A Hierarchy of Ocean Models coupled to CESM1

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https://meteorologytoday.github.io

2023/02/21 @ CESM CLIMATE VARIABILITY AND CHANGE WINTER WORKING GROUP MEETING

Dr. Yannick Peings @ UC Irvine

Dr. Young-Oh Kwon @ WHOI

Dr. Paul Kushner @ University of Toronto

Department of Energy

UCAR CISL (Cheyenne supercomputer cluster)

Ocean processes modulates the tropical response towards Arctic sea-ice loss

Slab Ocean Model (SOM)

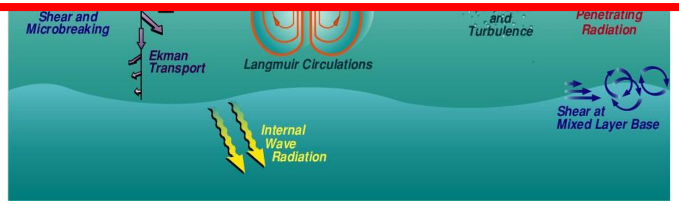
RESP_SOM

Ocean General Circulation Model (OGCM)

RESP_OGCM

Question: How do oceanic processes modulate the shift of the Intertropical Convergence Zone (ITCZ) forced with Arctic sea-ice loss?

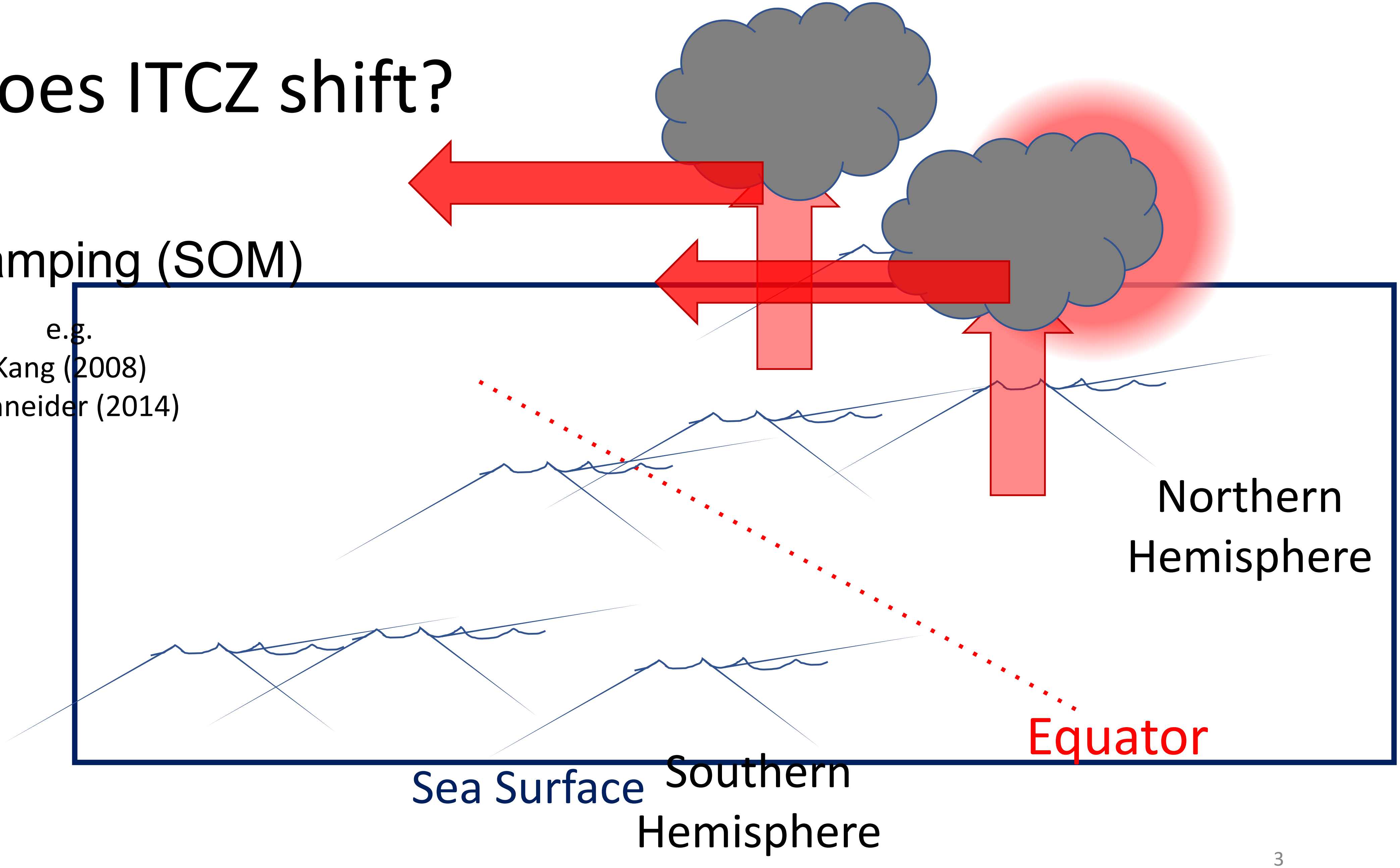
Flux correction (Q)
= missing processes



Why does ITCZ shift?

