Role of Mean States on Atmospheric Responses to High-latitude thermal forcing and Polar Warming

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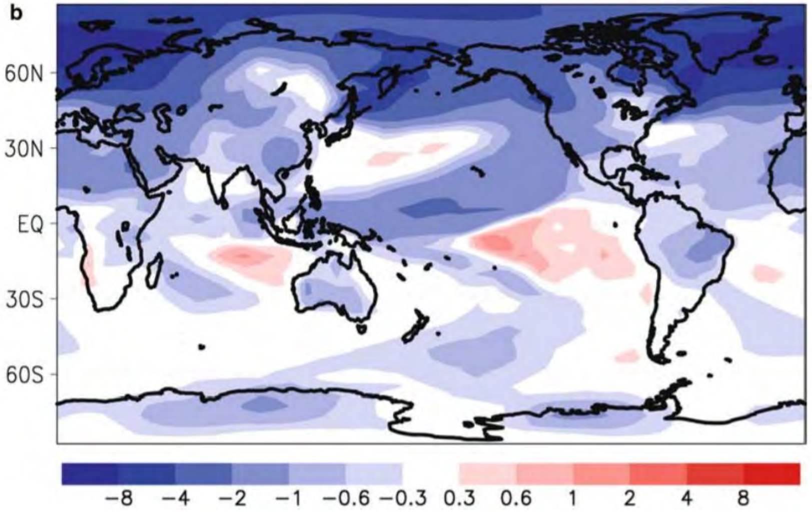
Introduction

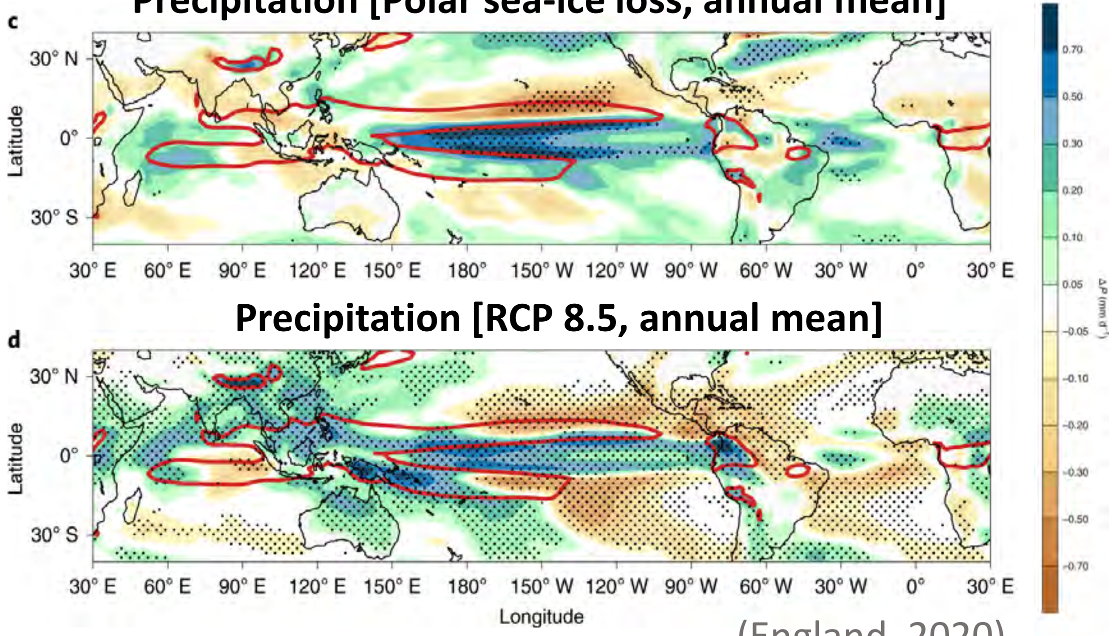
- Previous studies has indicated that changes in polar ice extent can impact tropical sea surface temperatures, the positioning of the Inter-Tropical Convergence Zone (ITCZ), and the intensity and location of the Hadley cell.

Response of SST and surface temperature (in K) to ice extent in a LGM



(Chiang and Bitz, 2005)

Precipitation [Polar sea-ice loss, annual mean]



Precipitation [RCP 8.5, annual mean]

(England, 2020)

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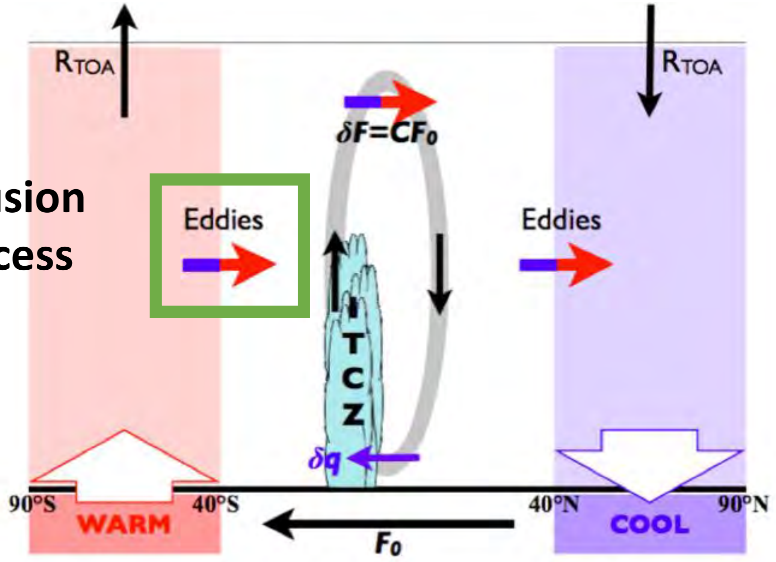
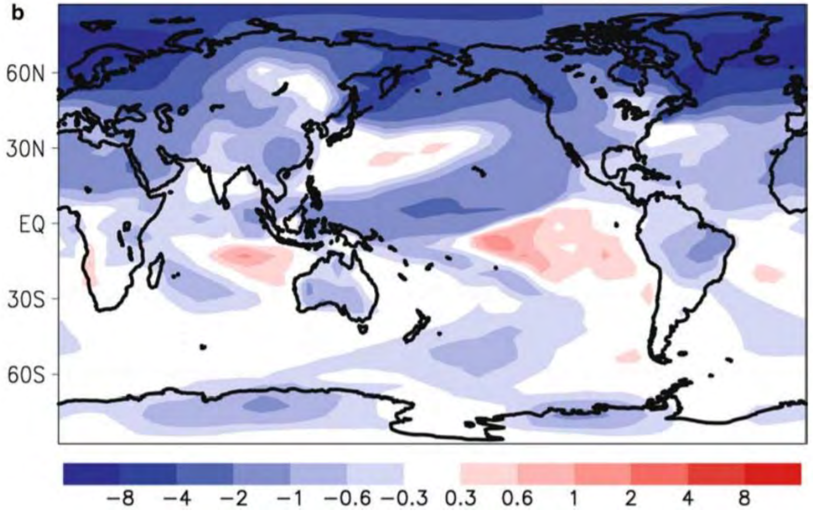
diffusion process



(Kang et al., 2009)

Response of SST and surface temperature (in K) to ice extent in a LGM



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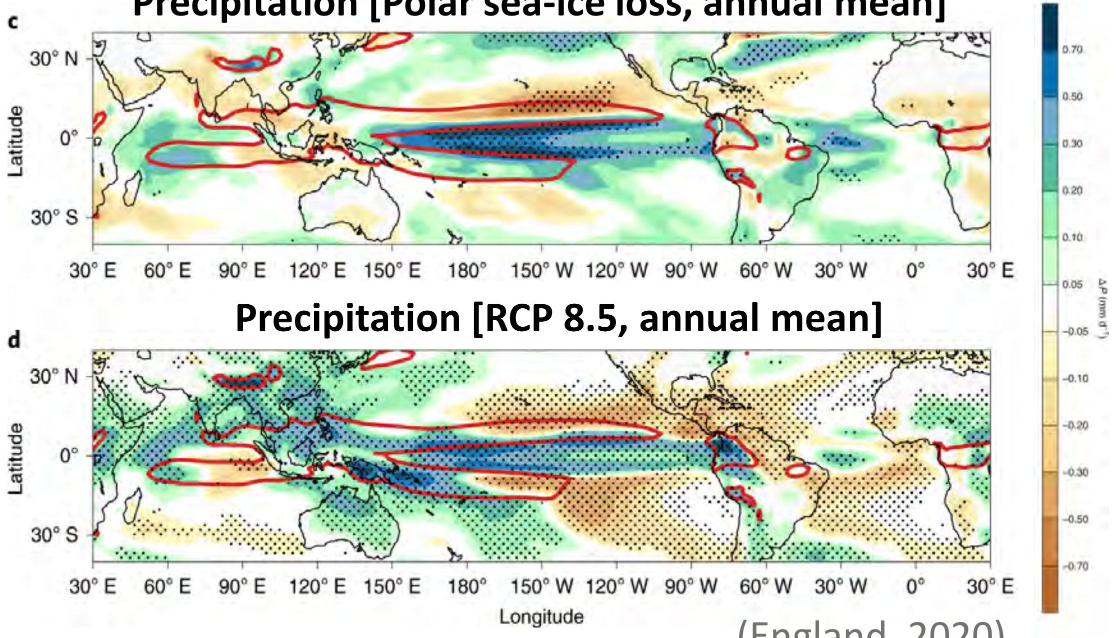

