Increased Model Resolution Amplifies Arctic Precipitation and Atmospheric Circulation Response to Sea Ice Loss

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Adam Herrington[3], Isla R. Simpson[3], and Melissa Gervais[4]

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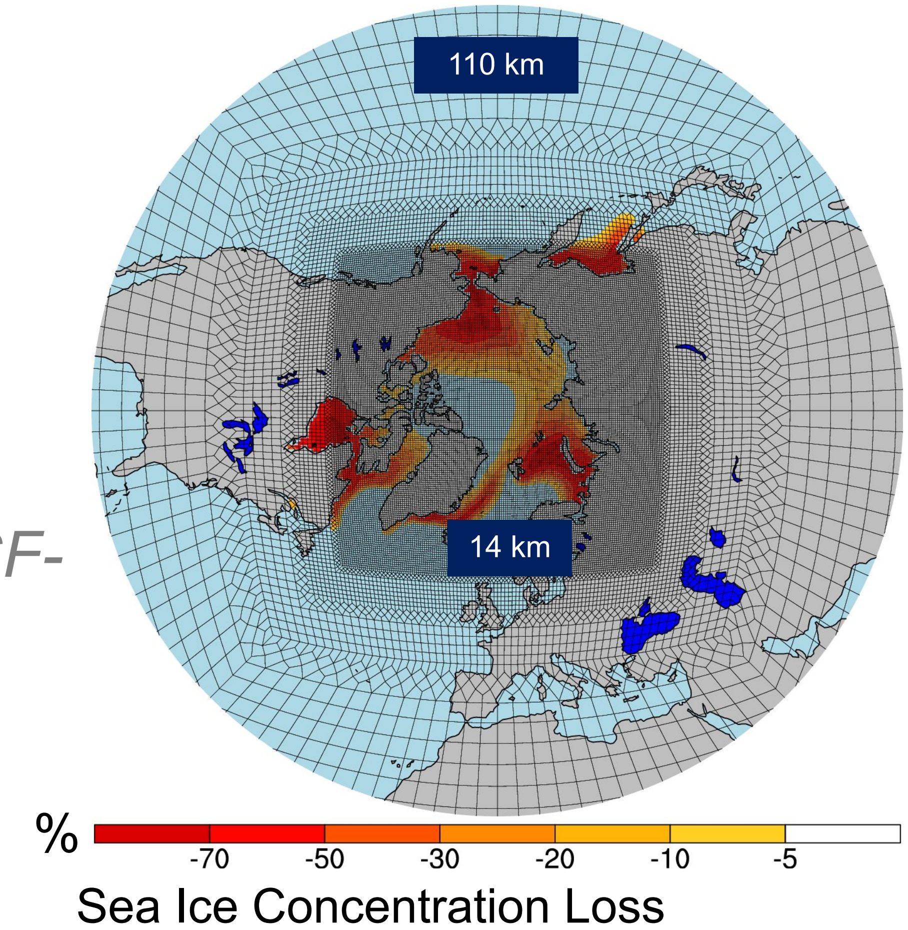
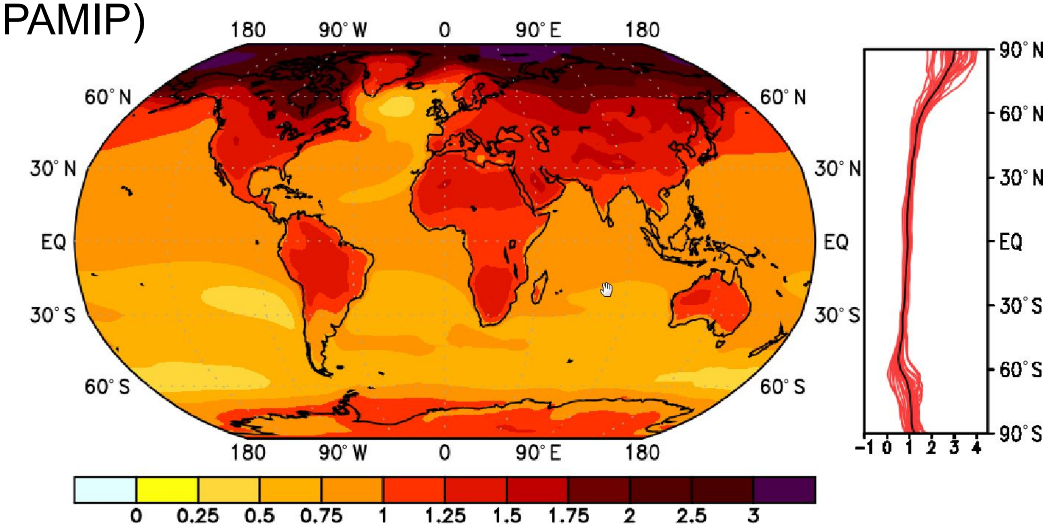


Motivation

- Sea ice loss has been identified as the key driver of Arctic amplification and local precipitation increase (Screen and Simmonds 2010; Deser et al. 2010; Bintanja and Selten, 2014).
- Impact of future Arctic sea ice loss on large-scale atmospheric circulation is robust but weak (Smith et al. 2021; Peings et al. 2021; Sun et al. 2022)
- Sensitivity of the Arctic sea ice loss effect to horizontal resolutions remains largely unexplored.

Polar amplification model Intercomparison Project (PAMIP)

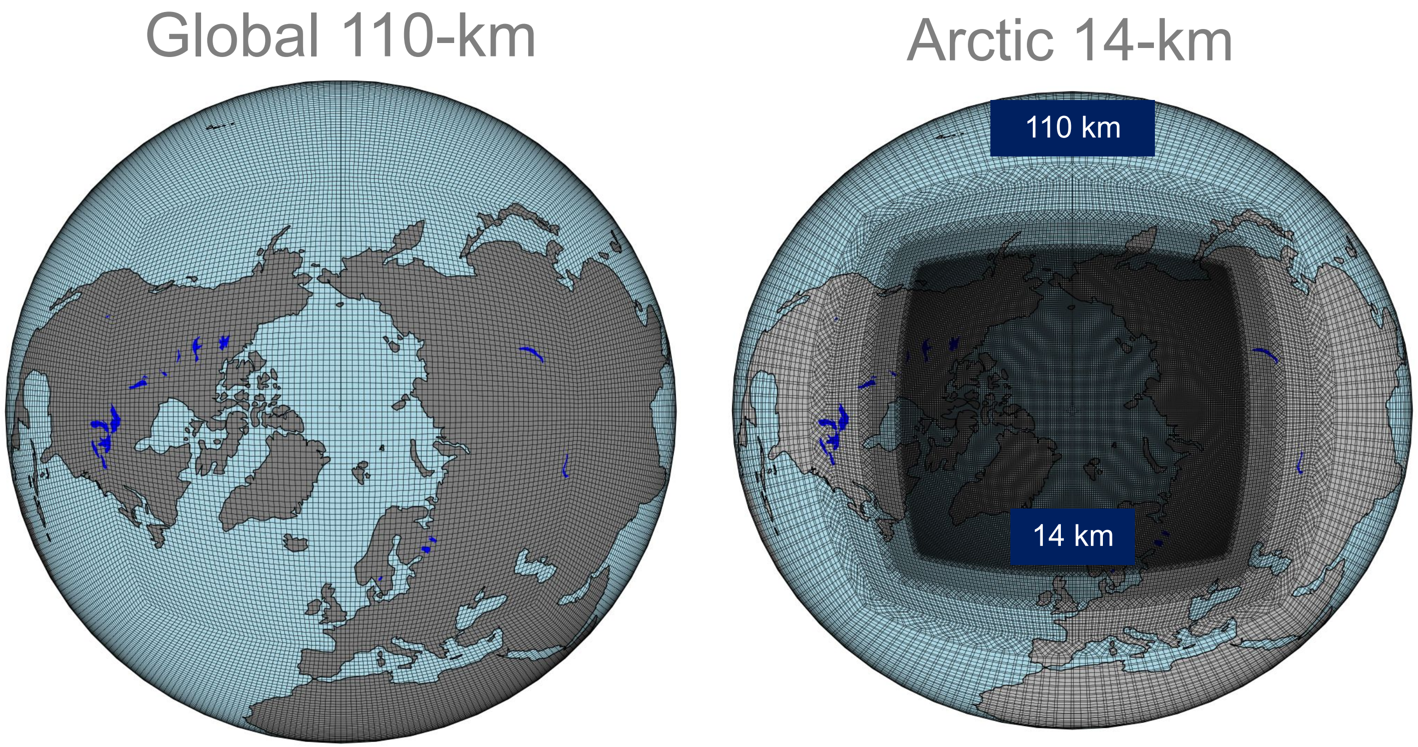


Smith et al. 2019

Objective

Investigate the sensitivity of the future Arctic sea-ice loss effect to horizontal resolutions and identify the underlying mechanisms