No damping (SOM)

e.g.
Kang (2008)
Schneider (2014)

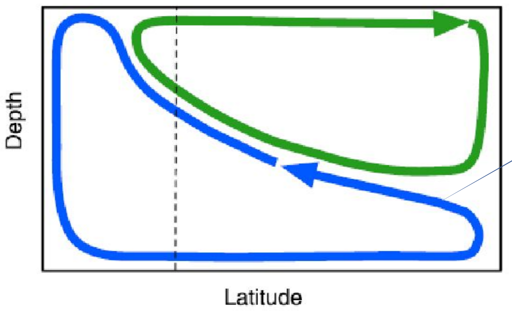


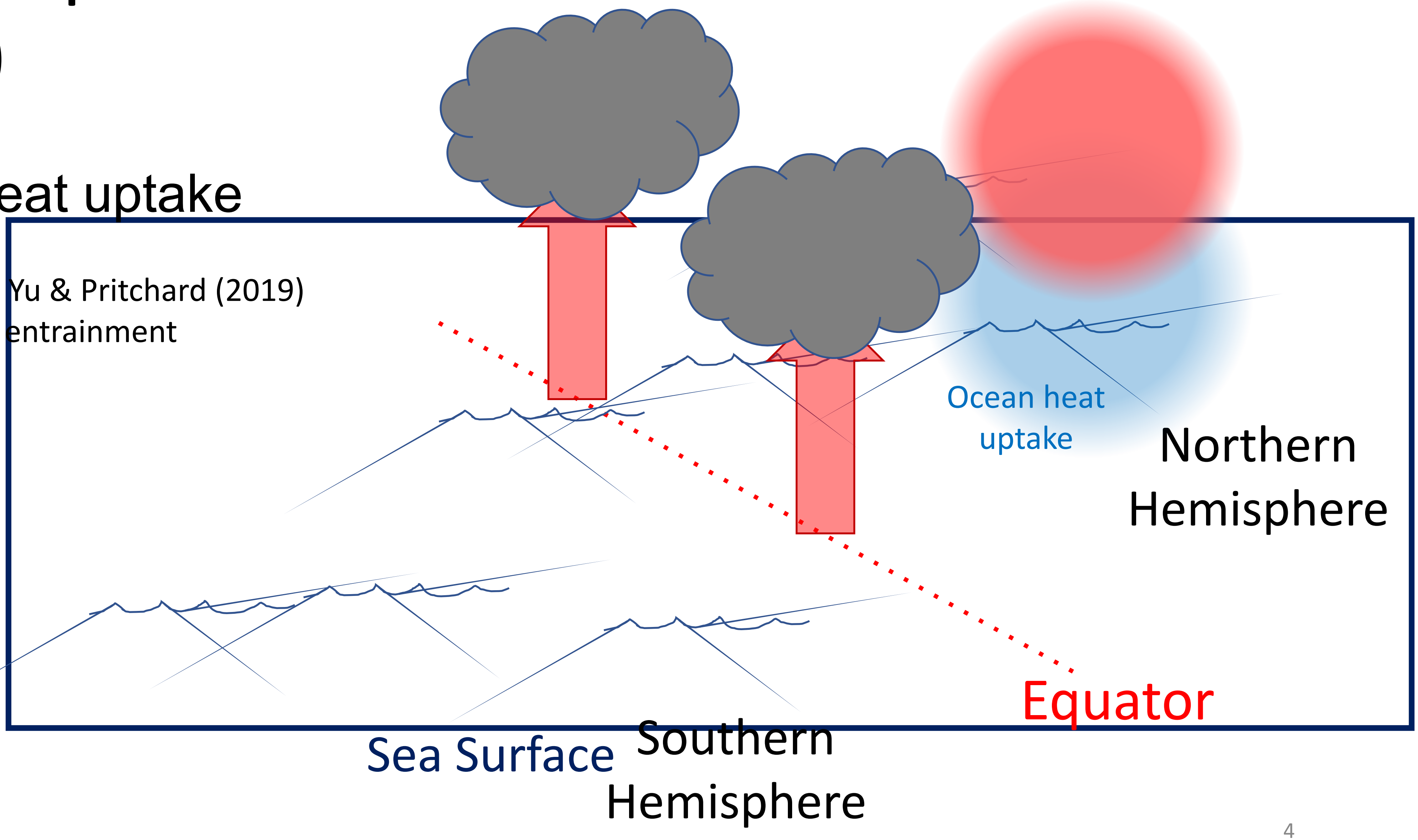
What damps the ITCZ shift? (1)

Ocean heat uptake

1. AMOC : e.g. Yu & Pritchard (2019)
2. Mixed layer entrainment

Atlantic Meridional Overturning Circulation (AMOC)

