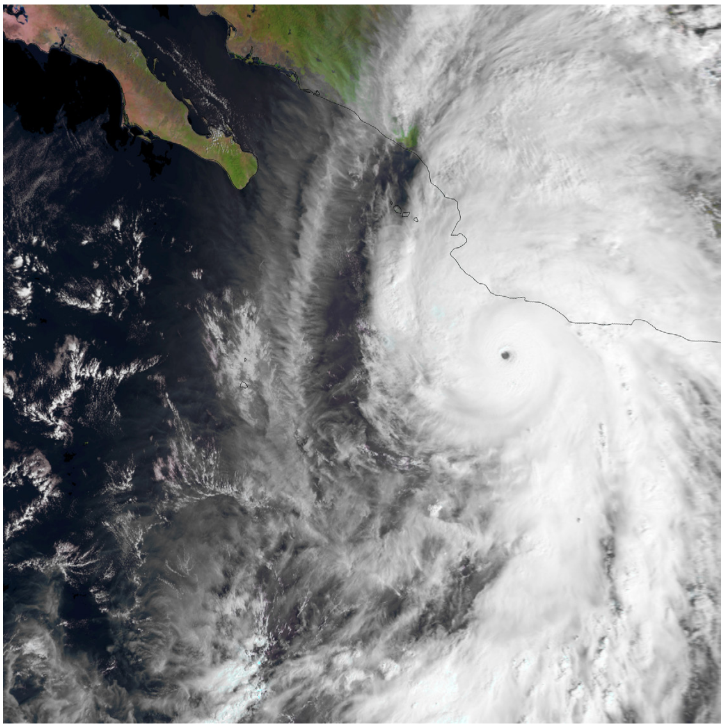
ECMWF Feature article

from Newsletter Number 152 – Summer 2017

METEOROLOGY

Monitoring thin sea ice in the Arctic



Hurricane Patricia off the coast of Mexico on 23 October 2015 (© 2015 EUMETSAT)

www.ecmwf.int/en/about/news-centre/media-resources

doi:10.21957/yp392k

This article appeared in the Meteorology section of ECMWF Newsletter No. 152 – Summer 2017, pp. 23-26.

Monitoring thin sea ice in the Arctic

Steffen Tietsche, Magdalena Balmaseda, Hao Zuo

As part of the new OCEAN5 high-resolution ocean/sea-ice model and data assimilation suite, which was implemented in November 2016, ECMWF now routinely obtains and processes a sea-ice thickness product for thicknesses of up to about 1 metre from the University of Hamburg. This innovative observational product can help ECMWF to improve the representation of Earth system interactions in the Integrated Forecasting System (IFS), in line with the emphasis on Earth system modelling in the Centre's new ten-year Strategy.

The product is based on satellite observations of brightness temperatures from the European Space Agency's SMOS mission. The sea-ice thickness data derived from it can be compared to the sea-ice analysis produced by OCEAN5, which does not yet assimilate sea-ice thickness observations. This comparison helps to evaluate the performance of OCEAN5 on the one hand and to assess the information content and uncertainties of the observations on the other. First evaluation results show encouraging similarities between observations and the OCEAN5 analysis although there are also some regional discrepancies.

Importance of sea-ice thickness

Sea-ice thickness is defined as the vertical distance from the air-ice interface at the top of the sea ice to the ice-water interface at the bottom of the sea ice. It has received far less attention in ECMWF's modelling and forecasting efforts than sea-ice concentration, which is the fraction of a given ocean area that is covered by sea ice. Current operational systems like the high-resolution forecast (HRES) and the 4DVAR analysis use observed sea-ice concentration but assume a constant sea-ice thickness of 1.5 m. In reality, any thickness from a few centimetres to more than 5 metres is possible. This results in very different surface heat fluxes especially in winter, when the temperature contrast between the surface atmosphere and the ocean water below the sea ice can be as large as 40 K. Moreover, sea-ice thickness is indispensable for predicting the evolution of sea-ice cover days to months ahead: thin ice will evolve much more quickly than thick ice because it is more susceptible to dispersion or compression by winds. In addition, by allowing larger surface heat fluxes it can lose or gain mass much faster than thick ice. Small differences in the ice thickness at the beginning of summer can also make a large difference to the timing of its complete disappearance during the melt season, which in turn causes large differences in the forecast air temperature near the surface.

