Comparing CMIP6 sea ice simulations with the modern-era satellite altimetry record of freeboard and thickness

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Uncertain CMIP6 sea ice projections

Projections of Arctic and Southern Ocean in CMIP6 sea ice remain highly uncertain, due in large part to inter-model uncertainty. Our goal is to utilize the multi-year record of sea ice freeboard and thickness from ICESat-2 together with freeboard/thickness data collected from the original ICESat mission and other missions (e.g. ESA's CryoSat-2) to better calibrate model projections of polar sea ice change and reduce model uncertainty.

We are building on recent advances in constraining sea ice projections in a number of ways: (i) utilizing state-of-the art altimetry data to provide improved constraints on current sea ice freeboard/thickness/volume projections at basin-scales, (ii) assess the use of total freeboard as a more simple diagnostic compared to derived thickness estimates, especially in the Antarctic where snow loading is highly uncertain (iii) explore the relative merits of different model calibration methods.

Our overarching project hypothesis is that altimetric observations of sea ice freeboard, not just the derived estimates of thickness, can help better calibrate global sea ice projections and improve our understanding of polar climate change.

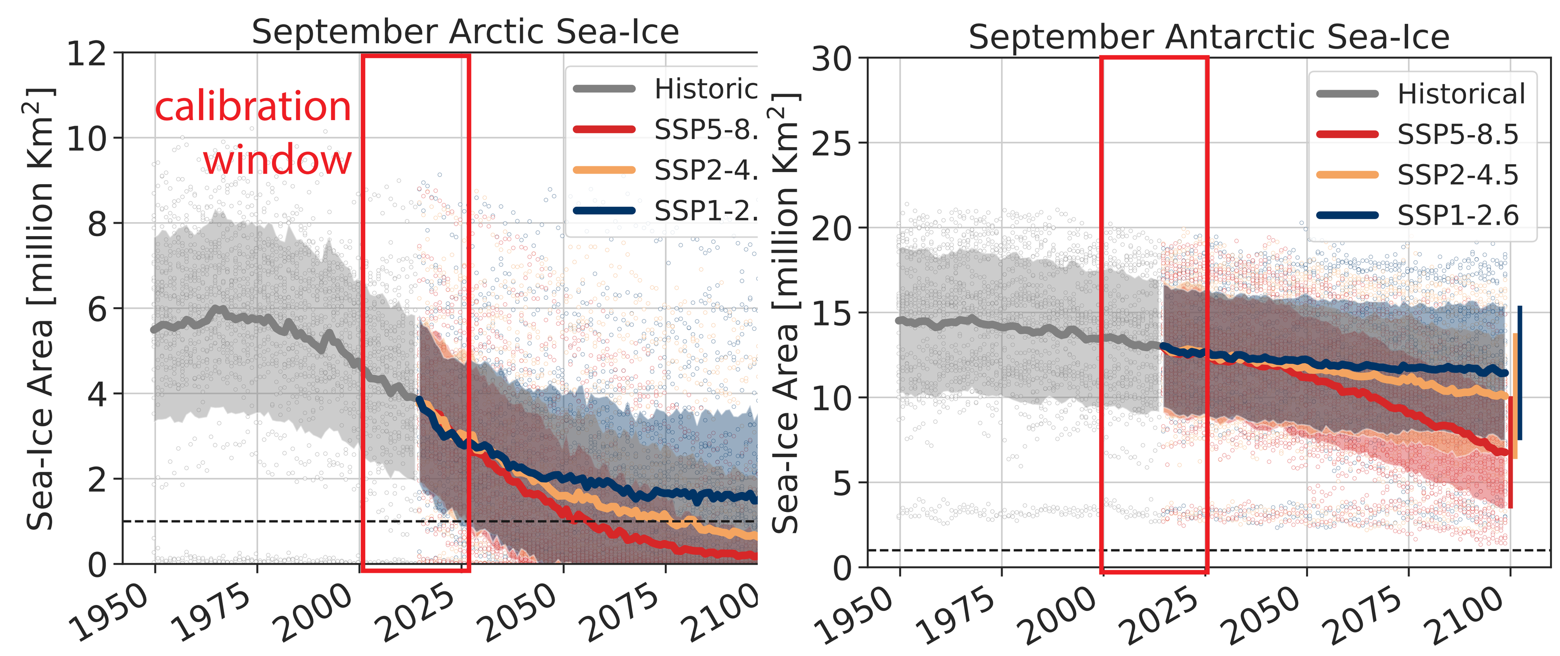

Figure: shows CMIP6 projections of September Arctic (left) and Antarctic (right) sea ice. Colors show the different scenarios. The red box highlights the calibration window, when active altimery observations are available.