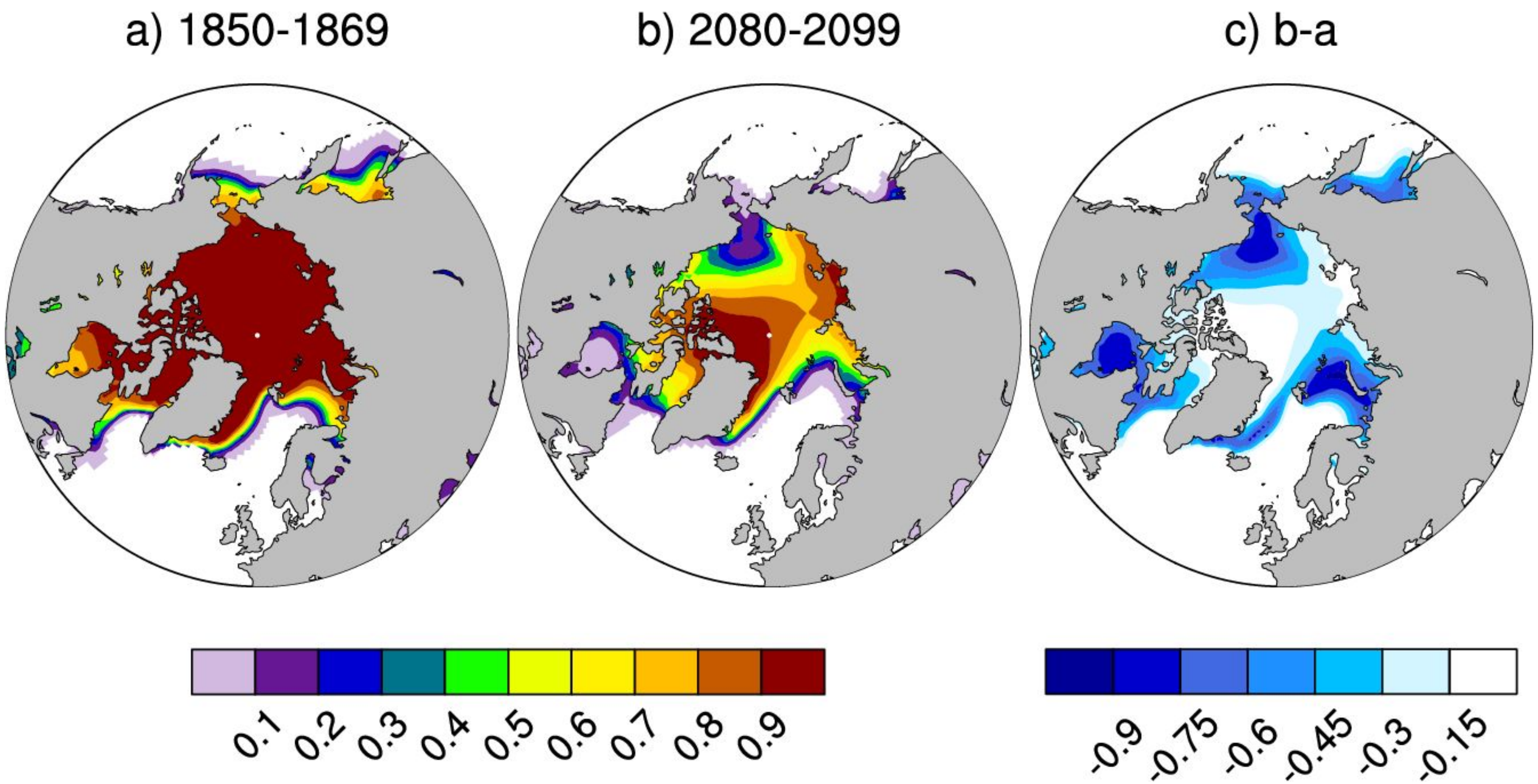
CESM2.2-CAM6 with SE dynamical core



Arctic Sea Ice Experimental Design

Exps akin to PAMIP #1.5 (piSST-piArcSIC) and 1.6 (piSST-futArcSIC):

- **Sea Ice Forcing**: Difference between 2080-2099 and 1850-1869 from CESM2-LE.



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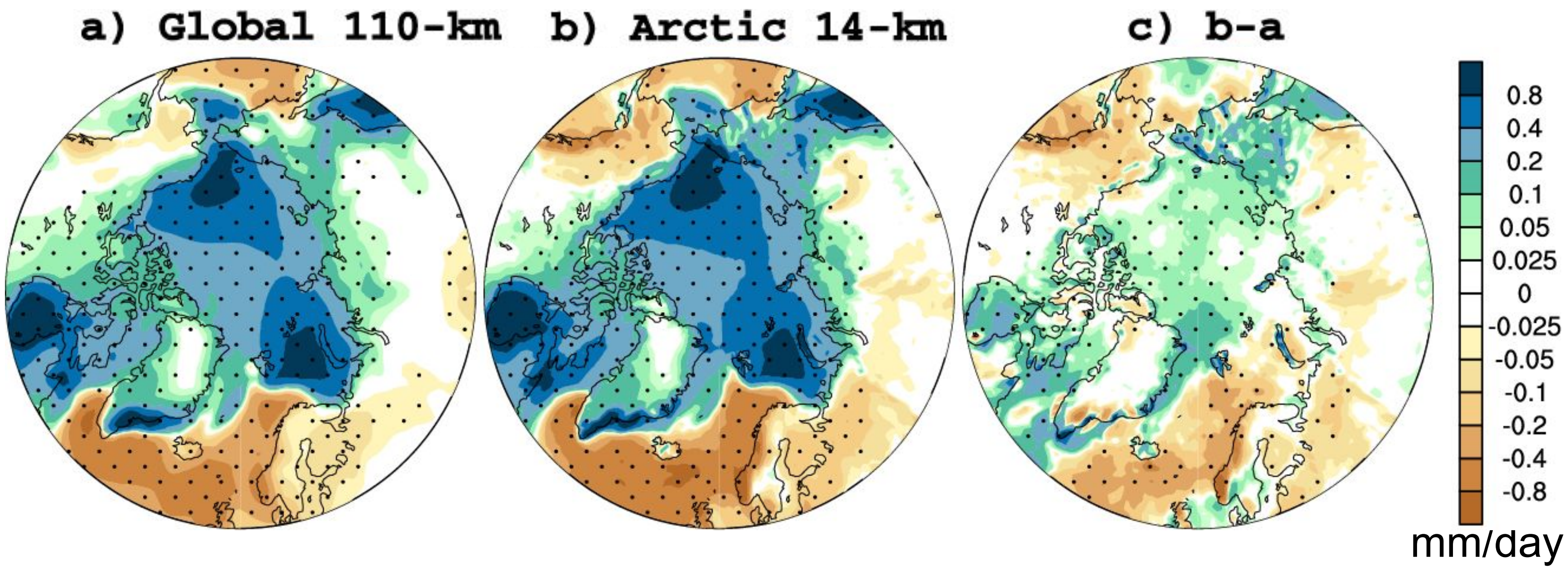
- **Sea Ice Forcing**: Difference between 2080-2099 and 1850-1869 from CESM2-LE.
- **Experiment Setup**:
  - Initialized in September with the same initial condition for all members within Global 110-km and within Arctic 14-km model, simulated through February.
  - Ensembles constructed using "pertlim" method. There are 100 members for Arctic 14-km, 600 members for Global 110-km model (2 initial conditions with 300 members each).
- **Data Analysis**:
  - Focus on Dec-Feb; Sep-Nov discarded.
  - Both model versions interpolated to the same grid (either NE30 native grid or 192x288 lat-lon grid) for comparison
  - Focus on Arctic precipitation and large-scale circulation atmospheric response

1. Arctic Precipitation Climatology and Response

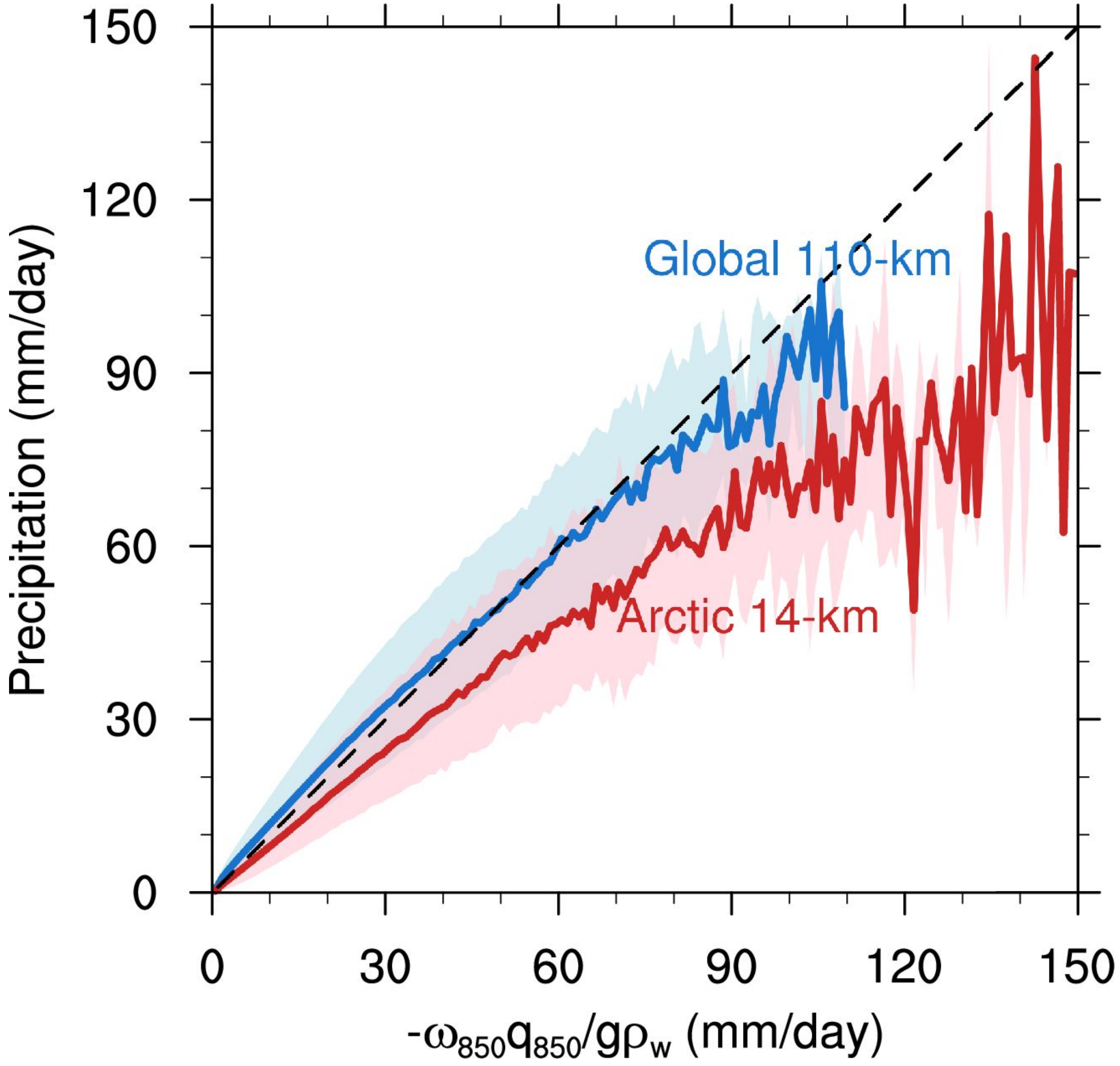
	Mean	Response
Global 110-km	0.945	0.238
Arctic 14-km	0.969	0.259



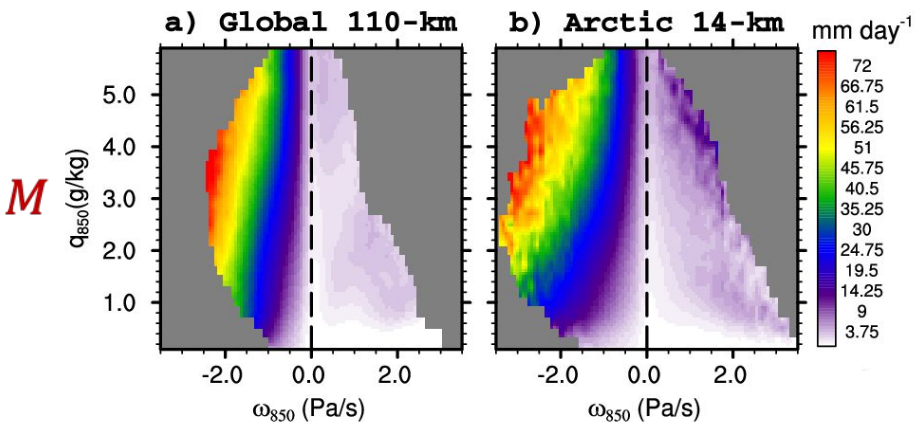
Arctic Precipitation Versus 850-hPa Upward Moisture Flux

$$P_{tot} \approx -\frac{1}{g\rho_w}\omega q|_{cb}$$

Rauscher et al. (2015);
O'Brian et al. (2016);
Herrington and Reed (2020)

