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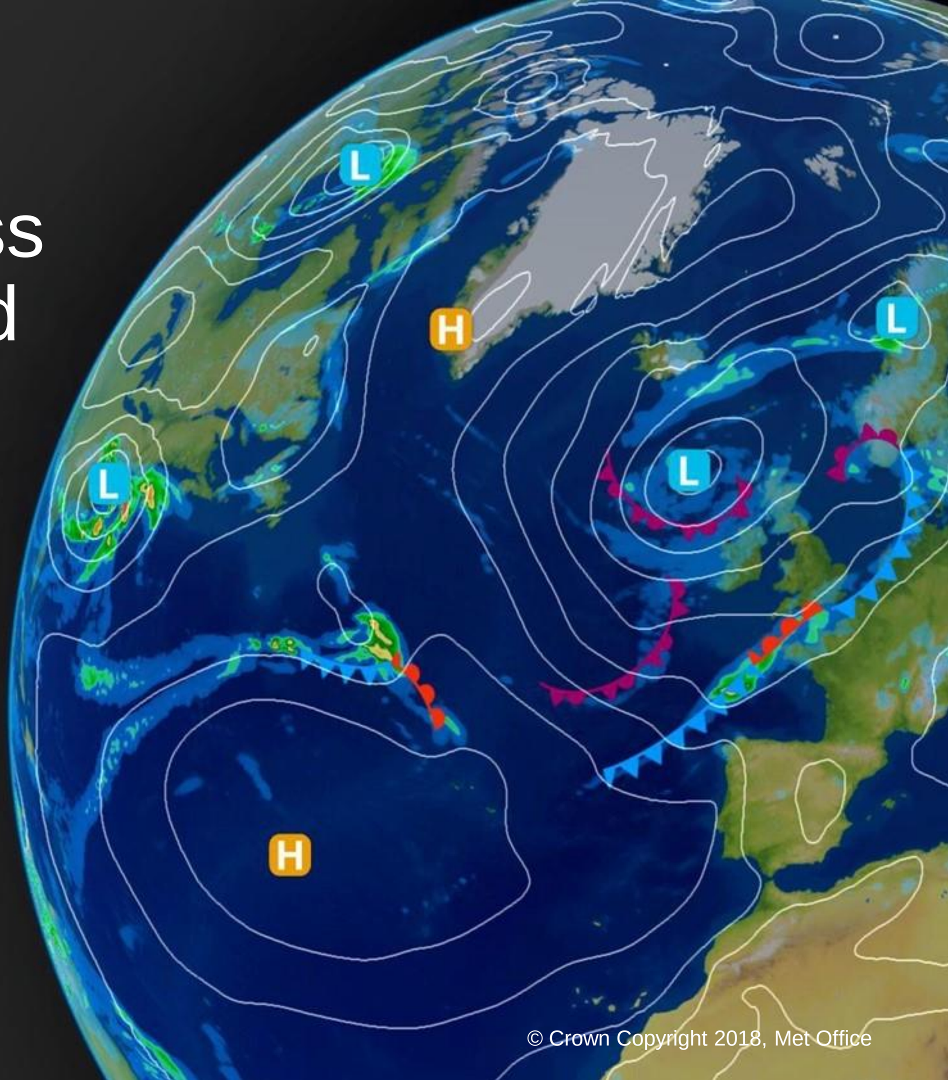
Intercomparison of the mass budget of Arctic sea ice and snow in CMIP6 models: a SIMIP activity



Ann Keen[1], <u>Ed Blockley[1]</u>, David Docquier[2] and Takahiro Toyoda[3]

1: Met Office Hadley Centre, UK,
2: UCLouvain, Belgium,
3: MRI, Japan

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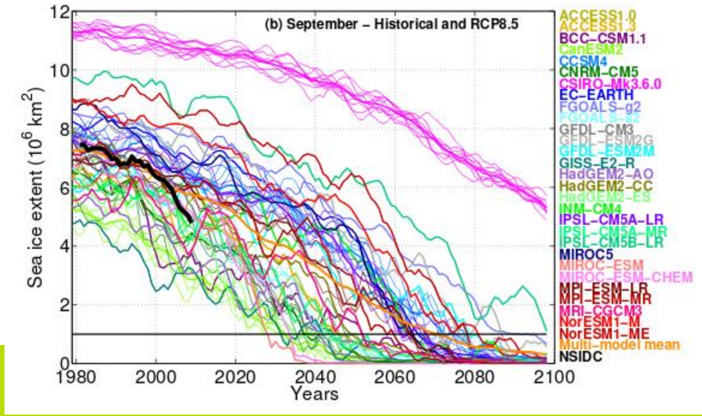
Advanced prediction in polar regions and beyond

Introduction and motivation

- Sea ice is a key component of the climate system, and a very visible indicator of climate change
- Arctic ice cover has declined at a rate of 13% per decade since satellite observations began, and there is much interest in how this decline will continue in future.
- Global coupled models are arguably the best tool we have for making future projections of Arctic sea ice, but generate a wide spread of projections of future decline



Massonnet et al, 2015

- Comparing integrated quantities (such as ice extent and volume) alone is not sufficient to understand the reasons for differences in model projections
- The Sea ice Model Intercomparison Project (SIMIP) has defined extra sea ice budget diagnostics for CMIP6 models, allowing easier intercomparison of underlying processes
- We aim to use these diagnostics to investigate how the balance of terms in the mass budget of CMIP6 models changes as the Arctic sea ice declines during the 21st century.

The plan

- Participating modelling centres will calculate area-weighted monthly mean budget terms, together with the mass and area of the sea ice and overlying snow, over a defined region of the Arctic for the period 1960-2100. Initially we will focus on the SSP5-8.5 forcing scenario

- Budgets for the sea ice and overlying snow will be calculated separately where possible.

- Initial comparisons will be based on the analysis of Keen and Blockley (2018), and will include:
    - Seasonal cycle of budget terms for the reference period 1960-89
    - Evolution of annual mean budget terms as a function of time and ice state.

