicknesses late in the freezing season.

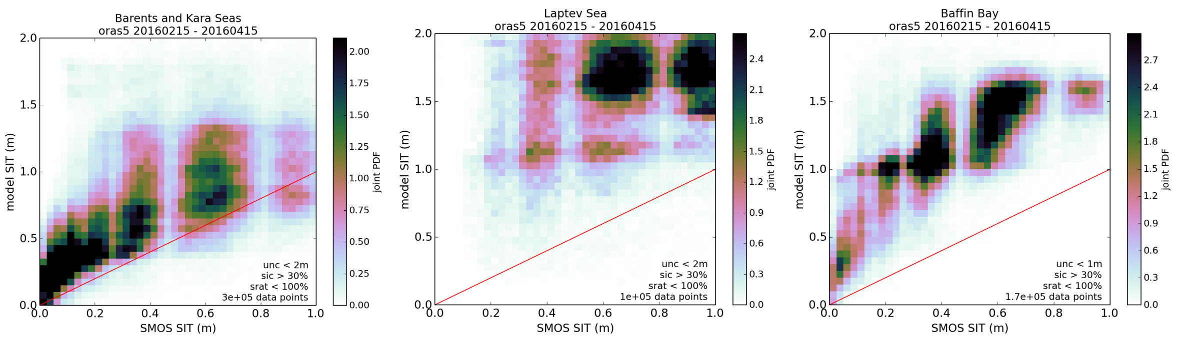

Figure 4: Joint frequencies of observed and analysed thin sea ice for Feb-Apr 2016, (left) Barents and Kara Seas, (middle) Laptev Sea, and (right) Baffin Bay.

3.2 Regional contrasts

There is considerable regional dependence of the departures late in the freezing Season, especially between February and April. Figure 4 demonstrates that for certain regions like the Barents and Kara Seas the departures are only slightly deteriorated in comparison to the freeze-up season, whereas the mismatch looks stark in other regions.

The regions shown have quite different physical characteristics, which might help explain the different departure characteristics: in the Barents and Kara Seas, sea ice is strongly affected by warm Atlantic water being advected towards and under the ice. At the same time, prevailing winds modulate the location of the ice edge by transporting the ice. Both processes are expected to be reasonably well simulated by ORAS5, because winds are prescribed as forcing, and the SST are ingested from an observational product. From the observational side, most of the calibration and validation campaigns for SMOSIce have been carried out in this area, which likely had an influence on the choice and tuning of the retrieval parameters. Thus, the Barents and Kara Seas can be expected to be the region where the analysis-observation agreement is best.

In the Laptev Sea, ice is still relatively well observed when it comes to SMOSIce validation, but it is more difficult to simulate in ORAS5. Because there is no ice edge in the Laptev Sea, SST information

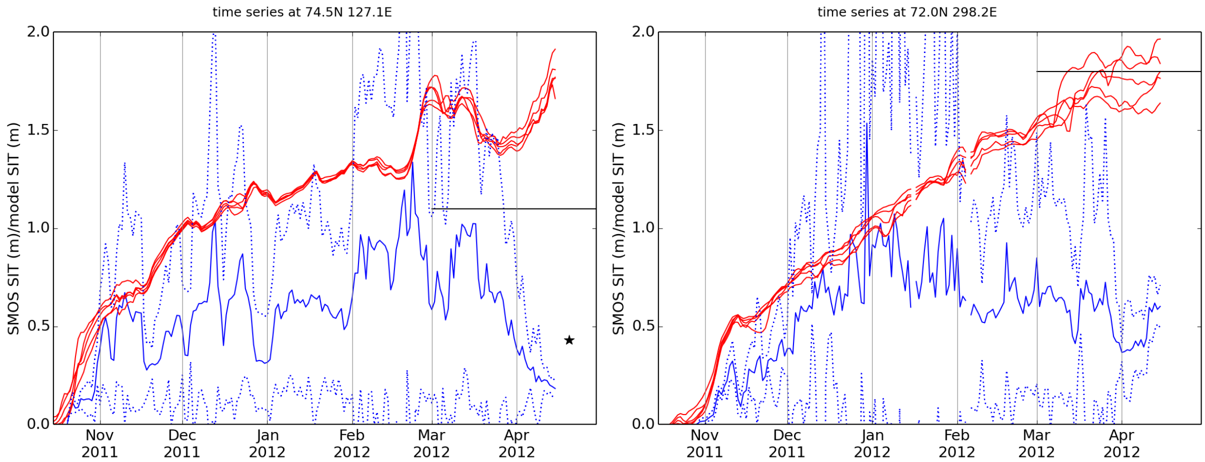

Figure 5: Time series of daily sea ice thickness during the 2011/2012 winter at (left) a representative location in the Laptev Sea at 74.5N,127E *and (right) a representative location in the Baffin Bay at* 72N,−62E*. Blue is SMOSIce with uncertainty estimate provided; Red are the five realisations of ORAS5; Black horizontal lines are the CryoSat2 average thickness for March/April provided by CPOM; black star is an EM-Bird overfly for the Laptev Sea on 20 April 2012.*

cannot be used to constrain the ice cover. Furthermore, as clearly visible in Figure 2, extensive polynyas form there in Feb-Apr, mainly when offshore winds push back the ice from land or land-fast sea ice. These processes are not well simulated by the sea-ice model, which tends to keep a compact thick sea ice cover even in the presence of offshore winds. As a result, major departures can be expected.