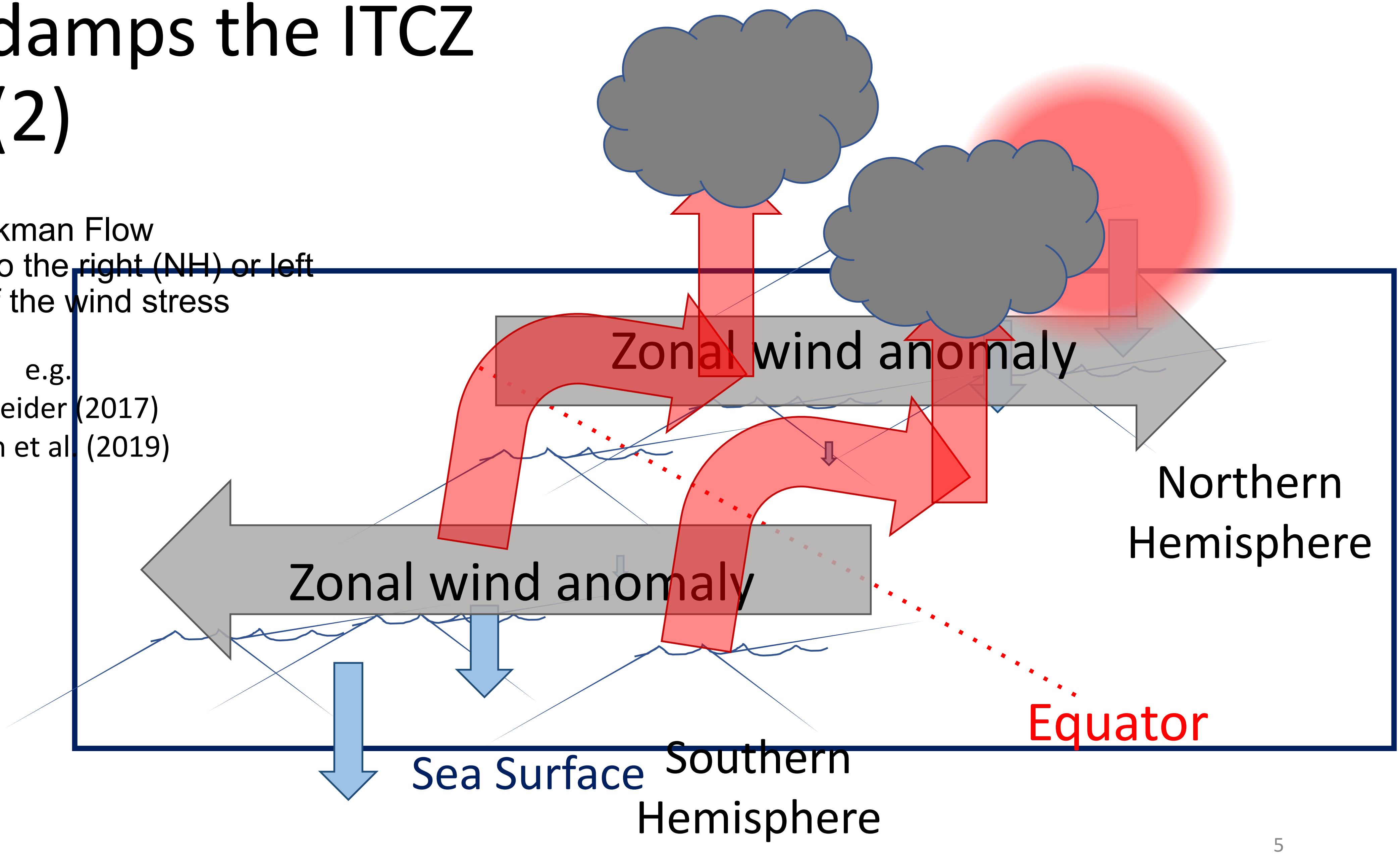




What damps the ITCZ shift? (2)

Ekman Flow
90 degrees to the right (NH) or left (SH) of the wind stress

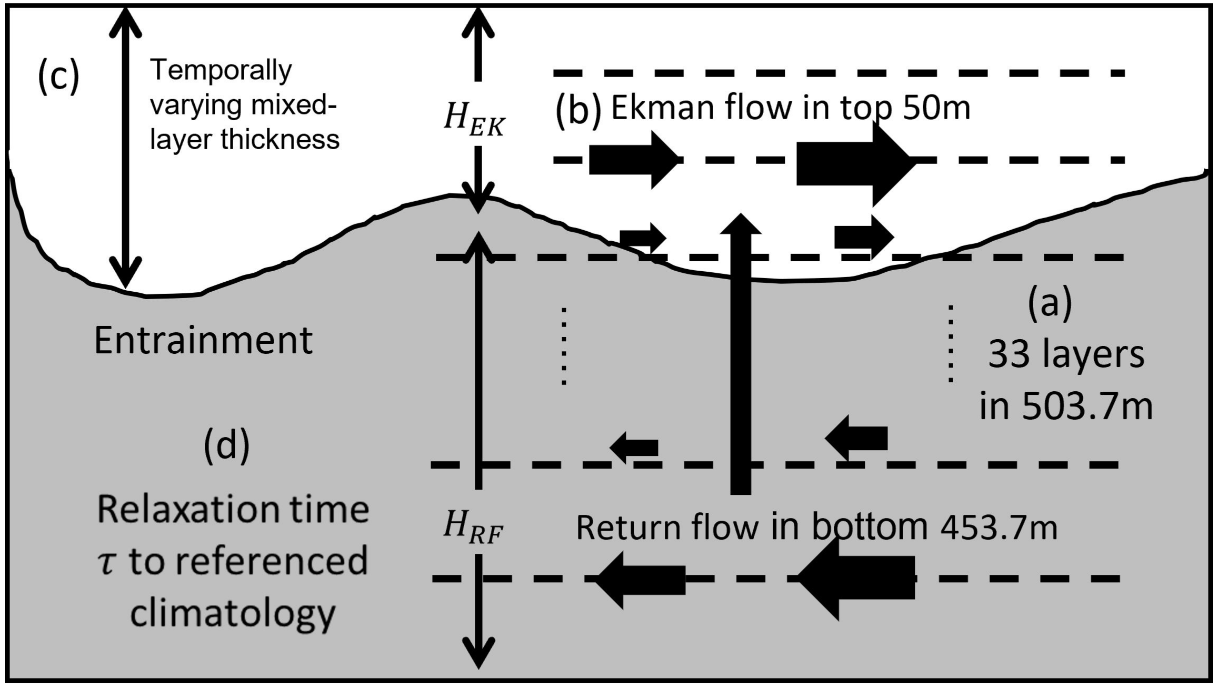
e.g.
Schneider (2017)
Green et al. (2019)



EMOM Model Hierarchy

Topic: Modulation of the dynamical air-sea coupling on global warming (Chapters 2 and 3)

Ekman mixed-layer ocean model (EMOM)



Hsu et al. (2022)

- POP2 (an OGCM)
- Ekman mixed-layer ocean model (EMOM)
- Mixed-layer ocean model (MLM)
- Slab ocean model (SOM)