- Subsequent analysis will be informed by the initial findings

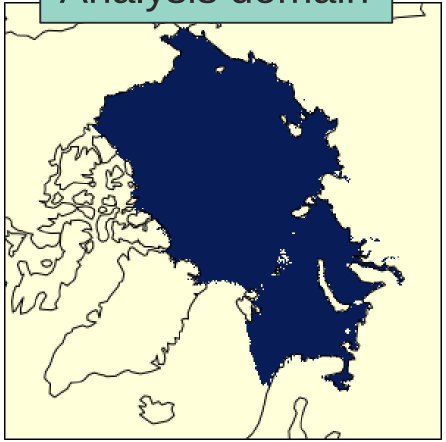
- Where possible, we will use observational datasets to investigate emerging constraints and identify the models that best represent the underlying sea ice processes.

Current status (early August 2019)

The Met Office has provided:

- Masks defining the analysis domain
- Templates for the processed data
- Example Python scripts for generating the data

Analysis domain



The following CMIP6 models/centres have expressed interest:

- IPSL
- CNRS-CERFACS (CNRM-CM6-1)
- Max Plank, (MPI-ESM)
- NCAR (CESM)
- CMCC
- MET Norway (NorESM)
- Tsinghua University, Beijing (CIESM)
- AWI (AWI-CM)
- UCLouvain, SMHI & AEMET (EC-Earth3)
- ECCC (CanESM5)
- MRI (ESM2.0)
- GFDL (GFDL-CM4)
- CSIRO (ACCESS-CM2; ACCESS-ESM1.5)
- Met Office (UKESM1; HadGEM3_LL; HadGEM3_MM)

So far we have data from 3 models:

- EC-Earth3-Veg *(from David Docquier, UCLouvain & Klaus Wyser, SMHI):*
  - 1 x historical simulation (ice only)
  - 1 x SSPR8.5 (ice only)
- ESM2.0 *(from Takahiro Toyoda, MRI):*
  - 5 x historical simulations (ice + snow)
  - 1 x SSPR8.5 (ice + snow)
- UKESM1 *(from Ann Keen, Met Office):*
  - 11 x historical simulations (ice + snow)
  - 5 x SSPR8.5 (ice + snow)

We are hoping to receive more very soon!

In addition there will potentially be comparisons with:

- CPOM forced NEMO-CICE model
- PIOMAS analysis
- Observational datasets

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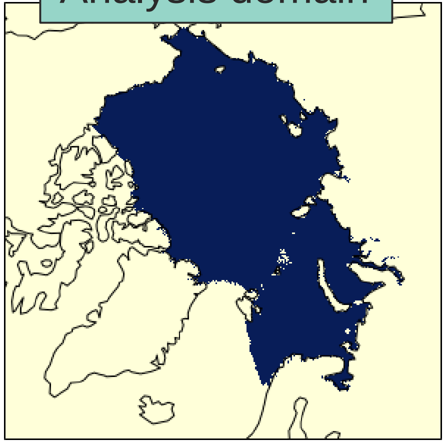

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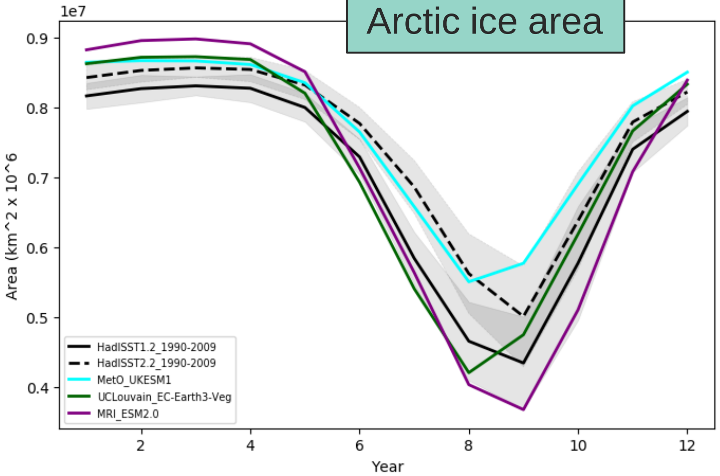
Ice state: Arctic ice area and mass (1990-2009)

- All data is averaged over the analysis domain
- Model results show the ensemble mean.
- Shading shows +/- 1 st dev for the HadISST observational dataset (ice area) and PIOMAS analysis (mass)

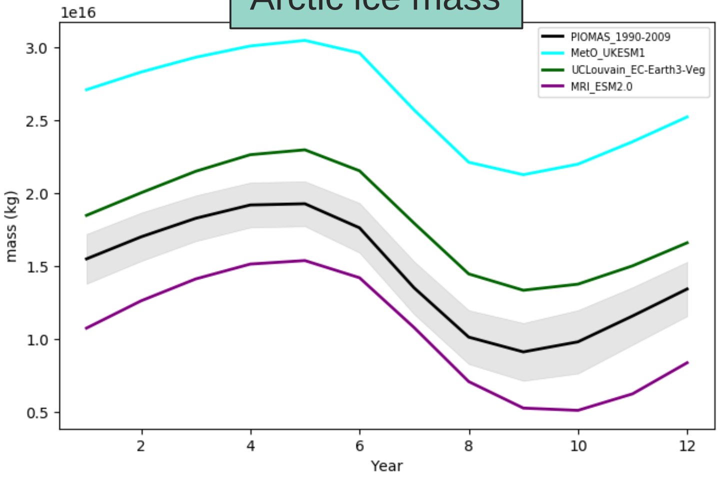
Ice area:
- Winter maximum is constrained by analysis domain
- Large spread in summer minimum values, and corresponding magnitude of seasonal cycle.
- UKESM1 and ESM2.0 have their seasonal minima in August, whereas the observations and EC-Earth-Veg3 have their minima in September.

Ice mass:
- Models show a large spread: UKESM1 has a lot more ice than the PIOMAS analysis suggests, ESM2.0 has rather less.
- Differences are similar year-round

Arctic ice area



Arctic ice mass



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Ice state: Evolution of Arctic ice area and mass (IPCC AR6 SSP5-8.5 scenario)

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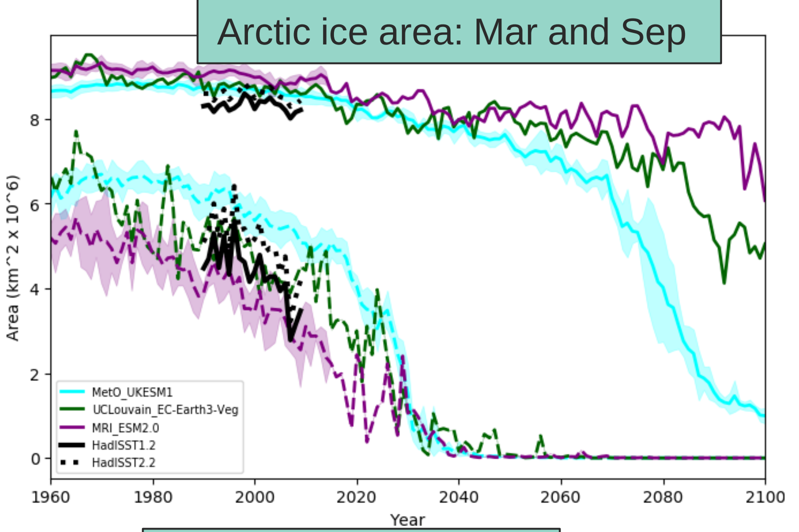
Values are ensemble means, and shading shows +/- 1 st dev where there are >1 ensemble members.