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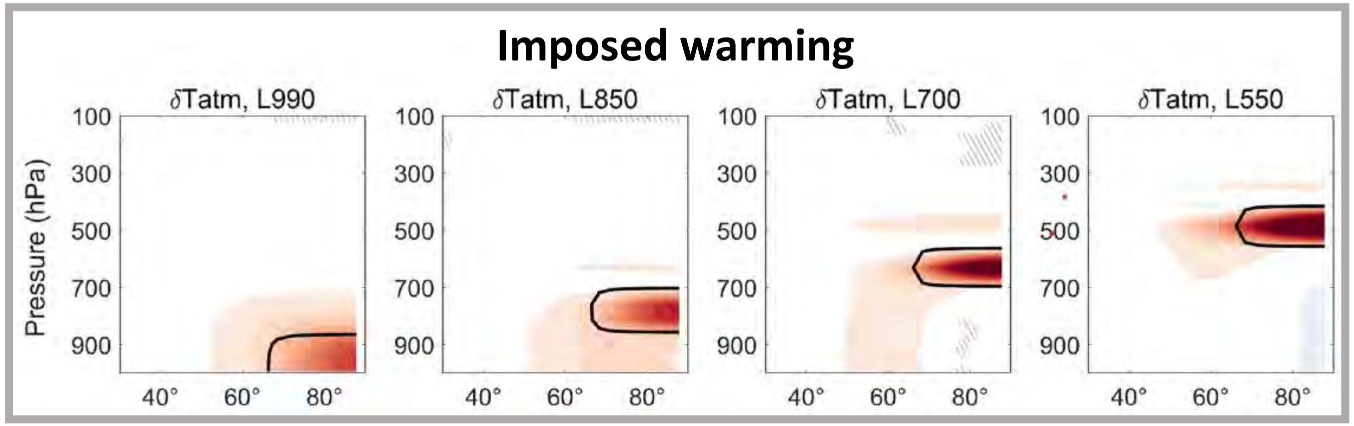
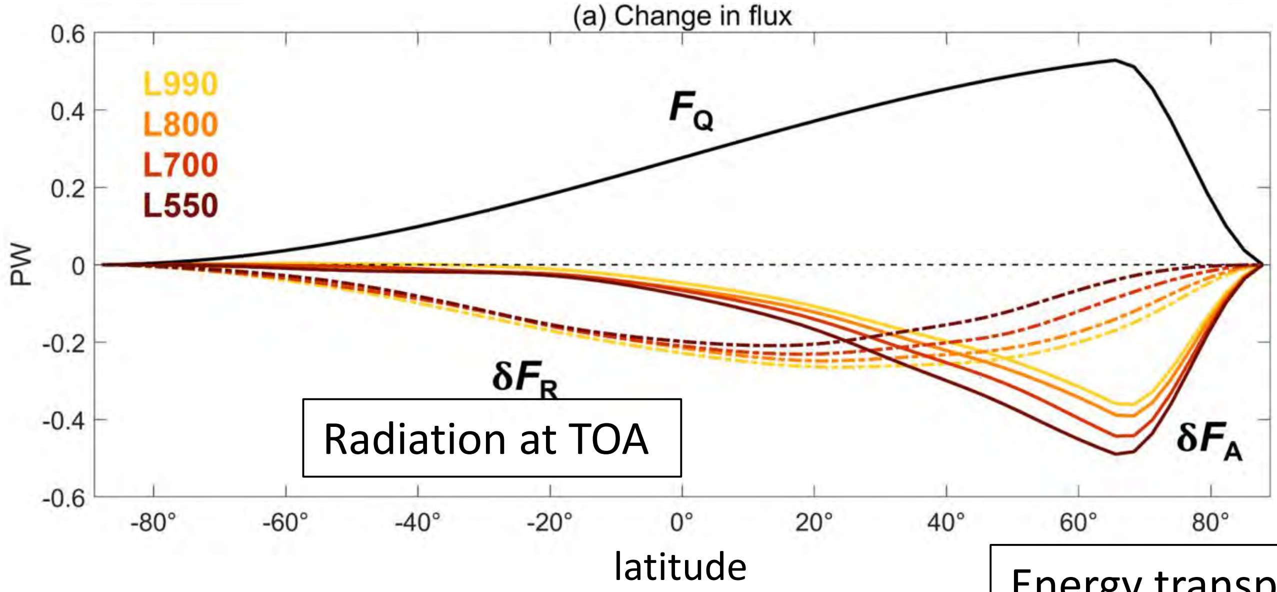
Introduction

The impact of polar heating on remote climate is sensitive to the altitude at which it is implemented.



Imposed warming



Radiation at TOA

Energy transport

(Kim et al., 2021)

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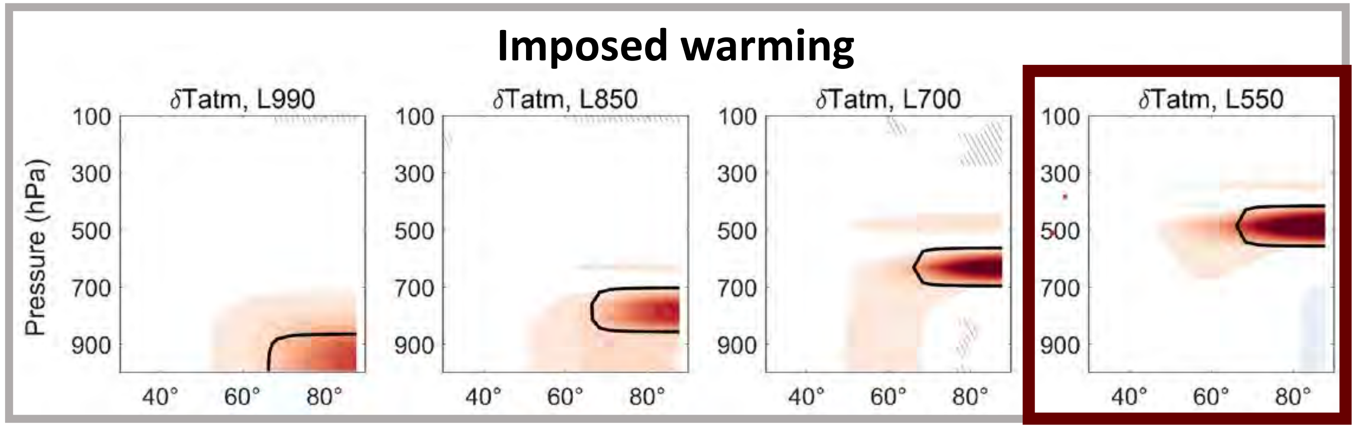
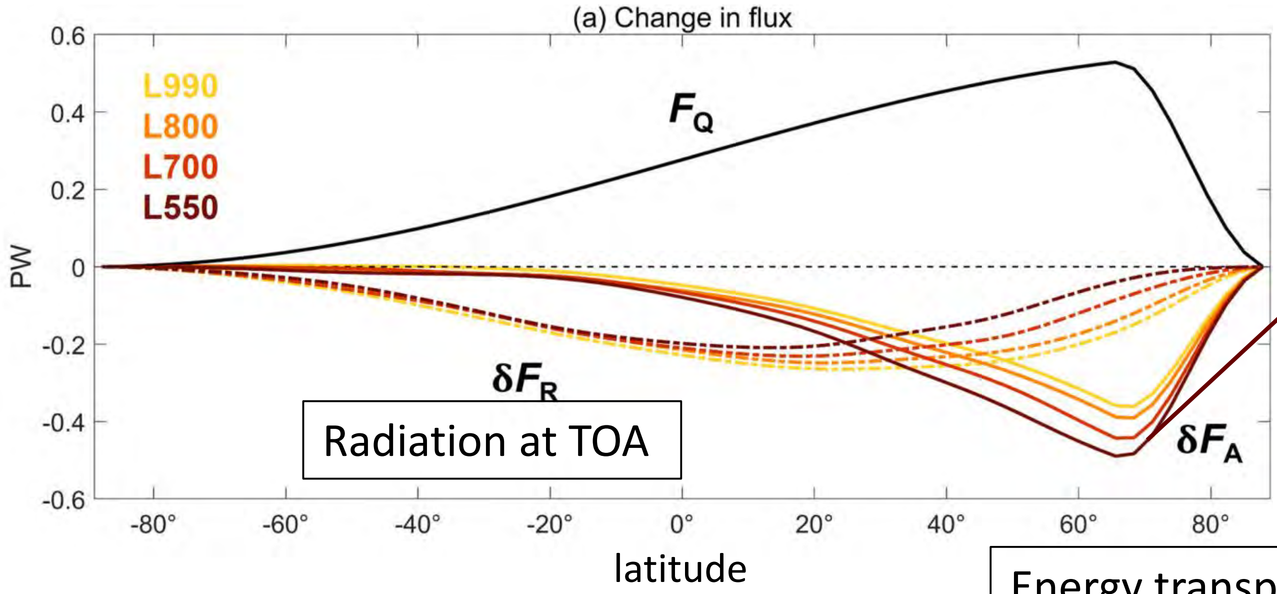


upper-level warming



Radiation at TOA

stronger responses of atmospheric energy transport (δF_A)

Energy transport

(Kim et al., 2021)

