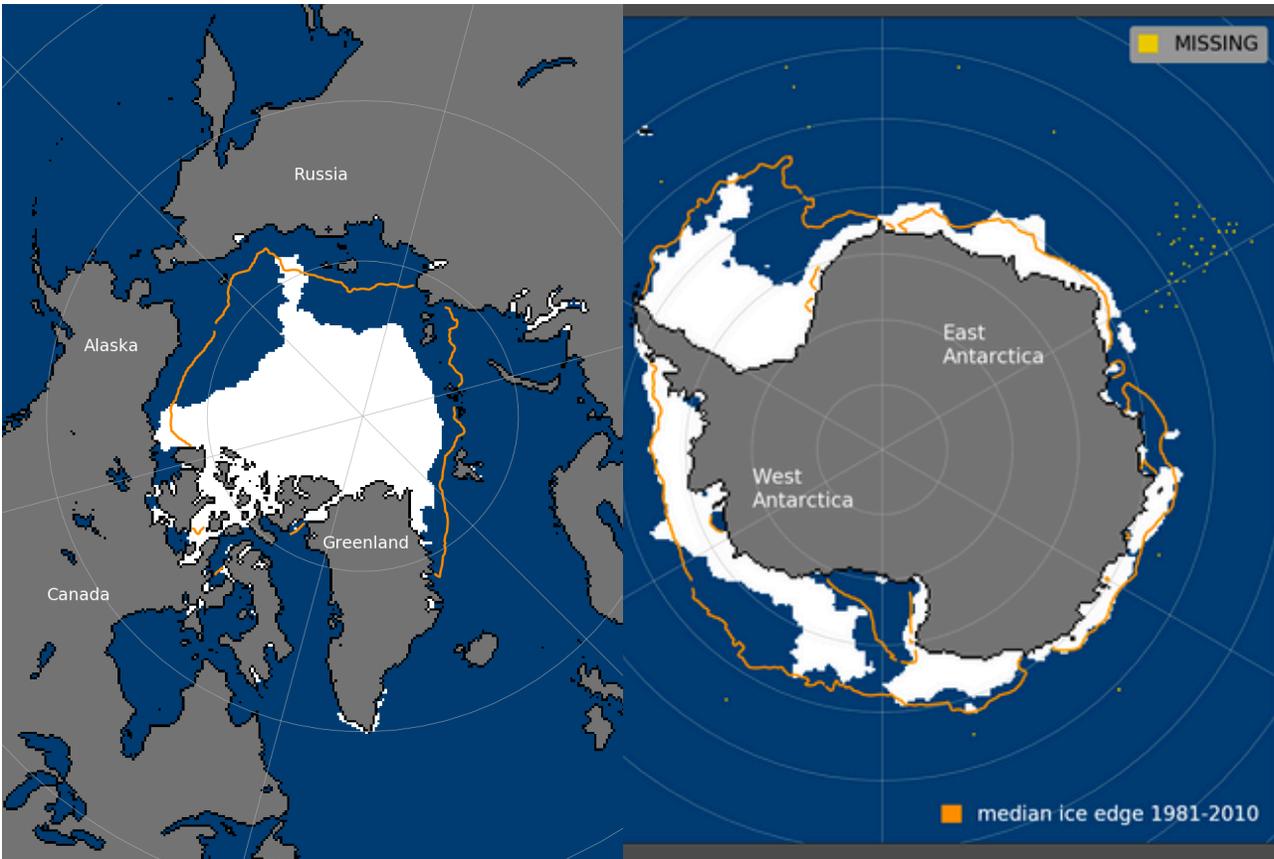


How Much should we Worry about which Method to Use for Melting Sea Ice in PAMIP Coupled Experiments?



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Introduction

Different methods have been used to melt sea ice in coupled ocean-atmosphere models:

1) **Energy-conserving** : altered sea ice parameters such as albedo (Bitz et al. 2006; Winton 2008; Scinocca et al. 2009; Graverson and Wang 2009; Blackport and Kushner 2016; 2017; Cvijanovic et al. 2017; Blackport and Screen 2018; Liu and Fedorov 2018).

- Effective in summer but not in winter

2) **Energy-not-conserving: “ghost forcing”** (Deser et al. 2015; Tomas et al. 2016; Oudar et al. 2017; Wang et al. 2018) **or nudging** (McCusker et al. 2017; Smith et al. 2017; Sun et al. 2018).

- Effective year-round

Does the Method of Melting Sea Ice Matter?

Multi-model results in Screen et al. (2018) suggest that atmospheric responses to Arctic sea ice loss are generally robust among different models and ice melting methods. However, different tropical responses have been shown.

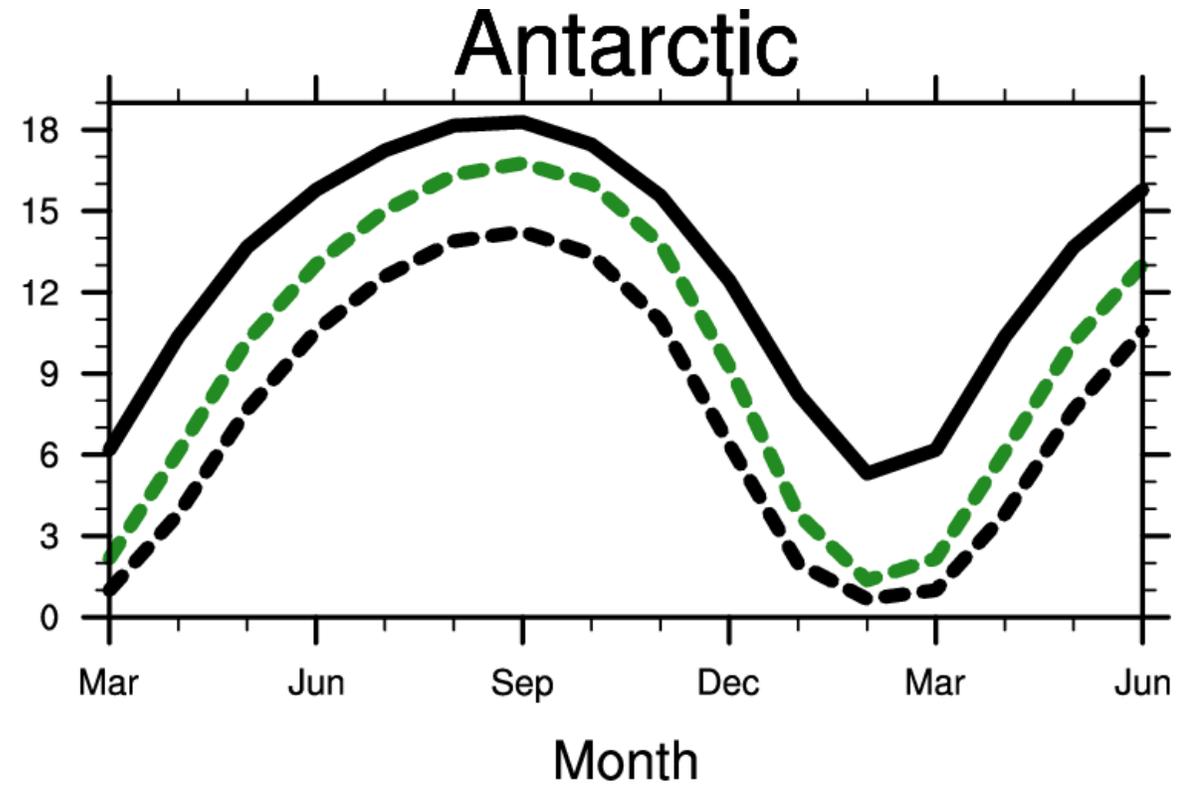
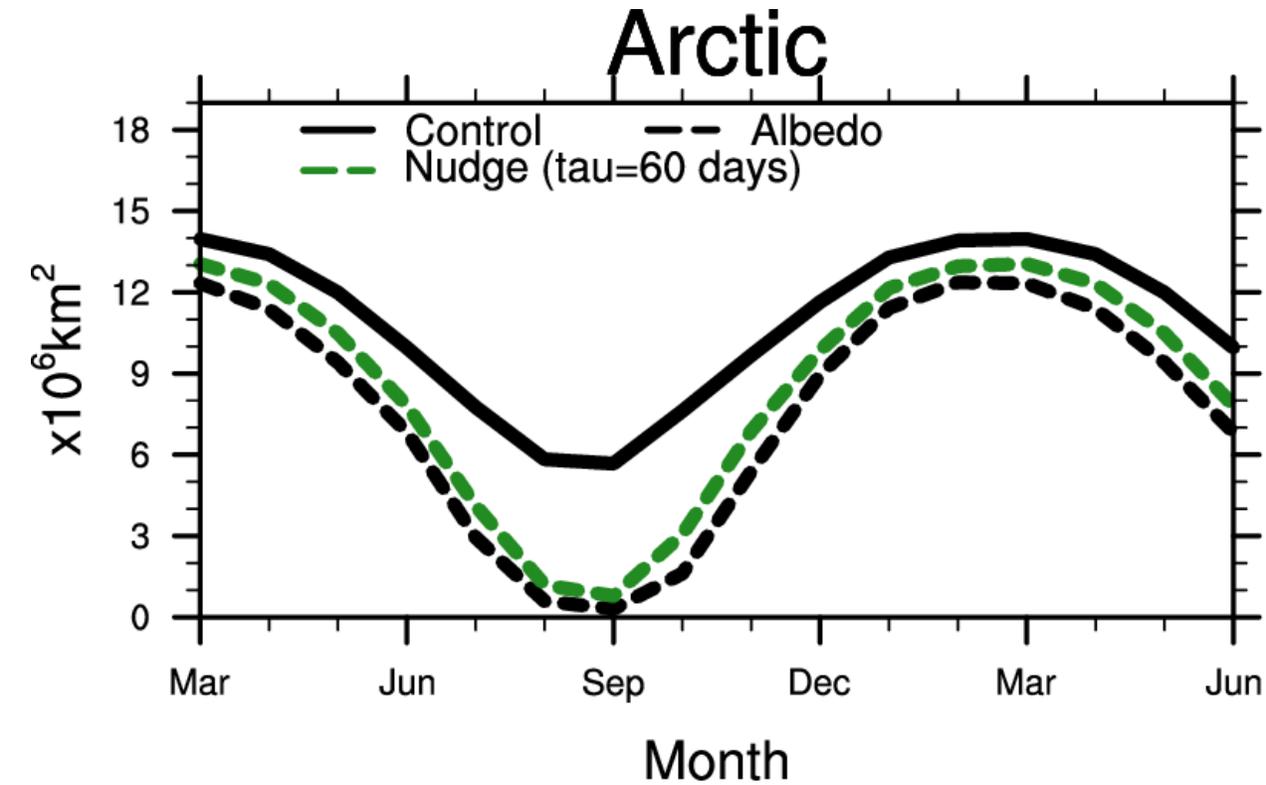
- Energy-conserving (albedo method): *ITCZ shifts northward in the first few decades then shifts southward (Liu and Fedorov 2018)*
- Energy-not-conserving: *Equatorward intensifying of the ITCZ (Deser et al. 2015; Tomas et al. 2016; Wang et al. 2018; Sun et al. 2018)*
- It is still unclear to what extent the different responses to future sea ice loss in previous studies are due to different ice-melting methods. In other words, if given the same sea ice loss, will two different sea ice melting methods generate different responses in the ocean and atmosphere?

