Comparing CMIP6/CESM2 sea ice simulations with the modern-era satellite altimetry record of freeboard and thickness

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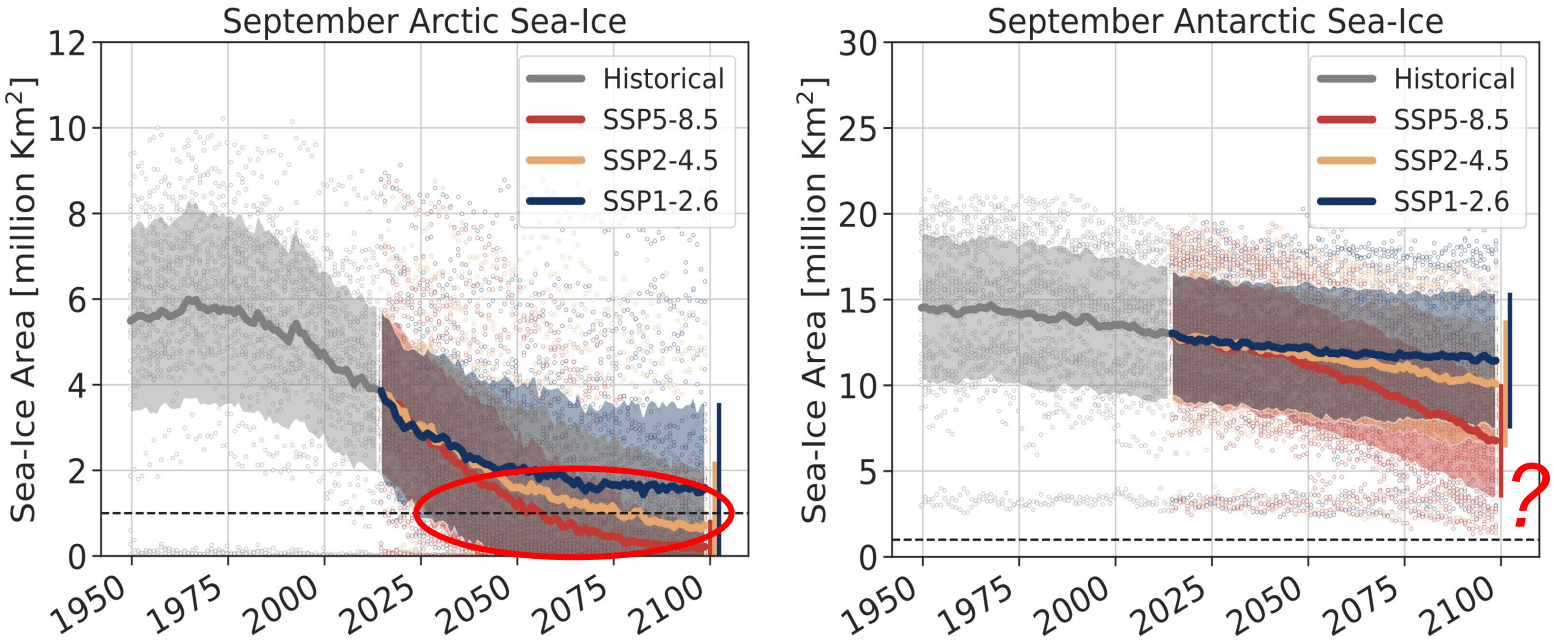
Future sea ice projections show wide inter-model spread



Figures by C. Cardinale; based on figures from SIMIP, 2020 and Roach et al., 2020

Inspired by various recent CMIP6 sea ice projection studies

SIMIP Community (2020)/IPCC AR6: "*define a model as plausible if its ensemble spread includes the observational record, considering observational uncertainty*" based on on mean Arctic SIA from passive microwave (didn't trust the thickness obs).

Roach et al., (2020): assessed Antarctic SIA and IIAE but did not use this to select models for the projection analysis, more of a comparison with older CMIPs.

Bonan et al., (2021): used a model linking Arctic SIA to temperature variability, a more fancy physical bias correction/recalibration approach.

Kim et al., (2023): model linking Arctic SIA to GHG forcing, another fancy recalibration approach.