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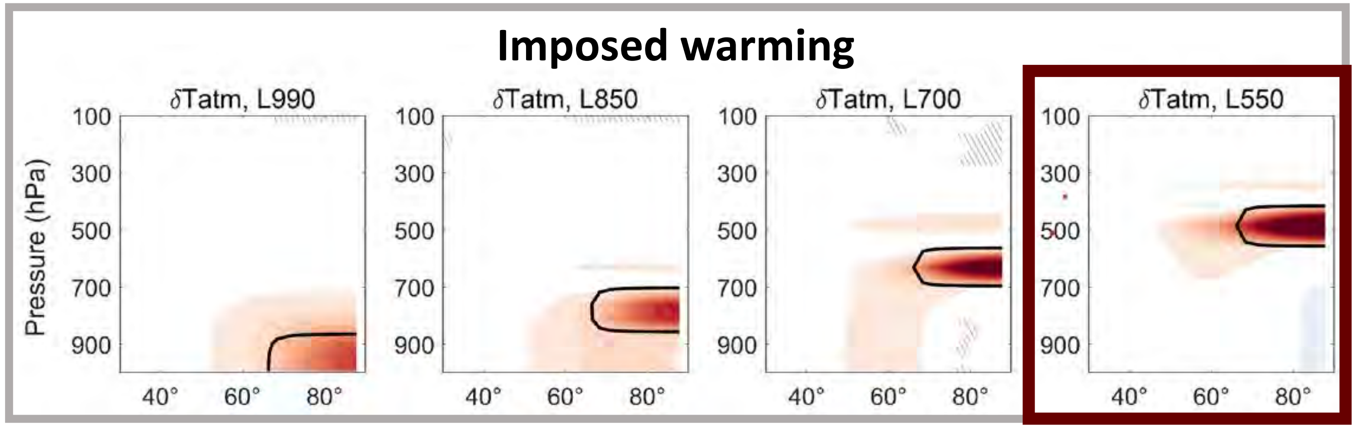
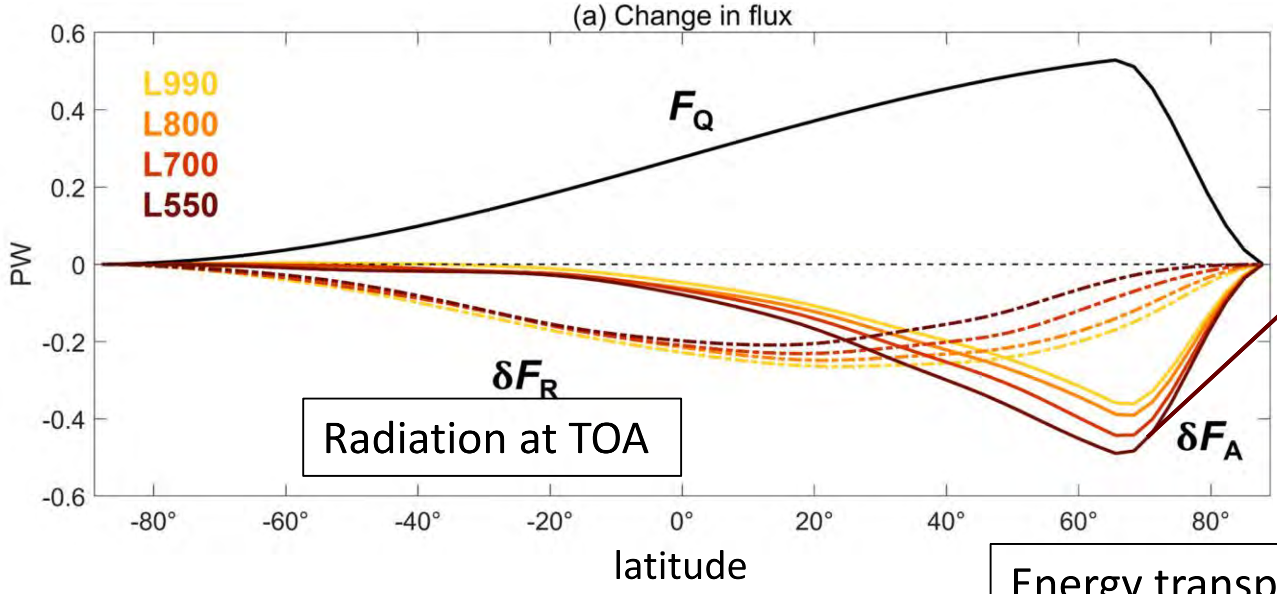


Imposed warming

upper-level warming



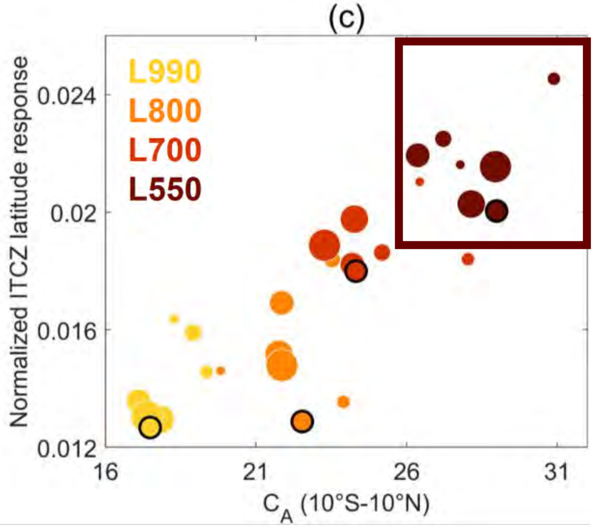
Radiation at TOA

Energy transport

stronger responses of atmospheric energy transport (δF_A)

&

larger ITCZ latitude response (non-local response)



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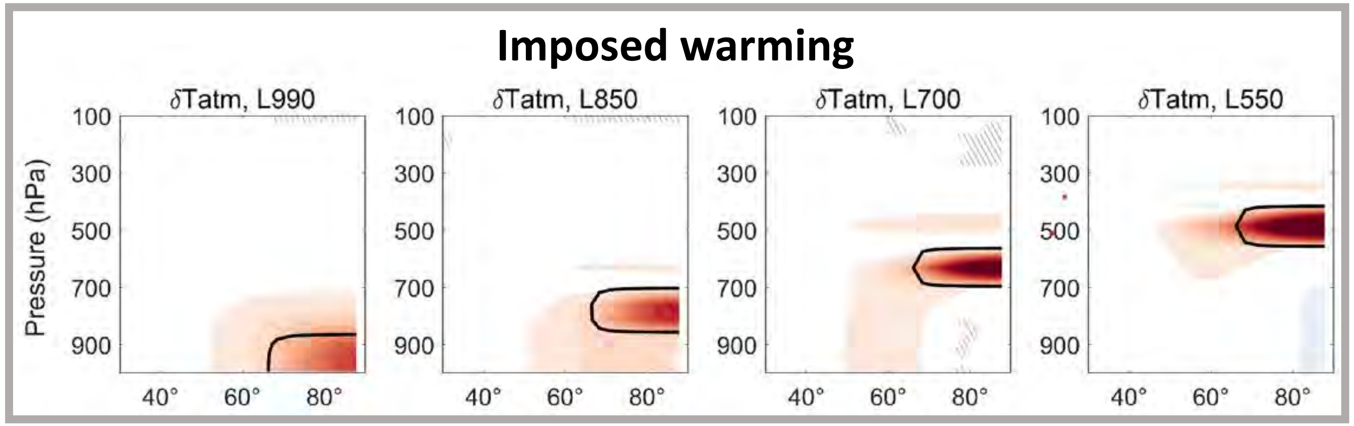
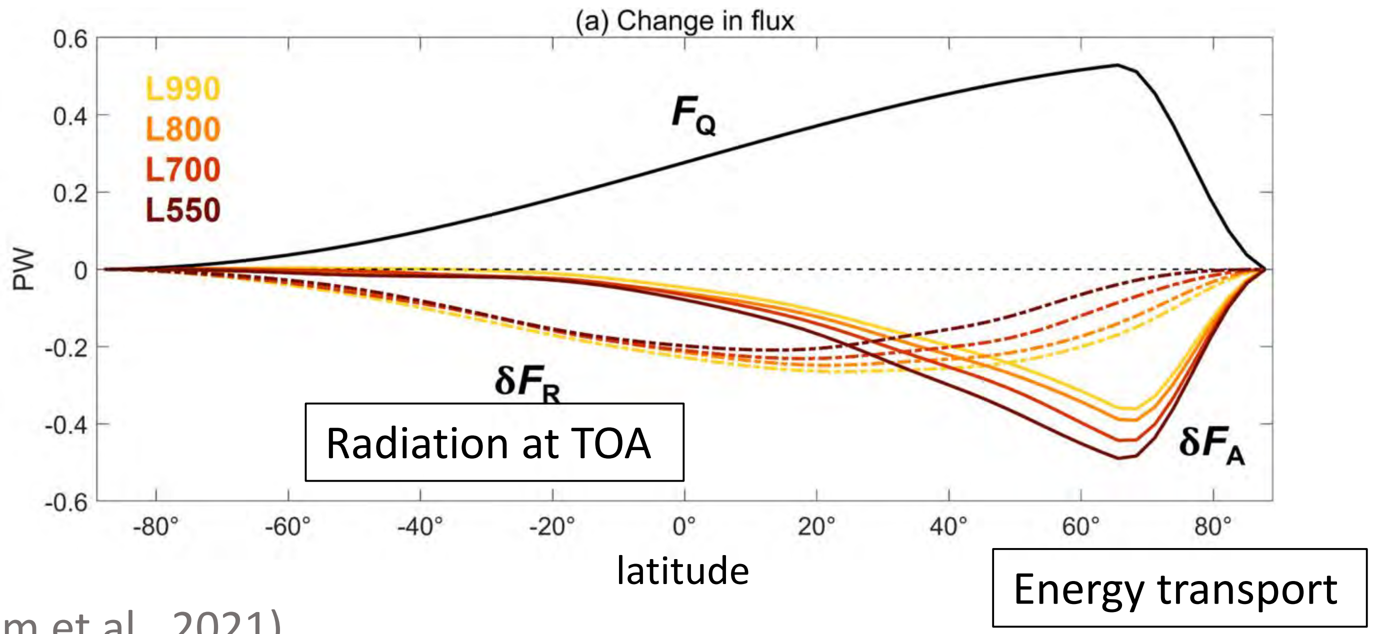