Despite the importance of sea-ice thickness for medium-range to seasonal predictions, two factors have prevented its explicit treatment until recently: the lack of a prognostic sea-ice model in the ECMWF forecasting systems and the scarcity of observations. The first obstacle was overcome in November 2016 with the implementation of OCEAN5 as part of an upgrade of ECMWF's Integrated Forecasting System (IFS Cycle 43r1). For the first time, the IFS now contains a fully prognostic sea-ice model, the Louvain-la-Neuve Sea Ice Model version 2 (LIM2) developed at the Belgian Université catholique de Louvain. This is used to produce physically-based analyses and forecasts of sea-ice thickness. The second obstacle, the lack of observations with sufficient spatial and temporal coverage, has diminished with the arrival of novel satellite observations over the past ten years.

New observations

Two types of satellite observations have recently made it possible to go beyond the sparse observations of sea-ice thickness from field campaigns and autonomous ice-tethered buoys that have been available for many years. First, high-resolution altimetry data from the ICESat and CryoSat2 missions have made it possible to directly measure the freeboard of sea ice (the vertical distance from the top surface of sea ice to adjacent water surfaces). From this its thickness can be derived. Second, the Aquarius, SMOS and SMAP missions have started to observe the radiance of the Earth's surface in the L-band frequency of 1.4 GHz. Emissivity at this frequency varies with sea-ice thickness. While altimeter measurements only work for thick ice (more than about 0.5 m), L-band radiances are only sensitive to differences in the thickness of sea ice which is less than about 1 m thick. Thus the two methods complement each other well, and the full range of sea-ice thickness can in principle be observed by combining them.

 doi:10.21957/yp392k

In the remainder of this article, we discuss ice thickness derived from L-band (1.4 GHz) observations made by the SMOS satellite (Box A) and how it compares to ice thickness in the OCEAN5 analysis. Figure 1 shows a recent example of daily-mean L-band brightness temperatures (T_B) from SMOS together with the sea-ice thickness from the Hamburg product (SMOS-SIT) derived from them. For reference, the sea-ice concentration from the OSTIA product for the same day is also shown. Although the sea-ice concentration is close to 100% throughout the interior of the ice pack, the ice thickness as derived from SMOS T_B is far from uniform. There is, for example, an extended zone of thin sea ice along the Siberian coast, where ice has been pushed offshore by the winds and the resulting open-water area has subsequently refrozen. These features within the ice pack are called coastal polynyas. They occur frequently throughout the Arctic winter. In the Beaufort Sea north of Alaska, a large fracture zone is visible with many individual, curved cracks.