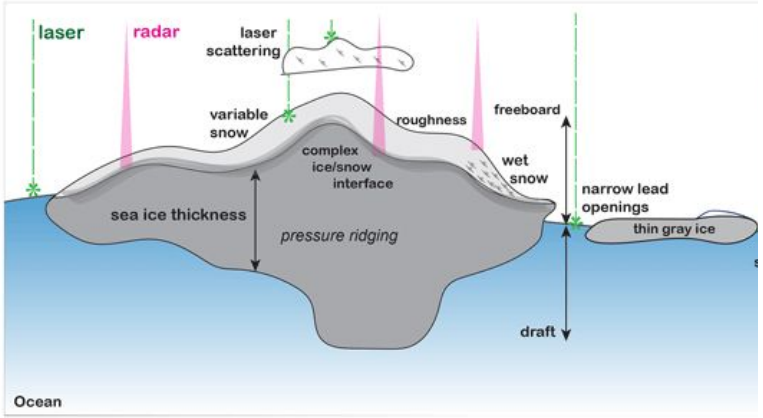
Topal and Ding (2023): model linking Arctic SIA to atmospheric circulation, another fancy recalibration approach..

Massonnet et al., (2018): found a robust relationship between sea ice growth/melt and mean Arctic sea ice volume, but found the observations were too uncertain to reliably constrain/exclude the models…doh!

Many more…hard to keep up!

Some thoughts on ice thickness uncertainty issues…

- Most of the uncertainty is introduced when we convert freeboard to thickness.
- Snow depth I generally consider the biggest source of uncertainty but no clear consensus/depends if you're doing laser or radar altimetry.
- Ice density uncertainty has been a bit ignored to-date but a more recent focus.
- Another big issue is how to deal with uncertainties when producing basin-scale means - how correlated are the errors?!
- Some new Antarctic sea ice thickness/volume data but limited validation.

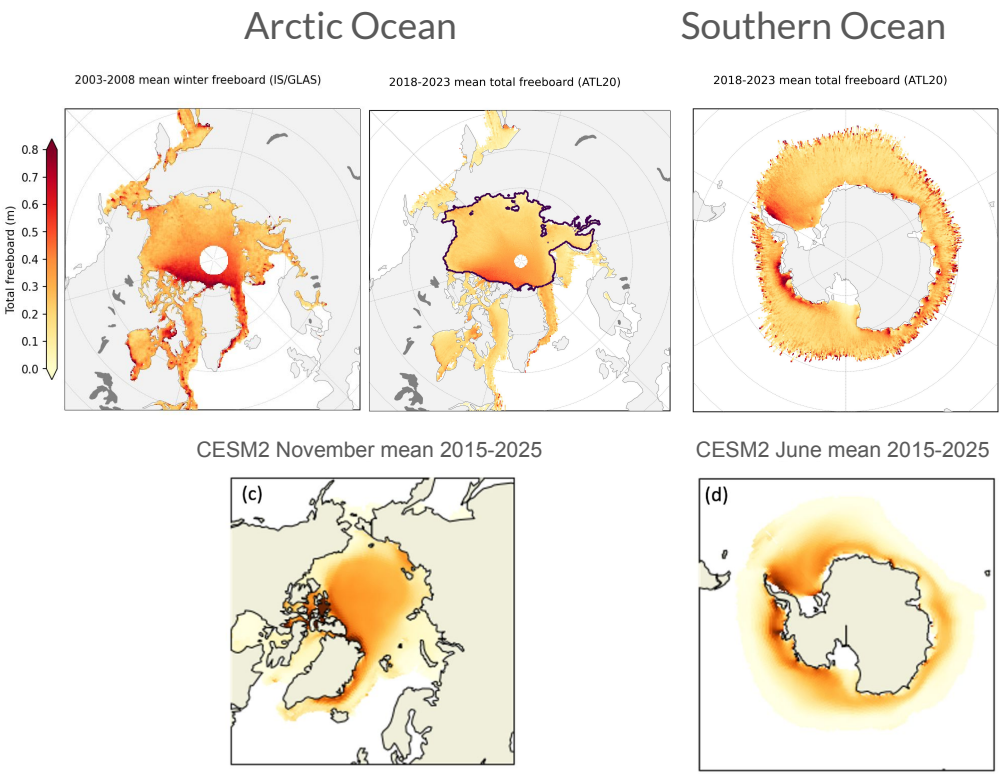


From Petty et al., (2023)

What about comparing estimates of freeboard instead!?

