3.1 Sea ice concentration and sea ice leads

As expected, the two assimilation experiments outperform the FREE experiment during summertime in terms of sea ice concentration coverage. In both hemispheres, FREE is not able to prevent excessive melting and shows a significant lack of sea ice, mainly in marginal areas, during July-October in the Arctic (i.e. Fig. 1(a) for July 2017) and in January-April in Antarctica (See Figures S1 and S2).

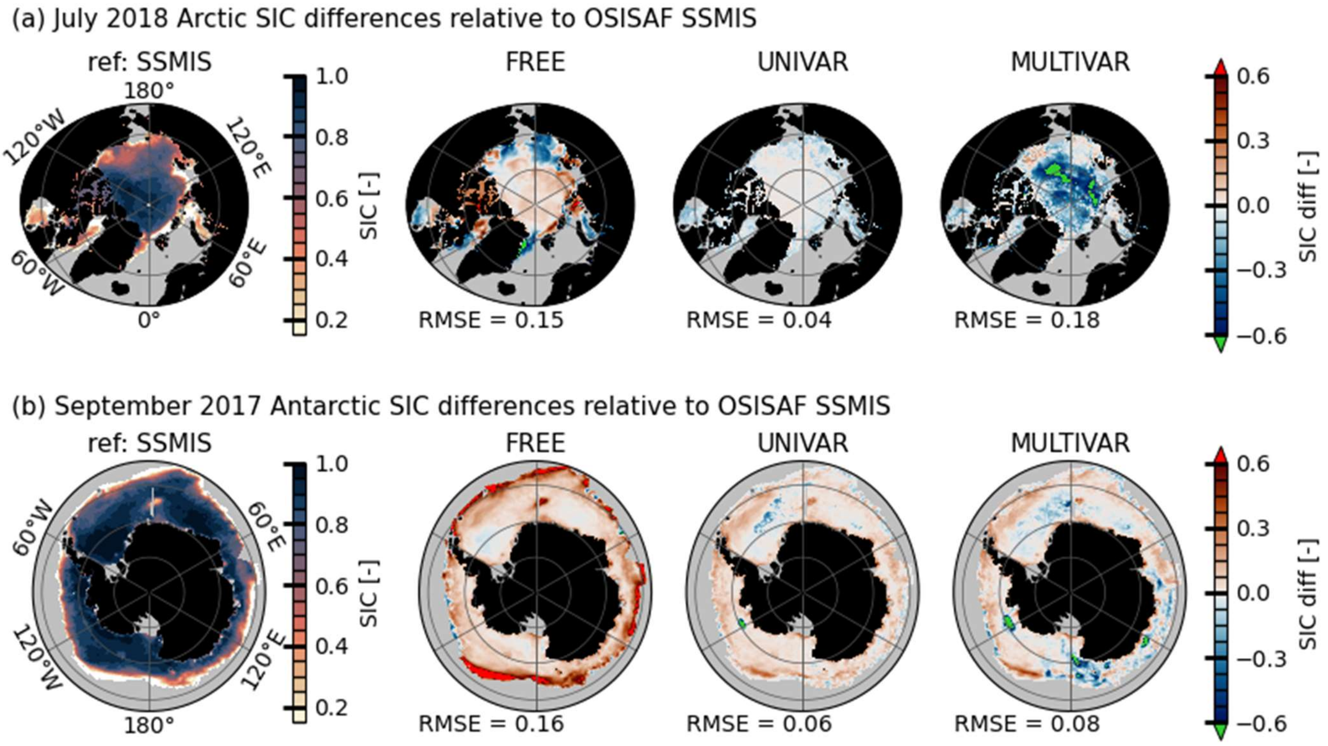

Figure 1: July 2018 in the Arctic (a) and September 2017 in the Antarctic (b) maps of the sea ice concentration, representing the observation SSMIS on the first column, and the difference between the experiments and the reference SSMIS observation on the following columns. The simulations are, in that order: FREE, UNIVAR and MULTIVAR. Root mean squared errors (RMS) are provided under each map.

Maps of the sea ice concentration in the assimilated observations and their difference to the experiments are shown on Figure 1 for both hemispheres. The well-known Weddell Sea "Maud-rise polynya" that appeared in winter 2017 (Jena et al., 2019) is not reproduced by the FREE experiment (Figure 1(b)). The UNIVAR and MULTIVAR experiments are able to reproduce this polynya. However, in the assimilated simulations, the Maud-rise polynya begins to take shape from June 2017, earlier than in the observations, and the system struggles to keep an ocean uniformly covered in ice in the Weddell Sea. Other polynyas are present in few locations around the Antarctic: in the Amundsen Sea offshore of Pine Island Bay at 120°W in the UNIVAR and MULTIVAR simulations (Figure 1(b)), and near Iselin Bank at 180°E in the Ross Sea in the MULTIVAR simulation. These events appear repeatedly during the ice freezing period in 2017 and 2018.