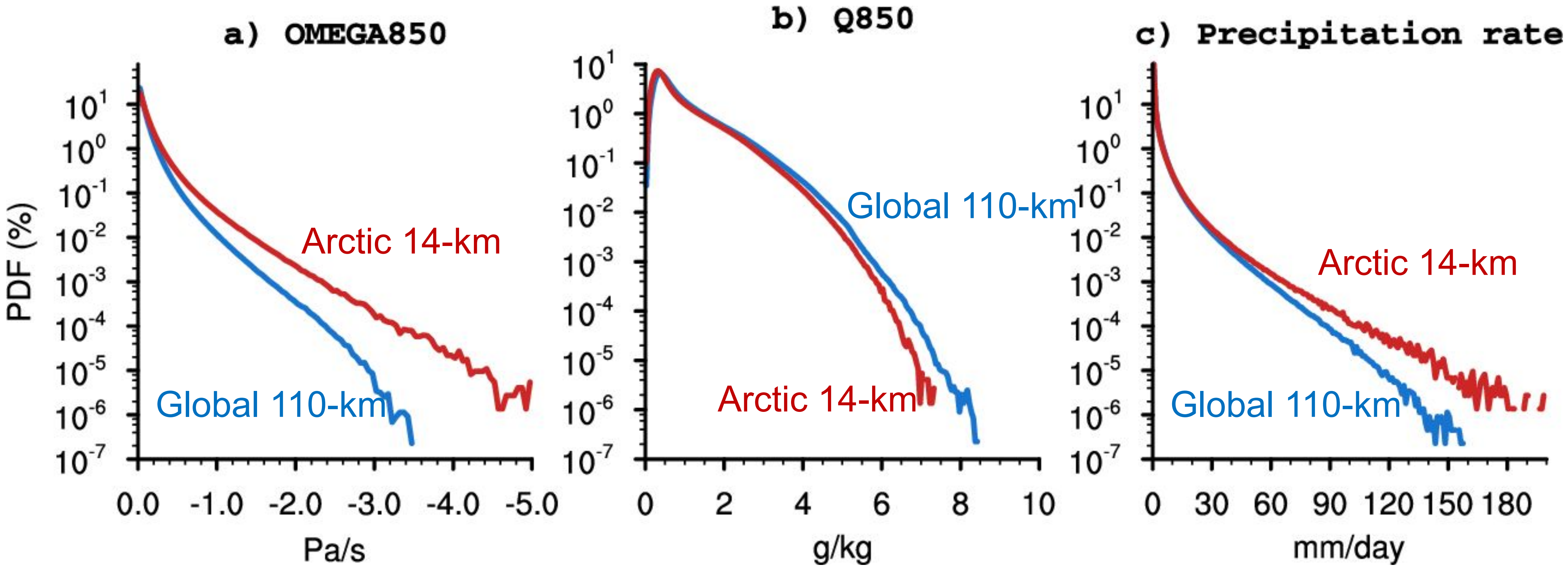


Arctic Precipitation Decomposition



$\overline{P} = \sum\sum \boldsymbol{f}(\omega_i, q_j)\boldsymbol{M}(\omega_i, q_j)$ where M is the time-mean magnitude and f is the time-mean spatial frequency of a particular combination (ω_i, q_j), both at 850-hPa (Terai et al. 2018; *Herrington and Reed 2020*)

Probability Density Function



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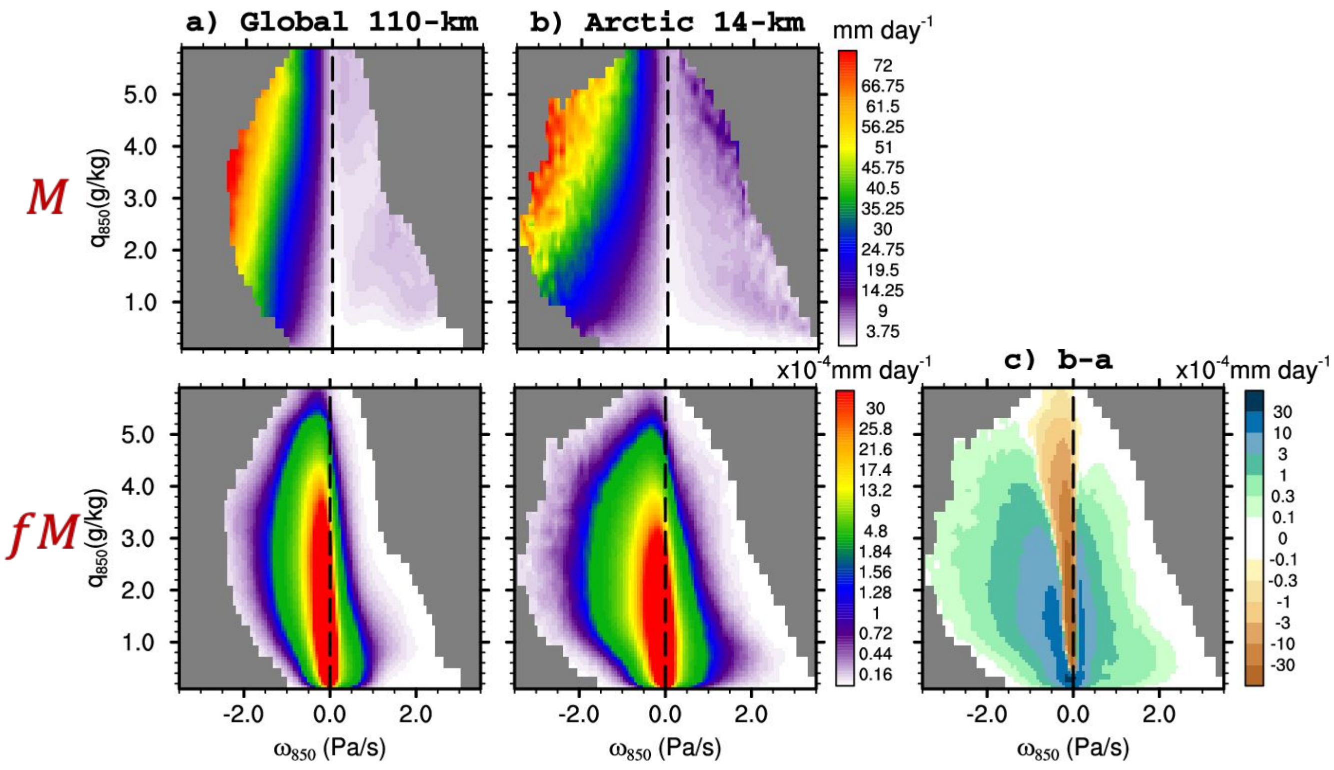

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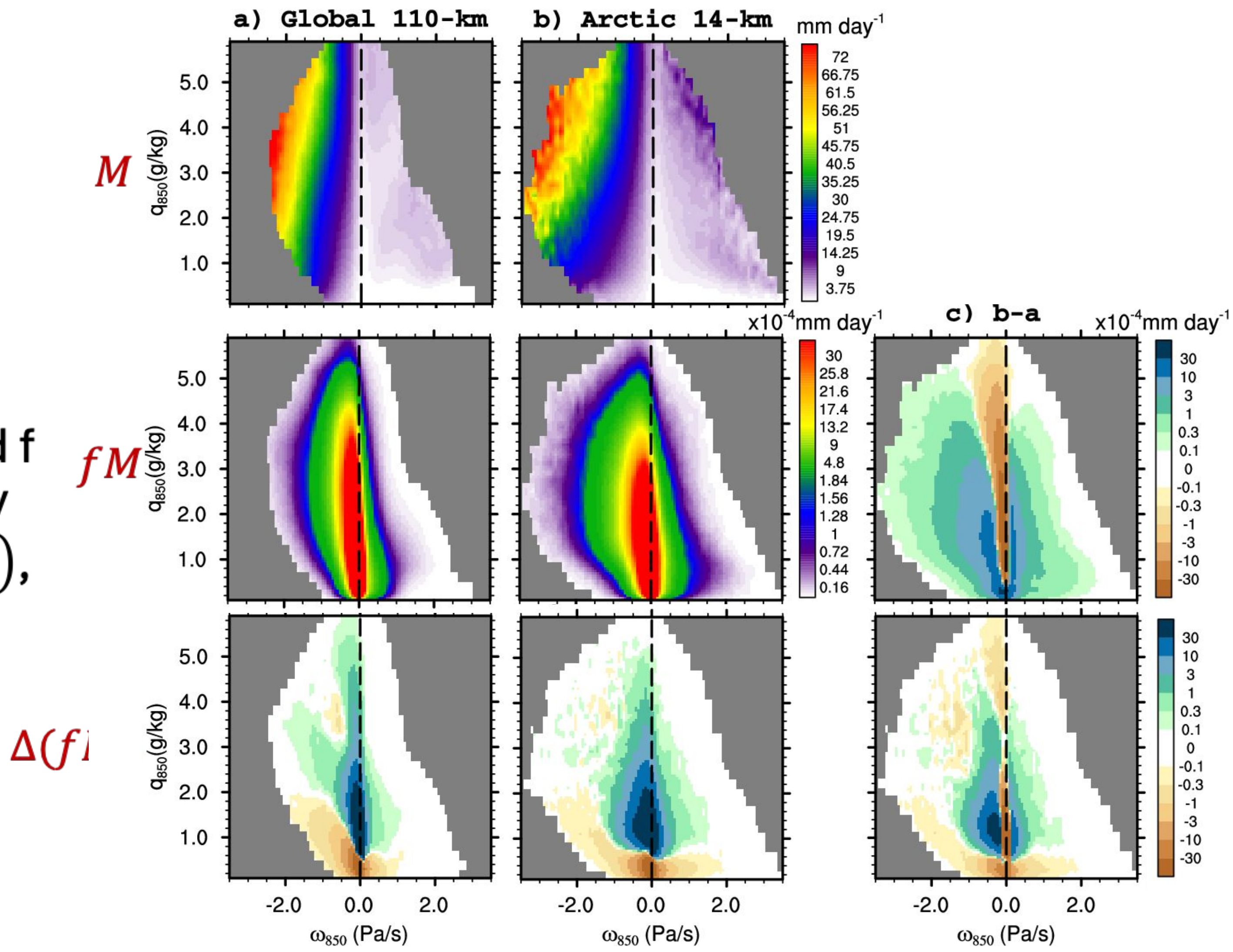
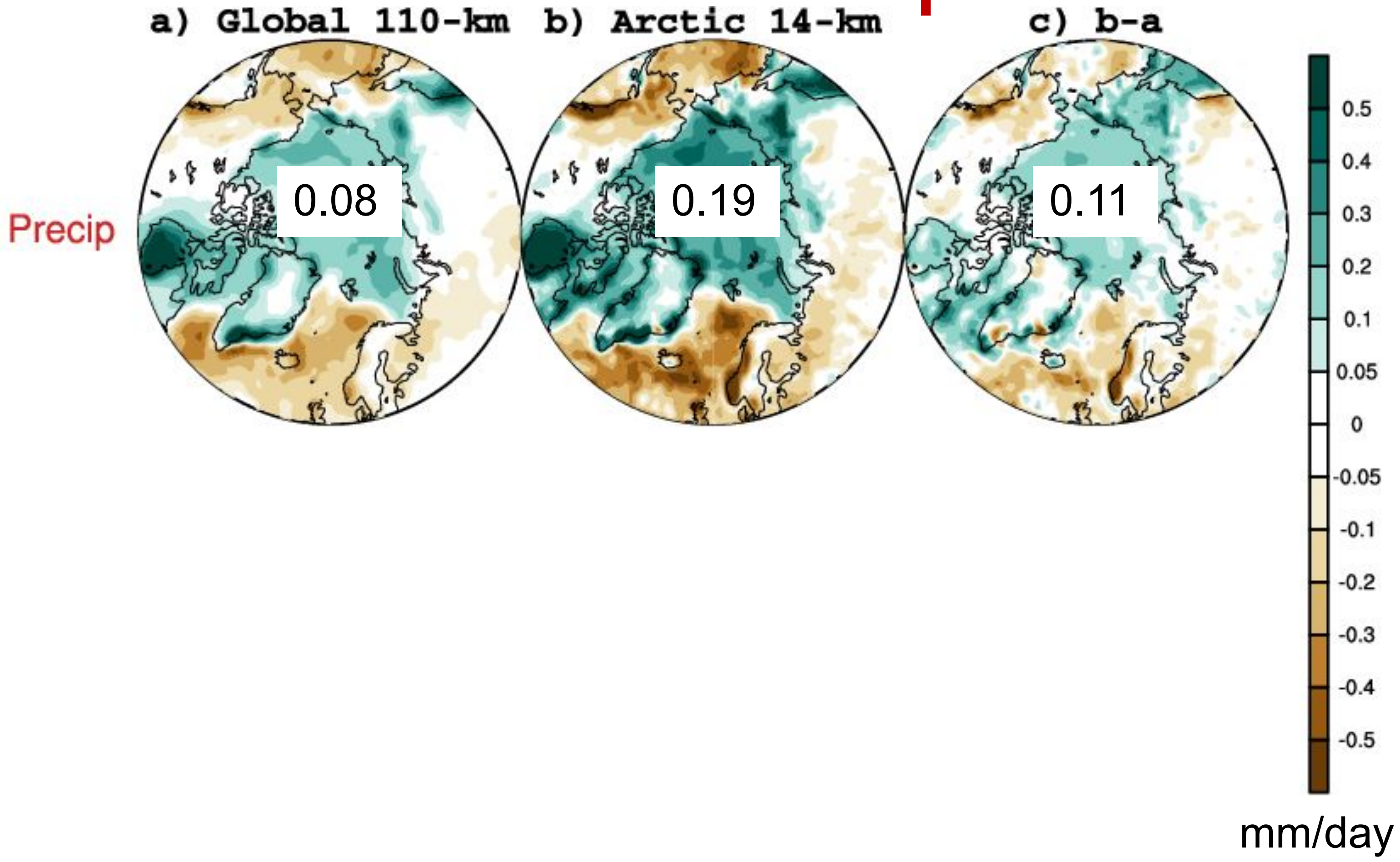