Experimental Design

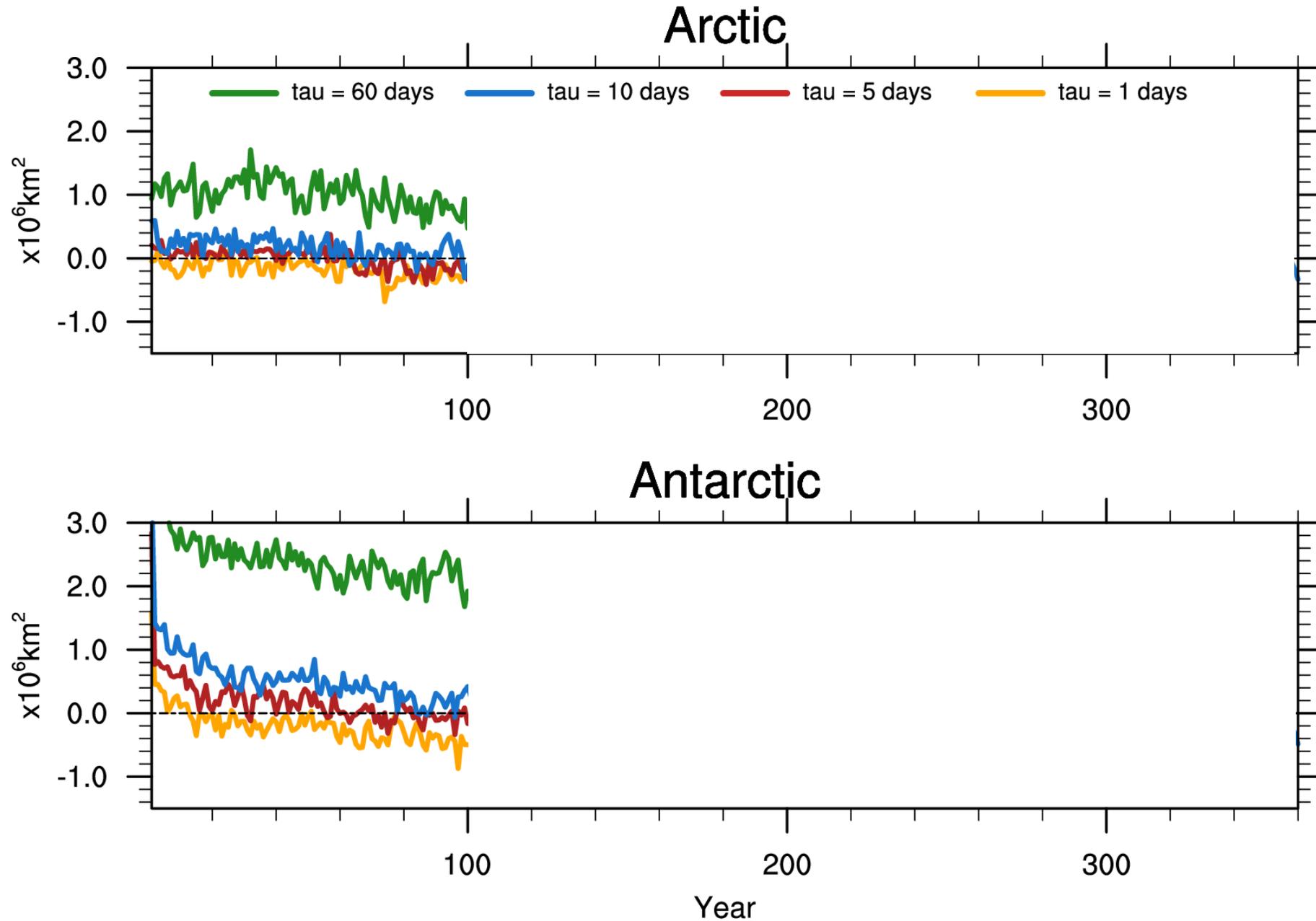
Three 360-year coupled CCSM4 runs (first 100 years discarded) with radiative forcing fixed at year 2000

- **Control:** 1980-1999 sea ice experiments from CCSM4 HIST
- **Albedo:** reduce the ice albedo to match summer sea ice to CCSM4 RCP8.5 2080-2099 conditions, but winter sea ice loss is underestimated (Deser et al. 2015).
 - $\Delta\text{Albedo} = \text{Albedo} - \text{Control}$
- **Nudge:** nudge the sea ice volume to match the albedo run in both hemispheres
 - Applying a time-varying “ghost flux” to the bottom of the ice and this flux does not directly interact with the ocean (Knutson 2003; McCusker et al. 2017; Sun et al. 2018)
 - Global water mass budget is conserved
 - $\Delta\text{Nudge} = \text{Nudge} - \text{Control}$

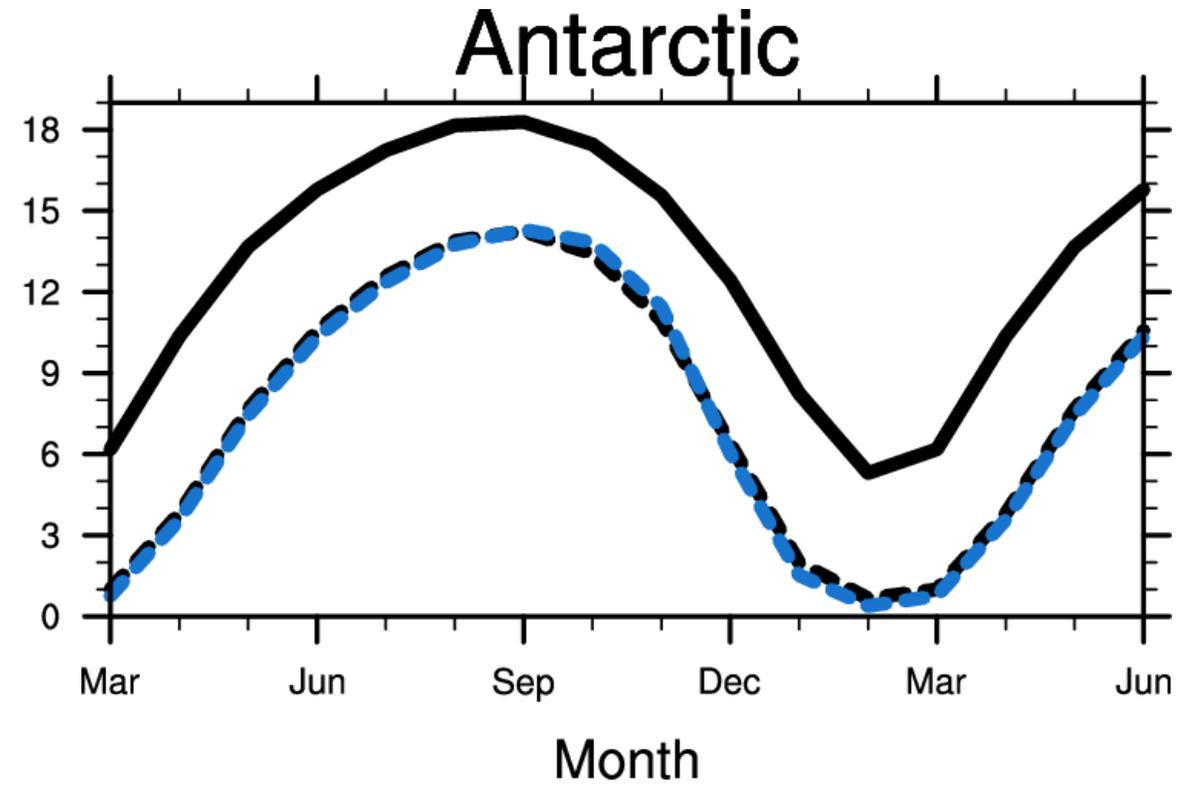
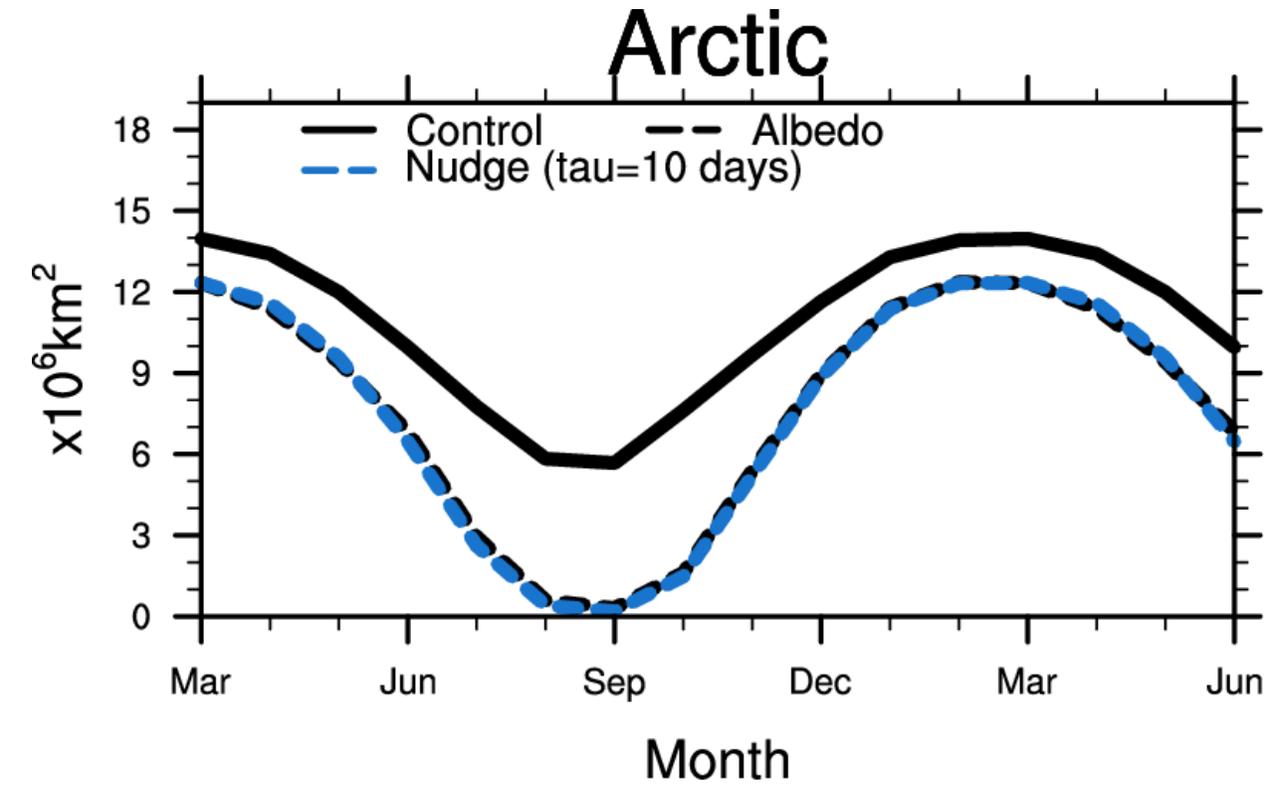
Sea Ice Area for 60-day Nudging Timescale (PAMIP protocol)