Finally, in the Baffin Bay, the occurrence of thinner ice of varying thickness is modelled and observed, but the modelled ice is roughly twice as thick.

There is independent information that suggests that SMOS ice thickness is biased low there. CryoSat2 estimates (Laxon et al. (2013), `http://www.cpom.ucl.ac.uk/csopr/seaice.html`) indicate that between February and April, the ice in this region is typically 1.5m thick. This is confirmed by independent expert judgement by ice chart analysts, who estimate that ice in this region and this season would typically be at least 1m thick (Nick Hughes, personal communication).

To further illustrate and consolidate the findings from the frequency distribution, we plot time series for two representative locations in the Laptev Sea and the Baffin Bay in Figure 5. Both show the typical behaviour of analysis-observation departures: SMOSIce observations and ORAS5 simulation match well early in winter, but later on the analysed ice keeps getting thicker while SMOSIce thickness saturates, albeit with some strong fluctuations. We chose to present a full freezing season in the winter 2011/2012, because this allows collocation with some independent data in both locations. For the Laptev Sea, there was an EM-bird overflight in April, confirming that the ice was indeed only about 0.5m thick, indicating the presence of new thin ice in the well-known Laptev-Sea Polynya. The model is not able to simulate that. The CryoSat2 estimate for this location is around 1m averaged over March/April, halfway between ORAS5 and SMOSIce.

For a representative location in the Baffin Bay, there is reasonable match between analysis and observations until January. After that, the sea ice in the analysis keeps growing to reach thicknesses of 1.5 - 2m in mid-April, whereas SMOSIce observations level off between 0.5 and 1m until mid-April. The CryoSat2 estimate for this location and averaged over March/April 2012 is 1.8m.

Given that ORAS5, CryoSat2, and expert judgement agree that sea ice in the Baffin Bay in this time of the year should be considerably thicker than SMOS-derived thicknesses, we tentatively suggest that there is a problem with the retrieval assumption of SMOSIce in this region. From Figures 6 (a),(e) it can be seen that the slight decrease in SMOS TB from February onwards is interpreted as a slight decrease in sea ice thickness by SMOSIce, in stark disagreement to the ORAS5 analysis. Sea ice concentration is unlikely to play a role, as it is close to 100% in both model and observations (Figure 6b). There was a considerable and varying amount of radio-frequency interference (Figure 6c), but it seems that its impact is successfully removed by the processing chain when calculating the daily-mean the daily-mean brightness temperatures. Surface temperature (Figure 6d) is consistently a few degrees colder than the analysed ice surface temperature, even though the modelled ice is much thicker towards the end of the freezing season, and the associated suppression of conductive heat fluxes should contribute towards colder surface temperature. This could contribute to the analysis-observations mismatch, as could the mismatch between snow thicknesses assumed by SMOS and analysed by ORAS5 (Figure 6c). Perhaps more importantly, sensitivity studies by Maaß (2013) suggest that the decrease in TB could be the result of the sea ice becoming fresher at a different rate than assumed by the empirical rate assumed by SMOSIce. We could not test this hypothesis, because neither does SMOSIce deliver the assumed sea ice salinity as part of the data product, nor does the ORAS5 sea ice model have a good treatment of ice salinity. Further investigation should be undertaken, and we suggest that the assumed sea ice salinity be made part of the SMOSIce data product.