Model Complexity

Ekman flow parameterization

Coriolis Friction Wind

$$f v_{EK} - \epsilon u_{EK} + \frac{\tau^x}{\rho H_{EK}} = 0$$

$$-f u_{EK} - \epsilon v_{EK} + \frac{\tau^y}{\rho H_{EK}} = 0$$

➡

$$u_{EK} = \frac{f\tau^y + \epsilon\tau^x}{\rho\, H_{EK}(\epsilon^2 + f^2)}$$

$$v_{EK} = \frac{-f\tau^x + \epsilon\tau^y}{\rho\, H_{EK}(\epsilon^2 + f^2)}$$

➡

Ekman Flow

$$\vec{U}_r = \frac{f(\tau^y, -\tau^x)}{\rho\, H_{EK}(\epsilon^2 + f^2)}$$

Frictional Flow

$$\vec{U}_f = \frac{\epsilon(\tau^x, \tau^y)}{\rho\, H_{EK}(\epsilon^2 + f^2)}$$

$\epsilon = 1.4 \times 10^{-5}/s$

➔ Frictional flow dominates within $5^{\circ}S - 5^{\circ}N$

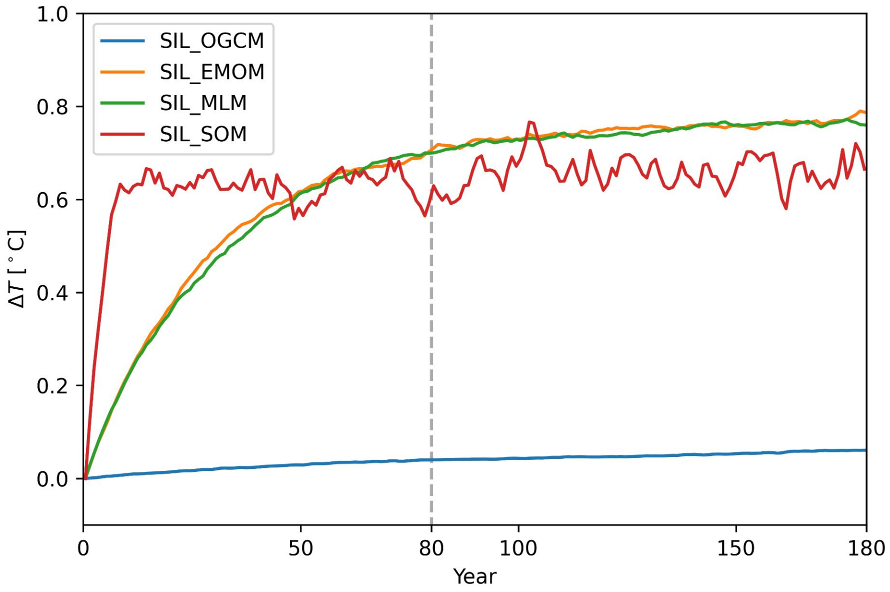
Perturbation exp: Arctic sea-ice loss (SIL)

$$F_{\text{ghost}} = \frac{L_{ice}\rho_{ice}}{\tau_{\text{nudging}}}(\text{SIT}_{\text{model}} - \text{SIT}_{\text{target}})$$

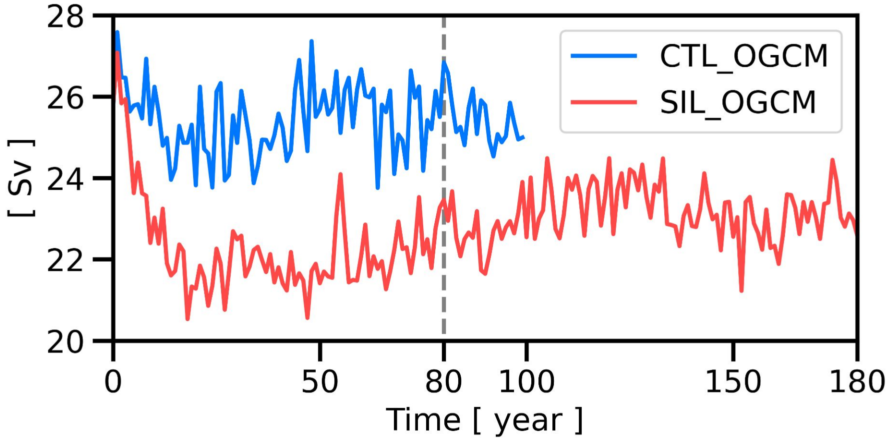
$$(\ \tau_{\text{nudging}} = 5 \text{ days}\ )$$

RCP8.5 2081-2100 years average of Arctic sea-ice thickness (SIT)