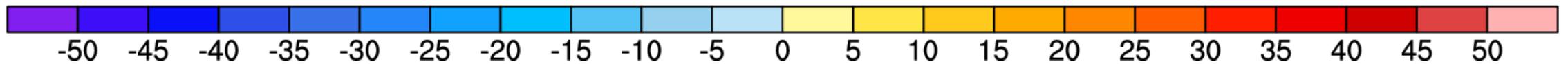
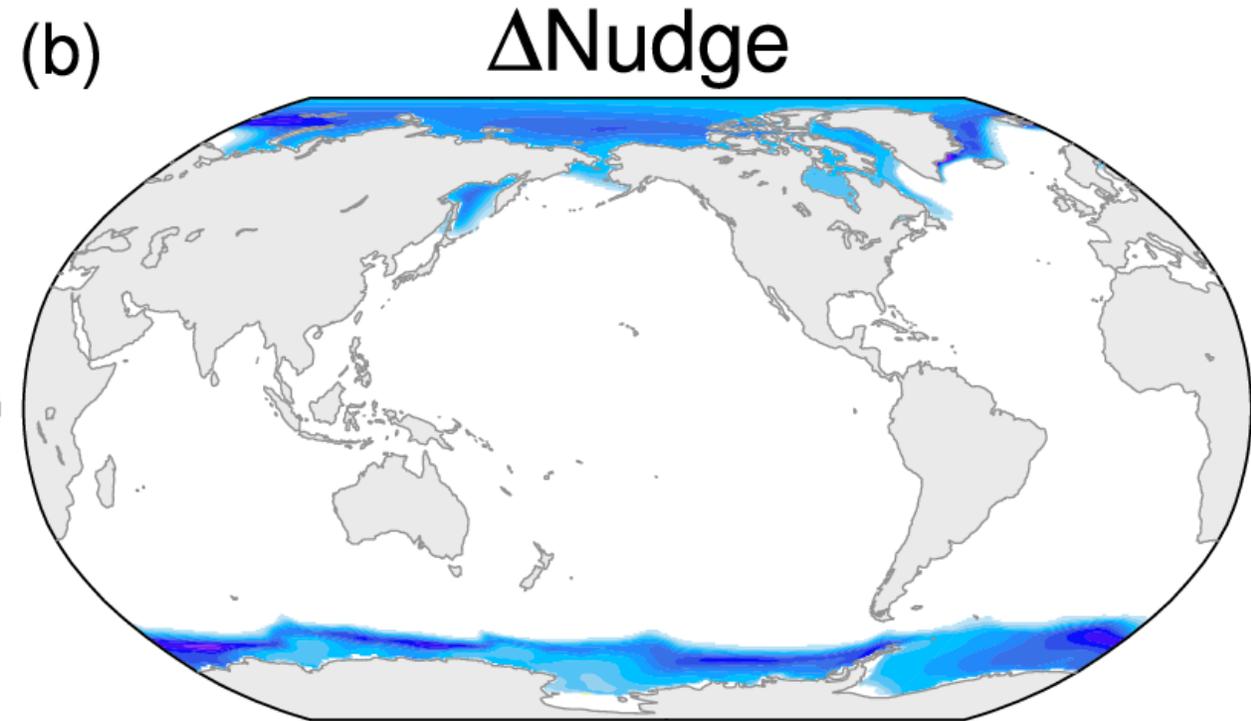
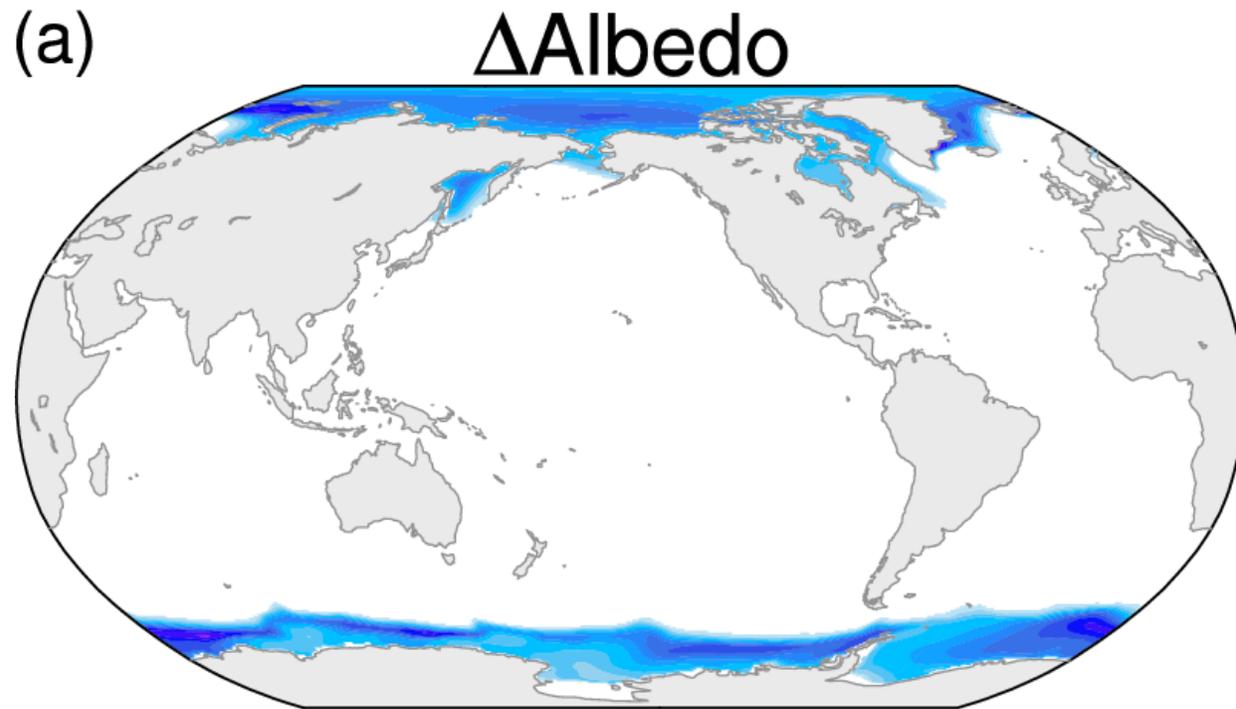
Annual Sea Ice Area Anomaly (Nudge – Albedo)