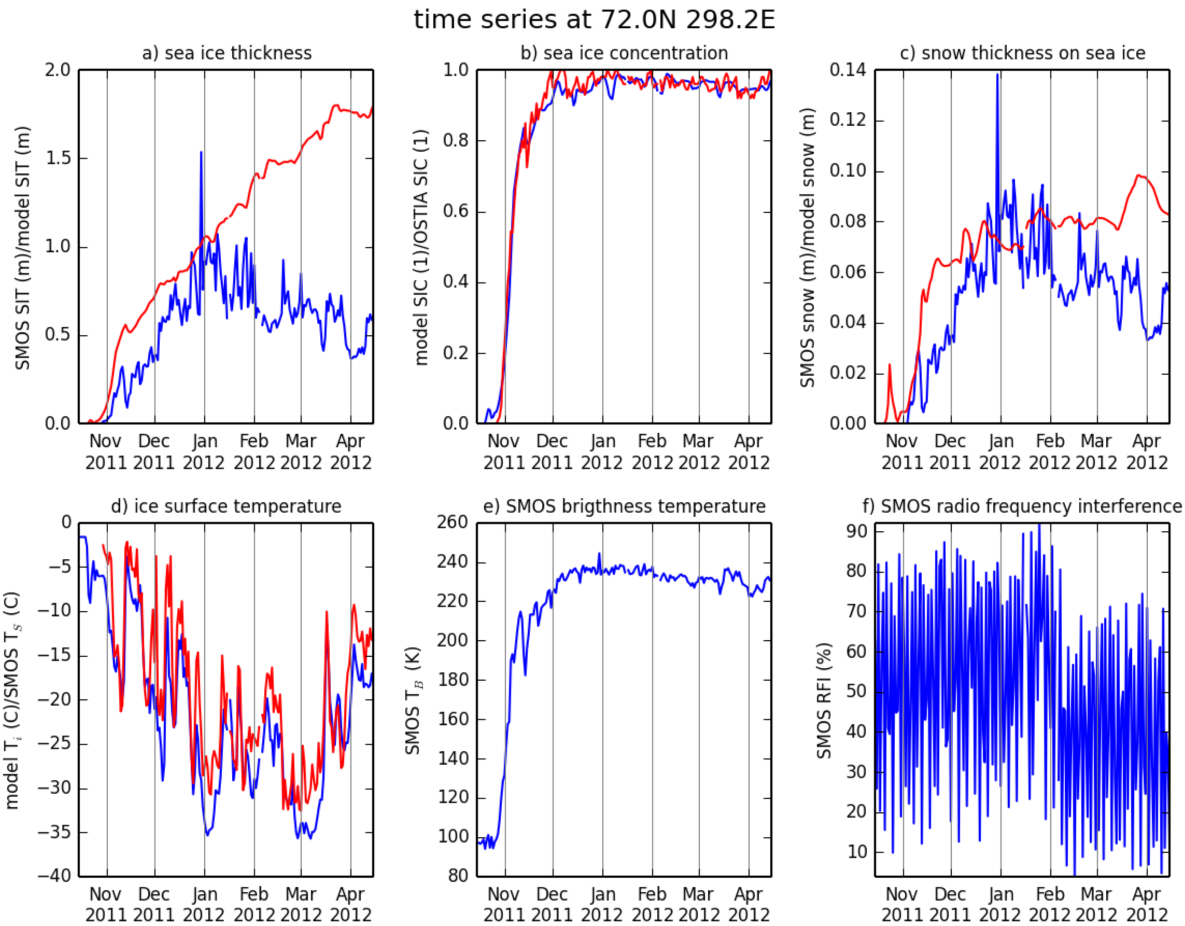

Figure 6: Time series for relevant SMOSIce and ORAS5 parameters for the Laptev Sea location $74.5N, 127E$ *for the full freezing season 2011/2012. Blue curves are SMOSIce parameters (except in (b), where blue is observed ice concentration from OSTIA), red curves are model parameters.*

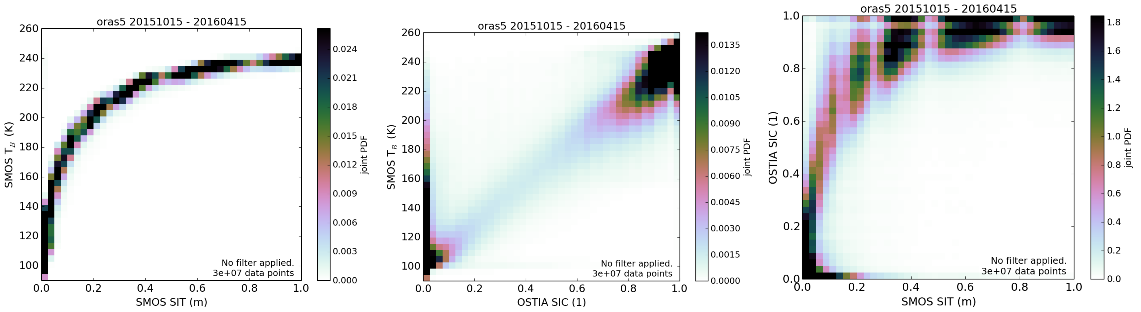

Figure 7: Frequency distribution of SMOS brightness temperatures and derived sea ice thickness for the winter 2015/2016.