Improved sea ice state understanding from NASA's ICESat & ICESat-2

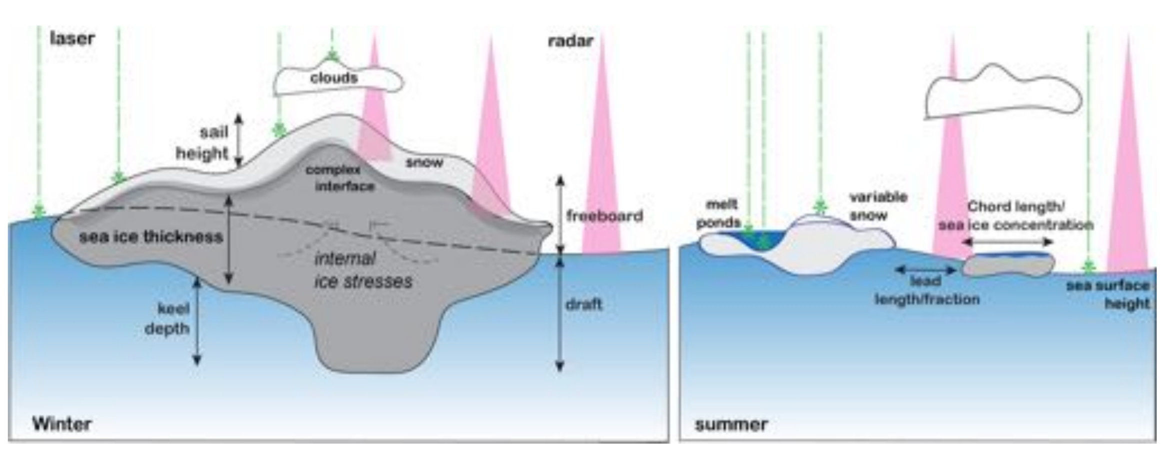

Figure: shows a schematic of active profiling of sea ice from radar and laser altimetry and the complications associated with clouds (laser scattering), melt ponds (complex surface returns), assumptions regarding sea ice state/isostasy, etc.

NASA's ICESat-2 mission was launched in September 2018 with the primary goal of monitoring our fast-changing polar regions. The original ICESat mission operated between 2003-2009.

Over sea ice, ICESat-2 measures freeboard, the extension of sea ice above sea level. Additional assumptions (snow loading, ice density) are used to convert freeboard measurements to an estimate of thickness, which introduces significant uncertainty.

What about instead assessing CMIP6 outputs of total freeboard instead?