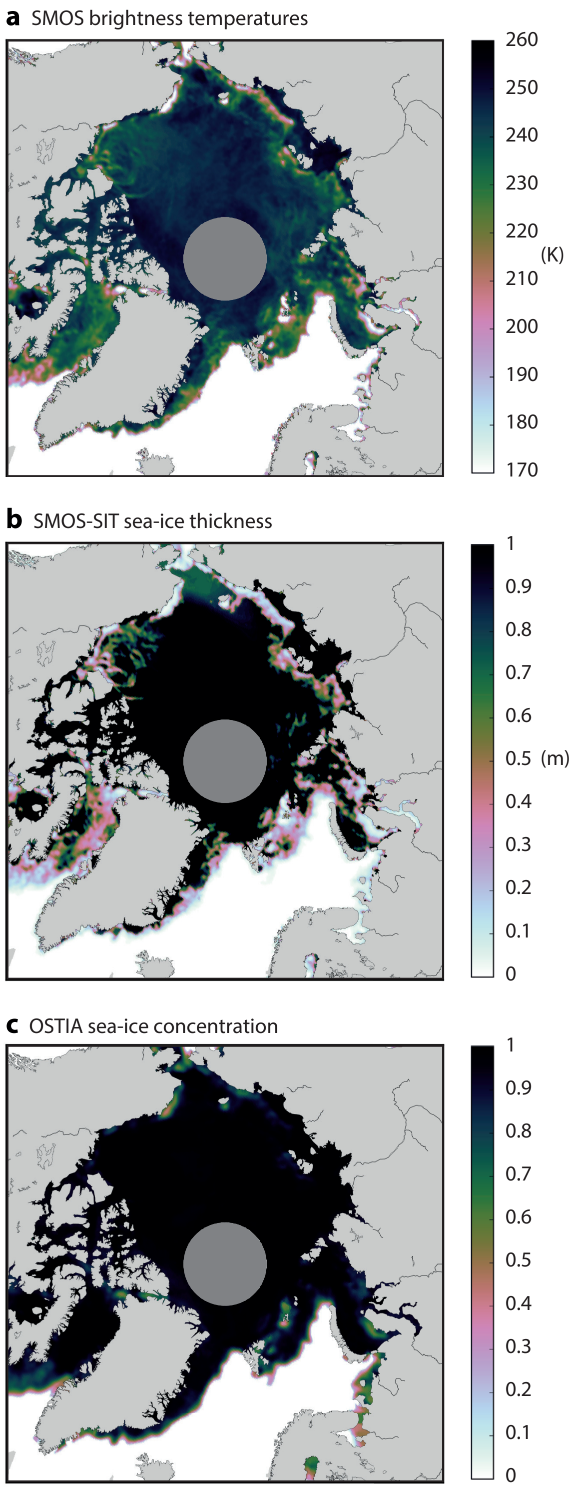


Figure 1 Daily-mean fields for 16 April 2017 showing (a) brightness temperature from SMOS, (b) sea-ice thickness from the SMOS SIT product, and (c) OSTIA sea-ice concentration. The area around the North Pole is greyed out because of a lack of satellite observations in this region.

These cracks are the result of shear arising from the rotation of sea ice in a gyre forced by the prevailing wind patterns. Importantly, polynyas and fracture zones in winter often refreeze so quickly that they seem continuously ice-covered. They are therefore hard to detect from observations of passive microwave radiation with shorter wavelengths that originates from near the surface of the ice. However, Figure 1 shows clearly that SMOS T_B is sensitive to these features: the derived ice thickness is often below 0.5 m here, whereas outside these features it is in excess of 1 m. Heat conduction through the newly formed sea ice can be substantial: an approximate calculation shows that the surface heat flux over some of the thin-ice regions was of the order of 100 W m^{-2}.

Sea-ice thickness from SMOS

A

The sea-ice thickness product provided by the University of Hamburg (SMOS-SIT) contains Arctic-wide daily means with 12.5 km nominal resolution. It is provided with a delay of less than 24 hours for the duration of the freezing period from mid-October to mid-April. The retrieval method makes it possible to measure the thickness of thin young ice up to a thickness of 1 m.

The retrieval algorithm of the University of Hamburg group (*Tian-Kunze et al.*, 2014) is applied to L-band (1.4 GHz) brightness temperatures (T_B) provided by the SMOS satellite, and it also works well for T_B provided by SMAP. The algorithm is based on the radiation intensity (average of horizontal and vertical polarisation), which is robust against instrumental and geophysical errors and relatively independent of incidence angle. The L-band wavelength of 21 cm is large compared to typical inhomogeneities in the ice in the vertical, and is of the same order as the ice thickness to be measured. Therefore, the expected emissivity from a slab of sea ice with sea water underneath can be calculated based only on the thickness d of the slab and its dielectric properties. The dielectric properties mainly depend on the bulk temperature and salinity of the sea ice, which are derived from ancillary fields and a simple thermodynamic model. The ancillary fields are mainly 2 m air temperature T_{air} from an atmospheric (re-) analysis and the ocean surface salinity S from an ocean model simulation. Given the observed brightness temperature T_B, the retrieved ice thickness d is then found by iteratively solving the equation $T_B = f(d, T_{air}, S)$, where the forward model f contains both the translation of the ancillary fields into the sea ice bulk properties and the radiative transfer model that calculates the emissivity. The retrieval works well when the sensitivity of T_B to changes in ice thickness is larger than its sensitivity to bulk temperature and salinity.

Uncertainties and biases

While this example demonstrates the additional value of L-band ice thickness observations, the question is how to make best use of the information contained in these observations. This requires a critical assessment of uncertainties and biases in both observations and the model. On the one hand, uncertainties in L-band sea-ice thickness are not small: as indicated in Box A, the thermodynamic and radiative transfer modelling that is required to derive sea-ice thickness from L-band brightness temperature is complex. It is sensitive to other co-located meteorological and oceanographic parameters, which themselves contain considerable uncertainties, and it relies on several simplifying assumptions which are not always valid. On the other hand, OCEAN5 has a simplified representation of thin sea ice, and its data assimilation scheme does not properly account for error covariance between sea ice concentration and thickness.