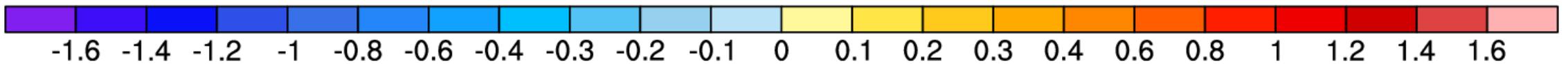
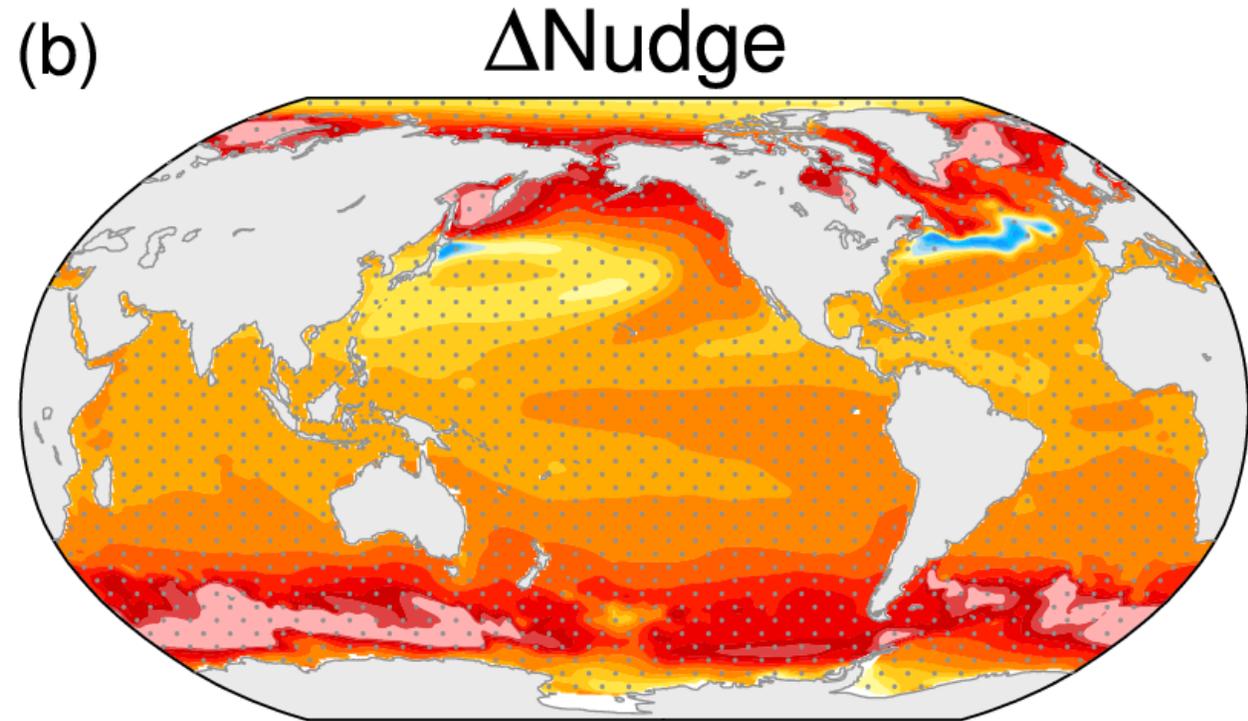
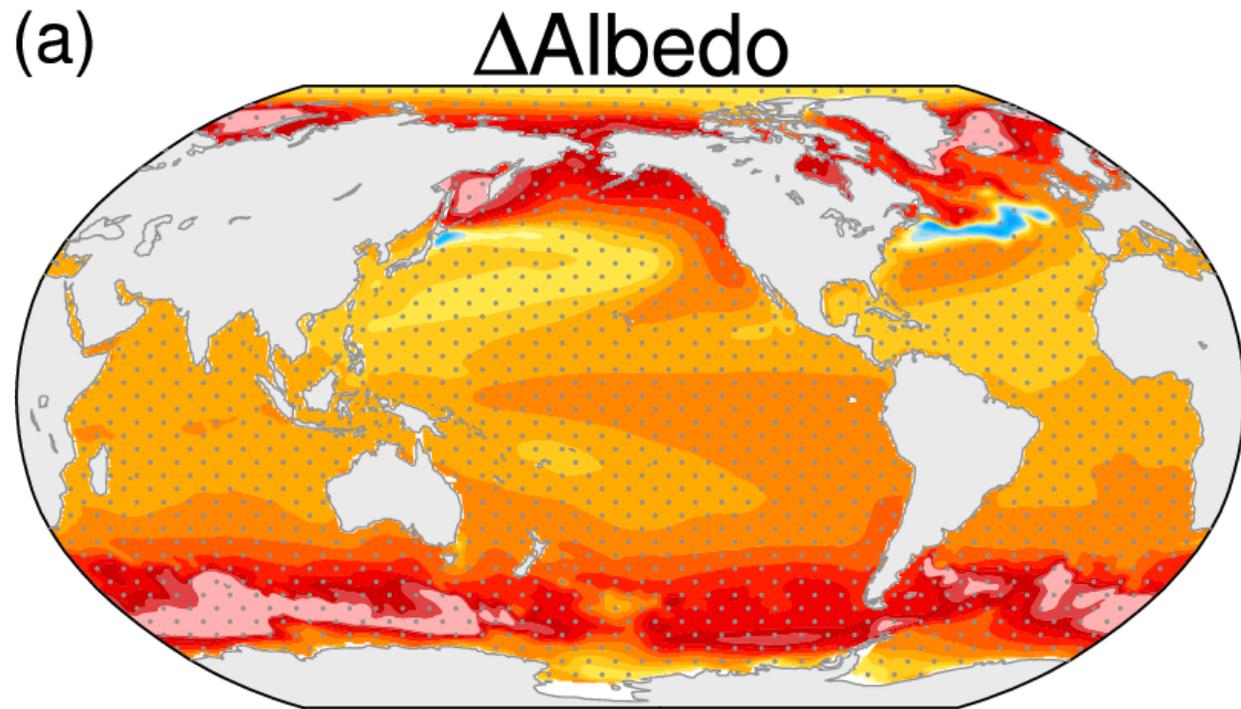
Sea Ice Area for 10-day Nudging Timescale



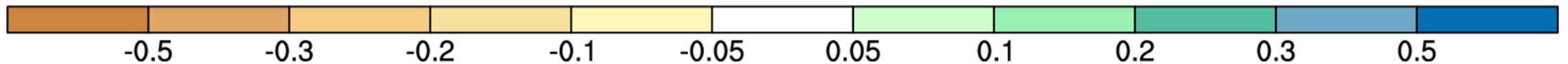
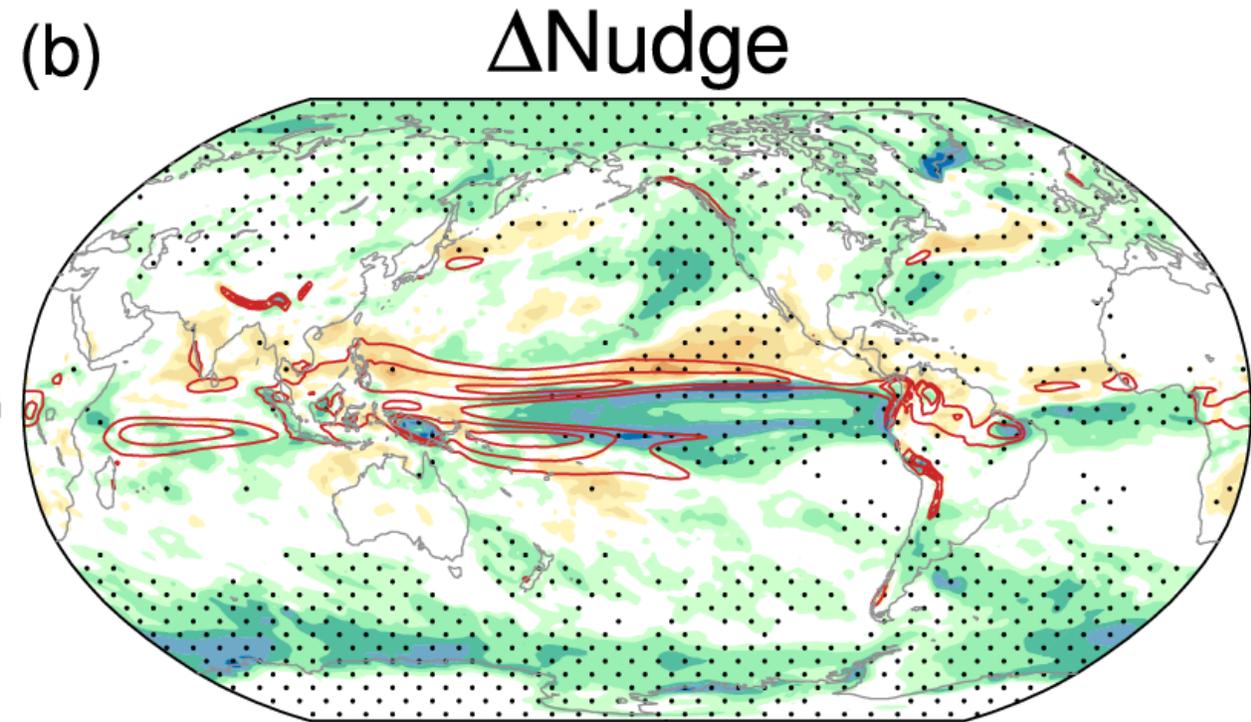
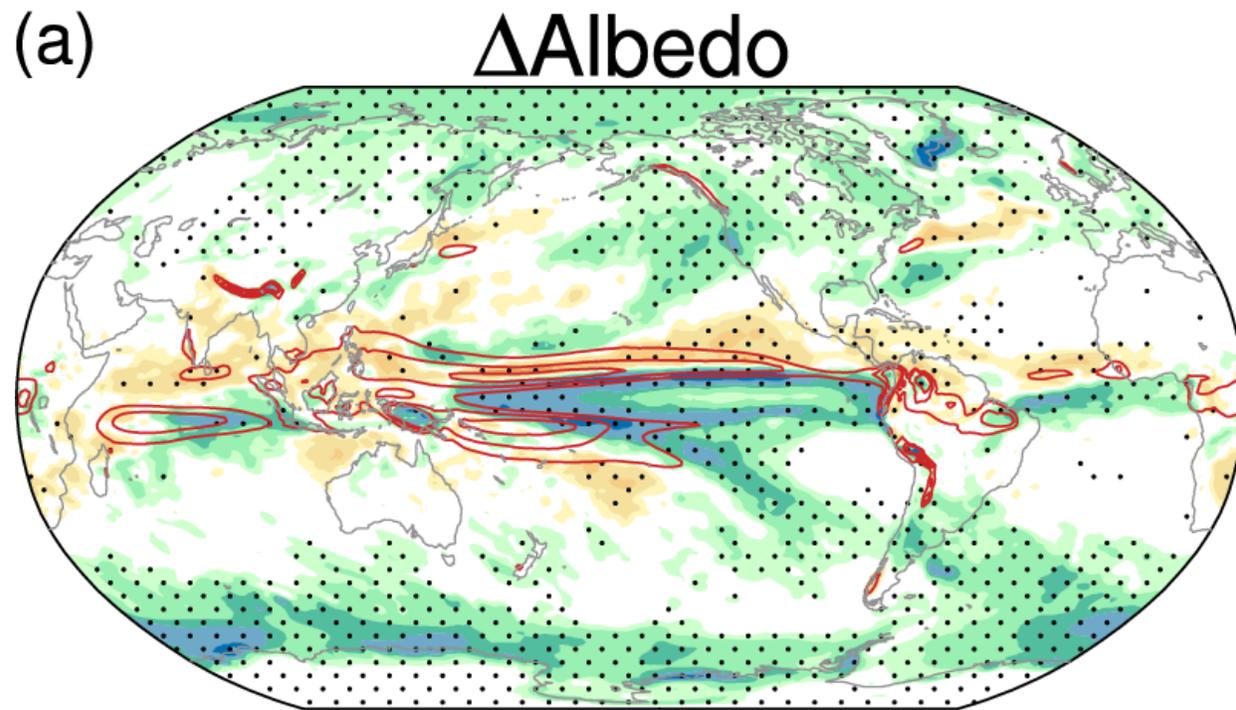
Annual Sea Ice Concentration Change (%)