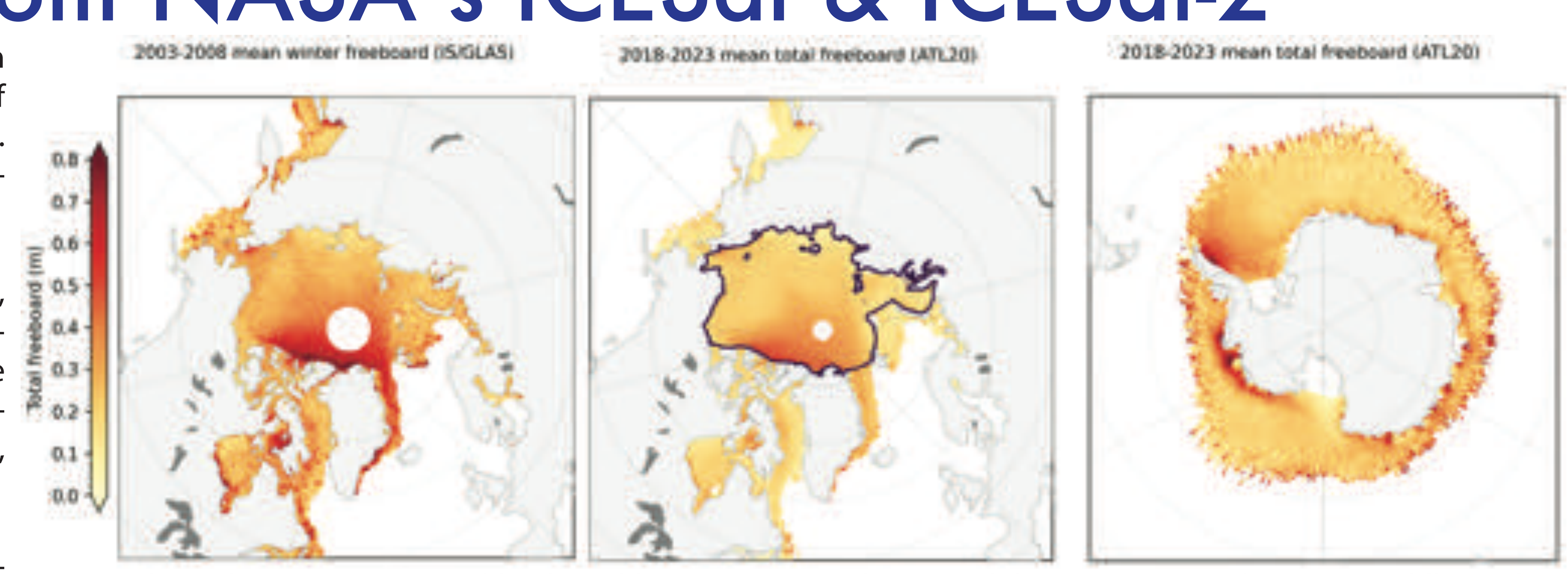

Figure: shows the mean winter total freeboard from ICESat over the Arctic (left), ICESat-2 over the Arctic (middle) and ICESat-2 over the Southern Ocean (right). Middle contour shows the Arctic Ocean domain used in the plots below.

New sea ice area, freeboard and thickness comparisons

The figure on the right shows seasonal comparisons of CMIP6 output with observations across specific time-periods and split up by hemisphere and variable. We focus mostly on the shorter ICESat-2 time period (2018-2023, red) but also show data from an earlier time-period (1981-2010, blue) to highlight potential trends/-shifts in either record.

Only a few of the CMIP6 models provide direct outputs of freeboard. Assumptions regarding sea ice/snow density need to be made to convert sea ice state information from the other models to freeboard. We are currently exploring the errors this introduces to the freeboard estimate. The equation used to make this conversion is shown below:

$$F_i = \frac{\rho_w - \rho_i}{\rho_w} H_i - \frac{\rho_{sn}}{\rho_w} H_{sn}$$

$$F_{total} = F_i + H_{sn}$$

Sea ice freeboard generally correlates highly with thickness, but we do note important differences in the seasonal cycle, e.g. the Arctic summer where snow depth and freeboard decline much more rapidly than thickness. The ability of models to capture this transition is an interesting and novel diagnostic we are currently exploring. In the Southern Ocean, we observe interesting seasonal model biases (in contrast to sea ice area, which shows a more consistent bias). The February biases occur when sea ice is near its minimum and observations are sparse, meaning representation errors are higher.