doi:10.21957/yp392k

A quite stringent comparison between ice thickness estimates from SMOS SIT and OCEAN5 is provided by the joint frequency distribution of co-located observations and model equivalents shown in Figure 2. It has been calculated for all days during the winter 2016/17 and at all locations where the diagnostic uncertainty parameters provided with SMOS-SIT suggest that the observational estimate should be reliable. There is a degree of correspondence between observed and analysed ice thickness, but there are also some major discrepancies. Most notable is the tendency for OCEAN5 to have greater ice thickness than SMOS-SIT, with a considerable amount of spread. For instance, the model equivalent of the SMOS-SIT thickness range 0.4–0.6 m has a wide distribution with a maximum between 0.6–0.9 m and frequently occurring ice thicknesses of up to 1.5 m. Decomposing this signal into different regions and months reveals a complex picture: independent data suggests that the true thickness is closer to the SMOS-SIT data in some cases, but closer to the OCEAN5 analysis in others (*Tietsche et al*., 2017). SMOS-SIT data tend to be better in the recently refrozen fracture zones and polynyas shown in Figure 1, which are often poorly represented in the model. The model seems to perform better in some specific regions, such as the Labrador Sea: as shown in Figure 1, SMOS-SIT detects thin sea ice there, whereas OCEAN5 and altimeter data suggest the presence of thick ice. It should be noted that agreement between the model and observations is generally quite good early in the freezing season, and throughout the freezing season in the Barents Sea. The agreement tends to deteriorate later in the freezing season, especially for regions with frequent polynyas and in the Labrador Sea.

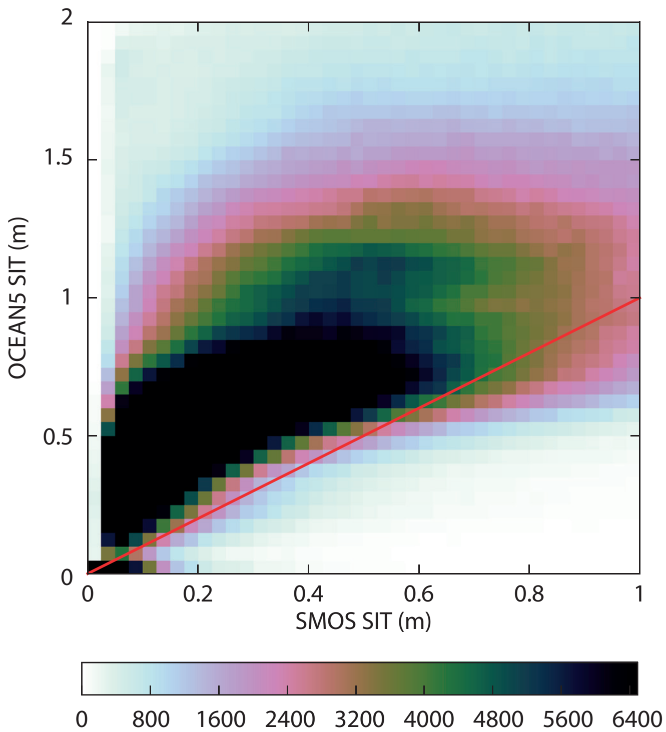


Figure 2 Scatter density plot showing the number of data points in each bin for daily co-located sea-ice thickness up to 1 m from the SMOS-SIT product and its OCEAN5 model equivalent from mid-October 2016 to mid-April 2017. Only those data points of SMOS-SIT are considered where the uncertainty diagnostics provided with the dataset indicate a reliable retrieval.

doi:10.21957/yp392k

Despite these uncertainties at a regional scale, there is good agreement in the large-scale distribution and interannual variability of thin sea ice. Figure 3 shows time series of the area covered by sea ice with thicknesses above various thresholds in November in the years 2011 to 2016. The uppermost curve is the area of sea ice which is at least 5 cm thick; it corresponds quite well to the sea-ice extent given by the US National Snow and Ice Data Center (NSIDC) if the observational gap around the North Pole is taken into account. The lowermost curve is the area of sea ice which is more than 1 m thick. There is generally good agreement between the magnitude, variability and trend of the areas of the various thickness classes as simulated by OCEAN5 and as derived from SMOS observations. The extreme summer minimum in 2012 left that year's November with markedly reduced sea-ice area for all thickness classes. In 2013, there was a clear recovery. Since then, there has been a downward trend in all classes. Figure 3 demonstrates that both OCEAN5 and SMOS-SIT capture important year-to-year variability and trends in the state of Arctic sea ice even though the OCEAN5 analysis does not use SMOS-SIT and is therefore independent of it.