(a) Mean anomalous temperature of top 500m ocean

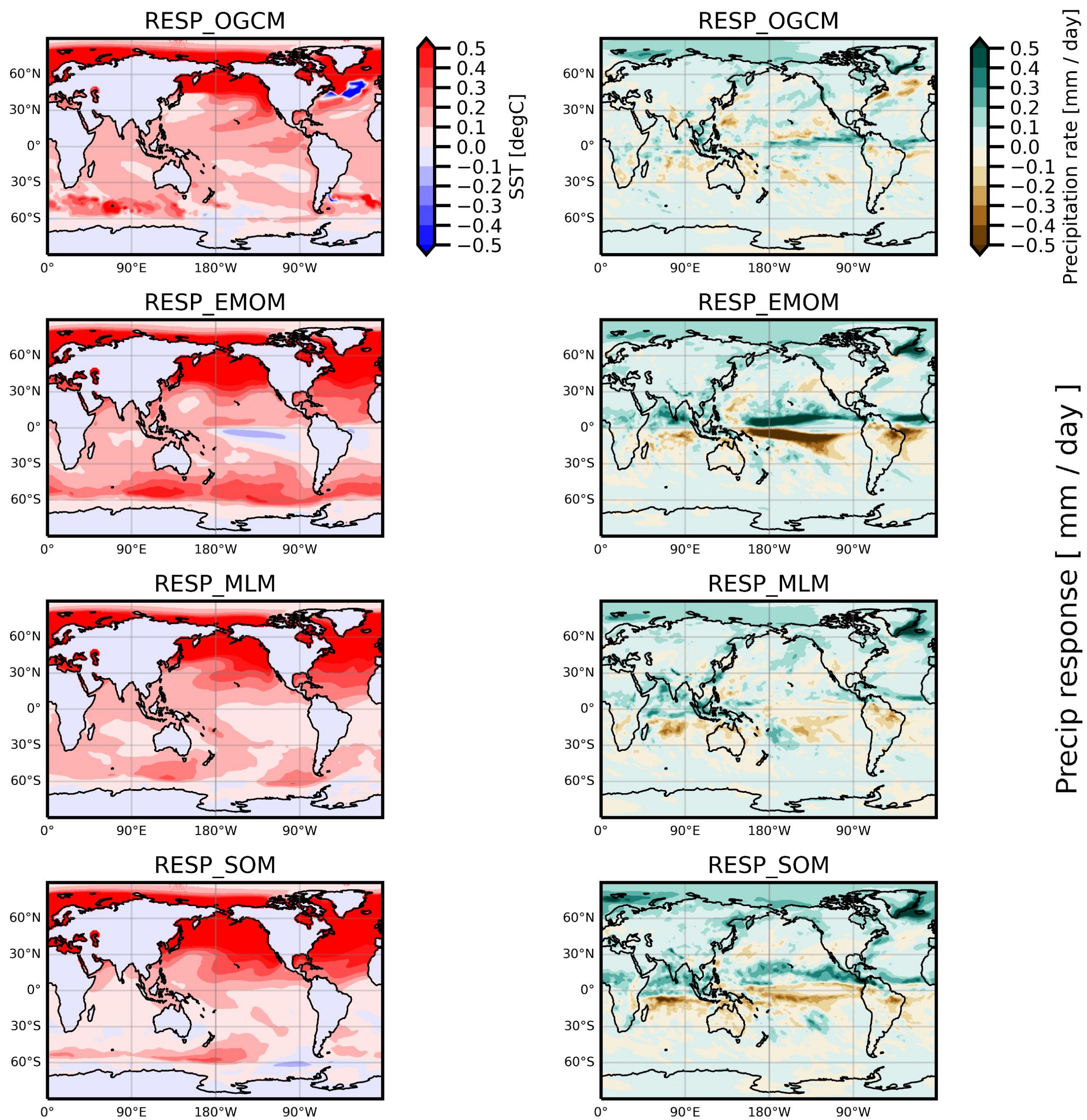


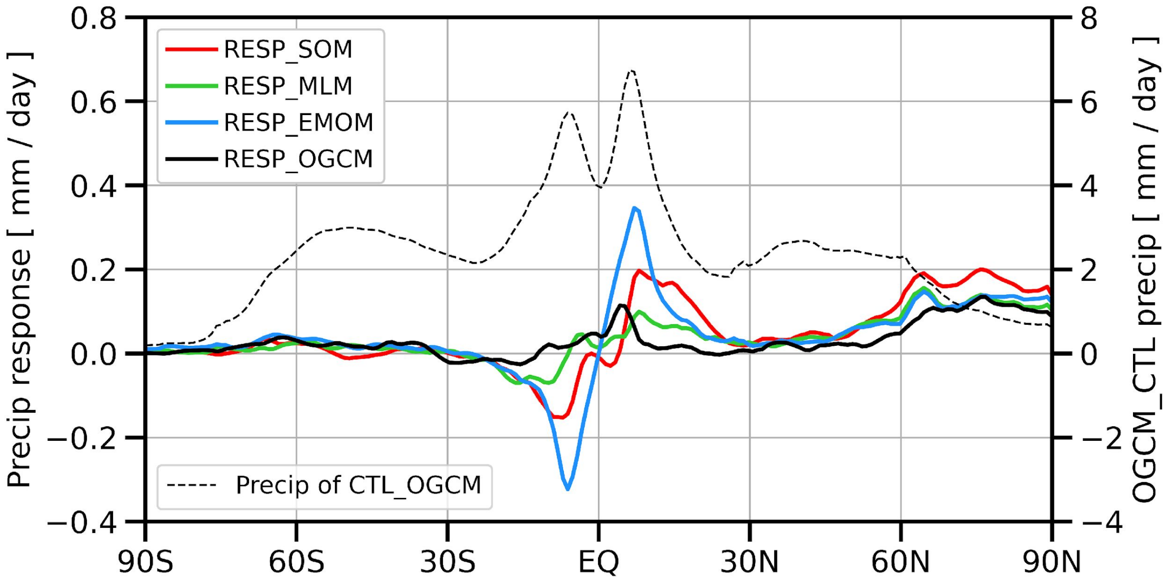
(b) AMOC's strength in OGCM



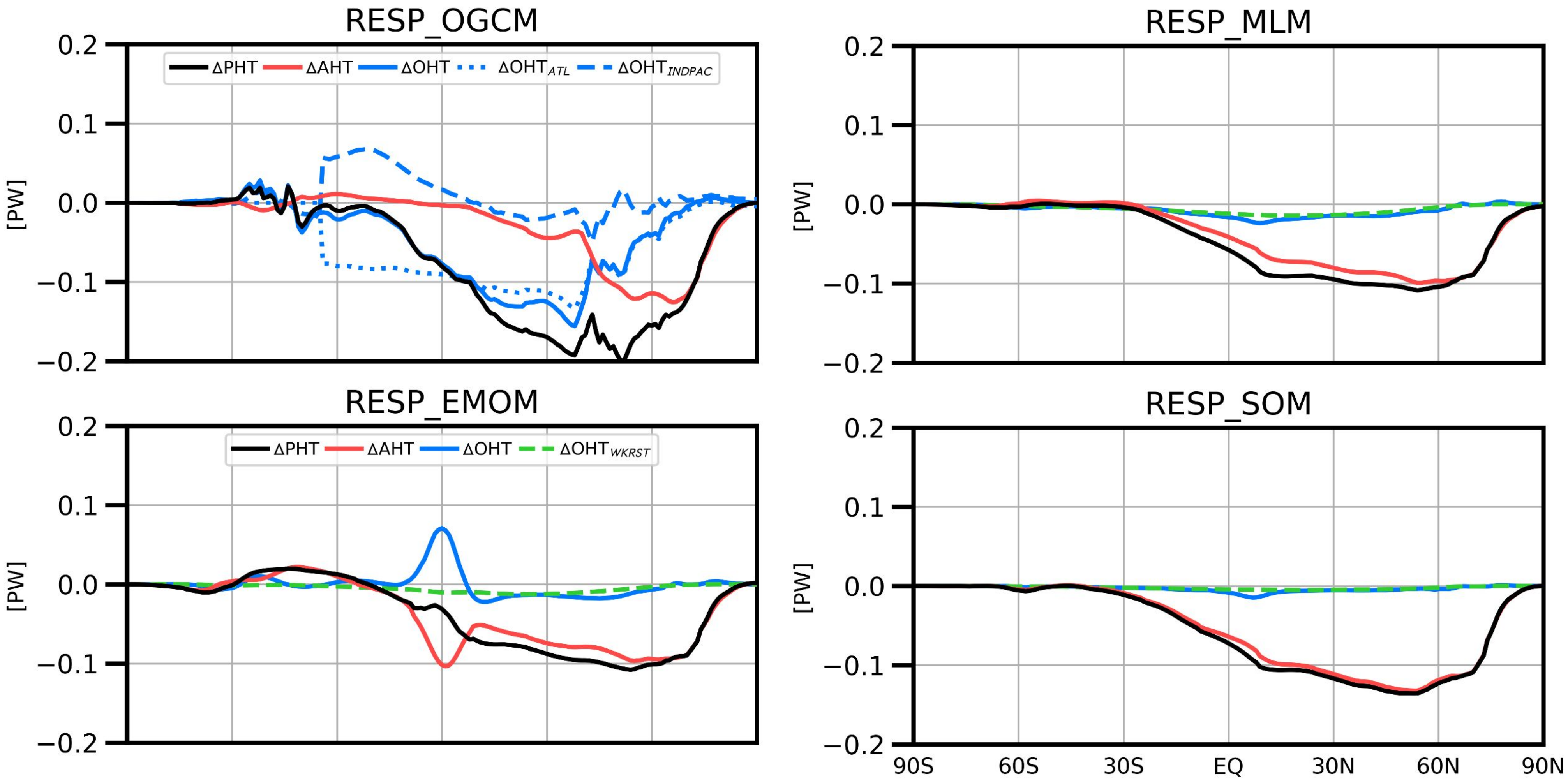
Sea-surface temperature (SST) response

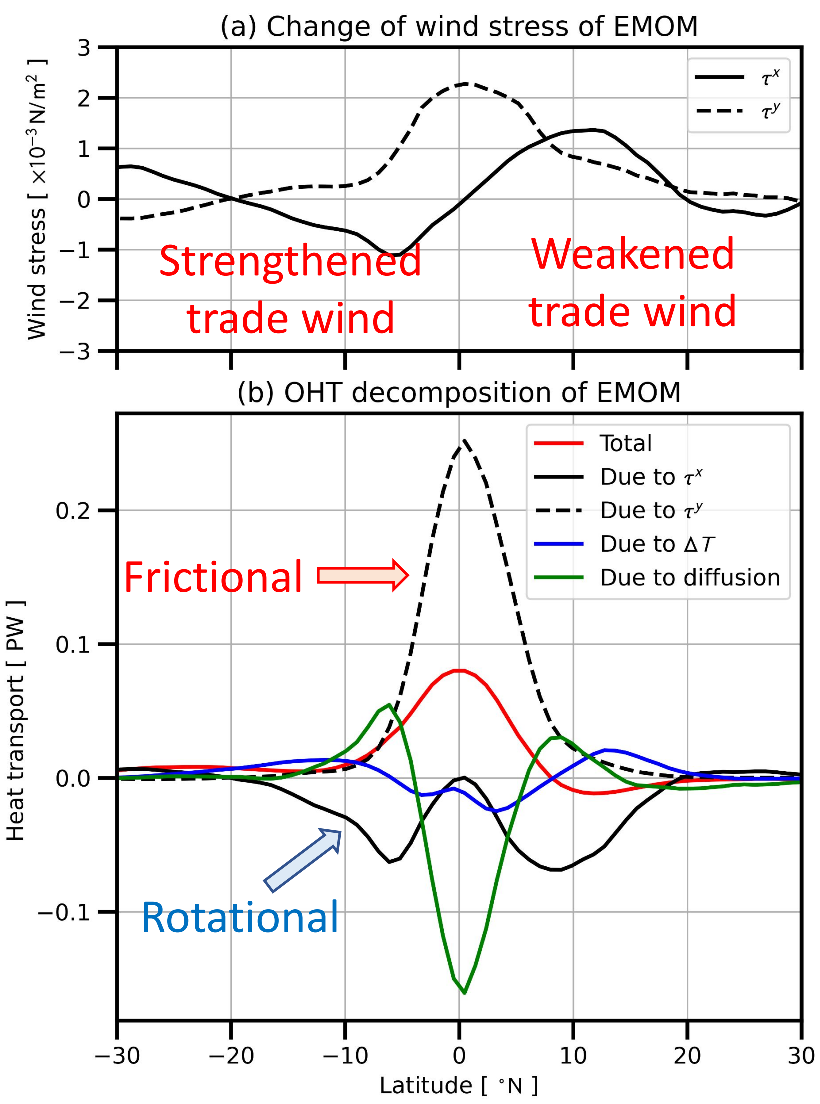
Precipitation response

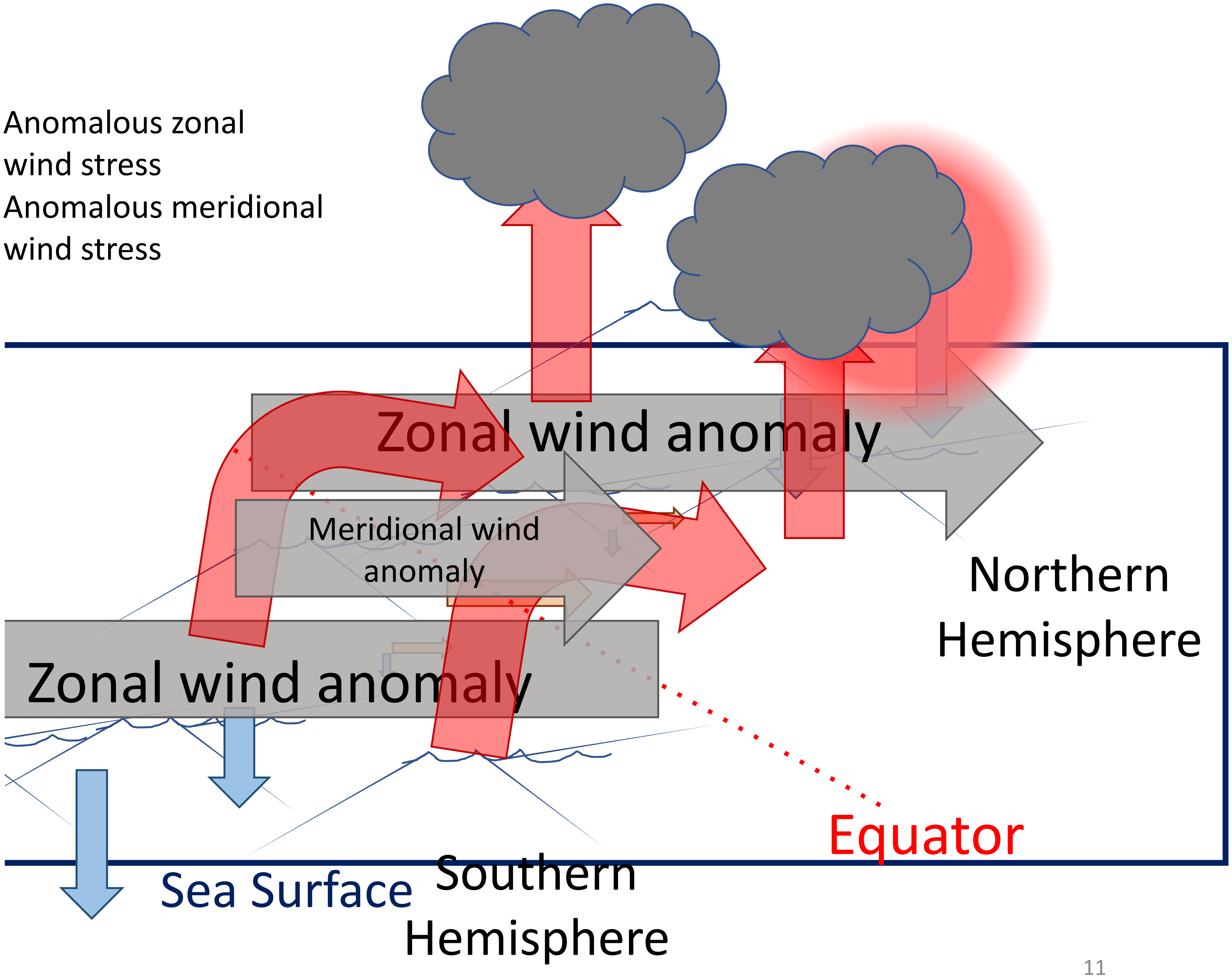