On the maps on Figure 1, sea ice concentration modelled by the UNIVAR simulation stands out and compares very well with the assimilated SSMIS dataset in the Arctic (RMSE of 0.04 in July 2018) and remains below the observation error in Antarctica (RMSE of 0.06 in September 2017). Multivariate assimilation of RFB and SNT data reduces the Arctic SIC compared to SSMIS, mainly in the central Arctic. This lower SIC in the central Arctic results in a RMSE of 0.18 for July 2018, the highest among the experiments. In that summer period, there are no RFB and SNT observations and the multivariate assimilation system creates the SIV and SNV increments from SIC observations and model covariances only. During the other months, the RMSE of 0.08 for the MULTIVAR simulation is lower, falling between the mean RMSEs of the UNIVAR and FREE simulations, which are 0.04 and 0.13, respectively. The Arctic mean RMSE of the UNIVAR and MULTIVAR simulations are similar in winter, but they differ in summer with the MULTIVAR simulation RMSE being 0.07 higher. In Antarctica, the FREE simulation presents mainly positive SIC biases in winter, particularly in the marginal ice zone (MIZ, defined by SIC values between 15% and 80%), and places the ice edge too far north compared to SSMIS observations (Figures 1 and S2) with mean RMSEs of 0.16 in September 2017 and 0.23 over the whole 2017-2018 months. The ice edge overestimation in the FREE experiment is corrected by the SIC assimilation in both UNIVAR and MULTIVAR simulations with comparable RMSEs of respectively 0.06 and 0.08 in September 2017 and the same values for the mean RMSEs over the whole 2017-2018 months.

We also assess the experiments on their ability to correctly reproduce the amount of open waters within the sea ice extent, referred to as "leads" hereafter. The area of sea ice leads offers valuable insights for predicting the Arctic sea ice extent (Zhang et al., 2018). The daily sea ice leads area timeseries are represented on Figure 2(a) in the Arctic and Figure 2(b) in the Antarctic. The sea ice leads area is computed by subtracting the sea ice area from the sea ice extent defined by cells where SIC>15%. We use two others different SIC datasets in order to quantify the spread among observations (Ivanova et al., 2015): the OSI-408 product (OSI SAF, 2017), derived from AMSR-2 satellite measurements and processed by the EUMETSAT OSISAF; and the Climate Data Record (CDR) dataset (Meier et al., 2017; Peng et al., 2013) from the National Snow and Ice Data Center (NSIDC). All SIC data are interpolated on the polar stereographic SSMIS grid and use a consistent continental mask, ensuring the same area coverage.

In the Arctic, the maximum lead surface area occurs in summer, more precisely at the beginning of the melting season. The daily surface area of leads peaks in July and then decreases with the retreat of the sea ice extent. The amount of leads remains constant from October to May in all the observations. In Antarctica, the lowest lead surface area is synchronous with the sea ice extent minimum in February-March. The observations then show an increase in leads area until its peak in November–December, corresponding to the first third of the melting season. The southern observational datasets show strong agreement regarding the minimum lead surface; but diverge as the lead area increases. In both hemispheres, NSIDC and SSMIS observations respectively display the smallest and the largest amount of leads. The FREE experiment shows the smallest amount of leads remaining outside the range of the observations for most of the year in both hemispheres, and has a weaker seasonal amplitude in the Arctic than the assimilated experiments and SSMIS and AMSR2 estimates, but comparable to NSIDC's amplitude. Despite leads metrics that moderately resemble the observations on average in the FREE experiment, its Arctic RMSE of 0.15 on Figure 1(a) highlights inconsistencies in the modelled spatial patterns of sea ice concentration. The assimilation process rapidly and realistically increases the amount of leads in both the Arctic and Antarctic sea ice cover. The two assimilated experiments remain very close to the NSIDC leads area estimates during the northern hemisphere constant sea ice leads period, and they reproduce very well the rapid increase in lead surface area during spring. The UNIVAR experiment remains within the range of observational estimates throughout the year. The MULTIVAR simulation exhibits the highest amount of leads during the peak period in July, even higher than the SSMIS observations.