Annual Sea Surface Temperature Response ($^{\circ}\text{C}$)

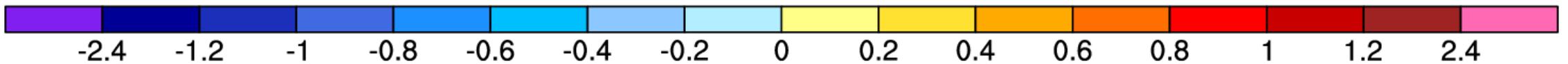
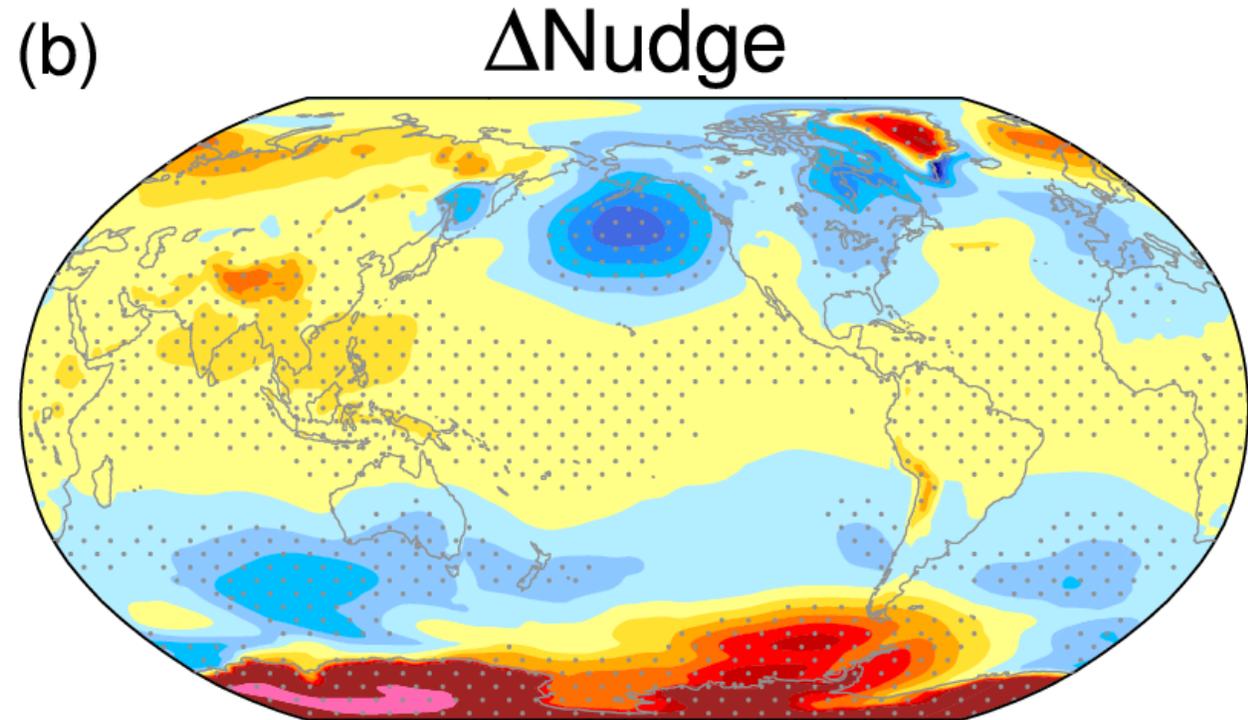
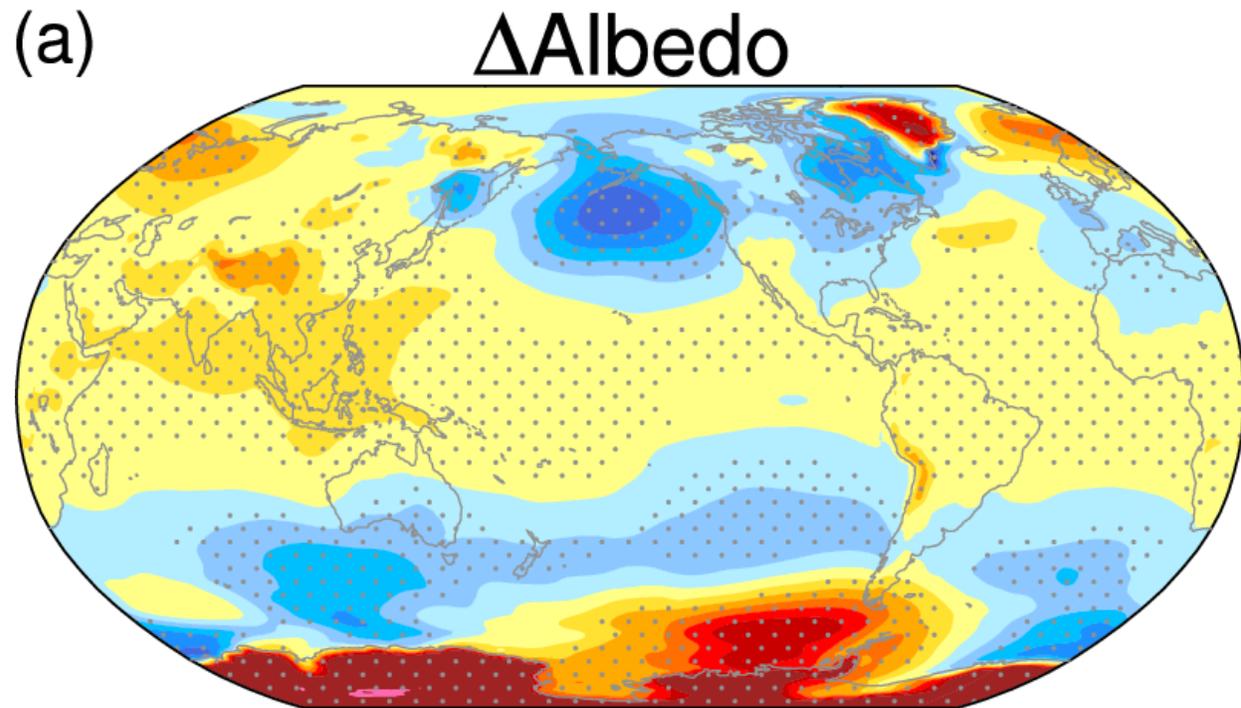


Annual Precipitation Response (mm day^{-1})



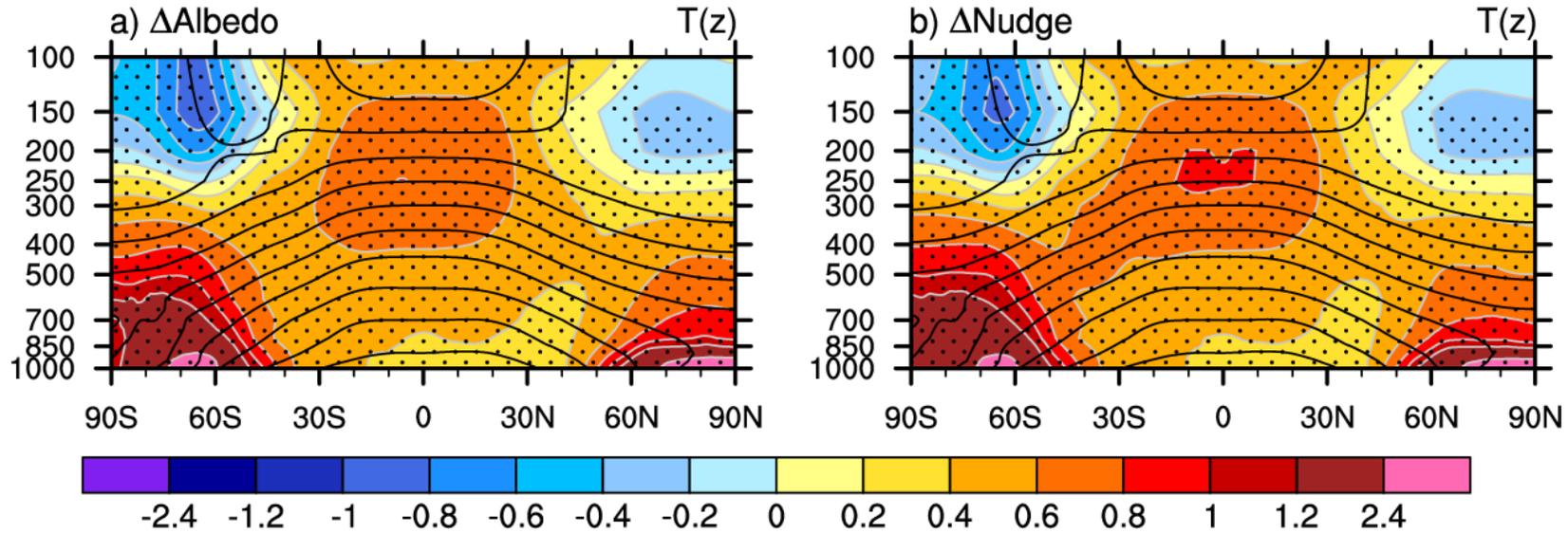
Contours: climatological precipitation

Annual Sea-level Pressure Response (hPa)