2. Arctic Daily Precipitation Variability Response



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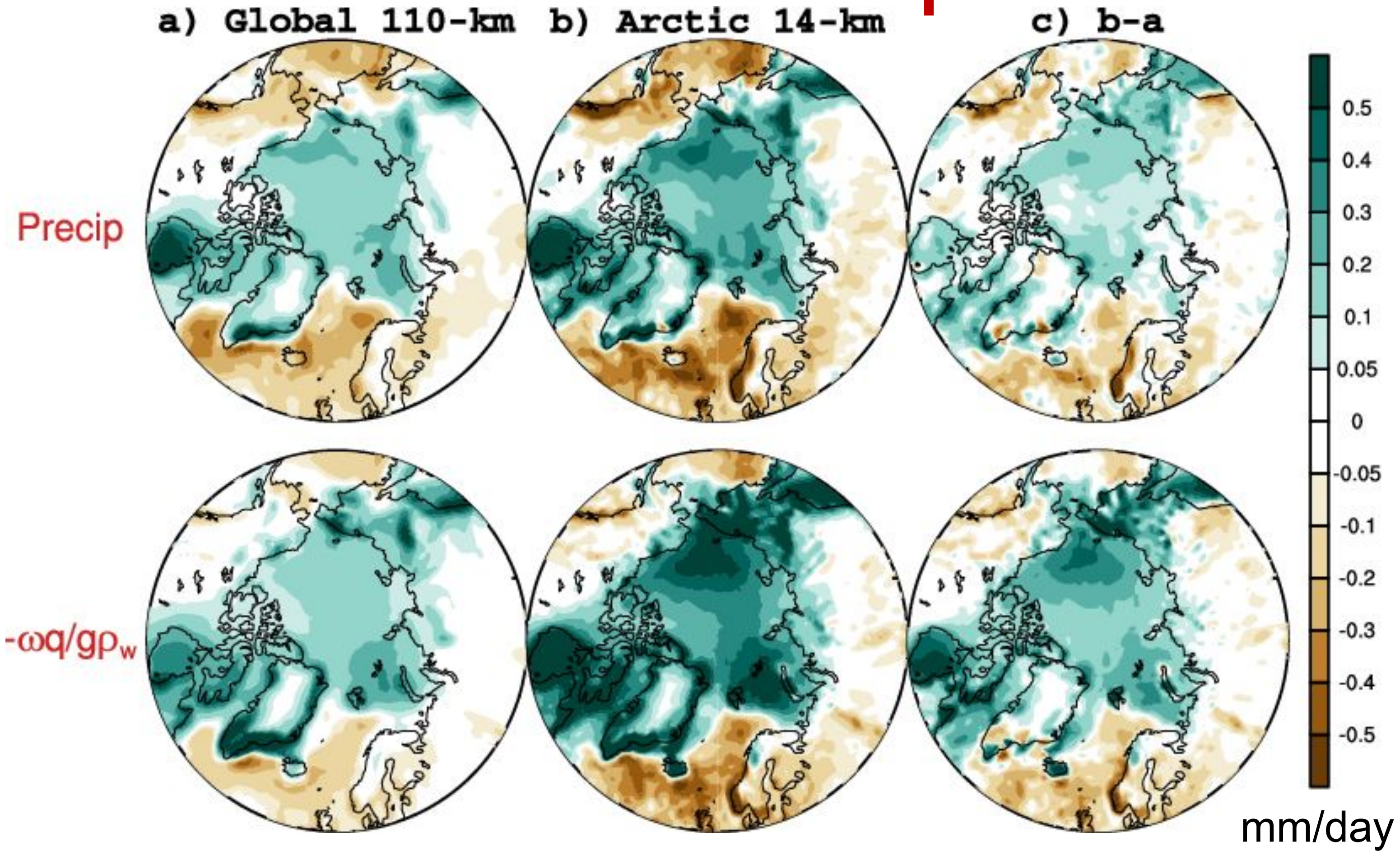