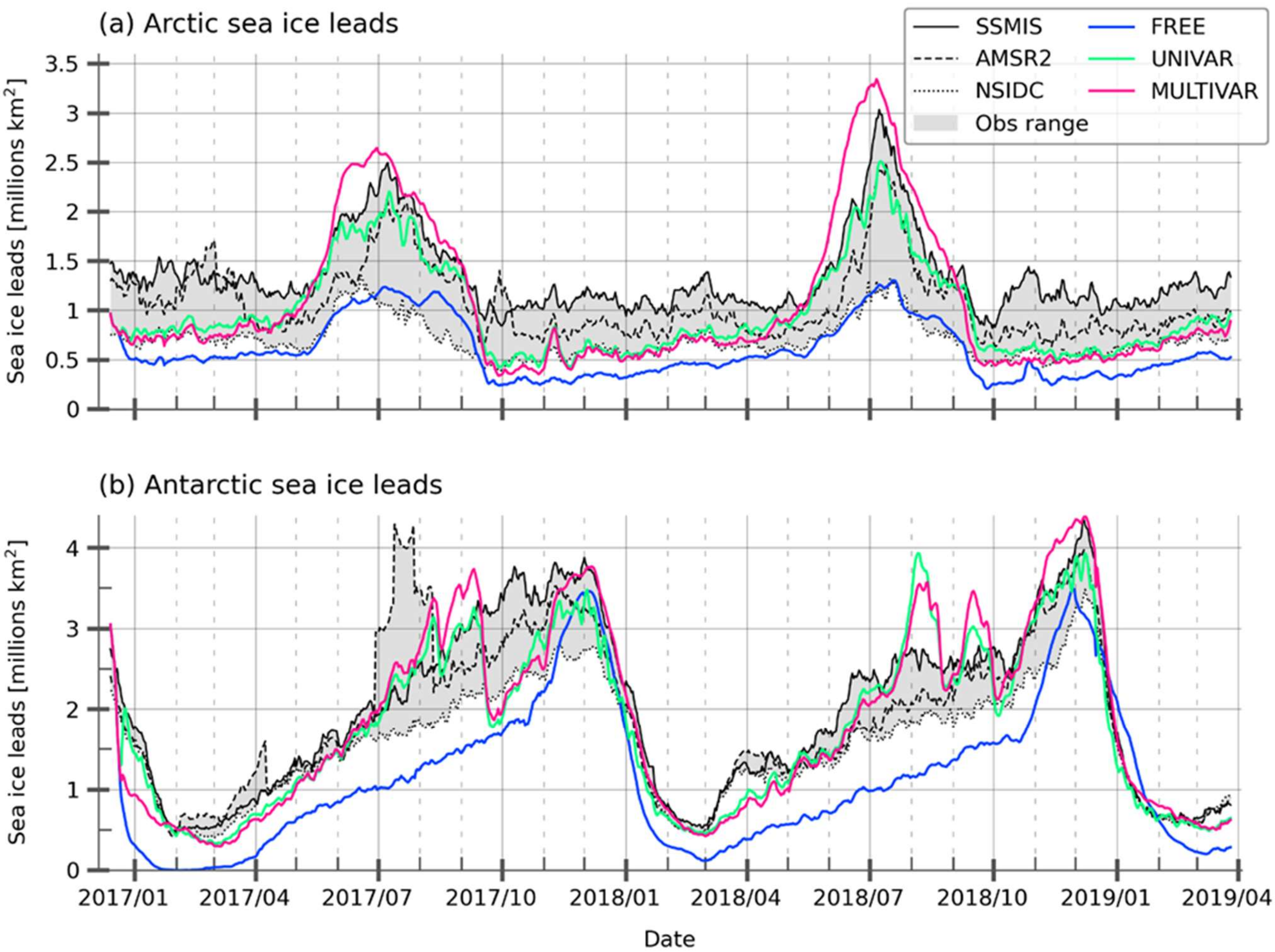

Figure 2: Daily time evolution of Arctic (a) and Antarctic (b) surface covered by sea ice leads in millions of km² for SSMIS (black), AMSR2 (dashed black), NSIDC (dotted black) satellite data with the range covered by them (shaded grey) and for FREE (blue), UNIV AR (green) and MULTIVAR (pink) experiments.

In Antarctica, both the UNIVAR and MULTIVAR experiments have a consistently higher sea ice leads area than the FREE experiment and are thus in better agreement with the observations. They correctly reproduce the minimum leads area and its maximum, with the MULTIVAR experiment showing the highest amount of leads during the peak period in early December, still coherent with the SSMIS observations. However, during the second half of the increase in lead surface, the assimilated experiments show significant fluctuations that exceed the range of the observations. The fluctuations are linked to the occurrence of localized low-SIC and thin ice areas in the ice cover, called polynyas when they become open-water areas.

In both hemispheres, the assimilation of SIC creates a larger lead area in the sea ice cover, in accordance with the SSMIS assimilated observations. The multivariate experiment alone even overestimates the quantity of leads during the seasonal maximum in the Arctic summertime. In the Antarctic, the two assimilated experiments generate a large number of polynyas that are not detected by the satellite observations, with the MULTIVAR experiment showing them more frequently and broadly across the region (Figure S2). While some smaller polynyas may go undetected in the observational data, the modelled polynyas are likely overestimated.