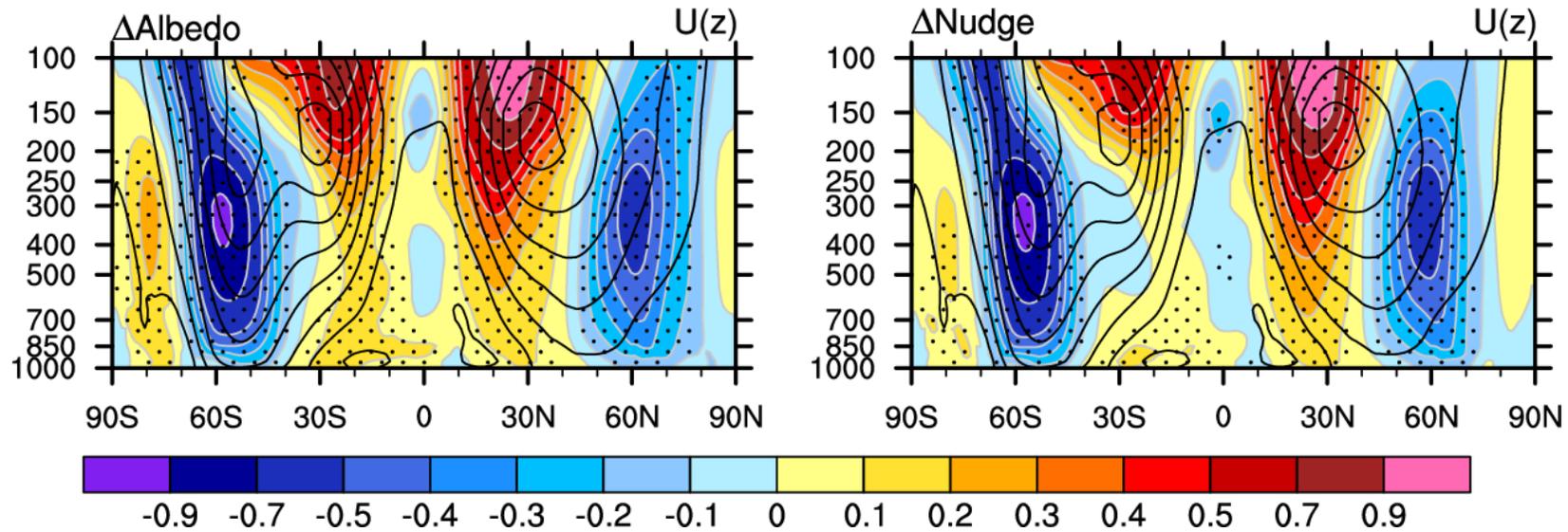


Annual Response to Polar Sea Ice Loss

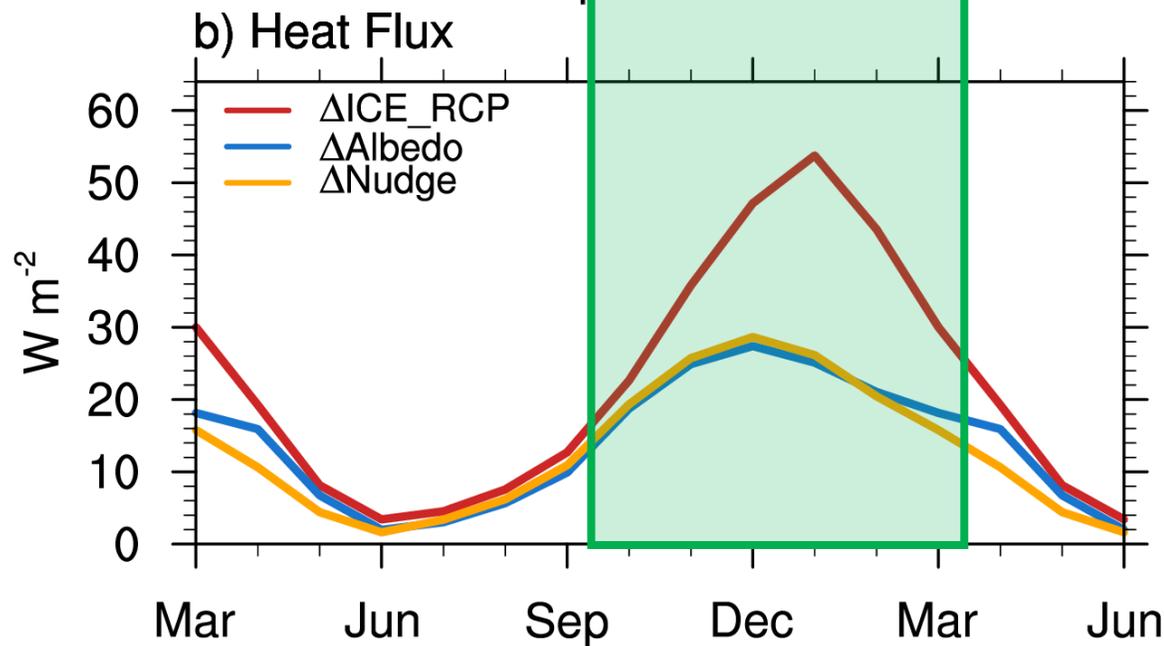
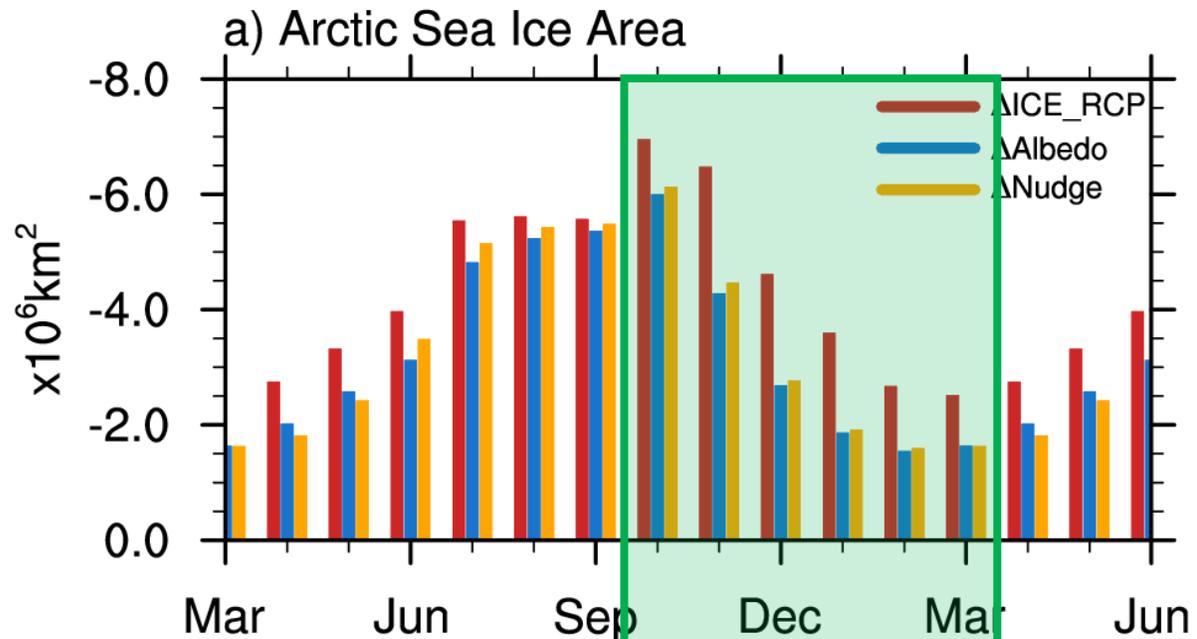
Temperature