Imposed warming



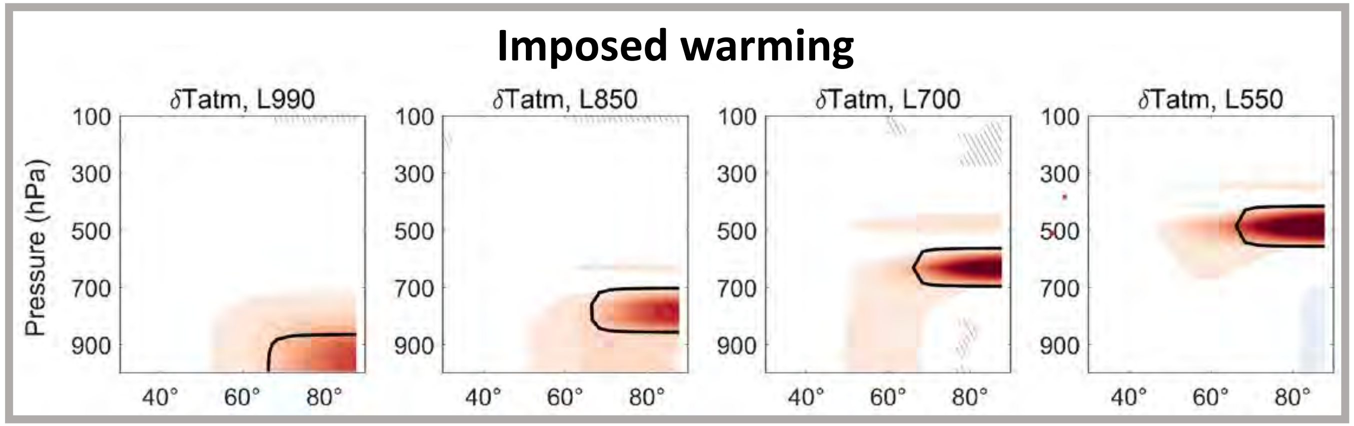
Radiation at TOA

Energy transport

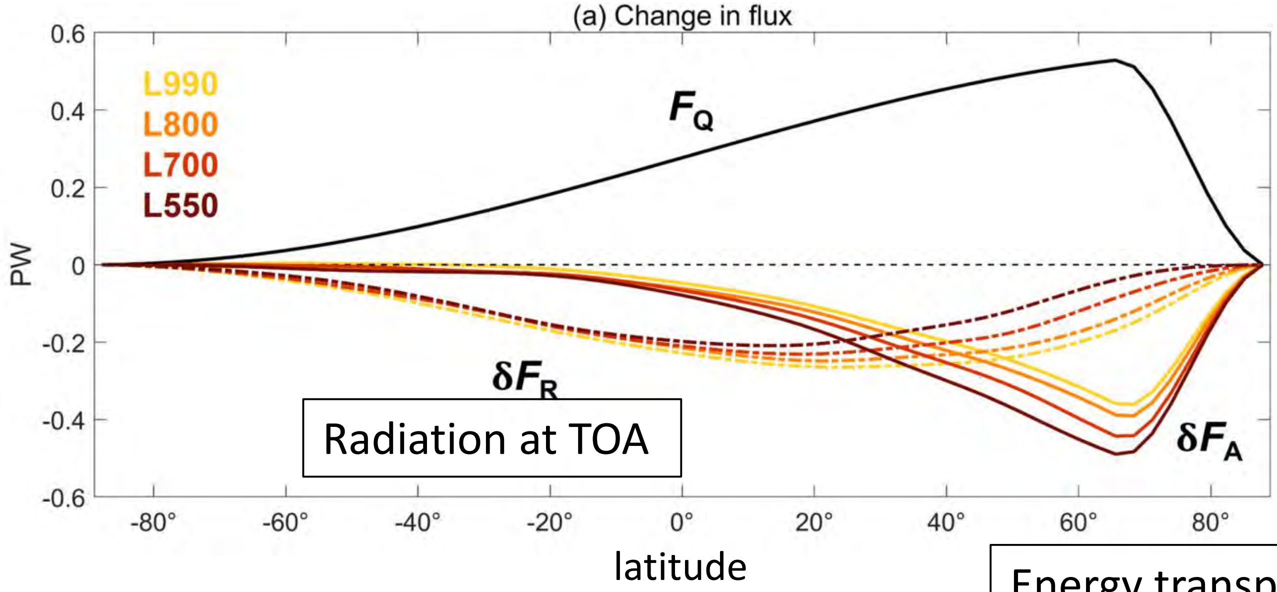
1. dynamic processes involved in this teleconnection

(Kim et al., 2021)

Introduction


Imposed warming

1. dynamic processes involved in this teleconnection
2. seasonality of the non-local effect of polar amplification


(a) Change in flux

Radiation at TOA

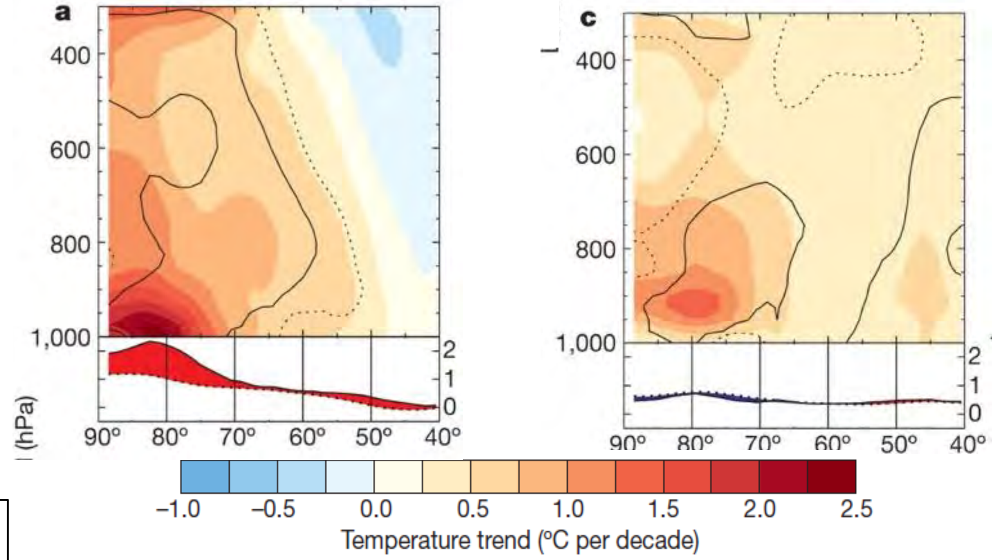
Energy transport

(Kim et al., 2021)

Arctic Temperature trend [1989-2008]

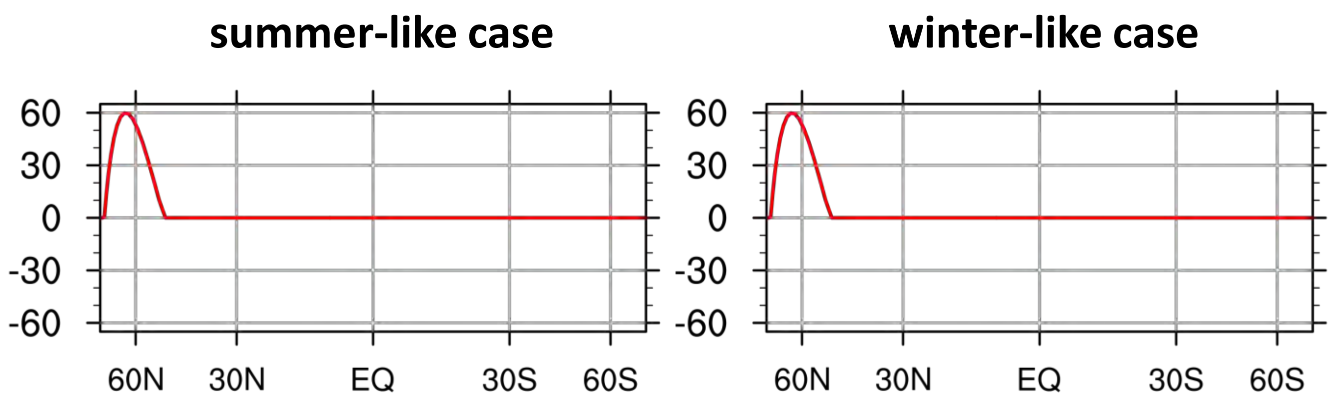
Winter (DJF)

Summer (JJA)



(Screen and Simmonds 2010)

Perpetual Control Climates with Thermal Forcing

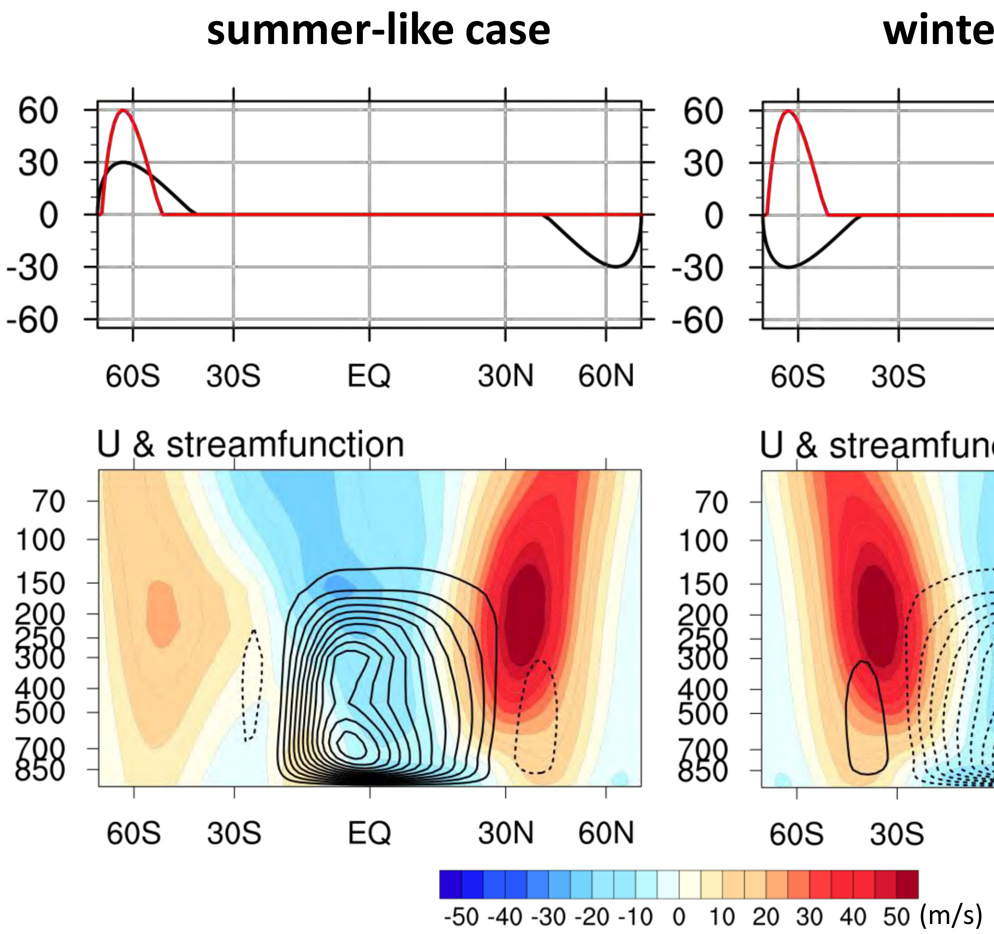

summer-like case

winter-like case

We impose a **polar warming forcing** in the mixed layer

Model & EXP. setting	• Aquaplanet version of the GFDL AM 2.1 coupled with a 200m mixed layer slab ocean • no seasonal cycle: the annual mean insolation is applied in the simulations.