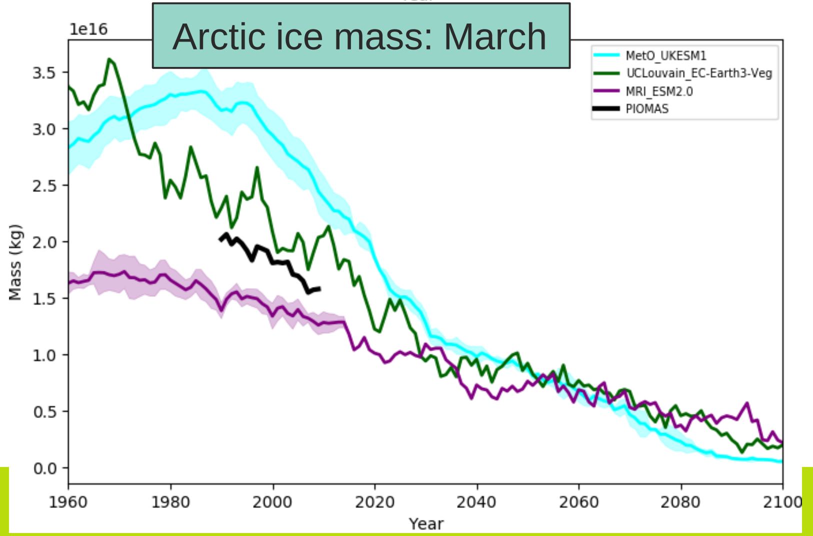
<u>Area:</u> (solid lines March, dotted lines September)

- All 3 models lose their summer ice cover at around the same time (2030-40)
- Rates of winter ice decline diverge once the summer ice is gone, with UKESM1 showing the greatest reduction.
- By the end of the 21st century, UKESM1 has lost 86% of its winter ice cover, whereas ESM2.0 has lost just 20%.

<u>Mass</u> (March):

- All 3 models show a slowing in the rate of decline from 2030-40 to the end of the century.
- This coincides with the time at which the Arctic becomes seasonally ice-free.
- Possibly due to the ice being relatively thin by this stage.





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Seasonal cycle of Arctic ice mass budget components for reference period 1960-89

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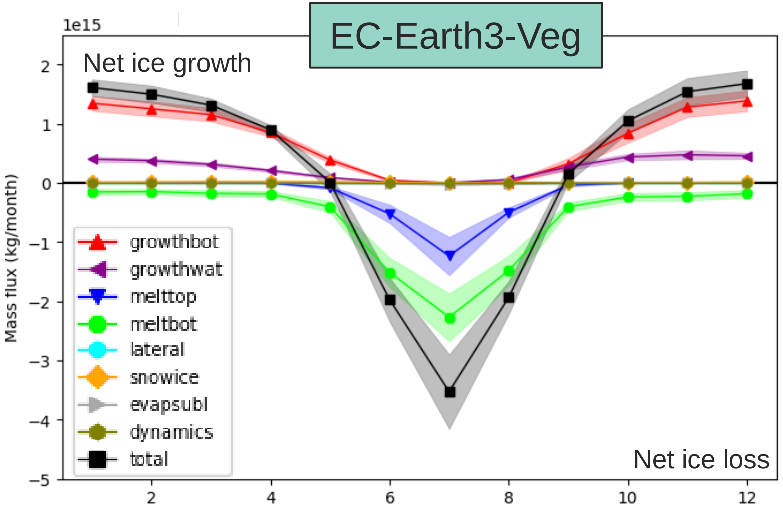
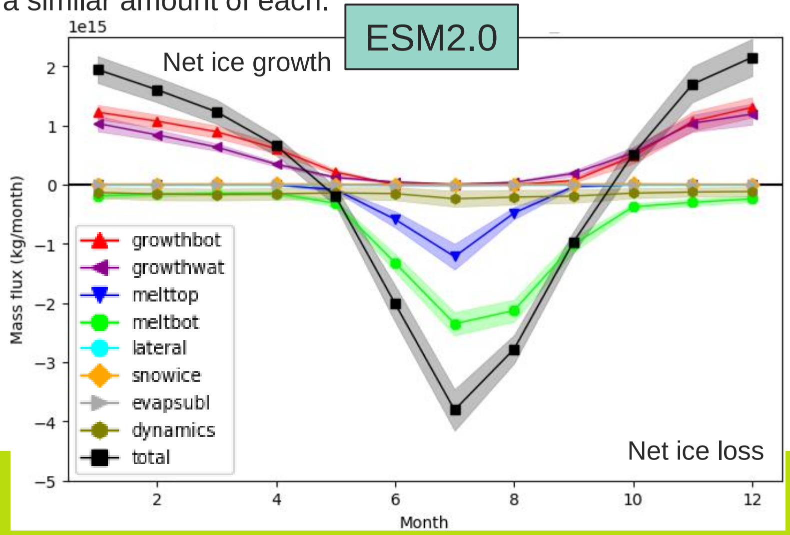
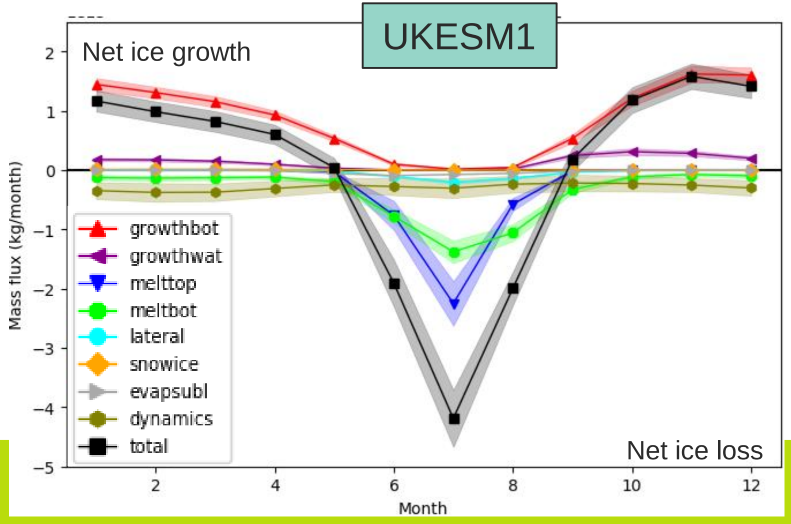
Key differences between the models:

- Ratio of summer basal and surface melting:
    - ESM2.0 and EC-Earth3-Veg have more basal than surface melt during the summer
    - UKESM1 has similar amount of each in June, more surface melt in July
- Frazil ice formation:
    - EC-Earth3-Veg and UKESM1 have significantly less frazil ice formation than basal growth
    - ESM2.0 has a similar amount of each.







Note:

- ESM2.0 has no explicit lateral melt
- EC-Earth3-Veg is missing the dynamic and lateral melt terms

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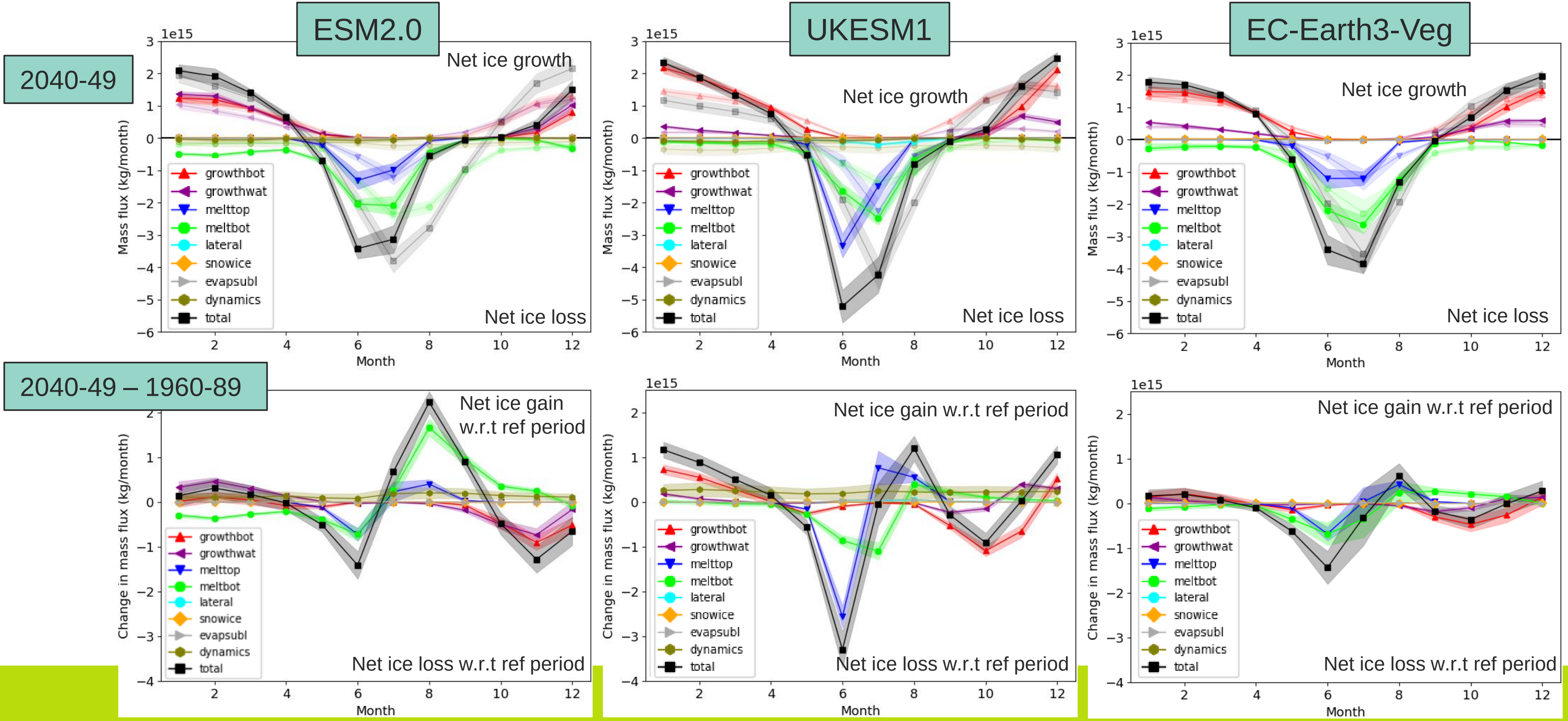
Changes in Arctic ice mass budget components: 2040-49 w.r.t. 1960-89



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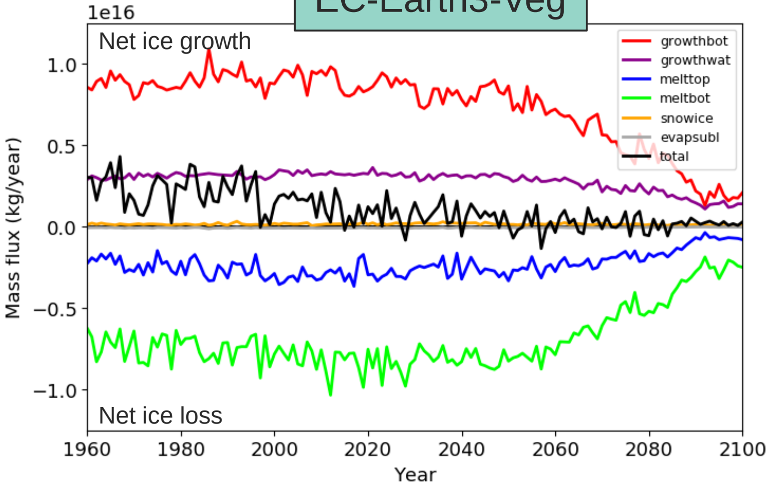
Evolution of annual mean Arctic ice mass budget components