Freeboard observations and model output

- Freeboard measurements more accurate than ice concentration (mostly, I think...)!
- Growing record from satellite altimetry:
  - 2003-2008 (ICESat)
  - 2010 onwards (CryoSat-2)
  - 2018 onwards (ICESat-2)
- Enough data to constrain current mean state/seasonal cycle/trends?
- Sea ice state information within the consolidated ice pack.
- HOWEVER:
  - Less *physical* than ice thickness.
  - Ice/snow density assumptions needed.



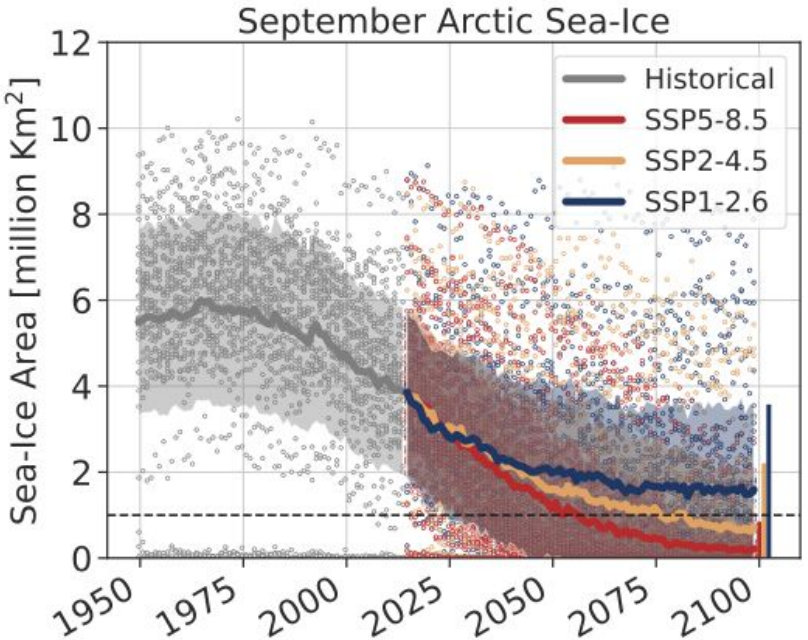
Our overarching project objectives

1. Characterize modern-era basin-scale polar sea ice freeboard and thickness (in models and observations)
2. Investigate optimal sea ice model calibration methods that can leverage this data.
3. Can we use this to improve future projections of sea ice.

Project outcomes thus far...

Quick note: CMIP6 cloud-based analysis

- Using the cloud-based (AWS/GCP) CMIP6 archive.
- Utilizing the new NASA-funded CryoCloud analysis hub (also hosted on AWS).
- Slight differences in model availability from the SIMIP/IPCC/Roach assessments.
- Requested (and recently obtained!) more data to the cloud stock:
  - ice freeboard
  - ice thickness distribution.



Freeboard (model output vs derived quantity)

- Analyzing CMIP6 models that provide estimates of ice freeboard.
- Add snow thickness to compare with total freeboard from obs.
- Also looking to 'derive' freeboard from the models that do not provide this output:
  - Need ice and snow density assumptions (we use the output of ice and snow thickness)