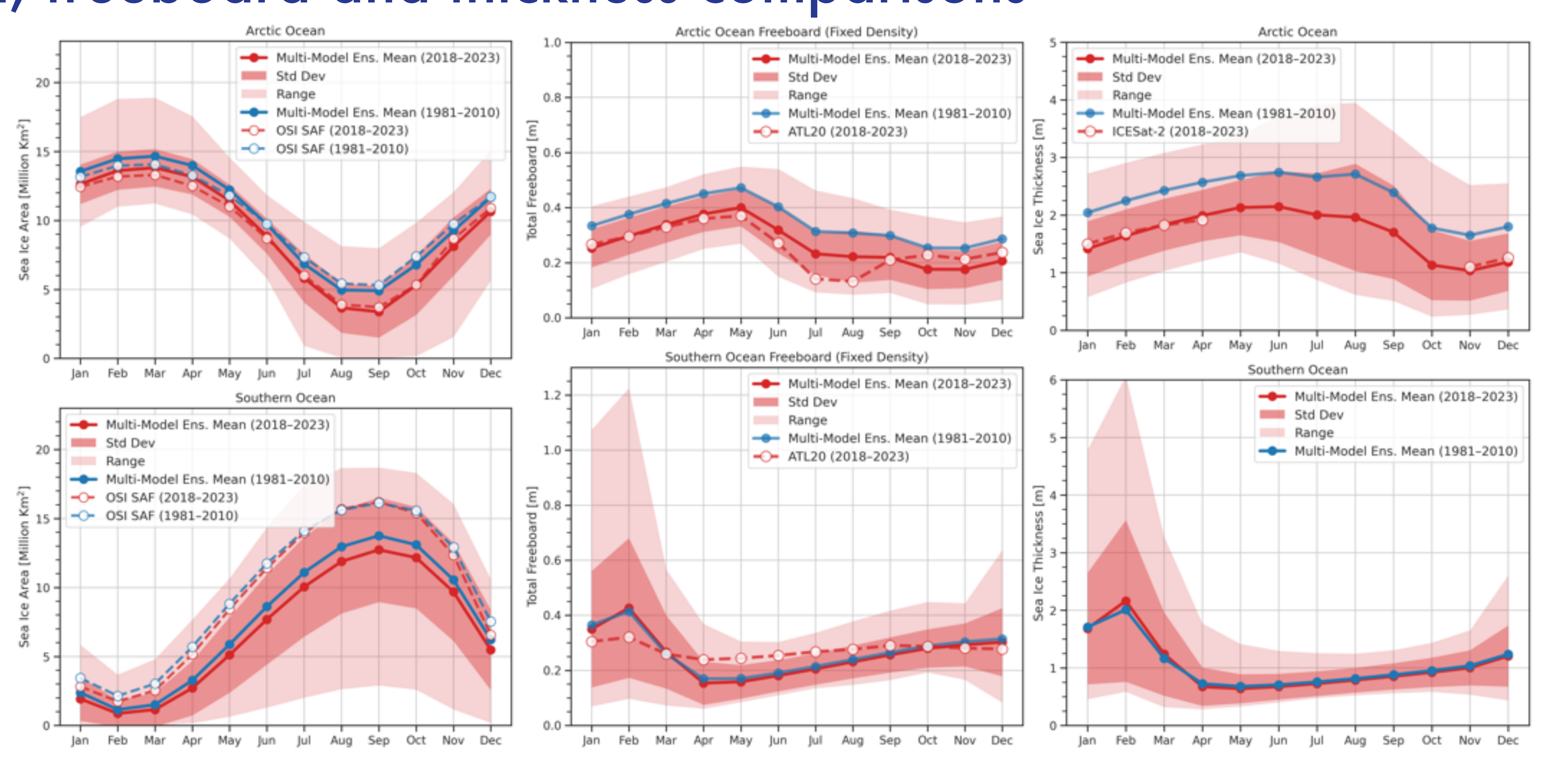

Figure: shows the seasonal cycle in core sea ice metrics from CMIP6 models and availabel ICESat-2 observations.(top left): Arctic Ocean (exl peripheral seas) sea ice area from CMIP6 and OSI SAF passive microwave data, (bottom left) same but for the Southern Ocean, (top middle) total freeboard from CMIP6 and ICESat-2's ATL20 monthly gridded freeboard product, (bottom middle) same but for the Southern Ocean, (top right) Arctic Ocean sea ice thickness from CMIP6 and ICESat-2's IS2SITMOGR4 winter Arctic sea ice thickness product, (bottom right) same but for the Southern Ocean, no IS-2 thickness estimates available.

With the models that provide direct outputs freeboard we can also derive the model bulk ice density, which has highlighted clear biases/outliers compared to field studies, an important consideration when analyzing freeboard outputs.

Current questions and future work (please do get in touch with ideas!)

- *Prescribing errors in basin-wide observations of sea ice area, freeboard and thickness is challenging. Sea ice observation errors and error correlations are poorly constrained as they generally rely on theoretical assumptions and sparse ground-truth data. How best to tell if we can robustly characterize trend biases too?*
- *How can we better deal with the limited temporal range of our observations, as well as the changing nature and quality of the observations when attempting exclusion/calibration/weighting in a highly non-stationary climate.*