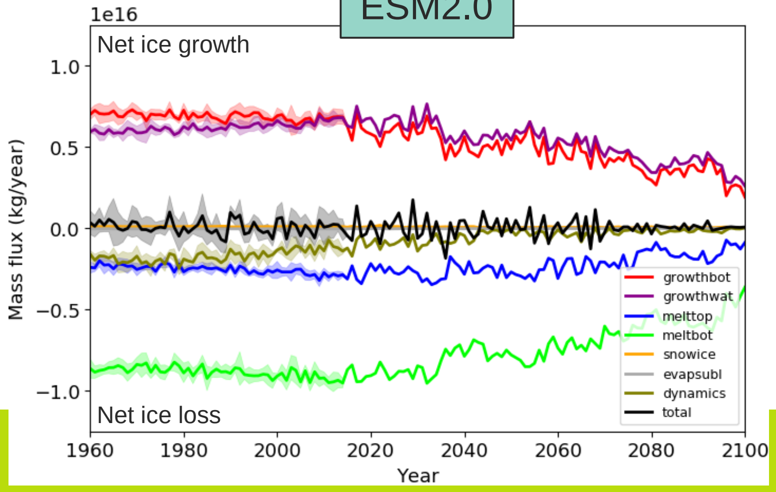
- The relative magnitude of the processes causing ice growth and loss is very different between the models, for example:
    - ESM2.0 has a much great proportion of frazil ice formation the other models
    - UKESM1 has less basal ice melt, and proportionally more top melt

- During the 21st century the magnitude of each budget component tends to decline
- For some of the budget components, there is initially an increase before the decline
- The magnitude of each budget component is affected by the atmosphere and ocean forcing, and also the ice state itself.

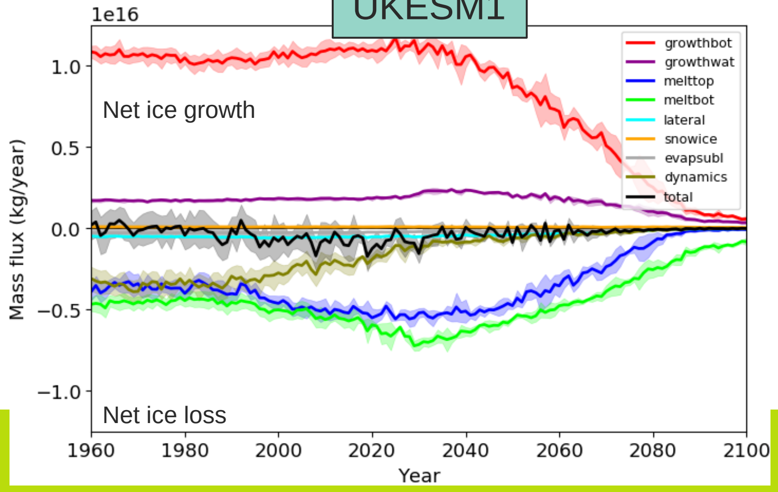
EC-Earth3-Veg



ESM2.0



UKESM1



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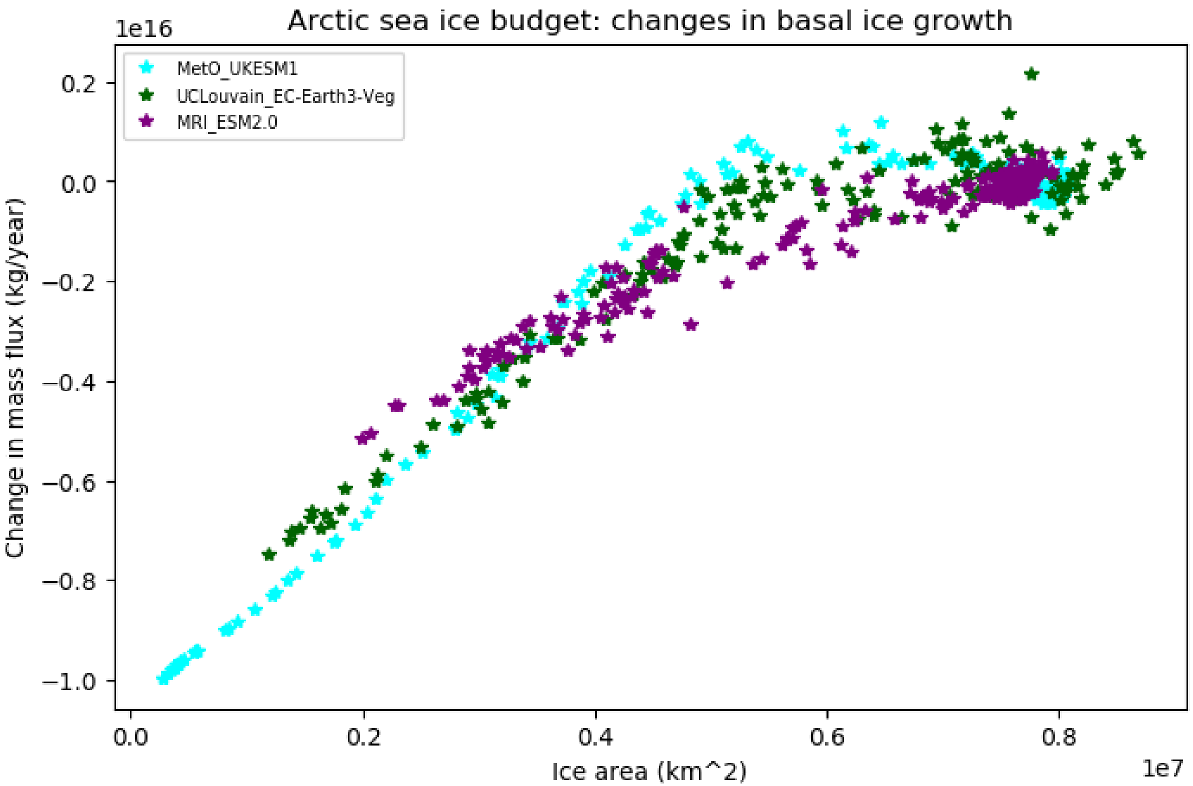
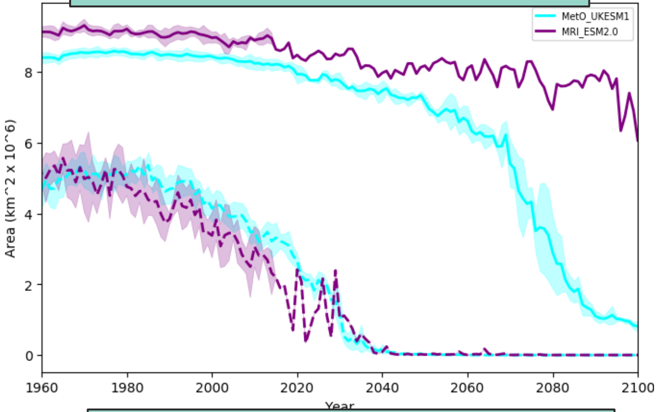
Changes in budget components as a function of ice state
Example: Ice area vs change in amount of basal growth