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

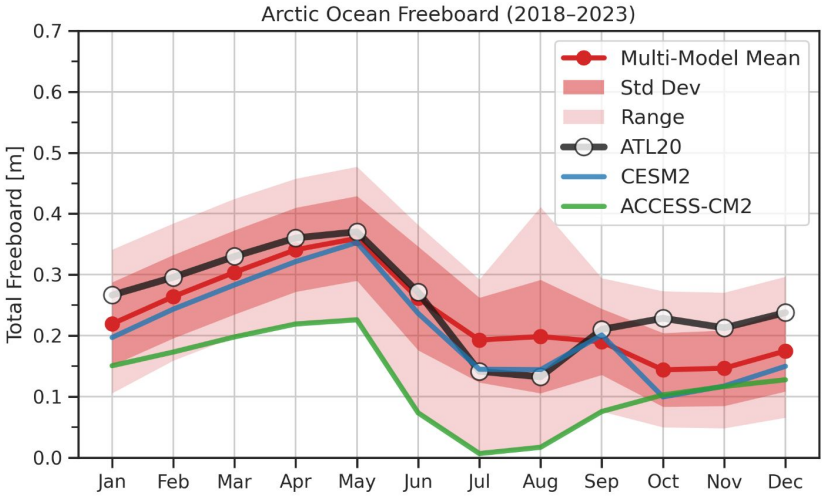
$$F_{total} = F_i + H_{sn}$$

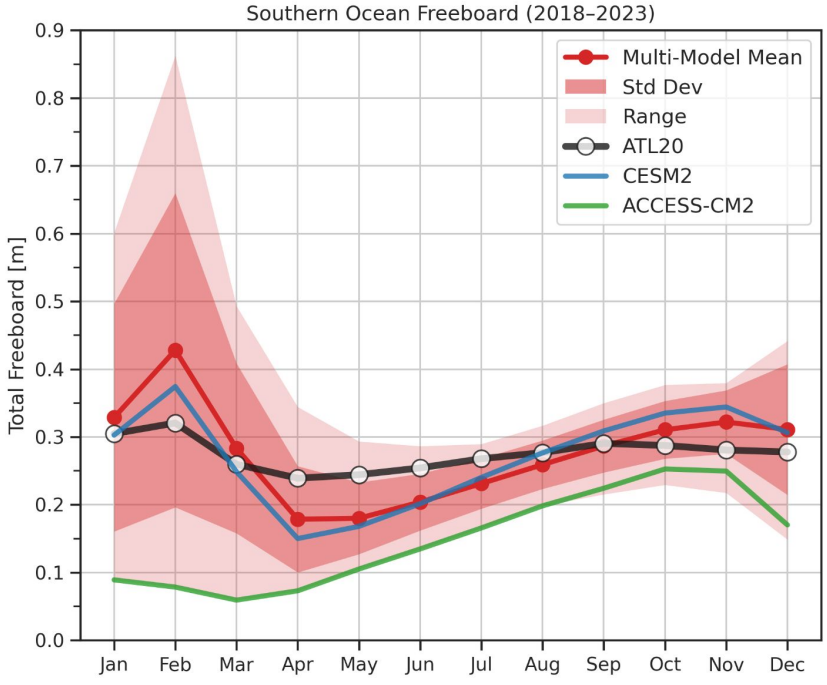
CMIP6 model variable	# of models	# ensembles
Grid-cell mean sea ice area (*siconc*)	35	303
Grid-cell mean ice thickness (*sithick*)	31	218
Grid-cell mean [ice] freeboard (*sifb*)*	13	44
Grid-cell mean snow thickness (*sisnthick*)	35	240
Ice thickness in each category (*siitdthick*)*	4	12

Historical and SSP2-4.5

Table 1: Sea-ice data variable availability in the CMIP6 archive on AWS S3 and Google Cloud public storage. Models and ensembles are only added if found in both historical and SSP2-4.5 ScenarioMIP outputs. All data output is monthly and on a native grid.
**Data is still being added to the cloud: 17 (7) models will be available for sifb (siitdthick).*

Total freeboard comparison (model subset vs obs)

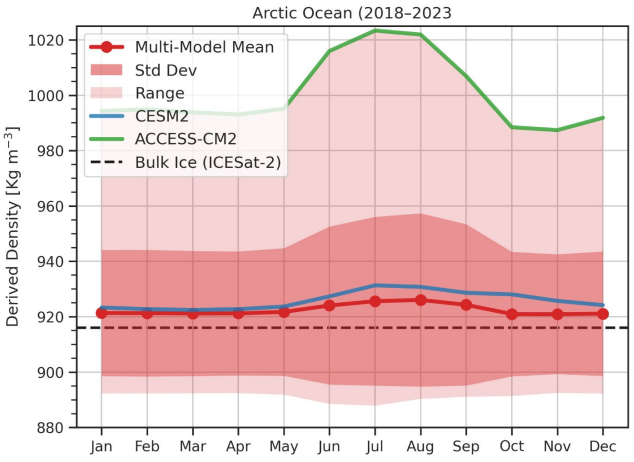


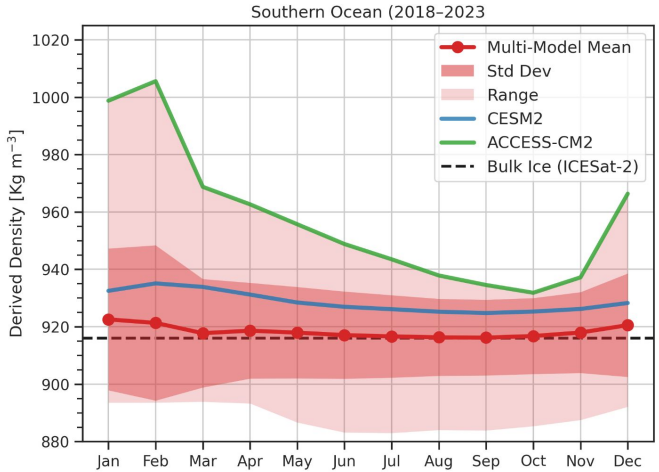


- Arctic Ocean excludes CAA and peripheral seas, Southern Ocean currently applies no region masking.
- Apply a 50% SIC filter across obs and models to mitigate some of the representation/sampling errors .