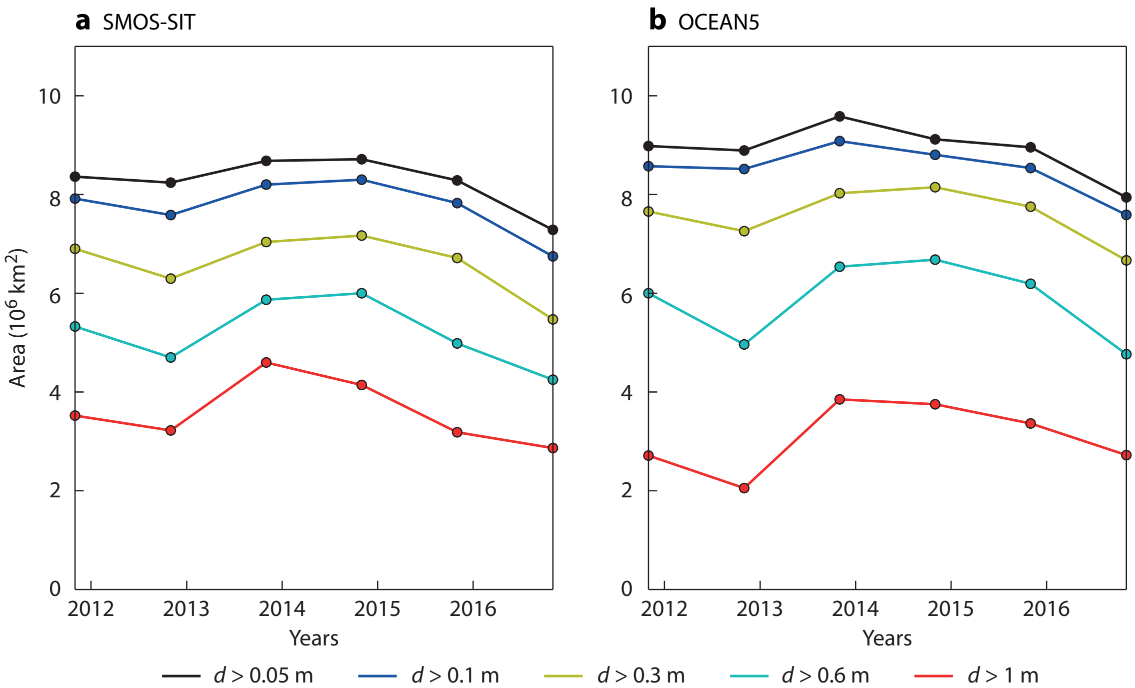


Figure 3 Area which is covered by sea ice exceeding various thickness thresholds in November for the years 2011 to 2016, showing (a) the area as derived from the SMOS-SIT observational product and (b) the area as derived from the OCEAN5 analysis.

Conclusion

Sea-ice thickness observations from L-band radiometry are a novel and innovative technology with great potential. We are only just beginning to harness it. It needs to be borne in mind that it is fundamentally limited to thin sea ice, and much more research is needed into its sensitivities to ancillary data and the assumptions in the complex physically-based retrieval model. At the same time, prognostic sea-ice modelling at ECMWF has been operational for less than a year, and many modelling and data assimilation improvements are imminent. In this light, the results presented here are encouraging. To make progress in better characterising the uncertainties in the data, it would be beneficial to integrate the retrieval model into the ECMWF system, i.e. to use the meteorological and oceanographic surface fields coming from the ECMWF atmosphere and ocean analyses to feed the retrieval model. The next step would be the development of stable and reliable multivariate sea-ice data assimilation schemes which can fully exploit the sea-ice thickness information provided by L-band radiometry to arrive at an improved sea-ice analysis. These steps will provide important building blocks in efforts to improve predictions in the polar regions.

doi:10.21957/yp392k

Further reading

Tietsche, **S.**, **M. Balmaseda**, **H. Zuo** & **P. de Rosnay**, 2017: Comparing Arctic winter sea-ice thickness from SMOS and ORAS5, *ECMWF Technical Memorandum* **No. 803**.

Tian-Kunze, **X.**, **L. Kaleschke**, **N. Maaß**, **M. Mäkynen**, **N. Serra**, **M. Drusch**, & **T. Krumpen**, 2014: SMOS-derived thin sea ice thickness: algorithm baseline, product specifications and initial verification. *The Cryosphere*, **8**, 997–1018.

doi:10.21957/yp392k