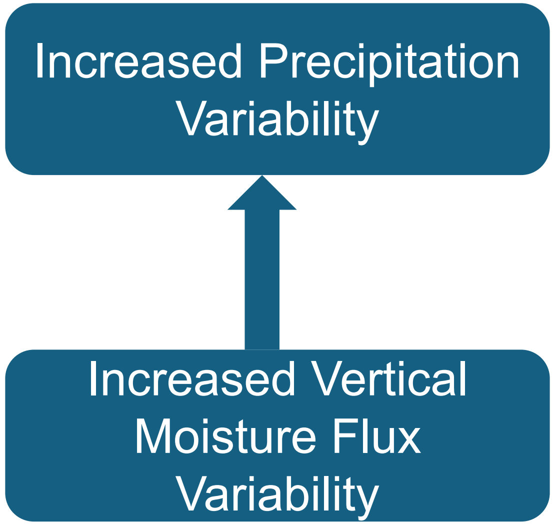

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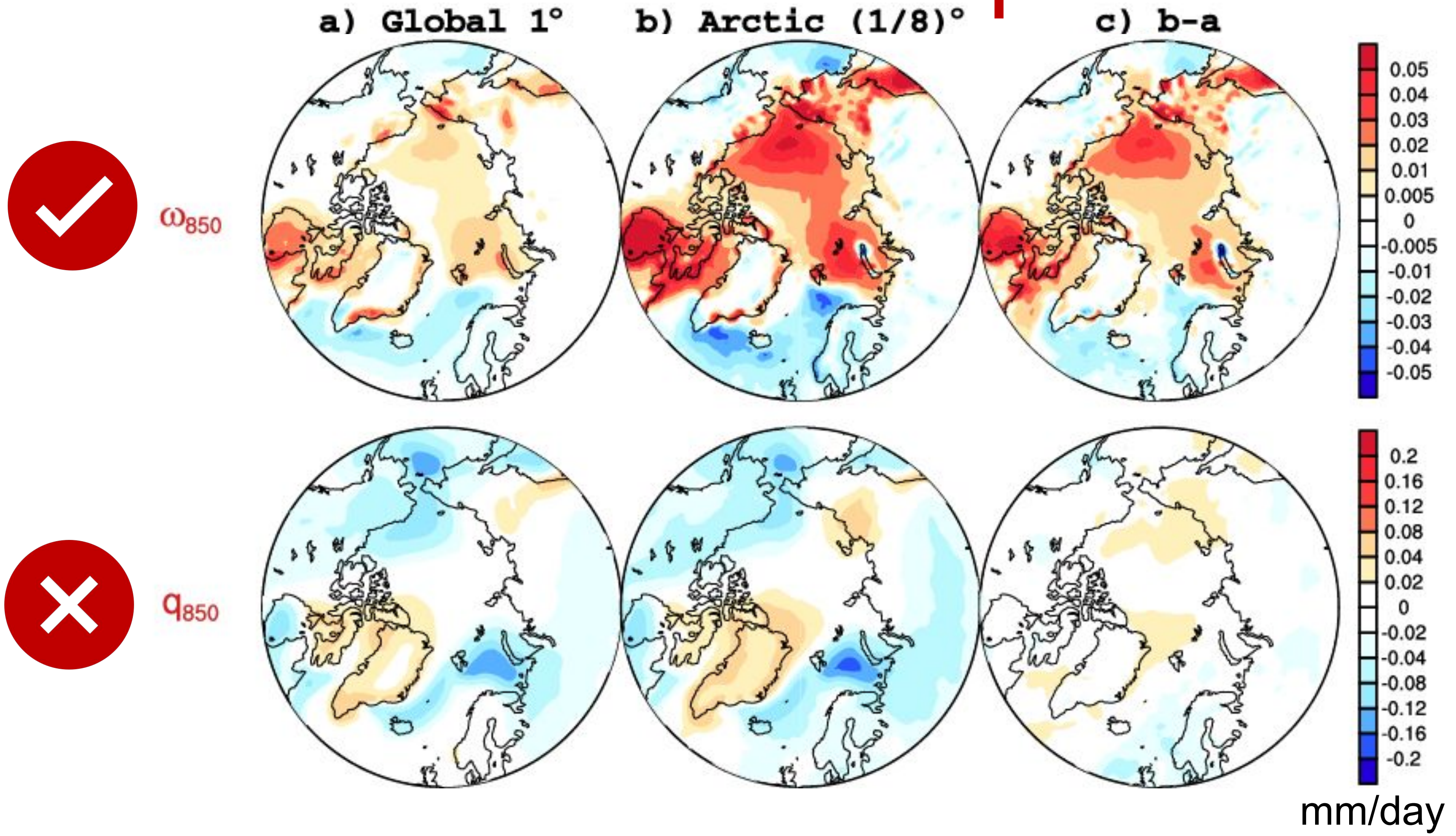
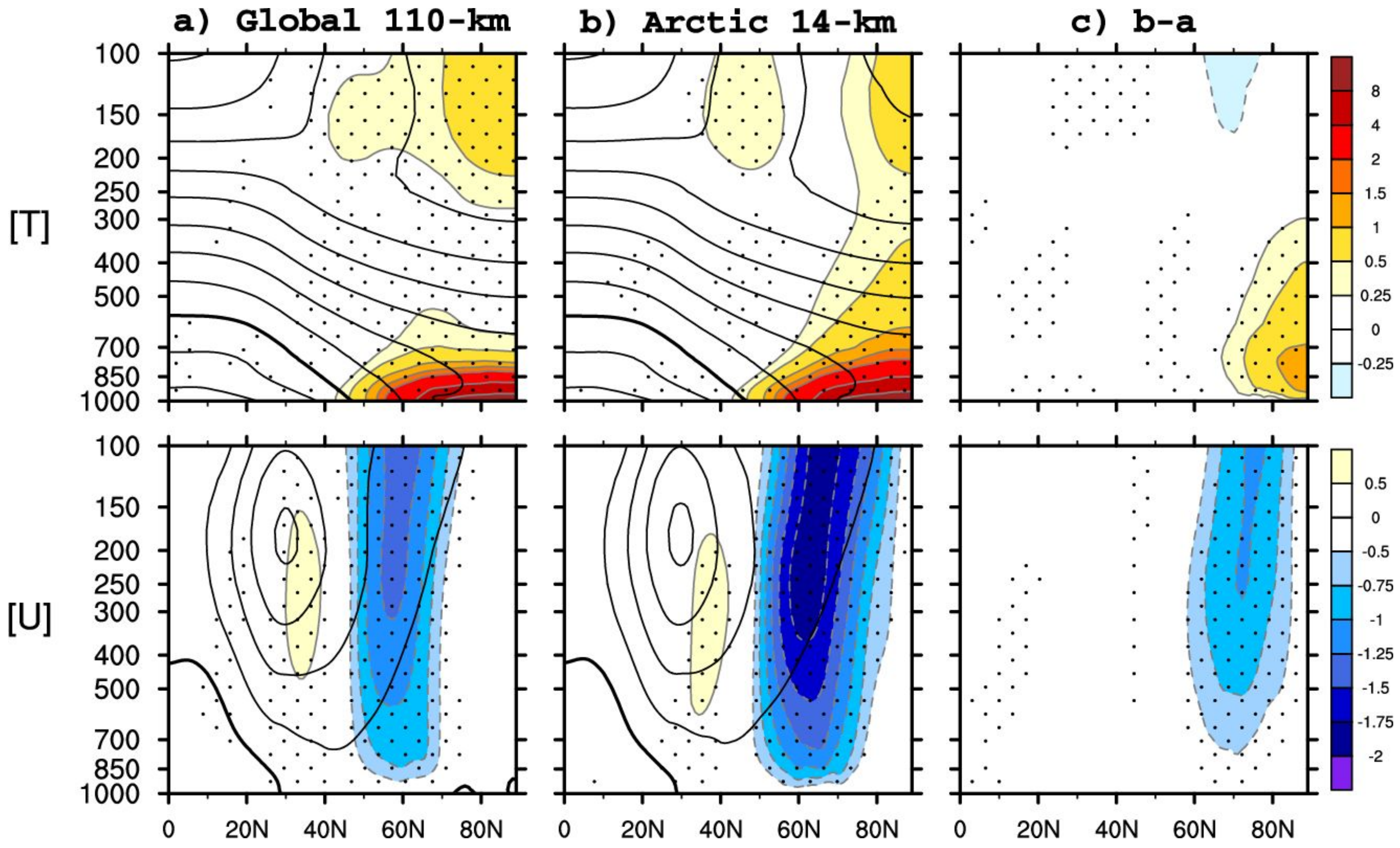


Increased Precipitation Variability

Increased Vertical Moisture Flux Variability

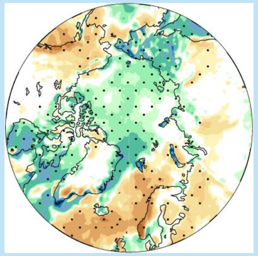
Increased Vertical Motion Variability

3. Atmospheric Circulation Response



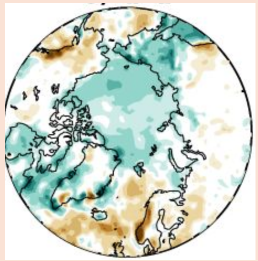
Transient eddy vertical heat transport likely play a causal role in the enhanced warming in the high-resolution model.

Increased Model Resolution Amplifies Arctic Precipitation and Atmospheric Circulation Response to Sea Ice Loss



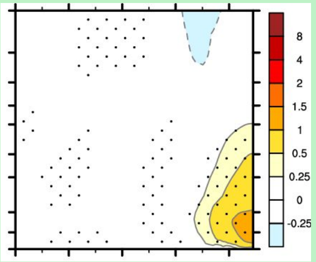
1. More pronounced Arctic precip increase

Stronger upward motion in the Arctic 14-km model leads to amplification of the total precipitation increase.



2. Enhanced daily precip variability

The increase in daily precipitation variability is closely tied to variability in vertical moisture flux, which in turn reflect variability in vertical motion.



3. Greater polar-cap warming & circulation response

Enhanced polar-cap warming in the Arctic 14-km model is linked to stronger transient-eddy vertical heat transport.

Sun, L., R. Wills, C. Deser, A. Herrington, I. Simpson, M. Gervais, 2025: Increased Model Resolution Amplifies Arctic Precipitation and Atmospheric Circulation Response to Sea-Ice Loss, ***J. Climate***, under review.

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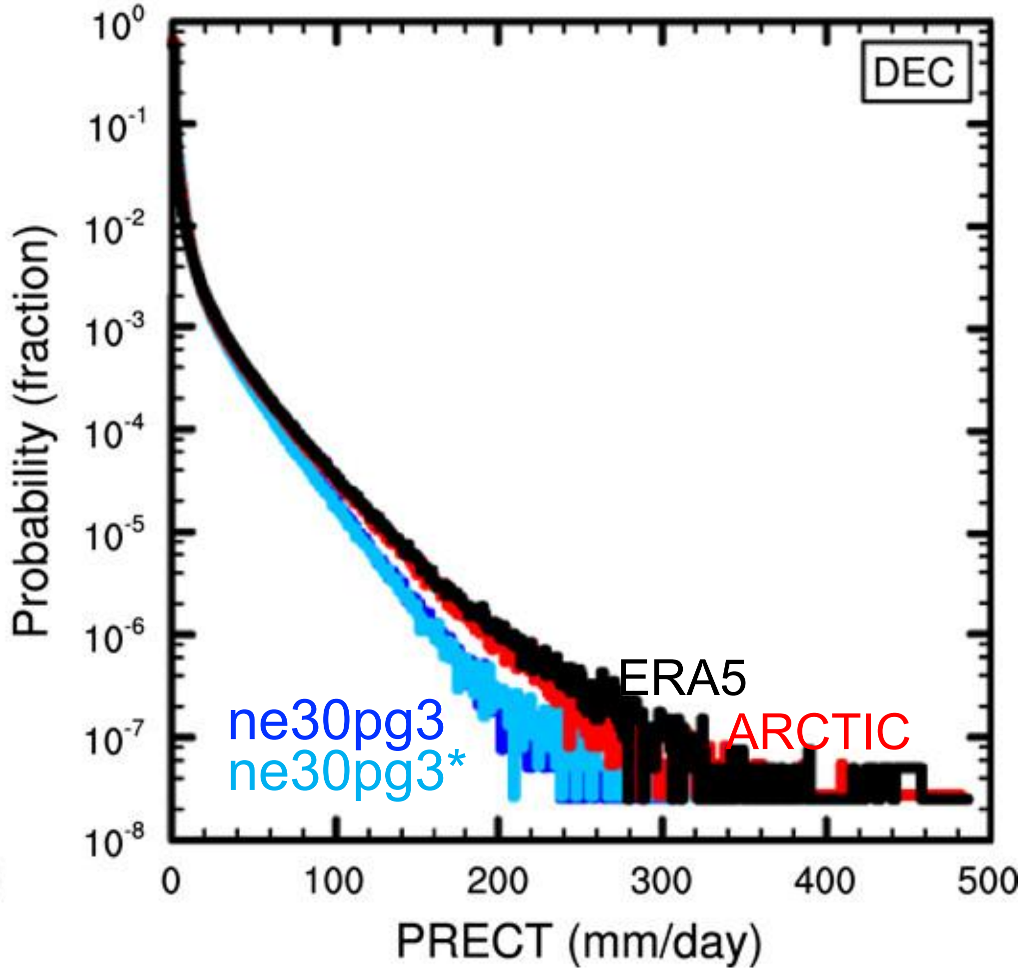
Supplementary Materials

Why Do We Need High-resolution Models?

High-resolution models have the potential to reduce mean biases, improve representation of climate variability, and enhance prediction and future projection (e.g., Yeager et al. 2023; Patrizio et al. 2023; Larson et al. 2024; Xu et al. 2024; Morris et al. 2024).