Derived ice density comparison (model subset)

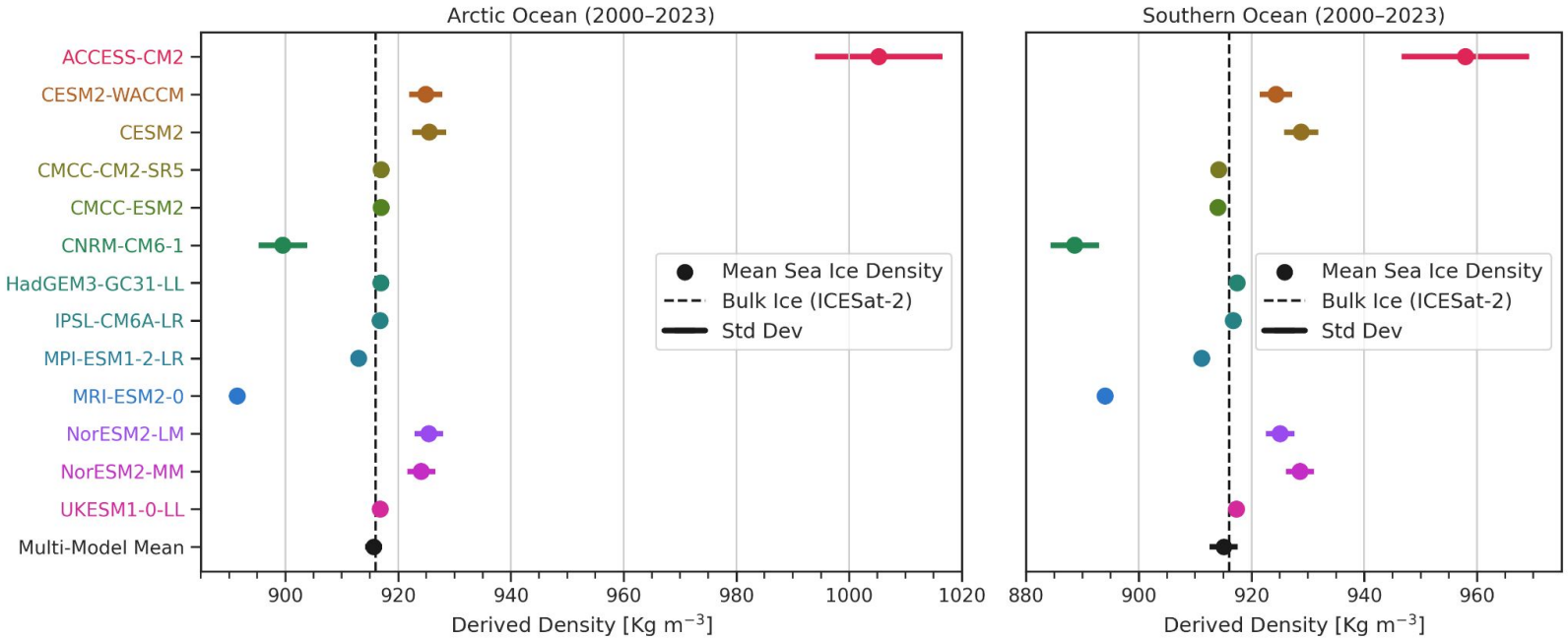
$$\rho_i = \rho_w - \frac{\rho_w F_i + \rho_{sn} H_{sn}}{H_i}$$