Perpetual Control Climates with Thermal Forcing



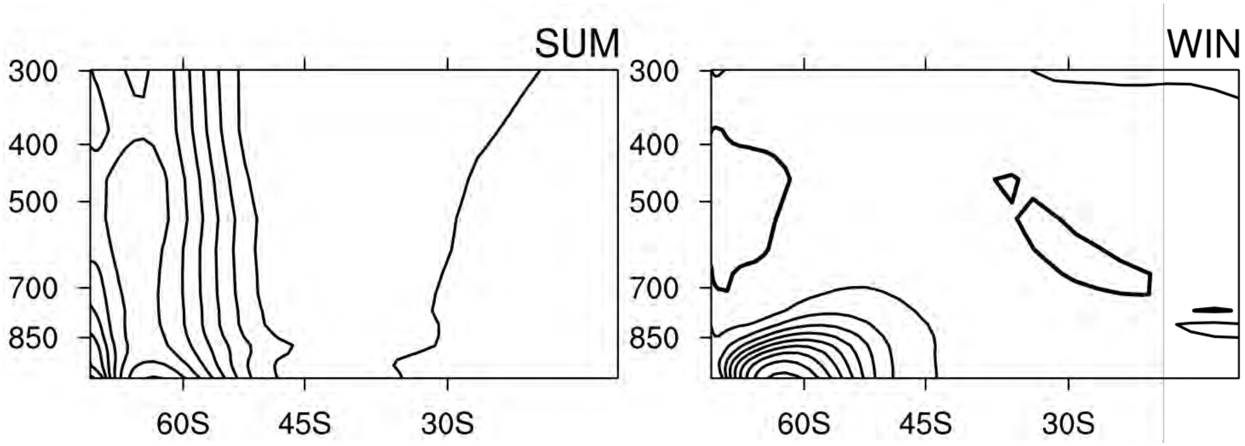
We impose a **polar warming forcing** in the mixed layer in two perpetual control climates:

1. **an austral-summer-like climate (SUM) :**
   - clockwise cross-equatorial Hadley Cell
   - a weak subtropical jet in the SH
   - more unstable atmosphere

2. **an austral-winter-like climate (WIN)** :
   - counter-clockwise cross-equatorial Hadley Cell
   - a strong subtropical jet in the SH
   - more stable atmosphere

Model & EXP. setting	• Aquaplanet version of the GFDL AM 2.1 coupled with a 200m mixed layer slab ocean • no seasonal cycle: the annual mean insolation is applied in the simulations.

Polar warming Responses



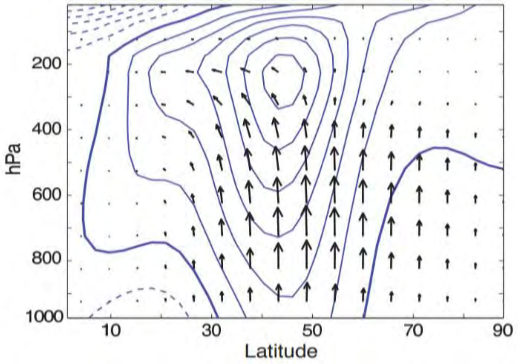
Contours: anomalous potential temperature (K)

Summer-like	Winter-like
Vertically-extending warming	Surface-trapped warming

Midlatitude Eddy Responses

- Definition of Eliassen–Palm flux (EP flux):

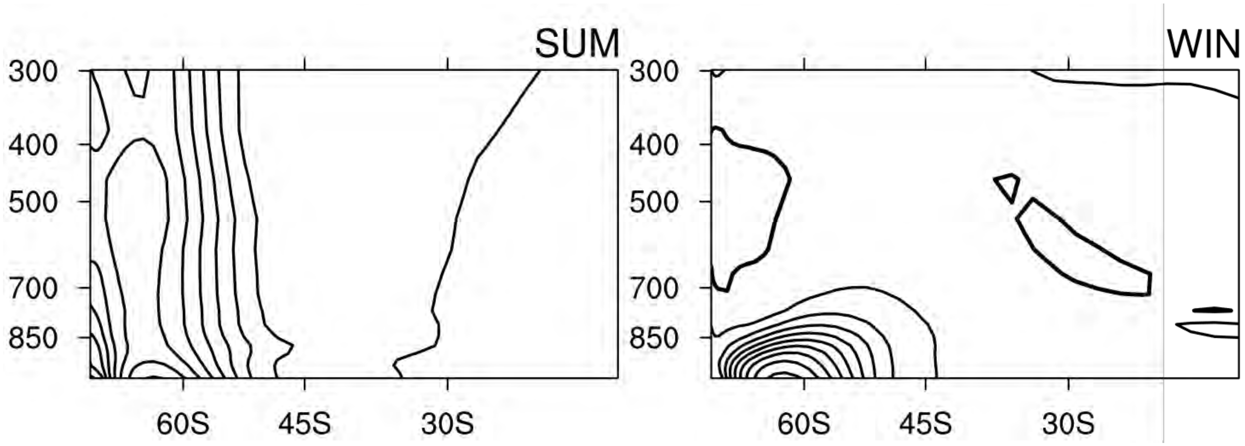
$$F = \left(F_\phi, F_p\right) = \left(-\overline{u'v'}, f\frac{\overline{v'\theta\prime}}{\partial_p\overline{\theta}}\right).$$



climatological EP flux

(Vallis, 2017)

Summer-like	Winter-like
Vertically-extending warming	Surface-trapped warming



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Midlatitude Wave Responses

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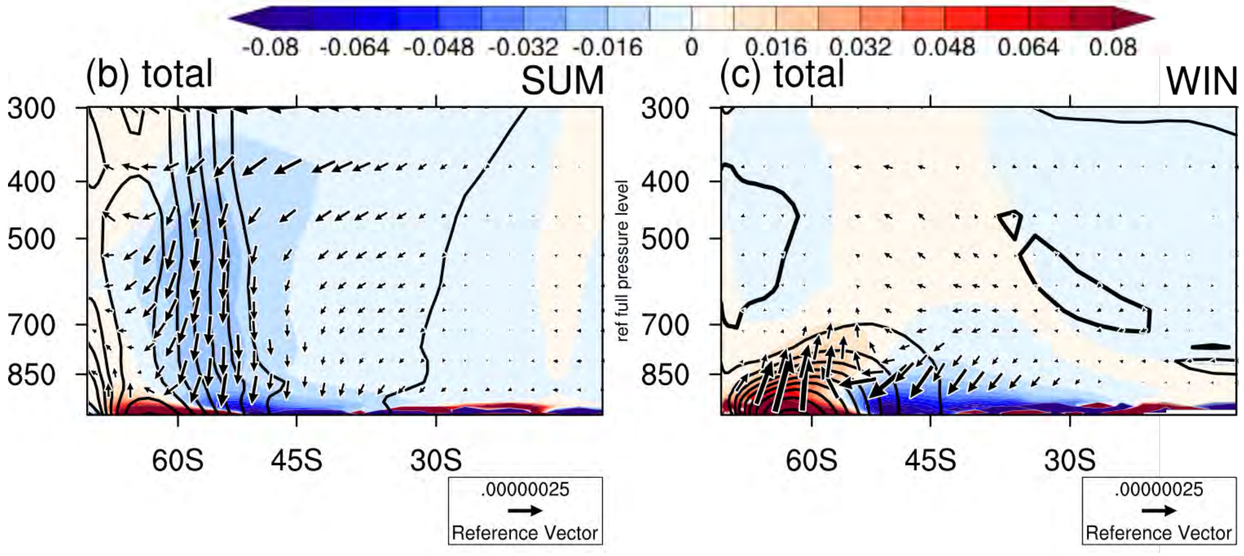

F_p

Contours: anomalous potential temperature (K)
Vectors: anomalous EP fluxes (m^2s^{-2})
Shading: anomalous vertical EP flux (m^2s^{-2})

Summer-like	**Winter-like**
Vertically-extending warming	Surface-trapped warming
Strong eddy responses (---)	Weak eddy responses (-)

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- Definition of Eliassen–Palm flux (EP flux):

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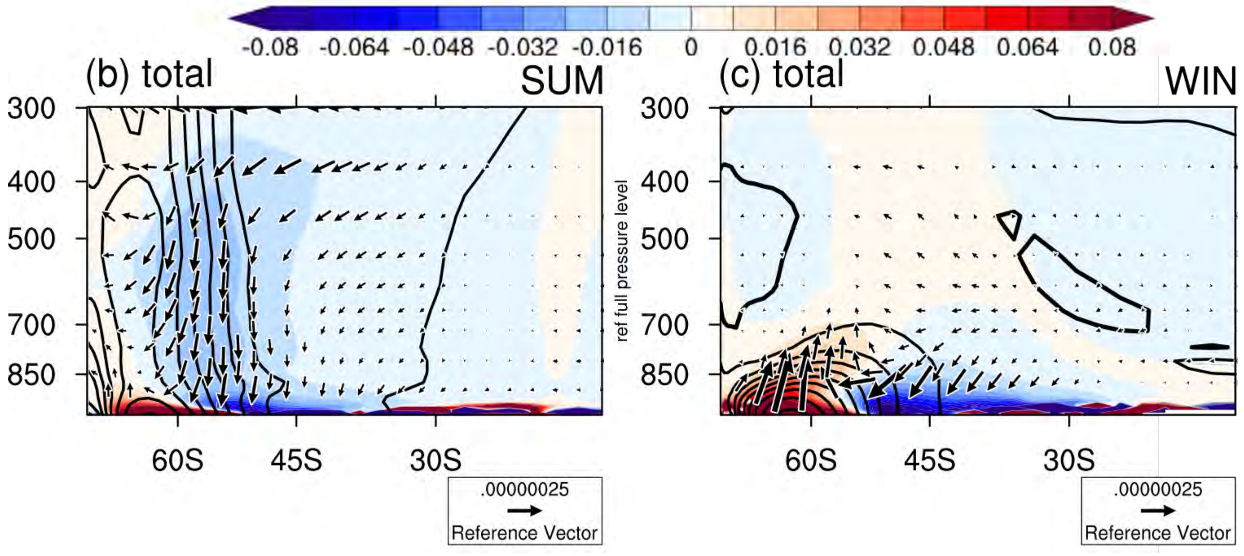
- Decomposition of F_p:

stability term

$$\Delta\frac{\overline{v'\theta'}}{\partial_p\overline{\theta}} = \frac{\Delta\overline{v'\theta'}}{\gamma} - \frac{\overline{v'\theta'}\Delta\gamma}{\gamma^2} + residual.$$

eddy heat flux (EHF) term

Summer-like	Winter-like
Vertically-extending warming	Surface-trapped warming
Strong eddy responses (---)	Weak eddy responses (-)