PDFs of the total precipitation rate



Herrington et al. 2022

Arctic Precipitation Decomposition

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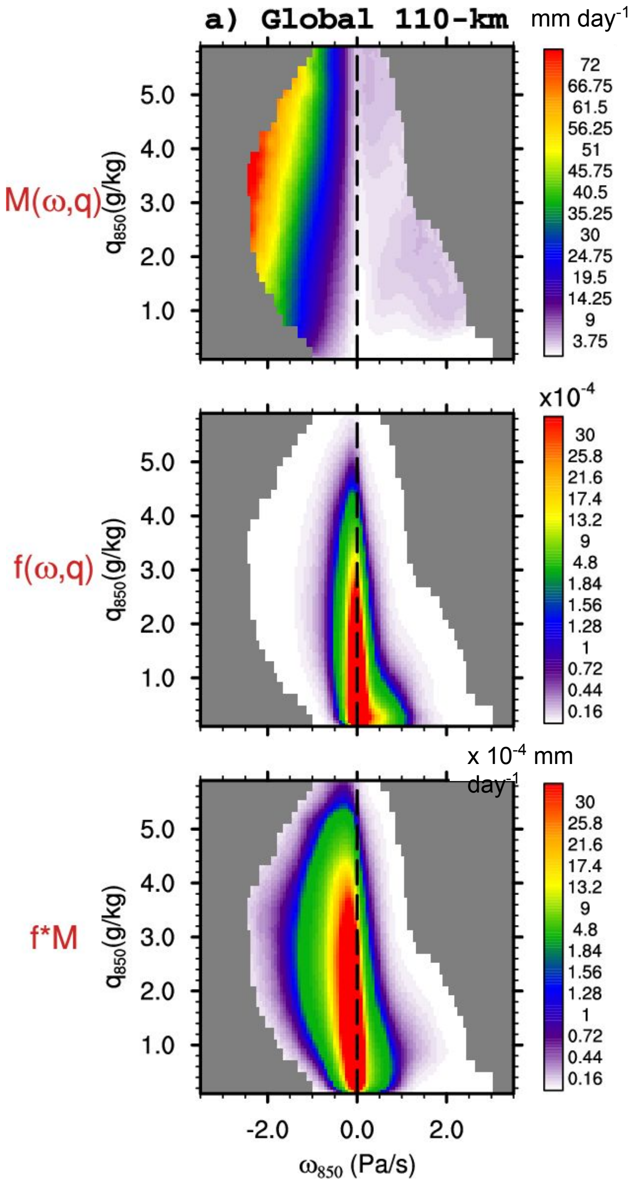

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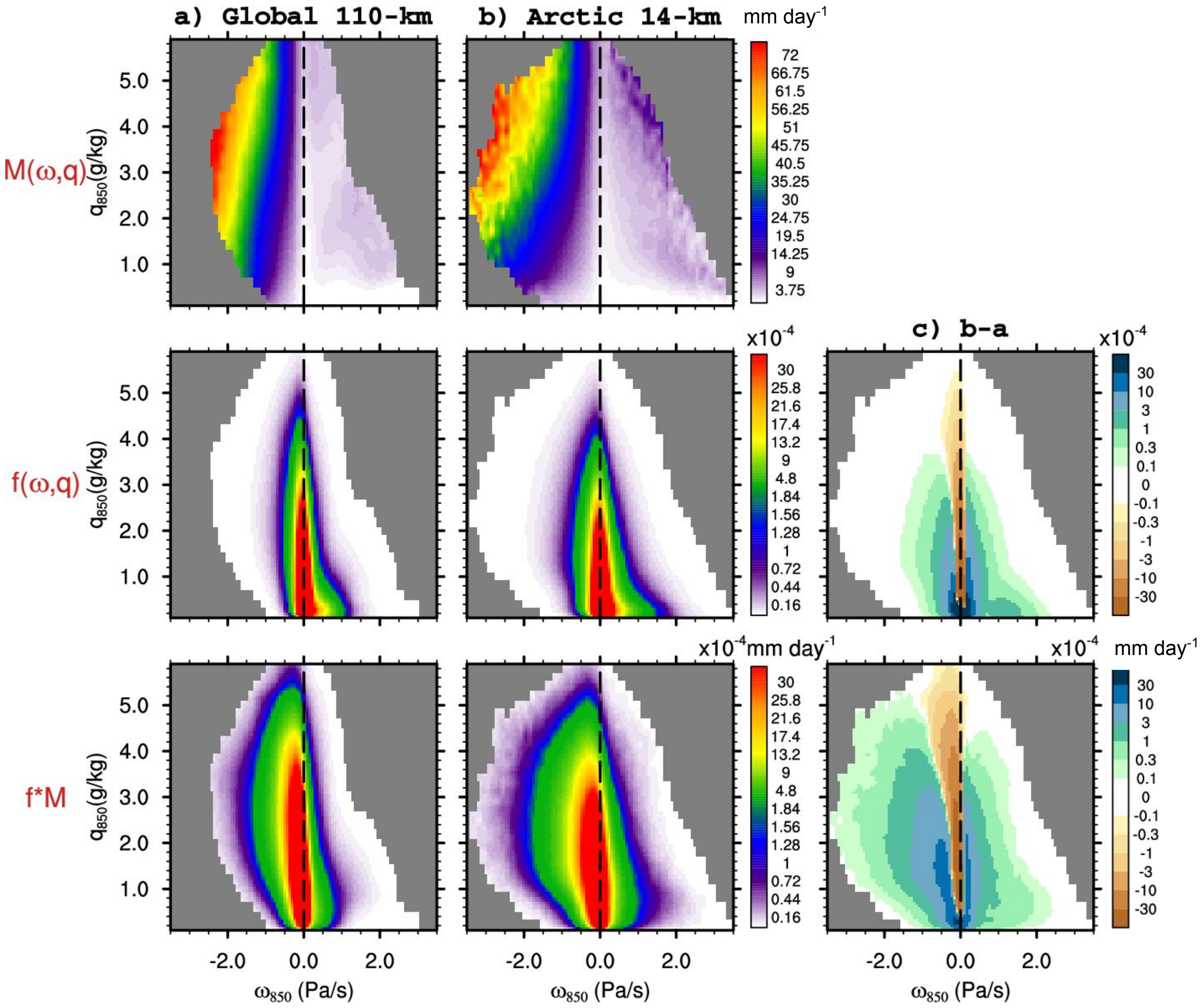
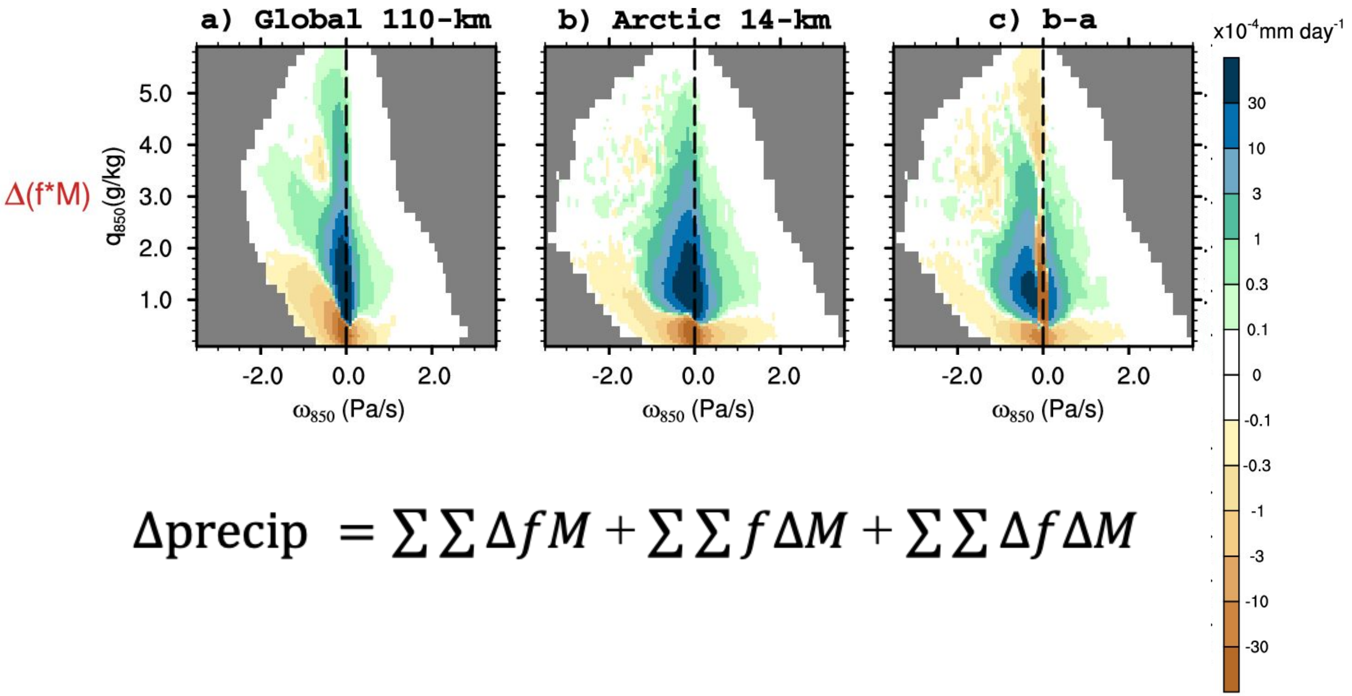
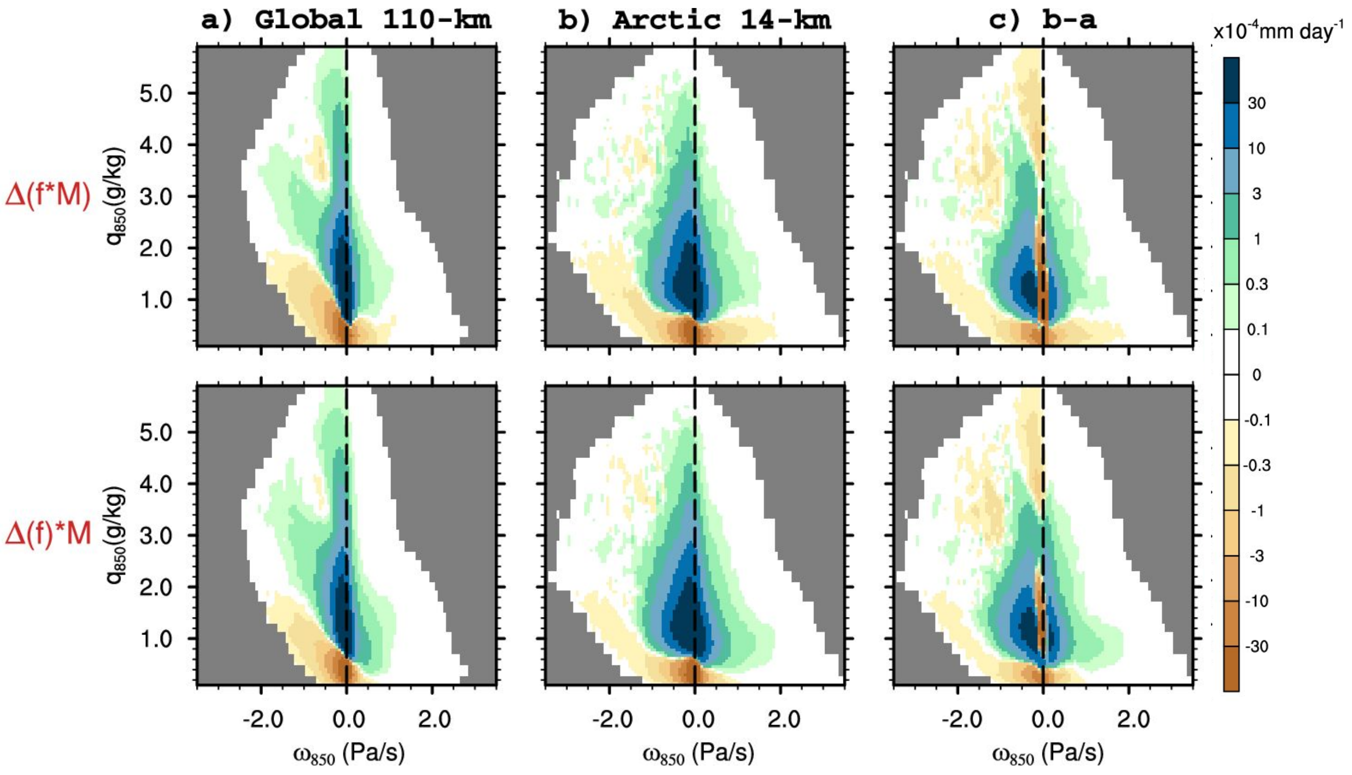