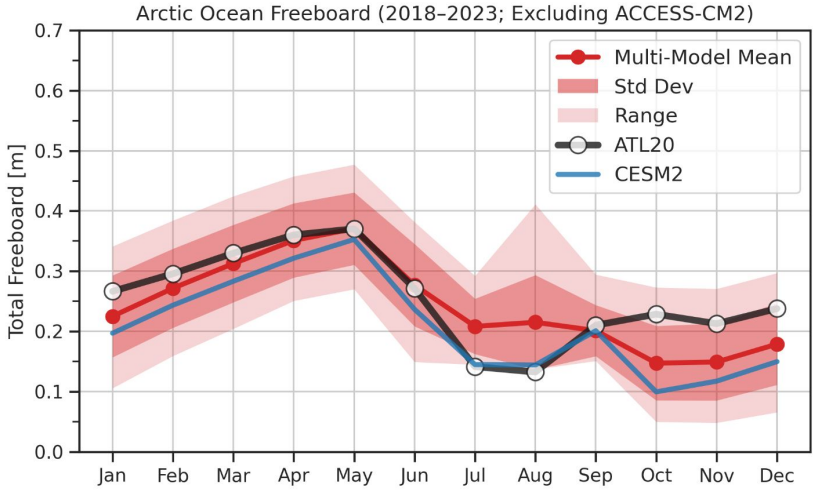
- ACCESS-CM2 derived density close to pure water…! (think we're safe to exclude that as an outlier).
- CESM2 uses the mushy layer thermodynamic scheme which calculates density as a function of temp/salinity - seasonal density cycle a bit higher than the 12 model mean (and the pure ice approx).

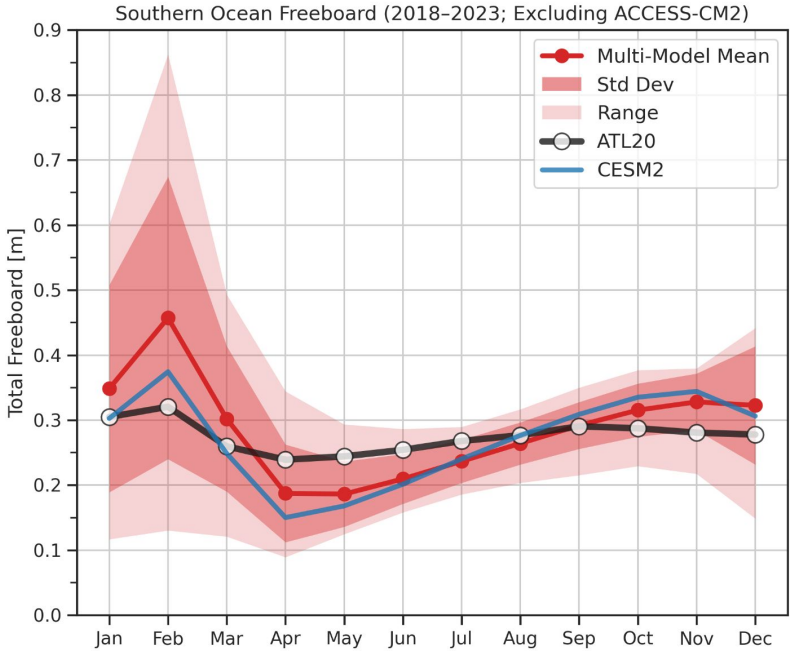
Derived ice density comparison (model subset)



**The std dev (horizontal bars) here show the seasonal cycle in the models (typically the first ensemble member).*

Preliminary total freeboard (models vs obs)