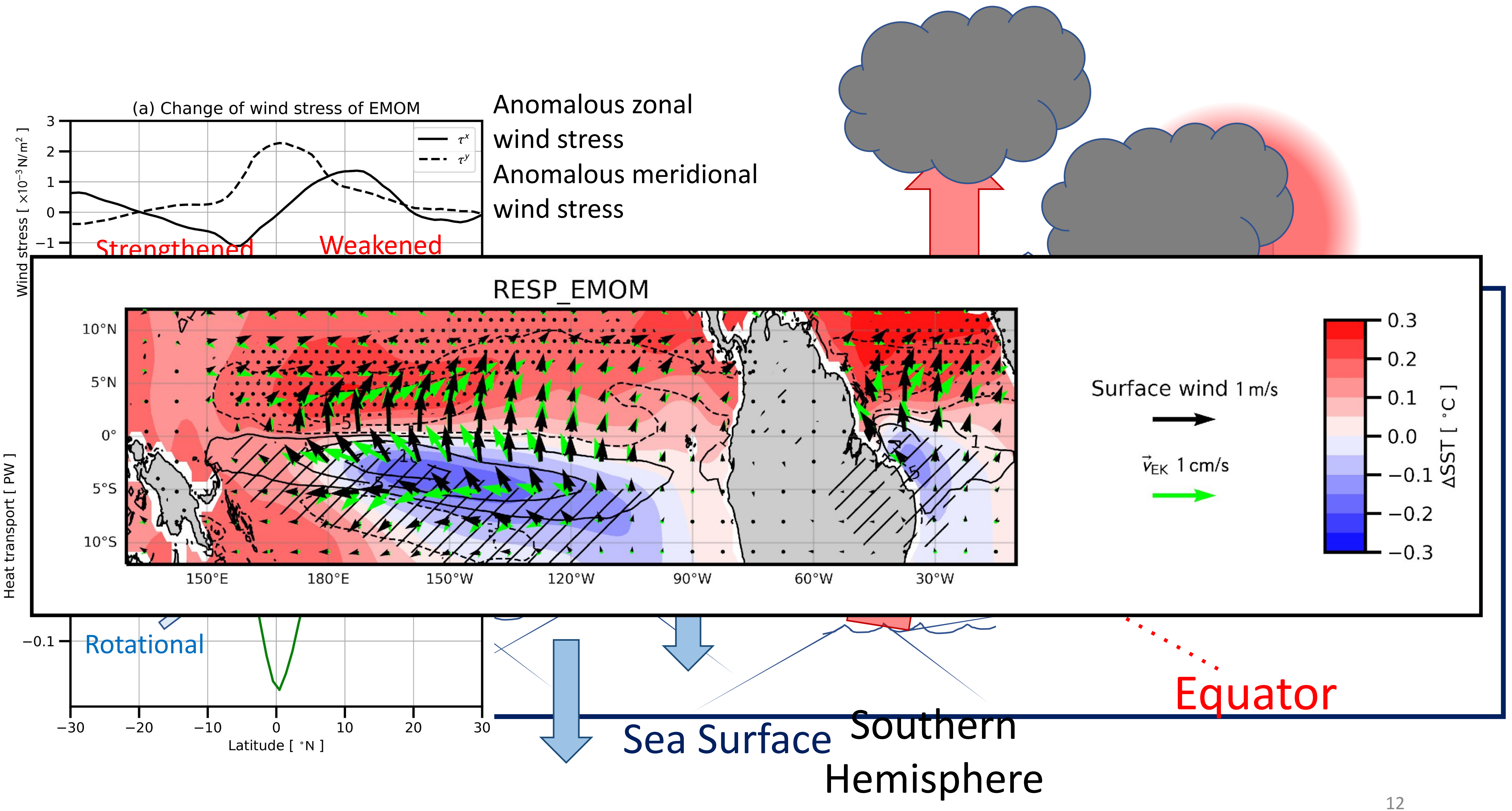


Analysis of the anomalous energy transport




(a) Change of wind stress of EMOM
Wind stress [×10^{-3} N/m^2]
τ^x
τ^y
Strengthened trade wind
Weakened trade wind
(b) OHT decomposition of EMOM
Heat transport [PW]
Total
Due to τ^x
Due to τ^y
Due to ΔT
Due to diffusion
Frictional
Rotational
Latitude [°N]


Anomalous zonal wind stress