Arctic Mean Precipitation Response

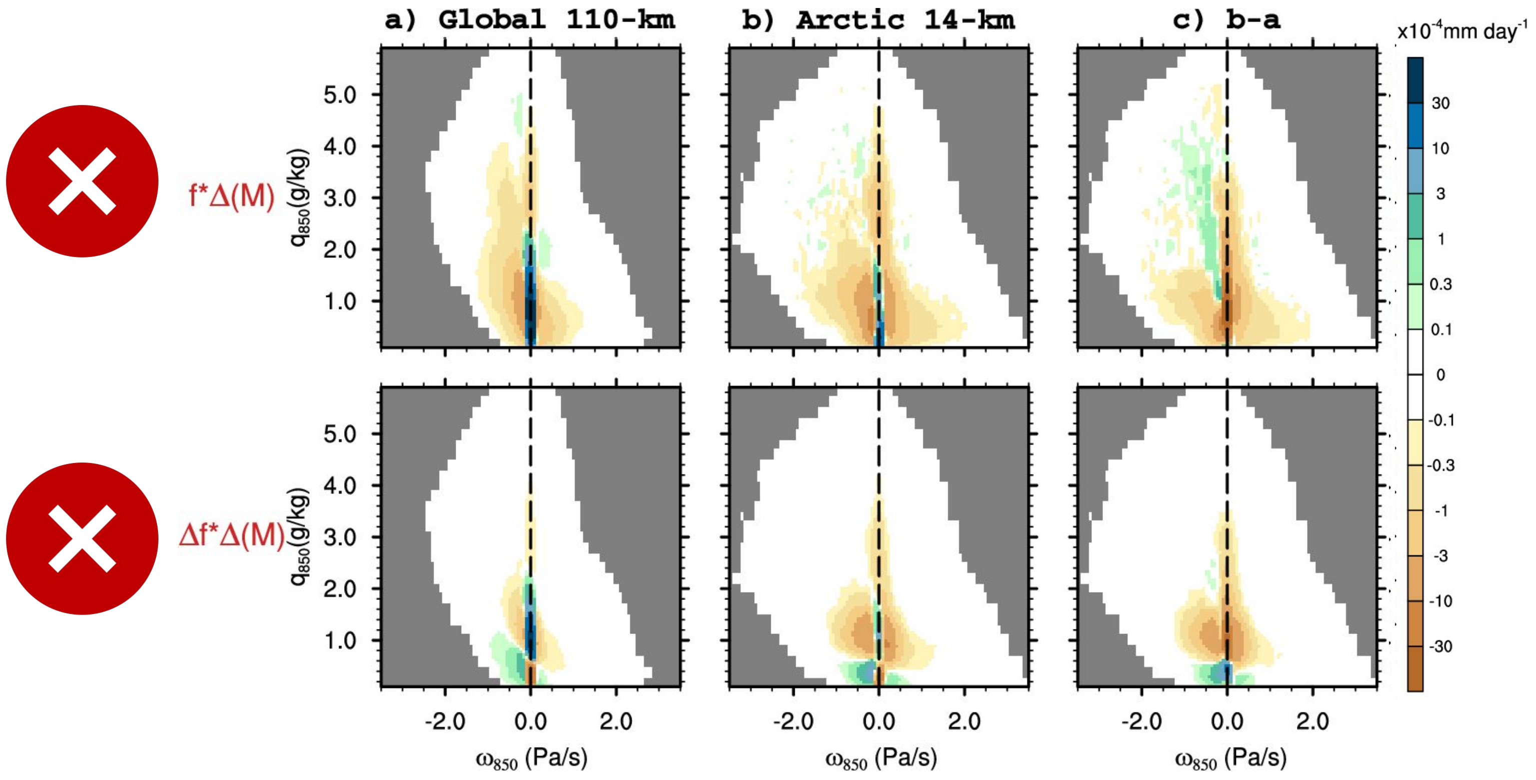


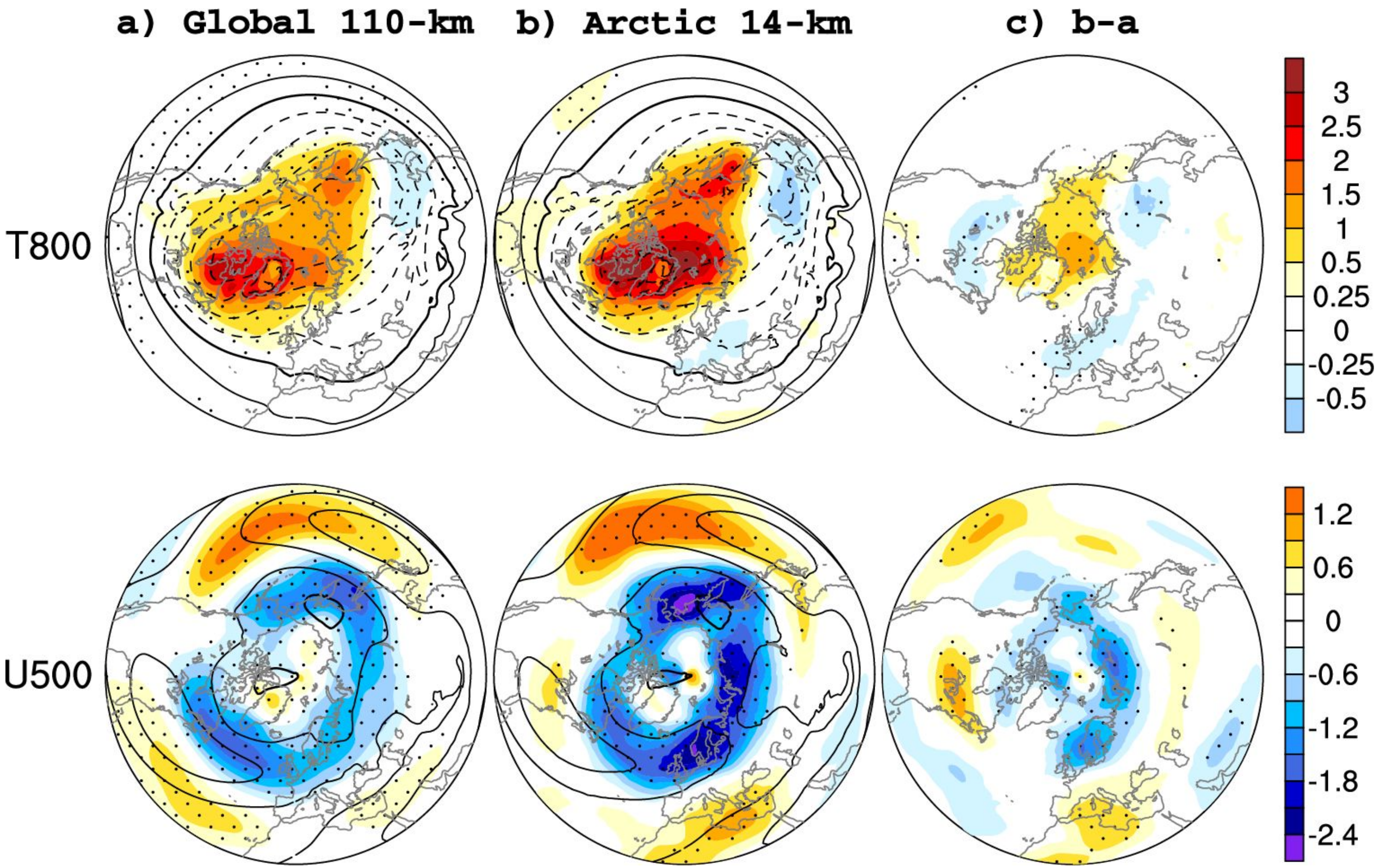
$$\Delta\text{precip} = \sum\sum \Delta f M + \sum\sum f \Delta M + \sum\sum \Delta f \Delta M$$