- Keen and Blockley (2018) found that changes in the budget components in a single model each follow a common trajectory w.r.t. the ice area for a wide range of forcing scenarios.
- We will investigate whether there is a similar relationship common to the CMIP6 models.
- Very early results for the first 3 models are encouraging.
- This plot shows annual mean basal growth as a difference w.r.t. the 1960-89 reference period.

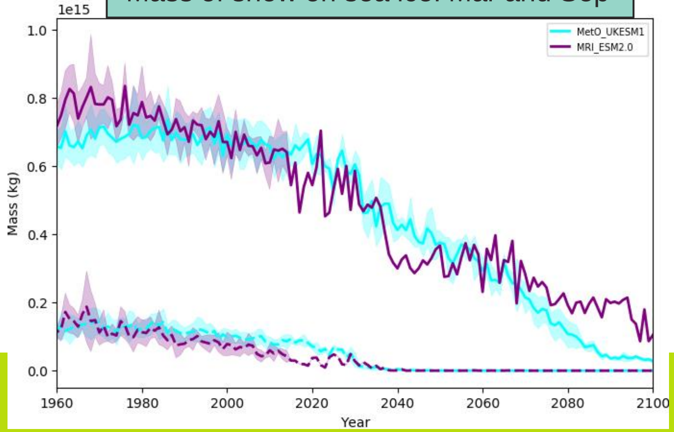


What about the snow?

Area of snow on sea ice: Mar and Sep



Mass of snow on sea ice: Mar and Sep



We have snow budget data for 2 models

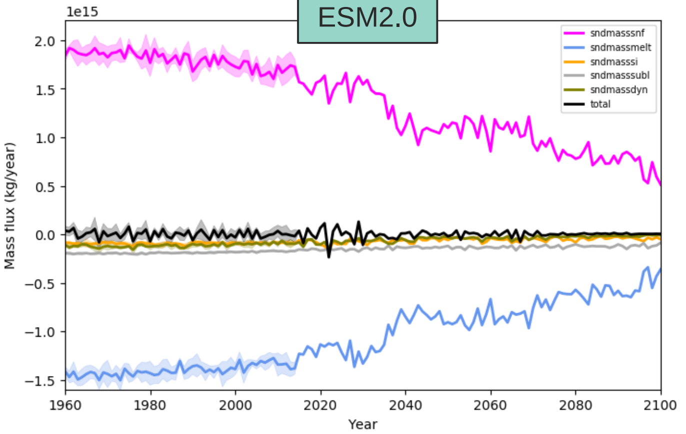
<u>Snow state:</u>

- The evolution of the snow areas follows that of the ice for each model.
- The mass of snow in the two models is remarkably similar

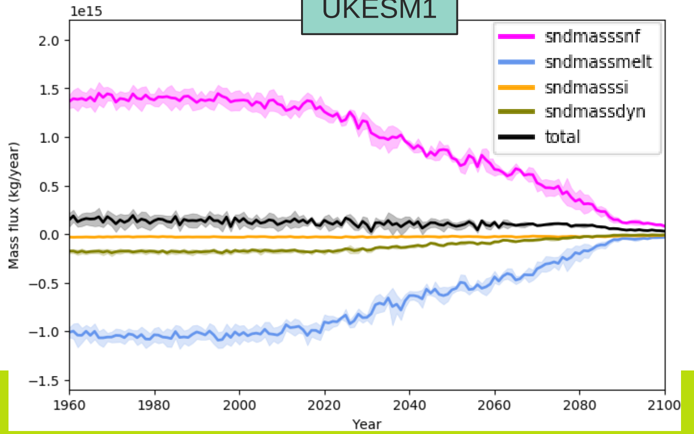
<u>Snow mass budget:</u>

- For both models the snow mass budget is primarily a balance between the amount of snowfall and the amount of surface melt.
- ESM2.0 has more snowfall and more melting than UKESM1
- For UKESM1 the budget total is offset from zero because the evap+sublim term is missing.