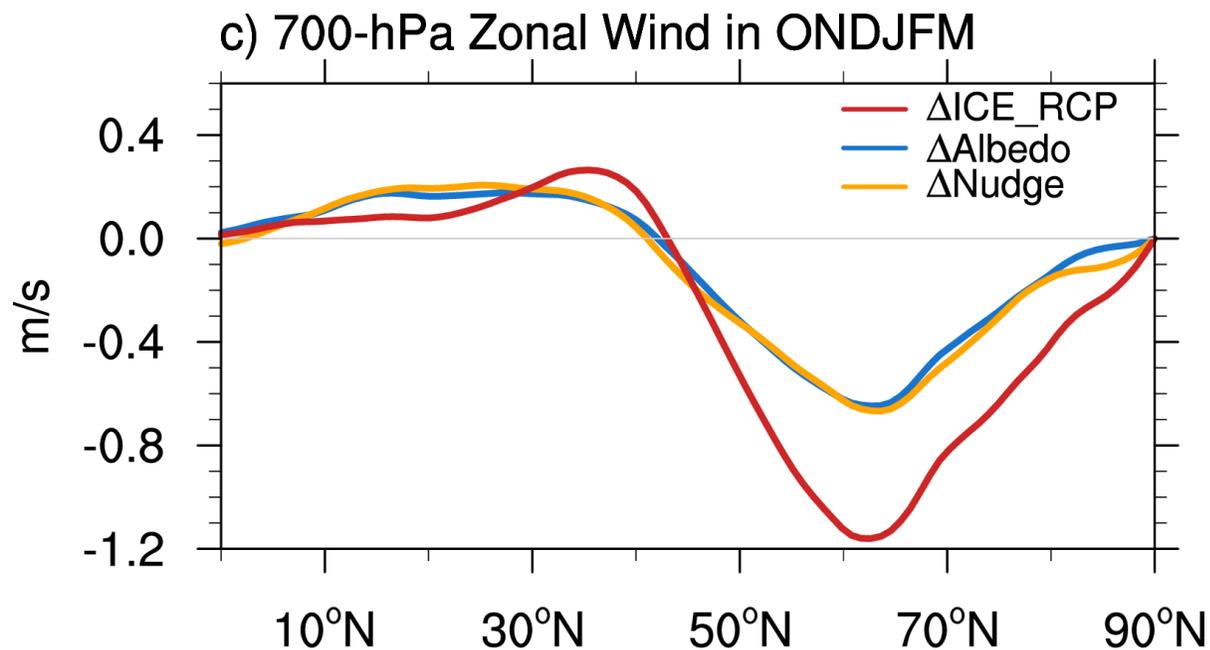
Zonal-wind



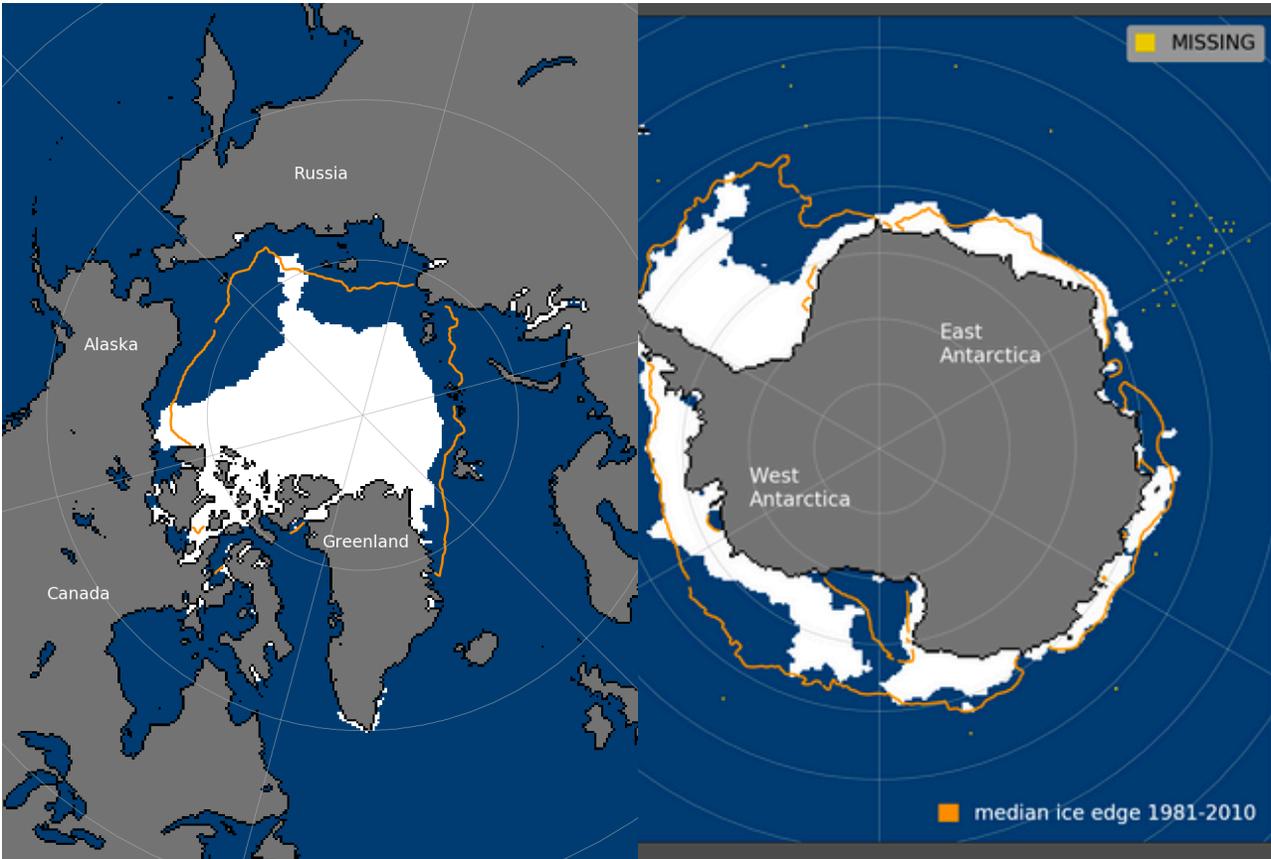
Δ ICE_RCP: coupled CCSM4 sea ice experiment where Arctic sea ice nudged to RCP8.5 2080-2099 conditions (Deser et al. 2015)



Albedo run underestimates winter sea ice loss, thus underestimates its local and remote effect.



Implication for PAMIP



- Sea ice volume nudging method can be used for PAMIP tier 3 coupled experiments, and an appropriate nudging time is around 10 days.
- Given roughly the same sea ice loss, albedo reduction and ice nudging methods generate very similar ocean and atmosphere responses.
- Since albedo method underestimates winter sea ice loss, ice nudging is a better choice for PAMIP.

Sea Ice Concentration (%)

September

March

Control

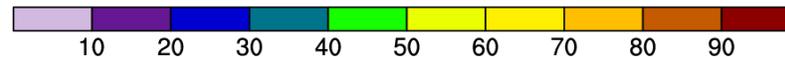
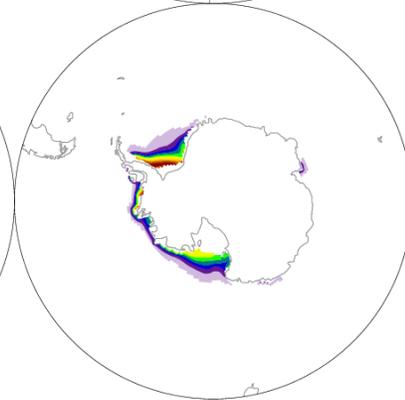
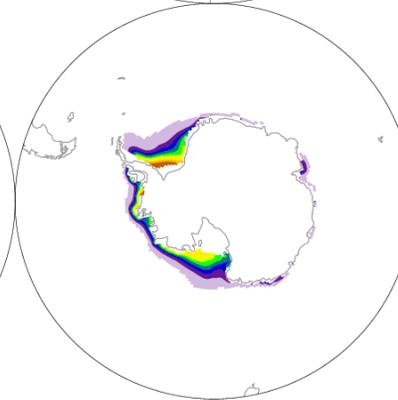
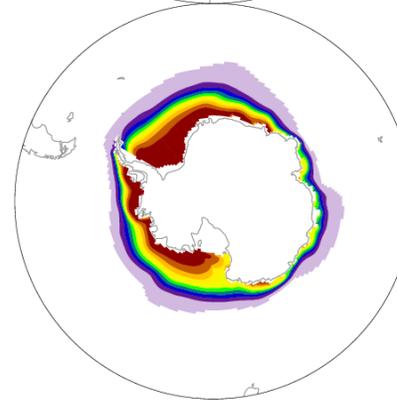
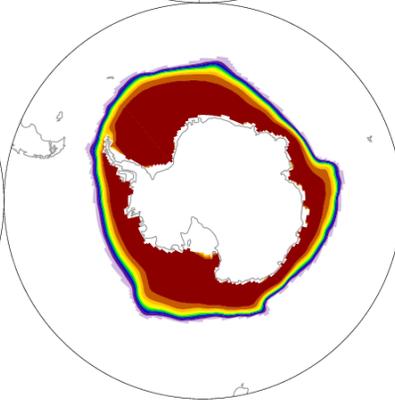
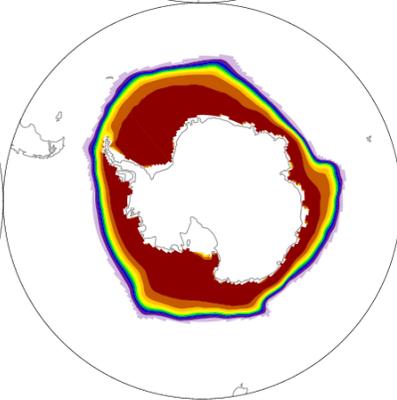
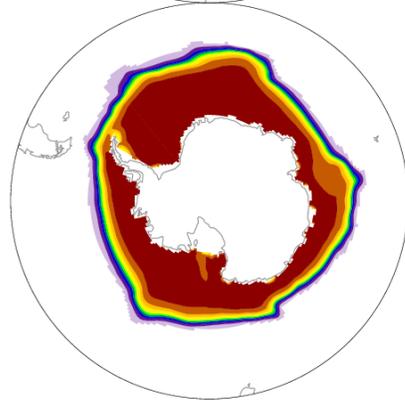
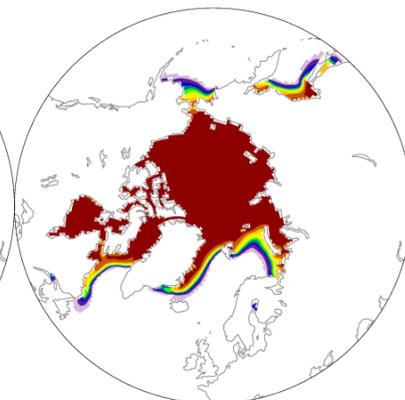
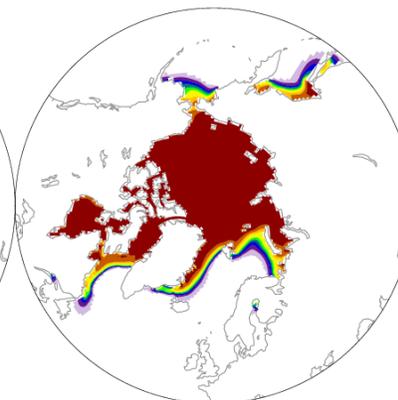
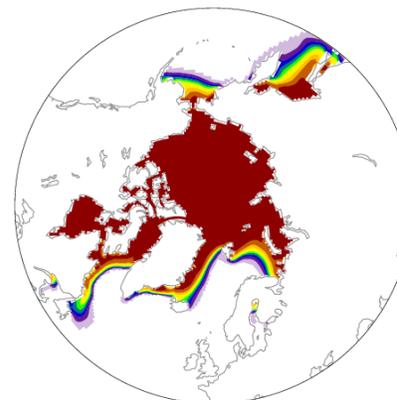
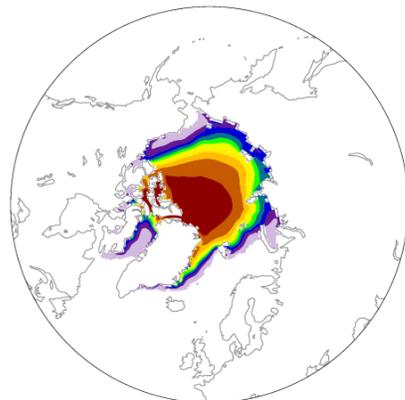
Albedo