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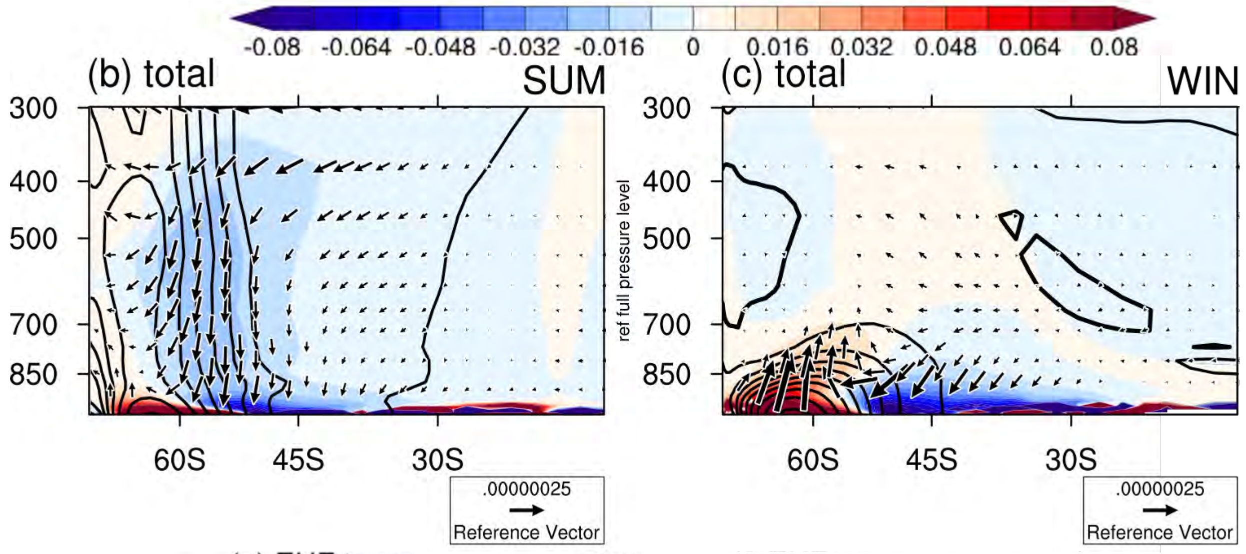
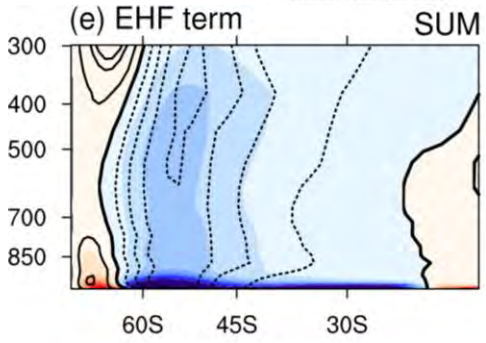
Summer-like	**Winter-like**
Vertically-extending warming	Surface-trapped warming
Decreased meridional temperature gradient (---)	
Weak stability changes (~0)	
Strong eddy responses (---)	Weak eddy responses (-)



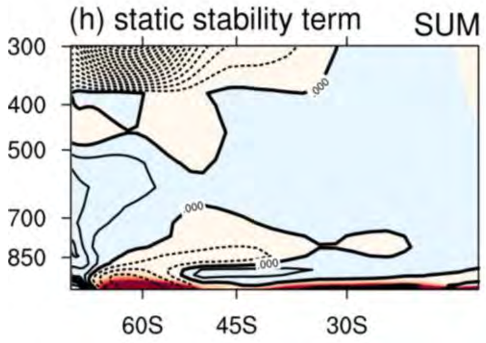
$$F_p$$

$$=$$



$$\frac{\Delta\overline{v'\theta'}}{\gamma}$$

$$+$$



$$-\frac{\overline{v'\theta'}\Delta\gamma}{\gamma^2}$$

Midlatitude Wave Responses

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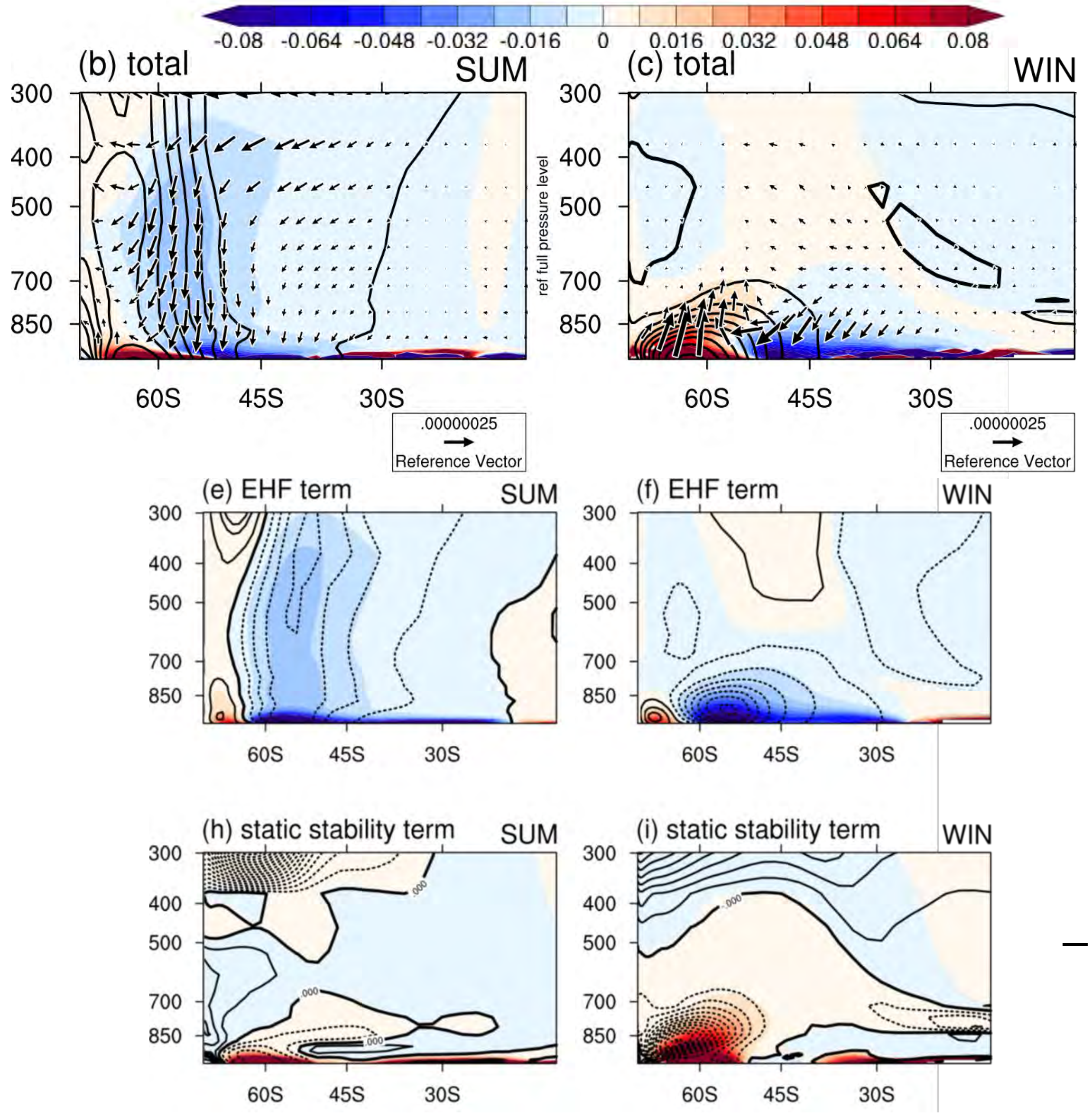
eddy heat flux (EHF) term