ESM2.0



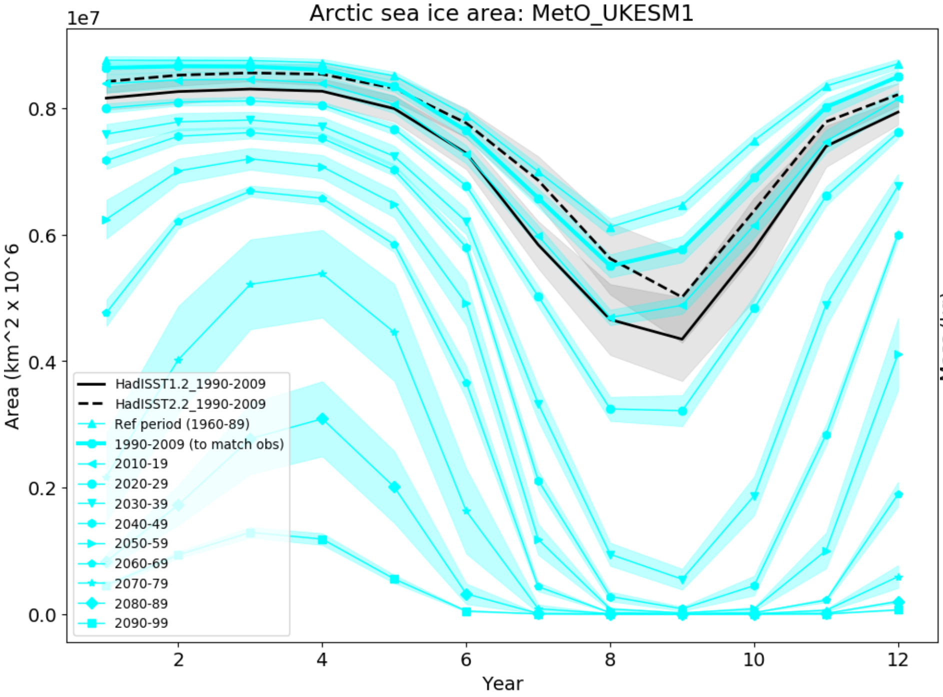
UKESM1

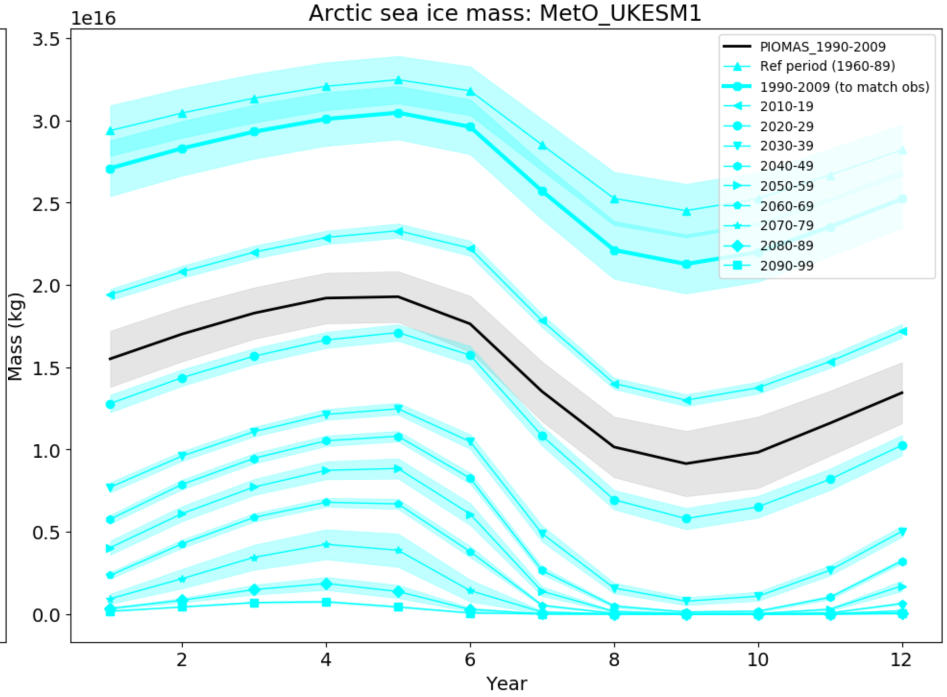


Summary

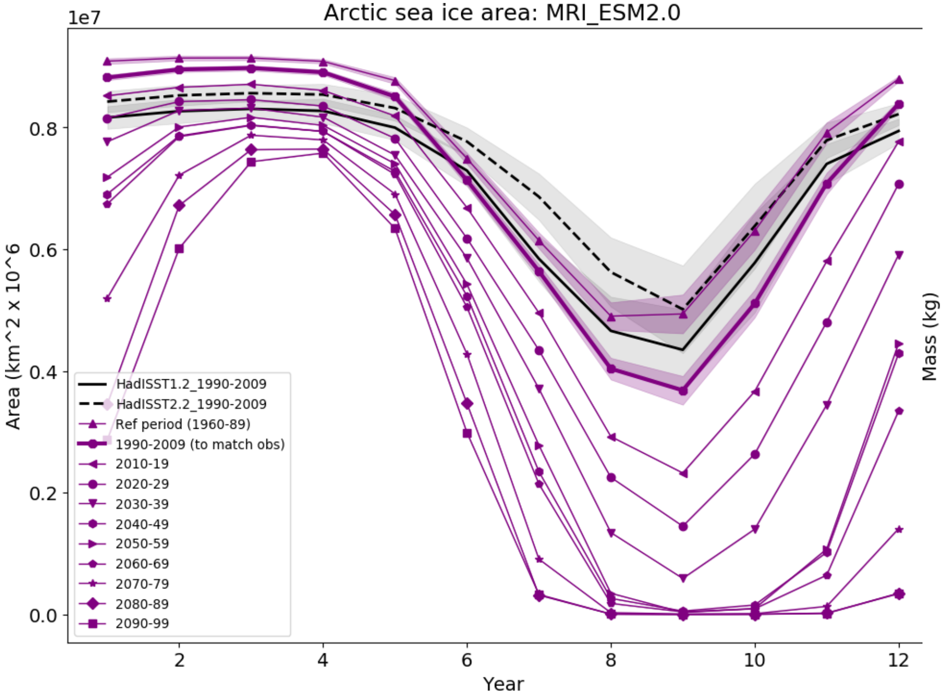
- We are coordinating an inter-comparison of the Arctic sea ice/snow mass budget from CMIP6 models as part of SIMIP - taking advantage of extra budget diagnostics specified by SIMIP
- This will allow us to better understand the processes causing the seasonal growth and loss of ice and snow in CMIP6 models, and how these processes change during the 21st century.
- Preliminary comparisons of the Arctic sea ice mass budget components (1960 to 2100) from the 3 CMIP6 models received so far have been shown here.
  - There is considerable spread in the relative magnitude of the processes causing seasonal ice growth and loss between the 3 models (during a reference period 1960-89)
  - As the ice declines during the 21st century, the models show a common seasonal signal in changes to the amount of ice growth and loss, with extra ice loss during June and October partly offset by reductions ice loss during August.
  - Early results suggest that the common relationship between changes in annual mean mass budget components and the evolution of the ice state found by Keen & Blockley (2018) for HadGEM2-ES may also hold for the CMIP6 models.
- We hope to receive data from more of the CMIP6 models soon, and aim to submit a paper by December 2019, in time for consideration for the IPCC AR6 assessment.
- **There is still time to contribute model data** - come chat with me and/or email me/Ann soon!