3.3 SMOSIce data uncertainties

Interpretation of TB changes Sea ice thickness retrieved from L-band microwave radiance is limited by penetration depth of the radiation in sea ice. The maximum retrievable ice thickness is reached when the L-band brightness temperature has no useful sensitivity to sea ice thickness any more, or when it is dominated by uncertain ice salinity and ice temperature (Tian-Kunze et al., 2014). Figure 7 shows that for SMOSIce, throughout the data set, there is a strong functional relationship between retrieved sea ice thickness and TB. TB is very sensitive to SIT of up to 50cm or so, but beyond that the slope TB/SIT of the relationship is small, meaning that SIT is only poorly constrained by TB, and auxiliary data become more important to determine the retrieved SIT.

Unfortunately, for footprints which are partially open water, SMOSIce does not take into account the emission of the open water. As shown in Figure 7 (middle and right), in the range 0-50cm, there is typically a sizeable open water fraction, and there is a linear relationship between ice concentration and SMOS TB. This suggest that SMOSIce erroneously ascribes low TB to thinner ice instead of to the open water contribution, and hence below 50cm we must expect SMOS to be biased low (see also Tian-Kunze et al. (2014)). However, this might be compensated by the fact that retrievals for sea ice concentration are often also biased low for areas of thin sea (Kwok et al., 2007). For retrieved ice thicknesses above 50cm, the open water fraction is usually low so does not contribute to the TB; however, in this range the retrieved thickness is dominated by poorly constrained assumptions about snow, ice temperature and ice salinity.

Retrieval artefacts In the current data version 2, look-up tables are used in the retrieval algorithm to speed up processing. The resulting discretisation leads to a substantial retrieval artefact. As Figure 8 demonstrates, the frequency distribution of retrieved sea ice thickness has an unphysical multi-mode structure, with local minima at around 15, 25, 45 and 80cm. These modes are very strong, for instance SMOSIce has four times more sea ice at 30cm than at 25cm. This artefact could potentially cause major problems in correct geophysical interpretation of the data, and could cause spurious results when using SMOSIce for data assimilation. In the upcoming version 3 of the data, the problem has been addressed by introducing more entries in the look-up table with a finer spacing (Tian-Kunze, personal communication).

Asymmetric and unreliable uncertainty estimates in the SMOSIce product The provision of uncertainty estimates in version 2 of the SMOSIce data product is very valuable. Correct interpretation of

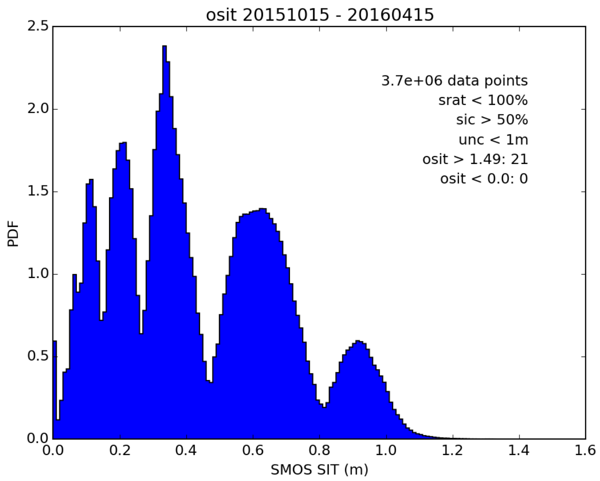

Figure 8: SMOSIce version 2 thickness frequency distribution for the winter 2015/2016. The unphysical multi-mode structure is an retrieval artifacts that will be fixed in later versions of the data.

the data, and their use in model evaluation and data assimilation crucially depend on them. However, the currently provided uncertainty estimate described in Tian-Kunze et al. (2014) are only a first estimate. They are symmetric around the provided value; given that sea ice thickness is bounded below by 0, this is unsatisfactory. The resulting relative uncertainty is often larger 100%, which makes it challenging to interpret and use the retrieved thickness (see Figure 5 for examples). Conversely, situations are often found where the provided uncertainty is small, but there are strong indications that SMOSIce is consistently underestimating the sea ice thickness (e. g. Figure 5 right).

Unrealistic daily changes of retrieved sea ice thickness Sea ice thickness at a particular location retrieved from SMOSIce varies much more from one day to the next than analysed by ORAS5 (Figure 9). Note that the distribution of daily SIT changes is much broader for SMOSIce than for ORAS5. Extreme daily thickness changes of more than 20cm occur around 6% of the time in SMOSIce, but less than 1% of the time in ORAS5. These changes can have either thermodynamic causes (ice mass changes) or advective causes (ice is moved in/out of grid cell). A SMOSIce grid cell has a width of 12.5km. That means, for references, an advective change of 20cm would require a nearby step change of 20cm in the ice thickness, combined with strong winds or ocean currents that are able to move the ice by 12.5km in a day. Alternatively, if the change was thermodynamic, a surface heat flux of 700 $Wm{-2}$ over that day for the whole 12.5km grid cell would be required. These extreme conditions should only be expected to occur near the ice edge, and in polynyas and fracture zones, and therefore daily changes of 20cm or more should be rare.