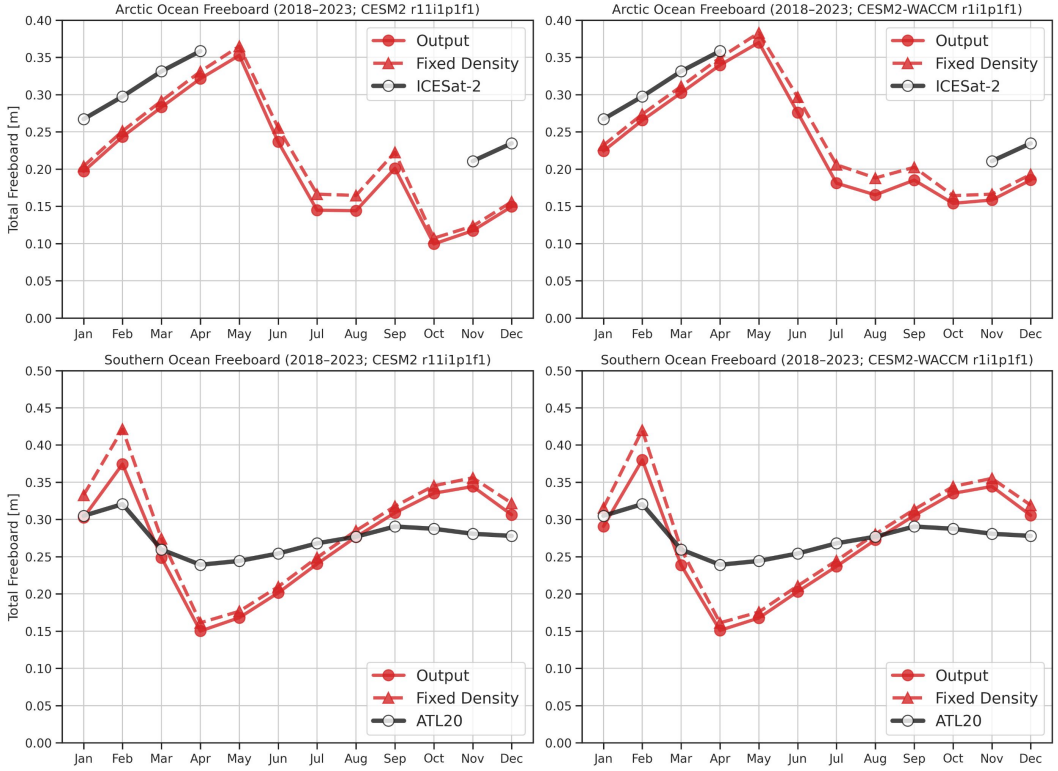




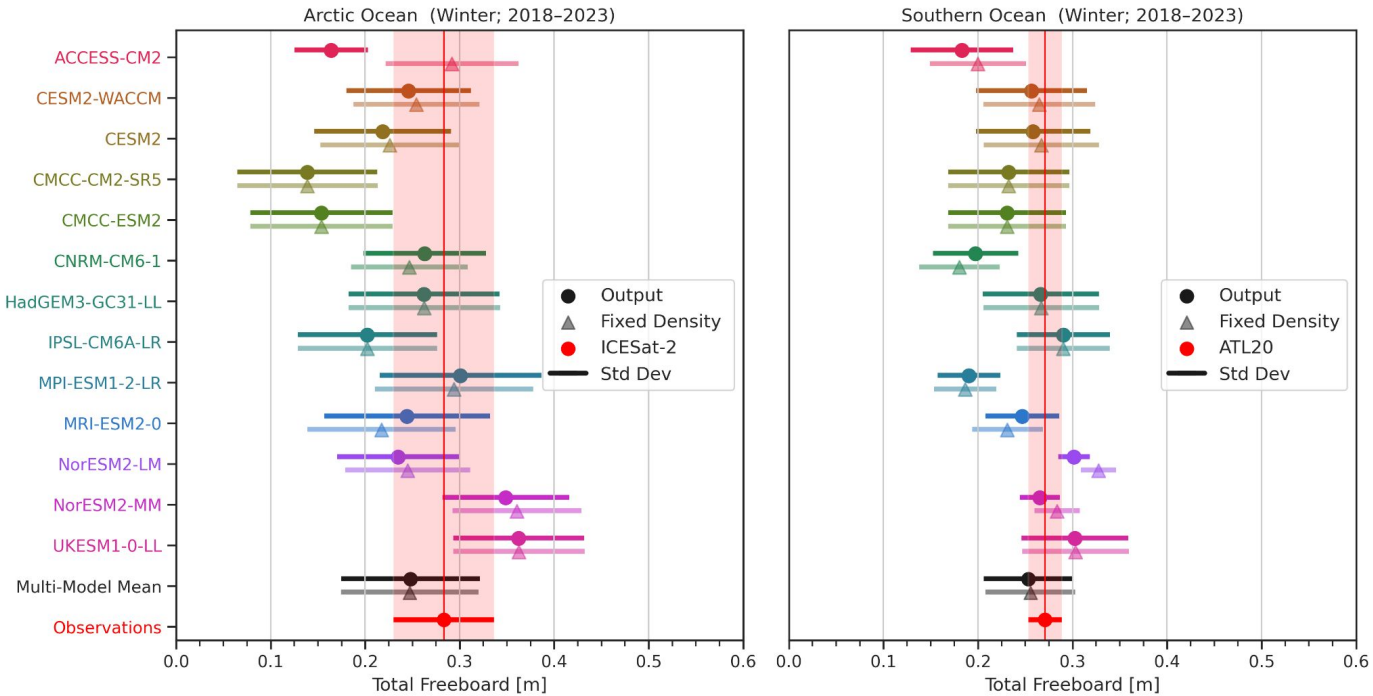
- Arctic Ocean excludes CAA and peripheral seas, Southern Ocean currently applies no region masking.
- Apply a 50% SIC filter across obs and models to mitigate some of the representation/sampling errors .