Nudge

Control

Albedo

Nudge



Sea Ice Thickness (m)

September

March

Control

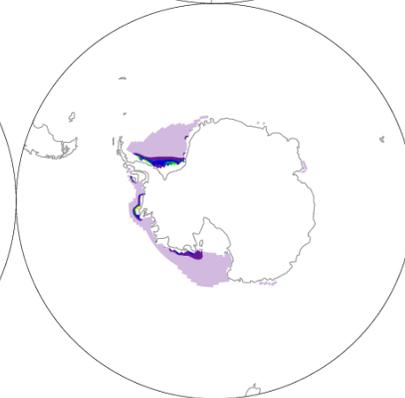
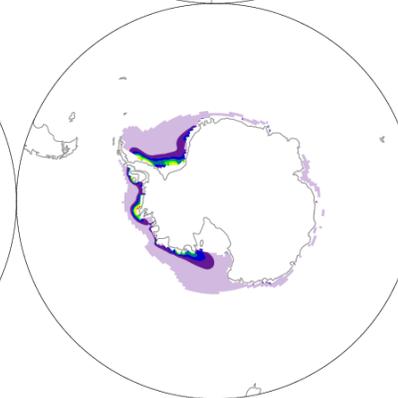
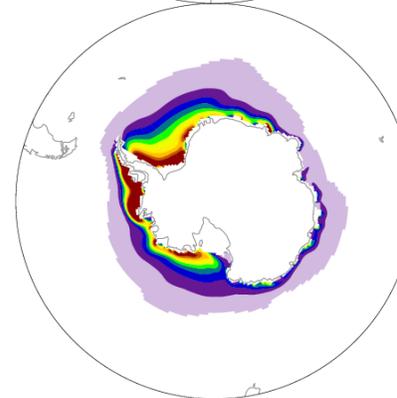
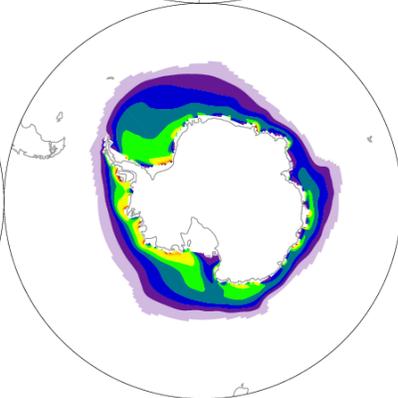
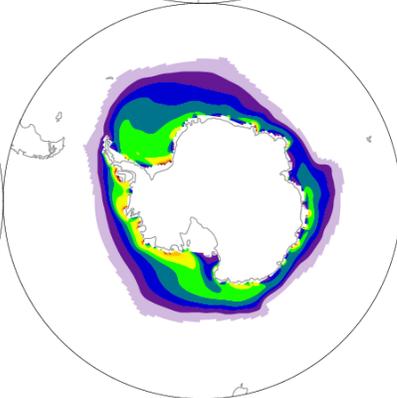
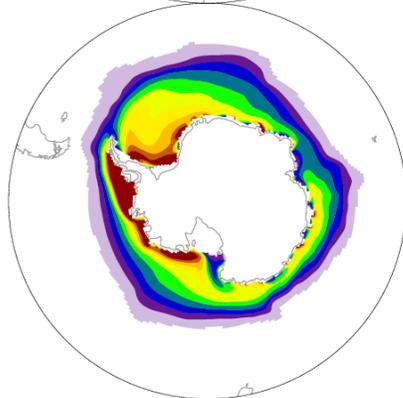
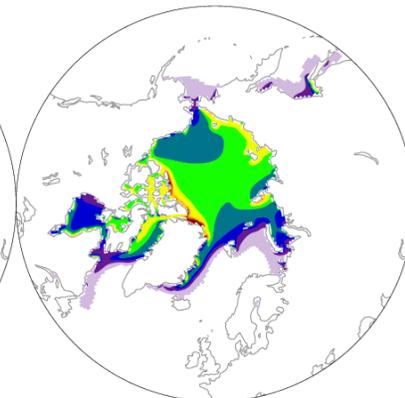
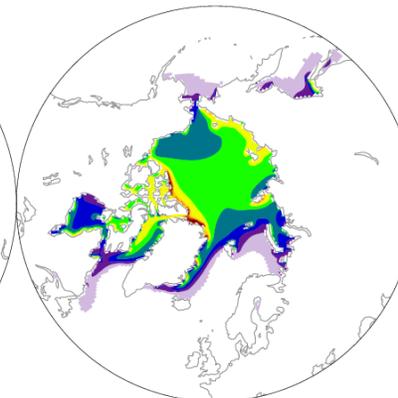
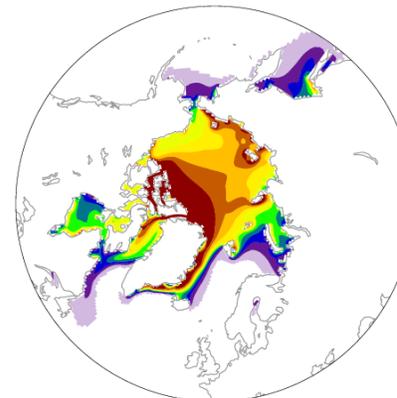
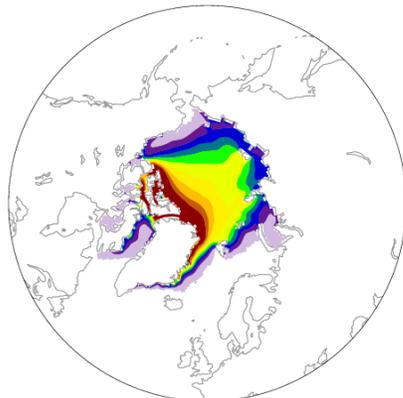
Albedo

Nudge

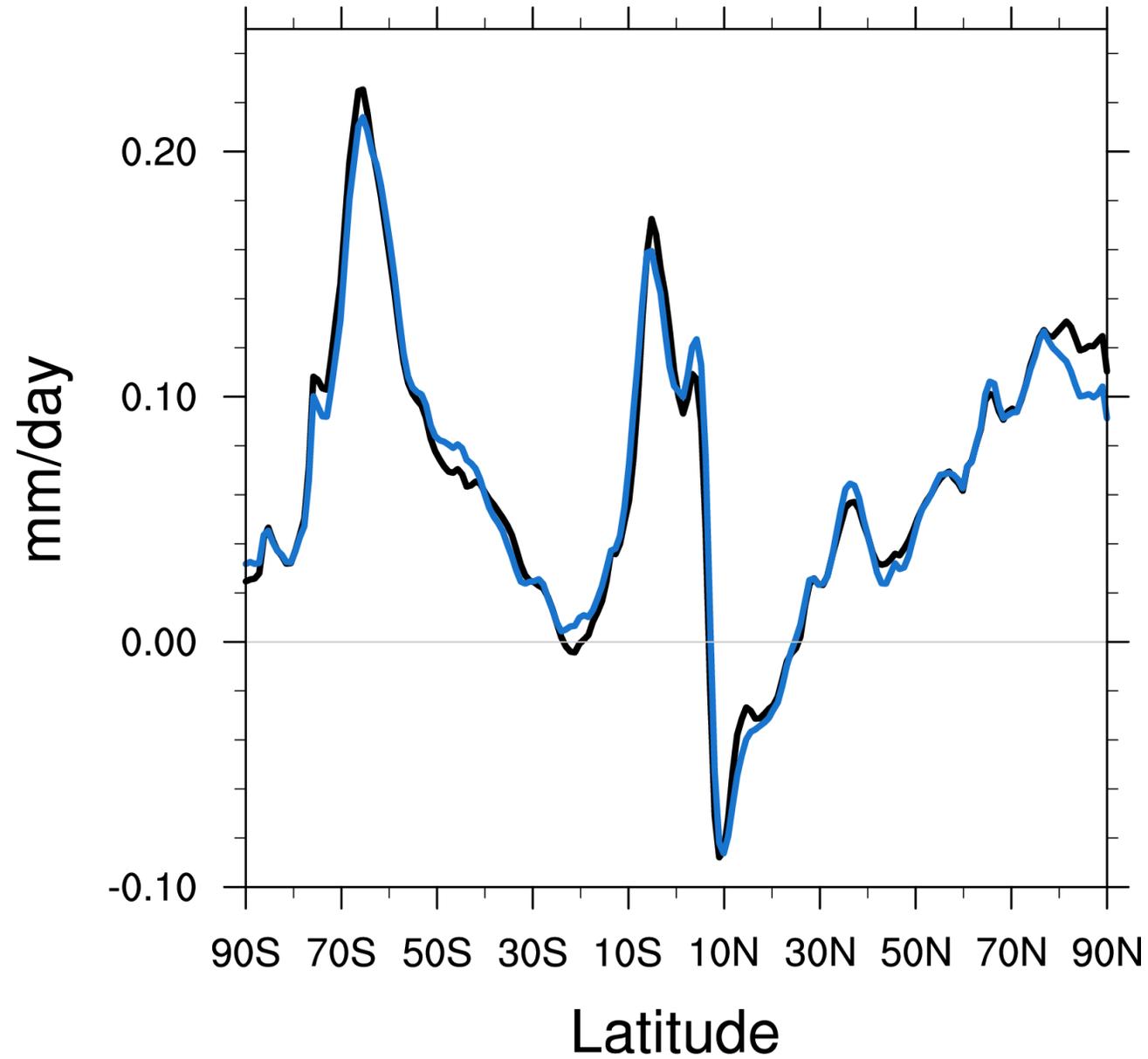
Control

Albedo

Nudge



Annual Zonal-mean Precipitation Response



Annual AMOC Time Series