Inspection of maps of daily changes reveals that large SIT changes in SMOSIce are not restricted to the ice edge, polynyas and fracture zones, but occur over extended large-scale areas that correspond to changing synoptic weather patterns. An example is given in Figure 10. On 16 Nov 2015, ice surface temperatures derived by SMOSIce were around -10C in the Laptev Sea and SMOS-derived ice thicknesses ranged between 0.5 and 1m. The next day, SMOS-derived ice surface temperatures in this region increased by 8C in a very coherent and homogeneous structure, while brightness temperatures decreased only slightly and with less spatial coherence. The SMOS-derived sea ice thickness over the Laptev Sea changed coherently by more than 20cm. Given that it is impossible for the ice to change that way in reality, taking into account both thermodynamic and advective forcing, it must be concluded that this wide-spread ice thinning by 20cm from one day to the next is an error in the retrieval algorithm: strong changes in the ice surface temperature, in reality caused by synoptic changes, together with unremarkable change in brightness temperatures, are erroneously interpreted as a strong thinning of the ice.

The unrealistic strong day-to-day fluctuations in the SMOSIce data are likely due to either errors in the ancillary fields, or due to the assumption of a linear temperature profile within the ice. If there are relevant errors in the ancillary fields, a quick change in the field will lead to a quick change in the retrieved ice thickness that is not realistic. The limits to the validity of the assumption of a linear temperature profile has been investigated in detail by Maaß (2013). They found that, after abrupt changes in the meteorological conditions, the temperature profile within the ice can take several days to adjust. Based on these results, we tentatively suggest that the assumption of the linear temperature profile within the ice is responsible for the unrealistic day-to-day changes in the SMOSIce data. However, this question can only be answered satisfyingly by further research which modifies the thermodynamic sea ice model embedded in the retrieval algorithm.

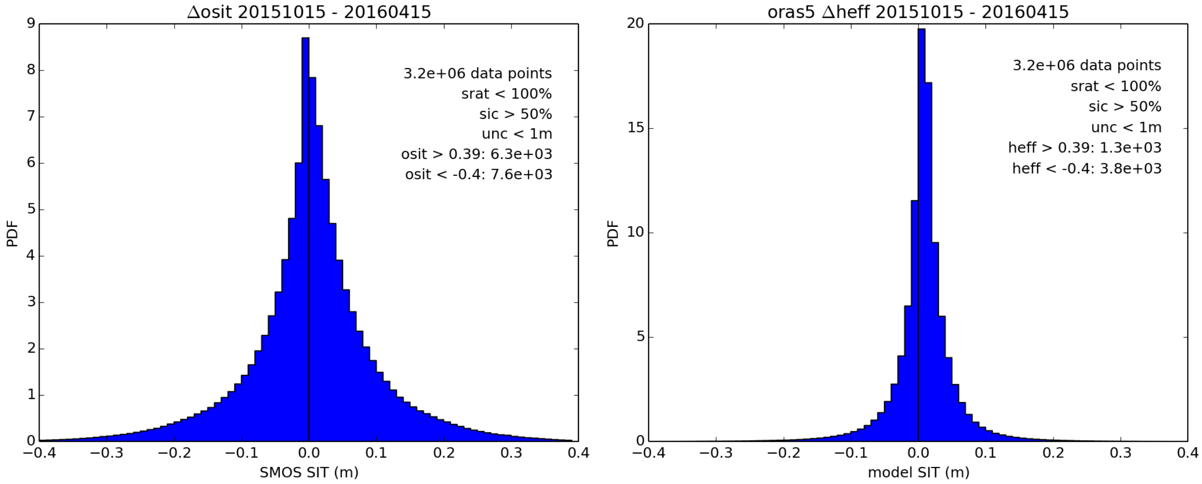

Figure 9: Frequency distribution of SMOSIce-derived (left) and analysed (right) daily sea ice thickness changes. Ice tickness changes of 20 cm requires a surface heat flux of 700 Wm−2 or very strong gradients and ice transport within a day, and should be expected to occur only very rarely.