CESM2 freeboard with prognostic and prescribed density

- Running experiments with different density assumptions to understand impact on freeboard.
- Applying the fixed ice density (916) generally results in a small increase in CESM2 freeboards, slightly closer to the Arctic obs?
- Differences larger (2-3 cm) in summer for both hemispheres!

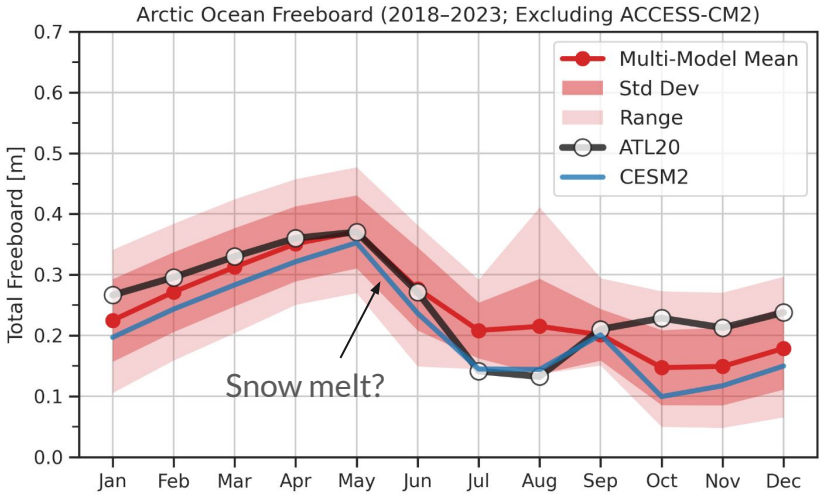


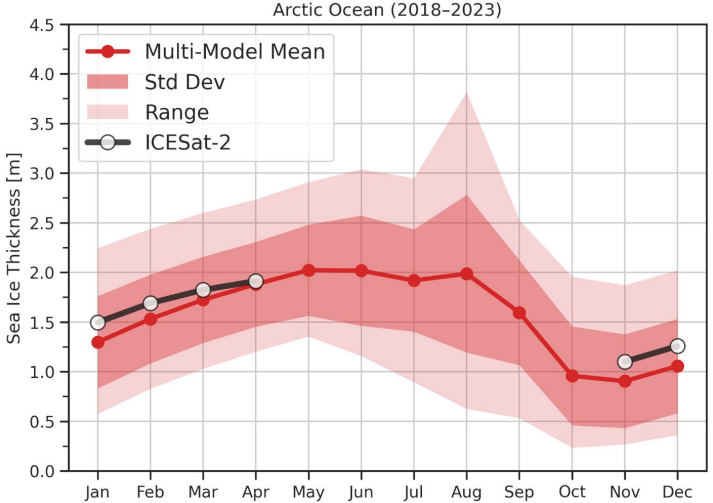
Winter total freeboard (models vs obs) - *preliminary*



**The std dev (horizontal bars) here show the seasonal cycle in the models (typically the first ensemble member) and observations.*

Freeboard vs thickness comparisons





- Small but important differences in the seasonal cycle (freeboard vs thickness).
- Next step: expand to all models by using the *derived* freeboard method (fixed density?)

Conclusions so far/active research...(still in year 1!)

- Comparing freeboard measurements and model output offers an interesting new path for sea ice model assessments (not the first to think of this for sure!)
- Freeboard comparisons increases the need to consider and assess the underlying ice density assumptions in models (compared to the thickness comps).
- Freeboard data more readily available/reliable for Antarctic sea ice, a key motivator.

Next steps...

- Bring in internal variability (easier with cloud-based analysis) and observational uncertainty estimates towards *plausible* assessments.
- Think more deeply about sampling/representation errors.
- Calculate and assess Integrated Total Freeboard Error (ITFE) as in IIAE.
- Reproduced Bonan et al., cumulative probability distribution approach and are exploring different models.
- Thinking beyond ice-free Arctic to shorter-time scales and different predictive metrics.
- Supporting **SIMIP** and the lead up to **CMIP7**!