Summer-like	Winter-like
Vertically-extending warming	Surface-trapped warming
Decreased meridional temperature gradient (---)	Decreased meridional temperature gradient (---)
Weak stability changes (~0)	Decreased stability (++)
Strong eddy responses (---)	Weak eddy responses (-)



$$F_p$$

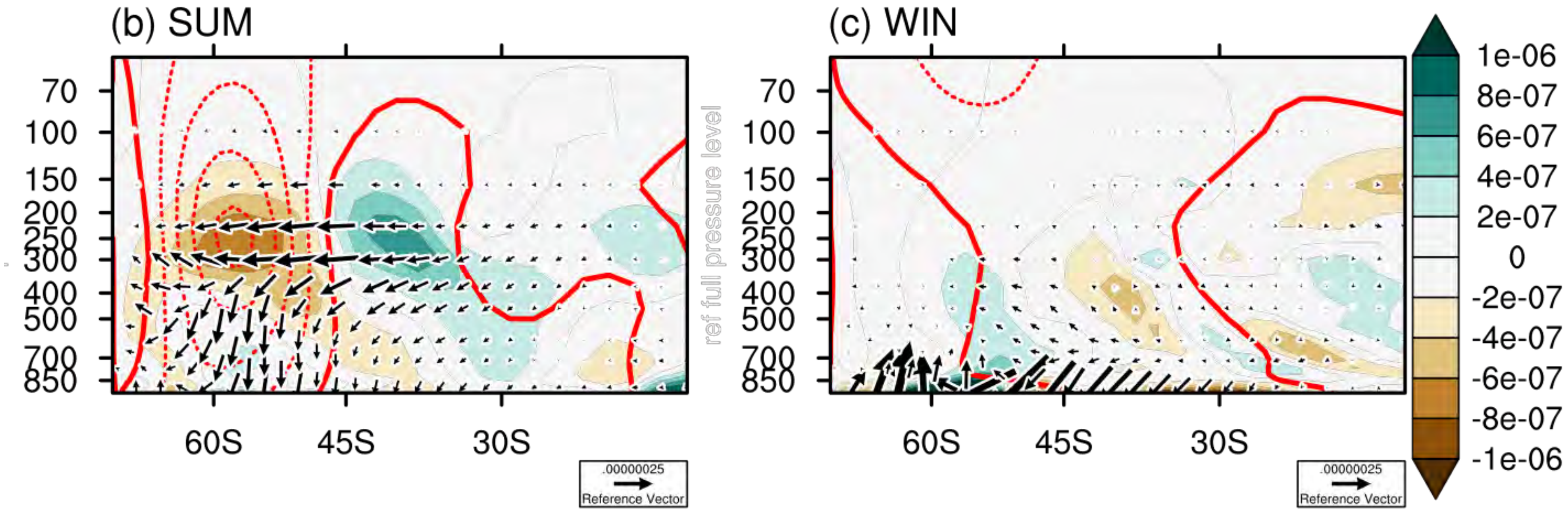
$$=$$

$$\frac{\Delta \overline{v'\theta'}}{\gamma}$$

$$+$$

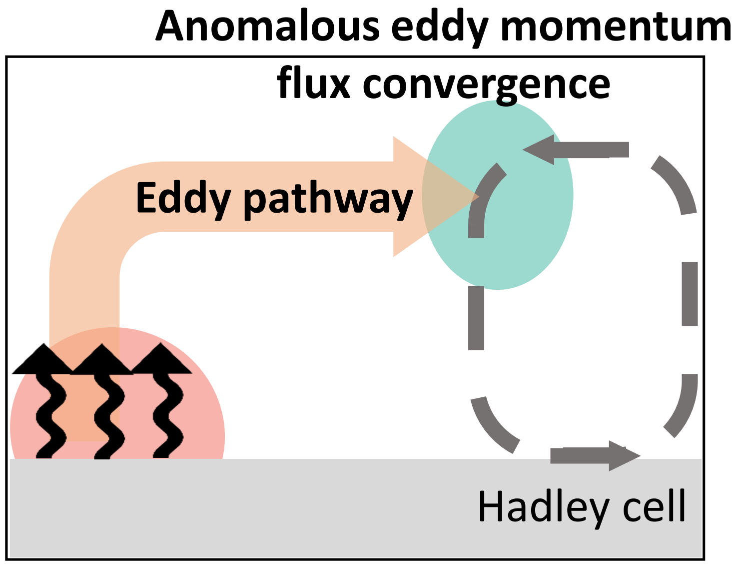
$$-\frac{\overline{v'\theta'}\Delta\gamma}{\gamma^2}$$

Midlatitude Wave Responses

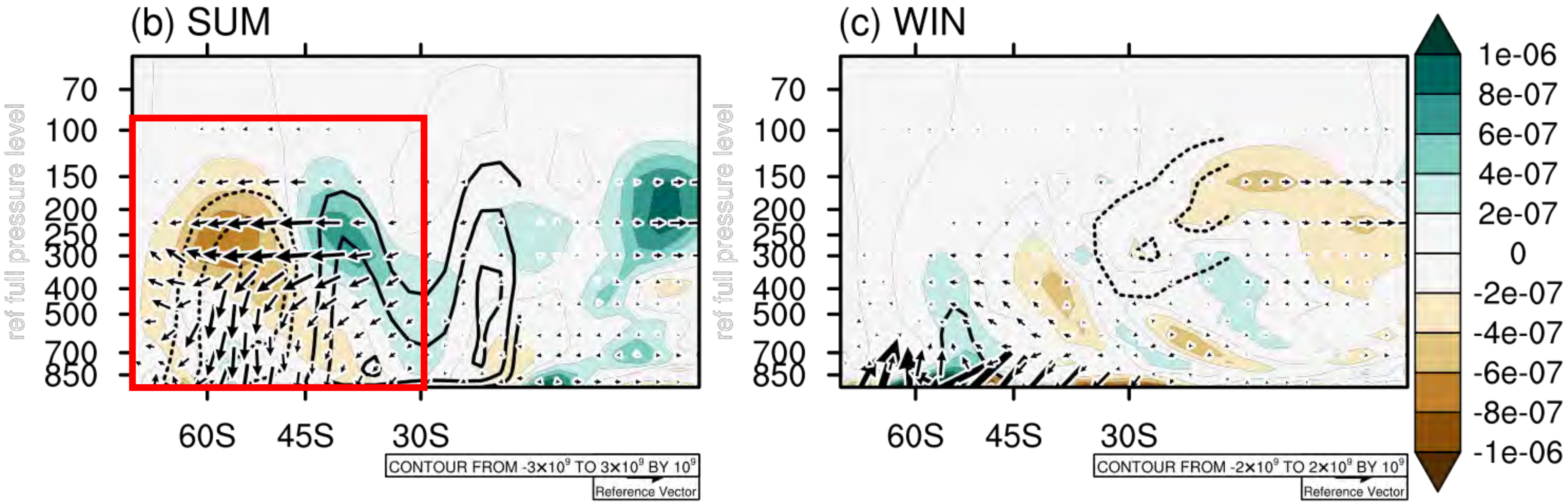


Vectors:
anomalous EP flux (m^2s^{-2})
Shading:
anomalous horizontal divergence of EP flux (m/s^2)
Red contour:
anomalous zonally averaged zonal wind (CI = 5 m/s)

- The decreased eddy activities in the lower levels would arise **poleward eddy activity anomalies (vectors)** in the upper levels, leading to **anomalous eddy momentum flux divergence in the midlatitudes** and **convergence in the subtropics**.



Circulation Responses

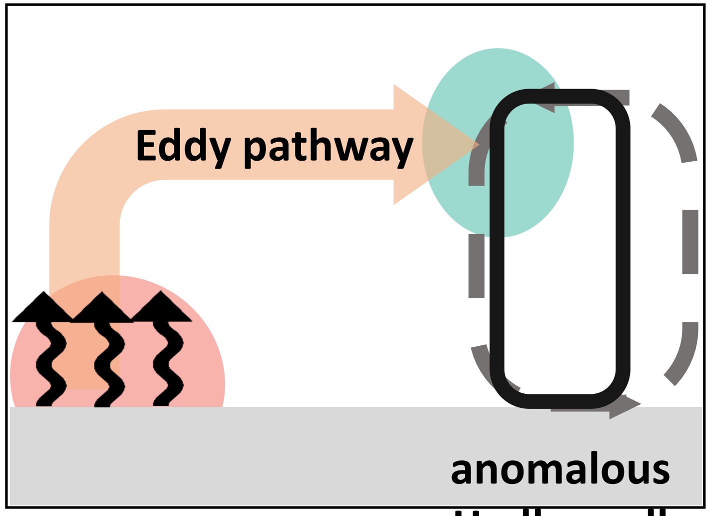


Vectors:
anomalous EP flux (m^2s^{-2})
Shading:
anomalous horizontal divergence of EP flux (m/s^2)
contour:
anomalous meridional streamfunction

EMF convergence anomaly (shading)
& ψ response (contours)

Weak EMF convergence

- The anomalous eddy momentum flux convergence would be balanced by Coriolis torque, resulting in the weakening of the Hadley cell.



Eddy pathway

anomalous Hadley cell

Comparing with Energetics Perspective

In Kim et al., (2021):

upper-level warming → stronger atmospheric energy transport (δF_A) & larger ITCZ latitude response (non-local response)

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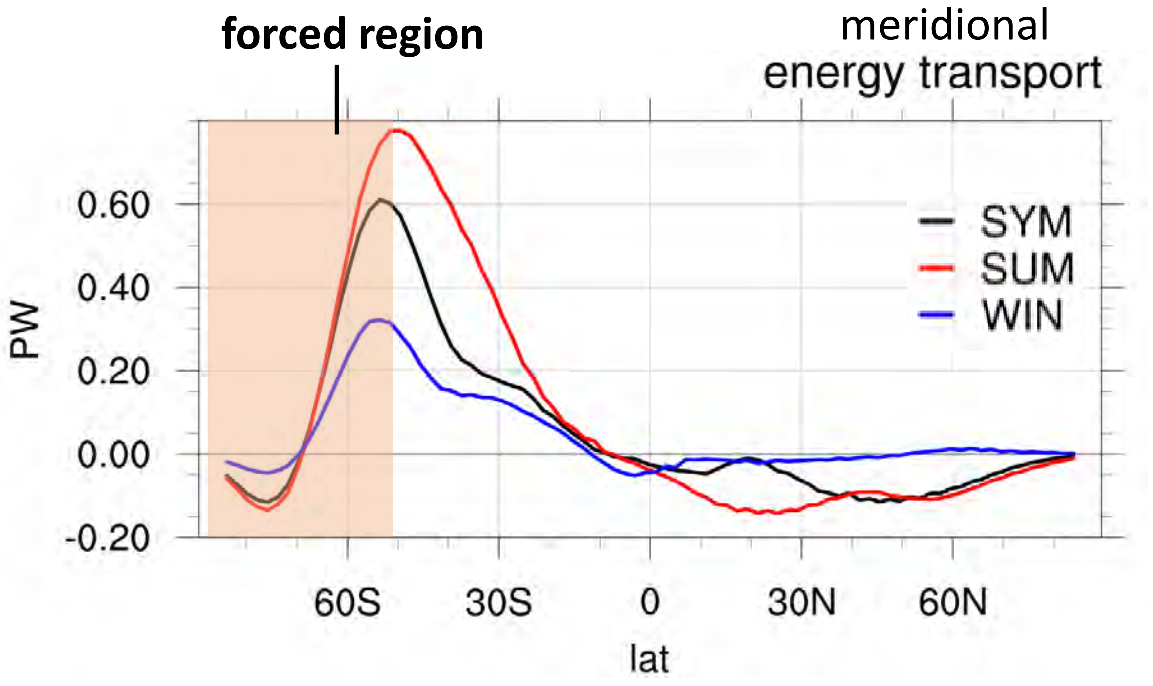