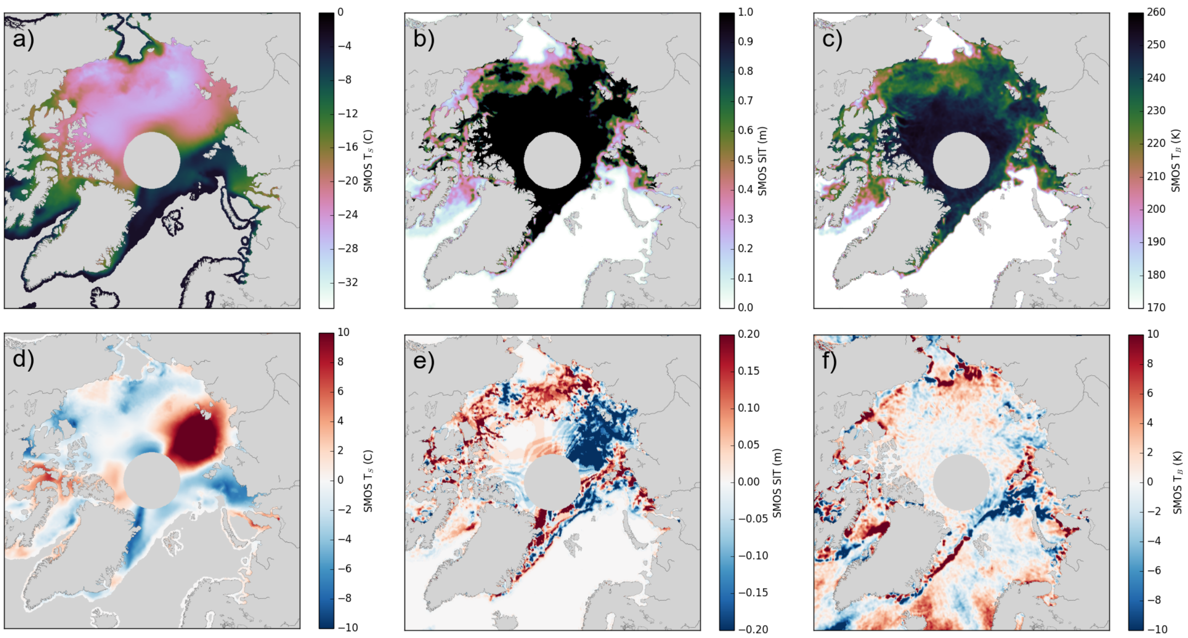

Figure 10: Maps of ice surface temperature (a,d), ice thickness (b,e) and SMOS TB (c,f) on 16 Nov 2015 (a–c) and changes from the day before (d–f). Correspondence between unrealistic SMOS-derived changes in ice thickness (e) and changes in ice surface temperatures (d) are evident.

4 Discussion

In light of the previously discussed shortcomings and uncertainties both in the current version of the SMOSIce data and the current version of the ECMWF sea ice model, we suggest to proceed with caution. It is clear that there is a generic trend for analysed sea ice to be thicker than what is retrieved from SMOS. Indications are that both problems in the model and in the observations contribute to this.

On the model side, the lack of thickness categories in combination with an artificial threshold of minimum ice thickness while freezing leads to overestimation of ice thicknesses during freeze-up season (October-December). Later in winter, the model is mostly incapable of simulating the polynyas and fracture zones present in the interior of the ice pack.

On the observational side, low sensitivity of the SMOS brightness temperatures for ice thicknesses larger than 50cm is compensated in the SMOSIce retrieval algorithm by heavily relying on auxiliary fields from external sources, such as 2m temperature and winds, sea ice salinity, and snow thickness on sea ice. These have considerable and poorly quantified uncertainties associated with them, which reflects in uncertainty in the retrieved ice thickness.

For the current state of the system at ECMWF, we suggest the best way of using SMOSIce data is as a means to *qualitatively* detect the presence of thin sea ice, and contrast that with the modelled fields. One could, for example, define an upper bound for what one considers to be thin sea ice, and then diagnose whether model analysis and observations agree or disagree on the presence of thin sea ice. We suggest a threshold of 1m to differentiate between "thick" and "thin" sea ice; SMOS brightness temperatures are typically still sensitive to changes in the ice thickness in this range (Figure 7), and typical conductive heat fluxes and associated ice growth rates drop off dramatically above 1m (Hibler III, 1979).

Figure 11 shows examples how maps of this thin-ice index look like. It can be directly computed from the information in Figures 1 and 2. The maps in Figure 11 immediately convey the important information in the analysis-observation departures, without drawing undue attention to details in the departures: in the freeze-up season (upper row), there are large areas where SMOSIce and ORAS5 agree, but the model has thick ice too early in December in the Beaufort and Chukchi Seas. In late winter (lower row), extensive fracture zones in the Beaufort Sea, as well as Polynyas in the Laptev and Kara Seas are detected by SMOS, but not simulated by ORAS5. As argued in Section 3.2, the mismatch in the Baffin Bay and Labrador Sea is probably due to underestimation of ice thickness by SMOS.

The previous example illustrates that analysis-observation departures have different fundamental reasons, and future data assimilation studies using SMOS should treat each of the following scenarios differently:

1. The model over- or underestimates large-scale ice thickness in the areas of first-year ice. Typical is an overestimation in October-December in the Arctic Shelf Seas. In principle, the model is capable of simulating sea ice thickness as seen by SMOS, so that data assimilation will unequivocally provide a better estimate of the truth than model or observations alone.