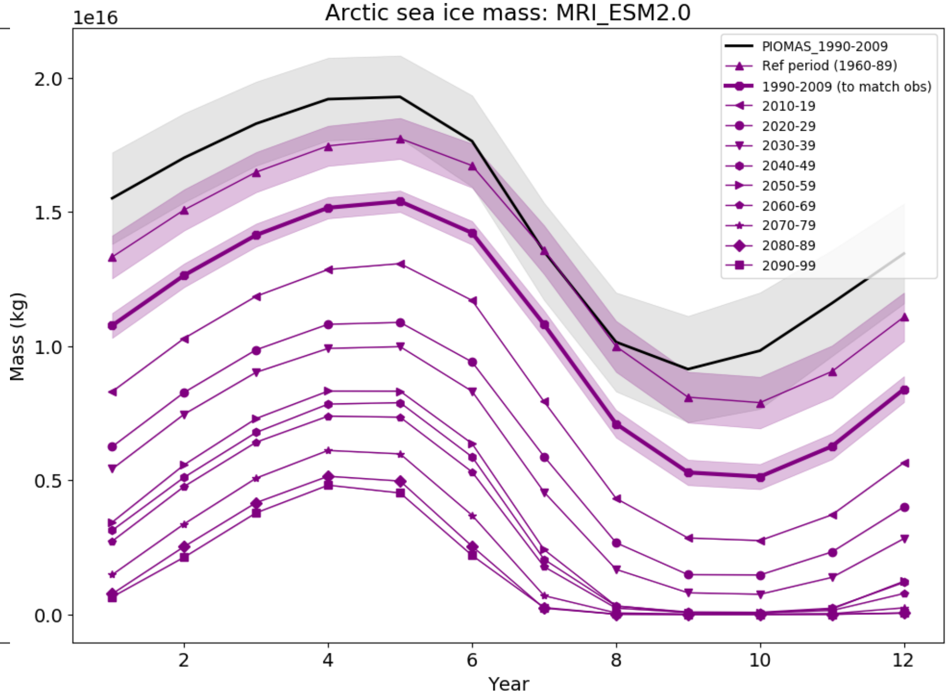
Evolution of ice area and mass: UKESM1



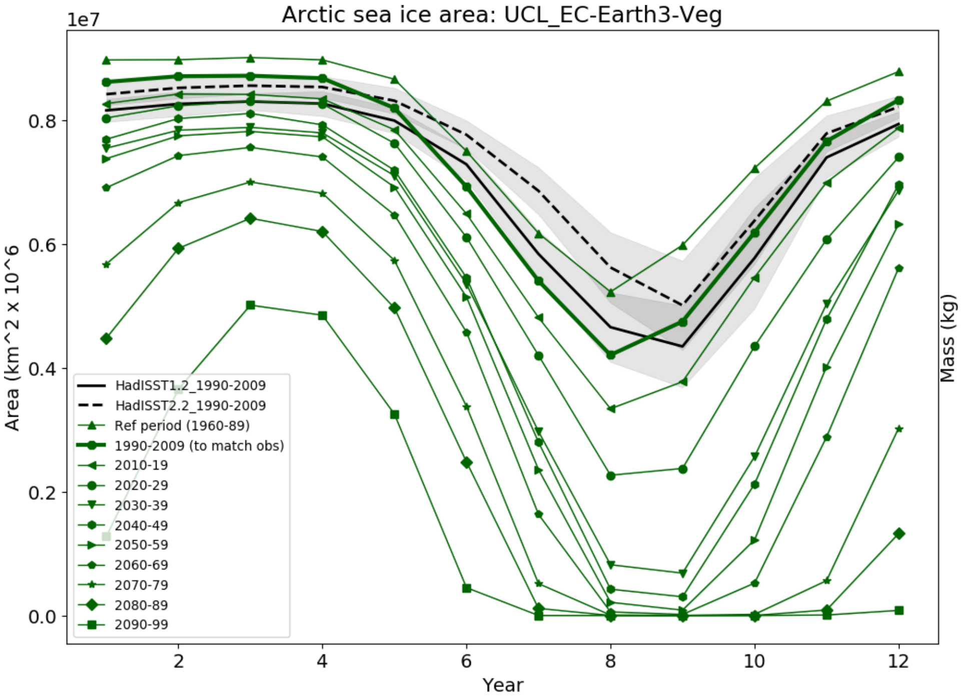


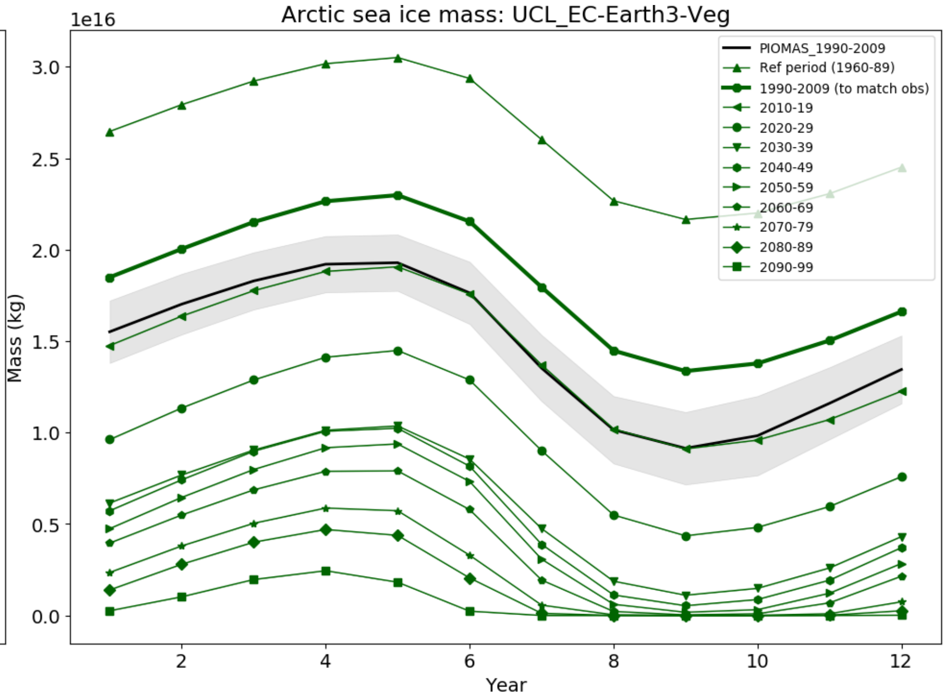
Evolution of ice area and mass: ESM2.0





Evolution of ice area and mass: EC-Earth3-Veg





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Evolution of anomalies in annual mean Arctic ice mass budget components