We offer a dynamical interpretation for the finding of Kim et al., (2021):

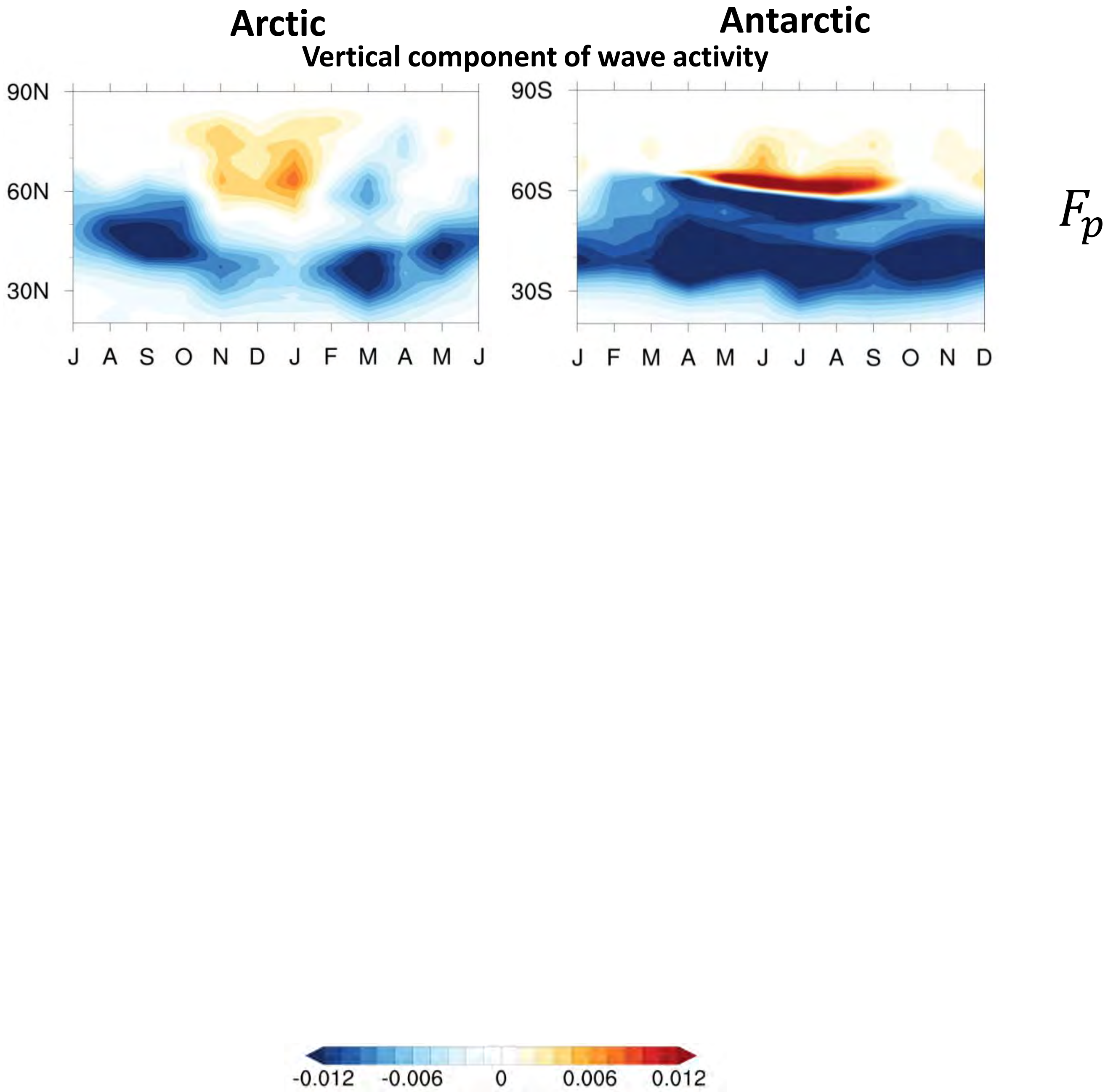
Vertically-extending warming (in summer-like case) cause stronger wave responses, leading to **atmospheric energy transport anomaly** and **non-local effect**.

Surface-trapped warming (in winter-like case) leads to weaker wave responses, resulting in **weak atmospheric energy transport anomaly**.

Midlatitude Wave Response in Doubled CO_2 Experiments

Apply our understanding to a set of more realistic climate change experiments:

CESM1 fully coupled model experiments
Forcing: 2xCO2



Shading: anomalous F_p and its decomposition
Contours: anomalous $\mathrm{F_p}$ (m^2s^{-2})

Midlatitude Wave Response in Doubled CO_2 Experiments

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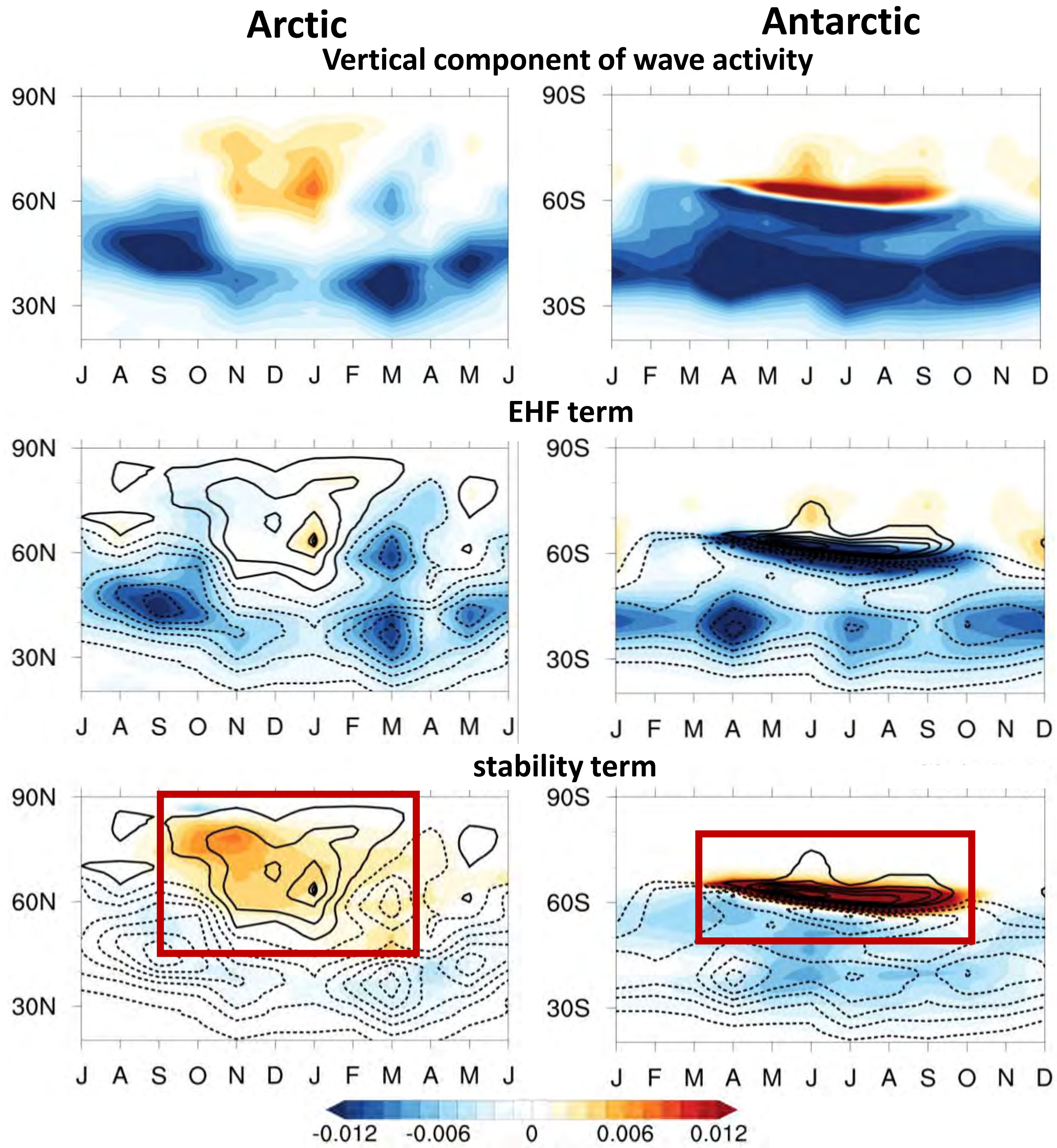
CESM1 fully coupled model experiments
Forcing: 2xCO2

- The doubled CO_2 experiments demonstrate that the stability term could contribute to the wave activity response, especially in winter.



$$F_p = \frac{\Delta\overline{v'\theta'}}{\gamma} + -\frac{\overline{v'\theta'}\Delta\gamma}{\gamma^2}$$

Shading: anomalous F_p and its decomposition
Contours: anomalous F_p (m^2s^{-2})

Summary

- The climatological stability plays a role in determining the warming structure, and the structure of the warming, in turn, influences magnitude of eddy response.

- The magnitude of midlatitude wave responses affect the efficiency of teleconnection: the significant reduction of midlatitude wave in response to a vertical extending warming would effectively cause subtropical Hadley cell weakening.

- In the idealized WIN case, as well as during specific seasons and latitudes in response to sea ice loss, the surface warming induces greater atmospheric instability, thereby enhancing eddy generation. This effect offsets the impact associated with the reduced meridional temperature gradient.

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