2. SMOSIce systematically underestimates ice thickness. We argue that this typically occurs in the Baffin Bay and Labrador Sea during late winter. Assimilating SMOSIce data here would deteriorate the simulated state

3. SMOSIce detects the presence of thin ice in fracture zones and polynyas, but the model has structural limitations that prevent it from simulating this. Here, assimilating SMOSIce data would lead to a better state estimate, but would force the model outside the range of states it would normally occupy. Assimilation is probably beneficial to arrive at better state estimates and initial conditions,

but investigation is needed to ensure no undesired unphysical side-effects are triggered during the assimilation.

With further progress in the retrieval algorithms and the modelling for thin sea ice, the distinction between the above three departure scenario might become obsolete, and direct, unqualified use of the data for model validation and data assimilation will become possible. Until then, we suggest to use SMOSIce data as a means of detecting the presence of thin sea ice, and design data assimilation studies with the above three departure scenarios in mind.

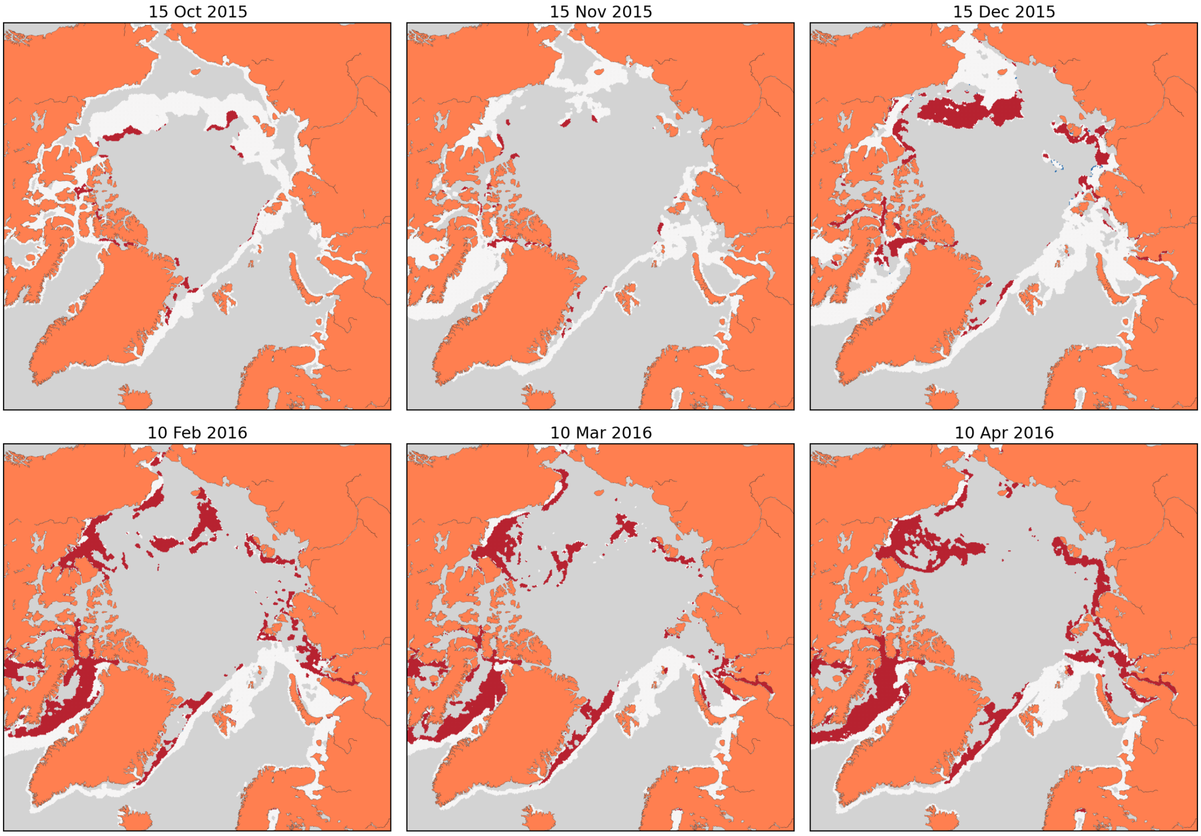

Figure 11: Maps of the qualitative "thin ice flag" suggested in the main text. The thin-ice threshold is set to 1m. Each grid point is coloured either white,red or blue. White means SMOS and ORAS5 agree on the presence of thin ice, red means SMOS detects thin ice that ORAS5 does not simulate, blue means ORAS5 simulates thin ice that SMOS does not detect. Grey points are no data, i.e. either no sea ice present, no SMOS observations available, or SMOSIce thickness should not be used (saturation ratio larger than 100% or uncertainty larger than 1m).