Arctic Mean Precipitation Response

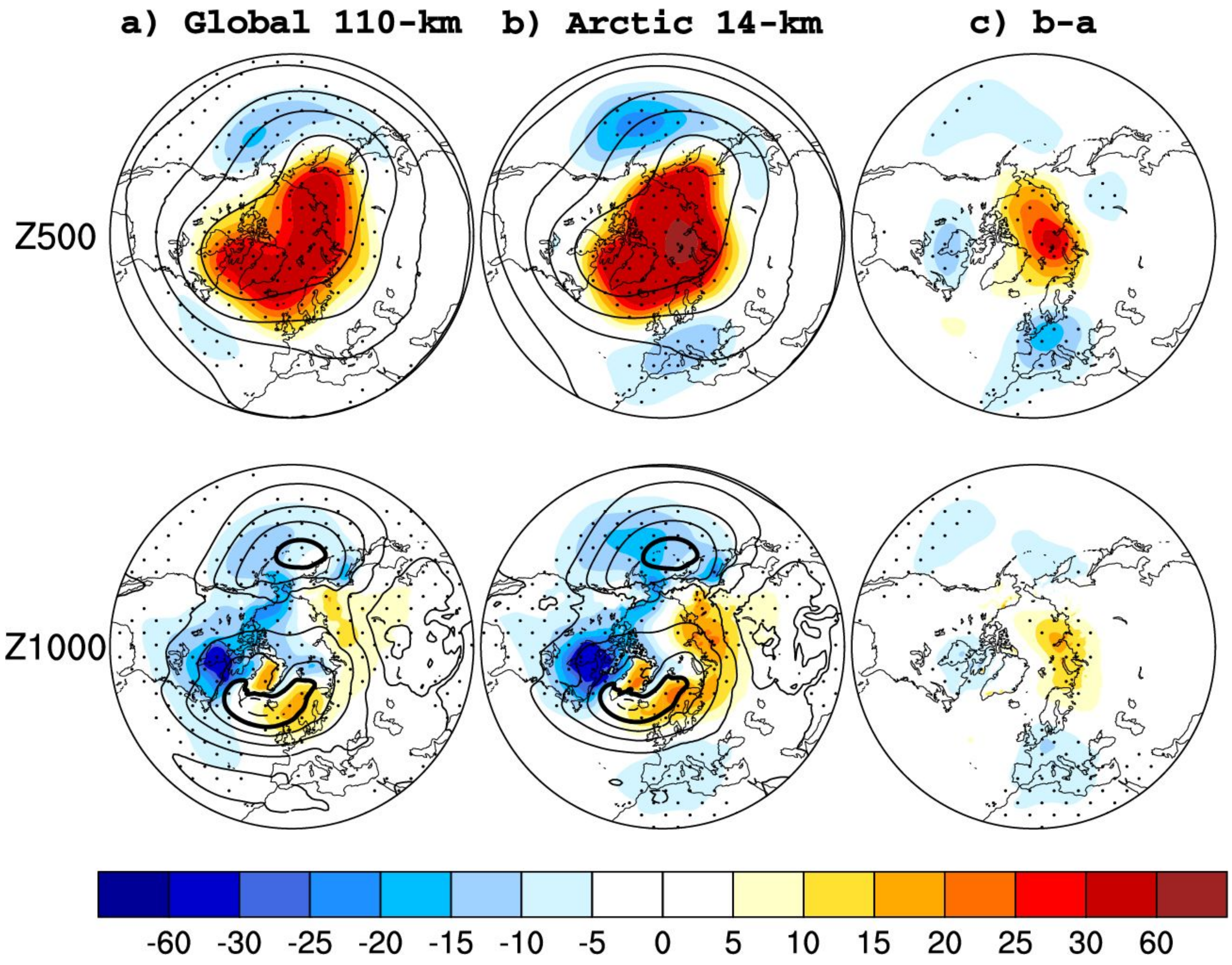


Arctic Mean Precipitation Response



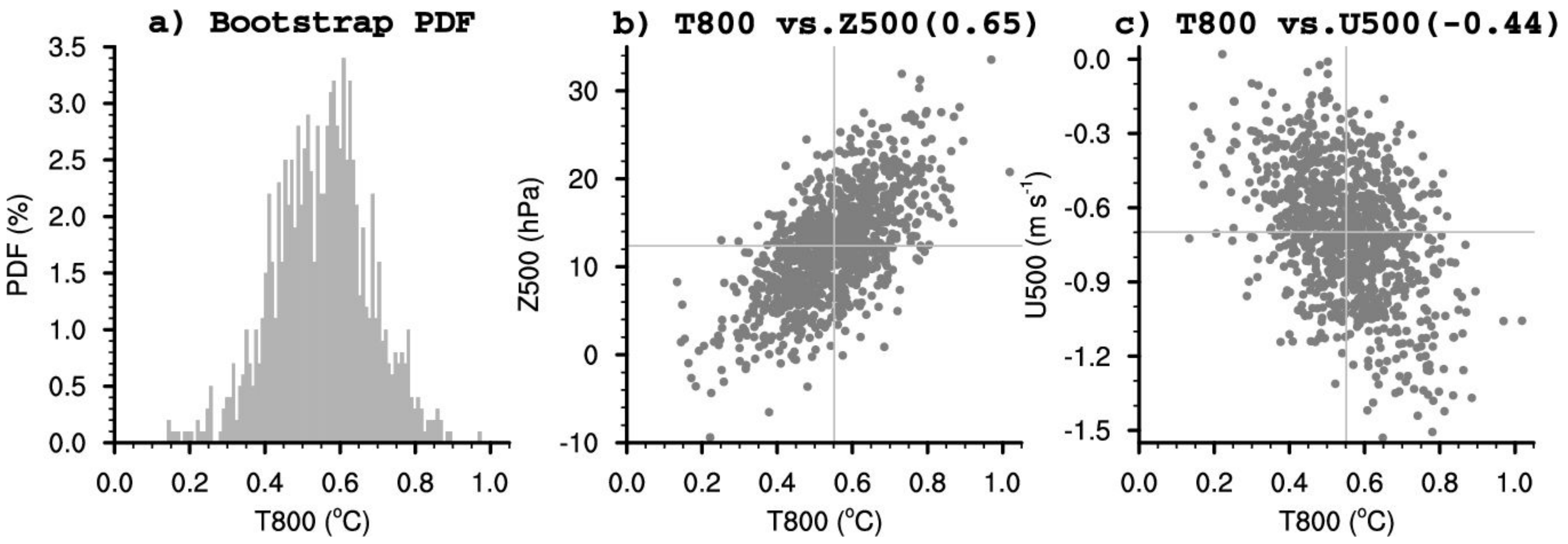


a) Global 110-km
b) Arctic 14-km
c) b-a
T800
U500
3
2.5
2
1.5
1
0.5
0.25
0
-0.25
-0.5
1.2
0.6
0
-0.6
-1.2
-1.8
-2.4



a) Global 110-km
b) Arctic 14-km
c) b-a
Z500
Z1000
-60 -30 -25 -20 -15 -10 -5 0 5 10 15 20 25 30 60

Bootstrapping for polar-cap T800



Thermodynamic Budget Analysis

Latent heating

Radiative & turbulence heating

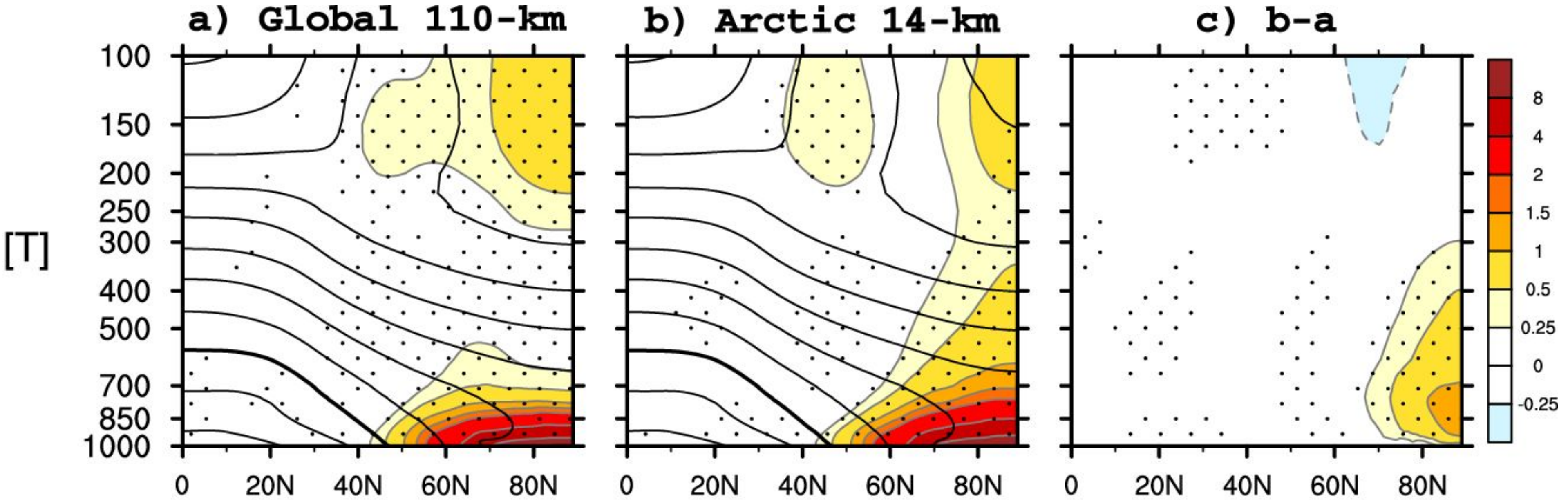
Transient-eddy v

Transient-eddy omega

Zonal advection

Meridional advection

Time-mean upward motion



Thermodynamic Budget Analysis

Latent heating	Radiative & turbulence heating	Transient-eddy v	Transient-eddy omega	Zonal advection	Meridional advection	Time-mean upward motion

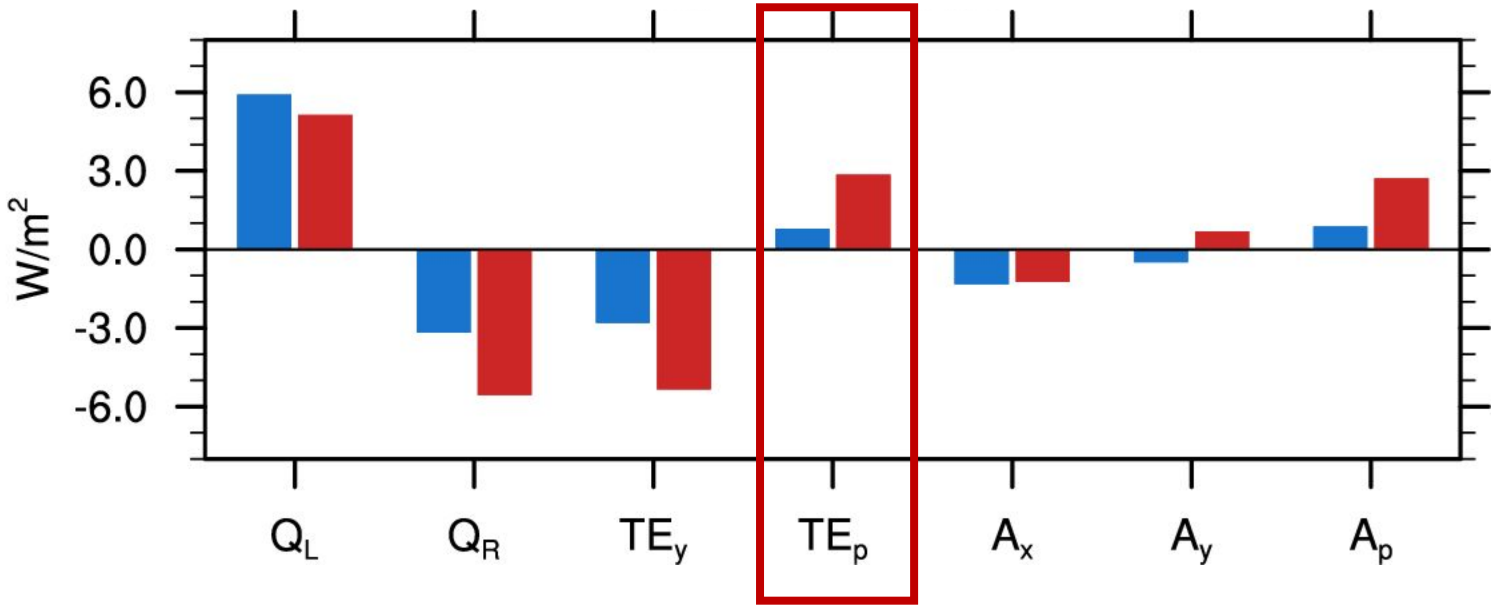


Table 1. Arctic precipitation climatology and its mean response to sea-ice loss during boreal winter (DJF) in Global 110-km and Arctic 14-km. The Arctic is defined as 65-90^{o}N polar cap.

	Mean Precipitation Climatology (mm day^{-1})			Mean Precipitation Response (mm day^{-1})		
	Convective	Large-scale	Total	Convective	Large-scale	Total
a) Global 110-km	0.030	0.915	0.945	0.042	0.197	0.238
b) Arctic 14-km	0.013	0.956	0.969	0.012	0.246	0.259
c) b-a	-0.017	0.041	0.024	-0.030	0.049	0.021

Table 2. As in table 1, but for the Arctic daily precipitation standard deviation and its response to Arctic sea ice loss.

	Daily Precip Variability climatology (mm day^{-1})	Daily Precip Variability Response (mm day^{-1})
a) Global 110-km	1.34	0.08
b) Arctic 14-km	1.42	0.19
c) b-a	0.08	0.11