5 Outlook on assimilation of SMOS sea ice thickness

The radiative transfer model needed to derive sea ice thickness from SMOS brightness temperatures is complex and nonlinear. It has assumptions that can be problematic (for instance, zero heat capacity of the ice), and it can exhibit sensitive dependency on ancillary meteorological and oceanographic fields. To better characterise how the uncertainty of the retrieved ice thickness depends on the uncertainty of the retrieval model assumptions and the ancillary fields, it would be beneficial to do the retrieval as part of an integrated analysis and forecasting system, such as the IFS implemented at ECMWF.

Immediate progress on increasing the usefulness of SMOS-derived sea ice thickness for ECMWF would be possible with the following activity: (1) install the radiative transfer model used by the University of Hamburg SMOSIce project to run at ECMWF, (2) implement acquiring Level-3 SMOS brightness temperature (daily means), and (3) modify the SMOSIce retrieval model to work with bulk ice temperature and salinity derived from the ECMWF ocean analysis ORAS5. With the thus-obtained system, a detailed study of retrieved versus analysed sea ice thickness would need to be performed, that would result in an in-depth understanding of the uncertainties and biases of both the analysed and retrieved sea ice thicknesses.

A second, more long-term activity, the assimilation of SMOS-derived sea ice thickness into the ECMWF model, possible even based on Level-2 or Level-1 data, would require the development of multi-variate sea-ice data assimilation schemes, which are currently not available. These multi-variate sea-ice data assimilation schemes would either extend the well-proven variational data assimilation system used for the ocean (NEMOVAR), or would have to be developed from scratch based on ensemble-based methods. Mixing the two complementary approaches in so-called hybrid methods might also be promising. However, these developments can only take place if there is a commitment to allocate sufficient time and resources to them. The Object-Oriented Prediction System (OOPS), which is currently being developed at ECMWF, will facilitate experimentation with these novel data assimilation approaches.

As a third possible activity, which bypasses the complex and long-term task of developing suitable multi-variate sea-ice data assimilation schemes, might be possible if improved sea ice thickness data sets become available that address the shortcomings described in this report. Combining future sea ice thickness data sets with lower and more reliable uncertainty estimates with future improved sea ice prognostic models might allow more simple data assimilation methods to be successful. For instance, uni-variate assimilation of sea ice thickness using NEMOVAR might be possible using a observational product that merges sea ice thickness from SMOS and CryoSat2 (like the AWI product to be released soon), combined with a multi-category sea ice model (like LIM3, planned to be implemented at ECMWF soon).

All three strands of activity suggested above will require substantial work. We estimate that the first strand could be performed by an experienced researcher in a year or so. The second is a collaborative basic research effort requiring several people to work on it for several years. The third activity should be achievable by an experienced researcher within a few years. Progress with assimilating sea ice thickness derived from SMOS brightness temperatures is conditional on the availability of these resources.

6 Summary and conclusions

In this report, it has been demonstrated that there is a huge potential for sea ice thickness from SMOS to be useful for validation of and data assimilation in prognostic ocean/sea ice models, but that there are outstanding questions on the uncertainty of the retrieved ice thickness.

Departures of ice thickness between the ice-ocean analysis ORAS5 and the SMOSIce observational product have a complex structure and depend on the region, season, and thickness range considered. In general, there is reasonable agreement between observed and analysed ice thickness early in the freezing season from October to November. Later on, in most regions the analysis shows ice thickness that are continuously growing, whereas SMOS ice thickness saturates. This saturation occurs even when filtering out data that is flagged as non-saturated and low uncertainty in the SMOSIce data product.

Some large late-winter departures are due to the occurrence of fracture zones and polynyas within the ice pack. These are well-detected by SMOSIce, but only poorly simulated by the model. Other late-winter departures, for instance in the Baffin Bay region, seem to be caused by SMOSIce data being biased low. Some hypotheses for the low bias have been suggested, but further investigation is needed here.

Thin sea ice is a fast-changing moderator of air-sea heat fluxes in the cold season, with clear relevance for numerical prediction of weather and climate. However, its properties are difficult to model, and difficult to observe in-situ and remotely. SMOS can provide crucial information about thin sea ice, with a temporal and spacial coverage that is unique. In the light of current shortcomings in both the observational data and the prognostic sea ice model, it might still be too early for successful and consistent data assimilation of sea ice thickness from SMOS. However, it is suggested in this report to establish a routine monitoring of SMOSIce sea ice thickness, so that the presence of thin sea ice can, at least qualitatively, be detected and contrasted with the ocean/sea ice analysis. Three possible routes of activities have been suggested that will – depending on available resources – push forward the use of sea ice thickness from SMOS for prognostic model validation and data assimilation.

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