Anomalous meridional wind stress
Zonal wind anomaly
Meridional wind anomaly
Zonal wind anomaly
Northern Hemisphere
Equator
Sea Surface
Southern Hemisphere


(a) Change of wind stress of EMOM
Wind stress [×10⁻³ N/m²]
Strengthened
Weakened
Anomalous zonal wind stress
Anomalous meridional wind stress
RESP_EMOM
10°N
5°N
0°
5°S
10°S
150°E
180°E
150°W
120°W
90°W
60°W
30°W
Surface wind 1 m/s
$\vec{v}_{EK}$ 1 cm/s
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
ΔSST [°C]
Heat transport [PW]
−0.1
Rotational
Latitude [°N]
−30
−20
−10
0
10
20
30
Sea Surface
Southern Hemisphere
Equator

Take home message.

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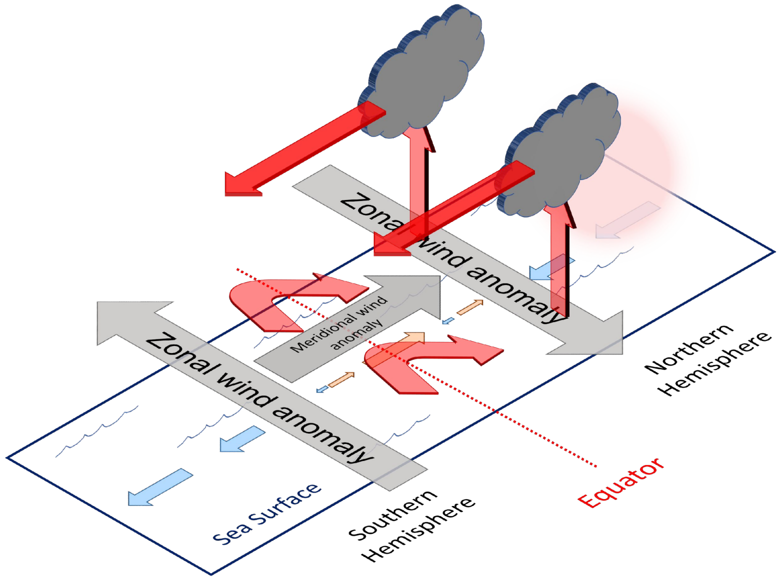
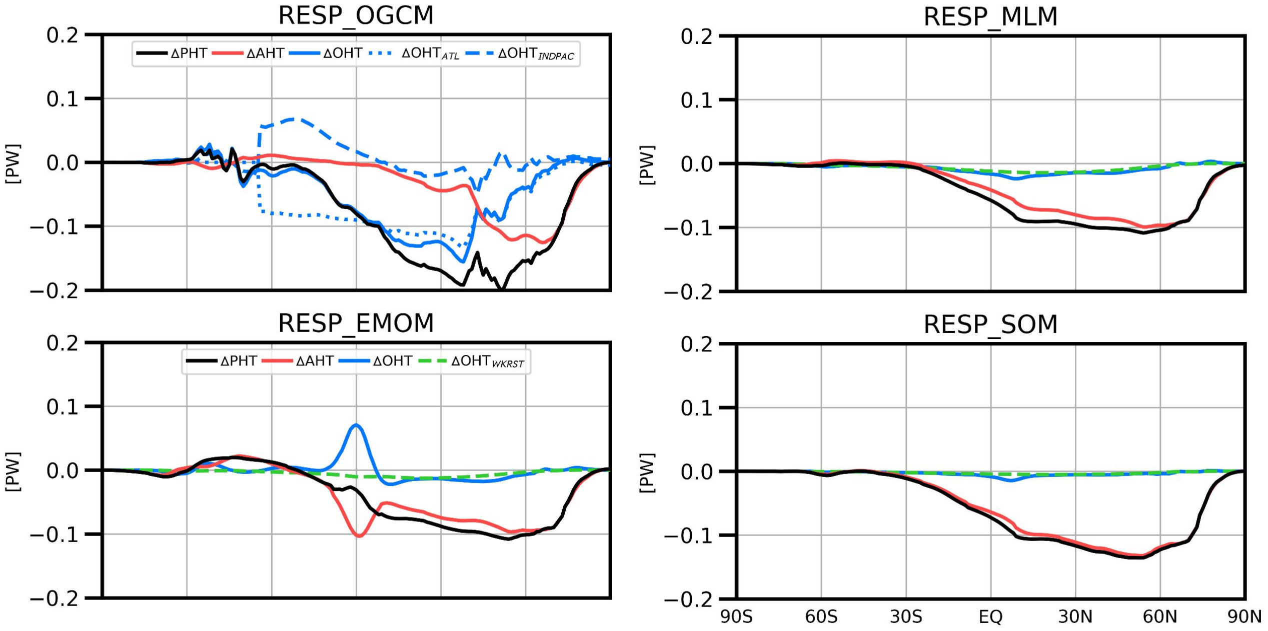
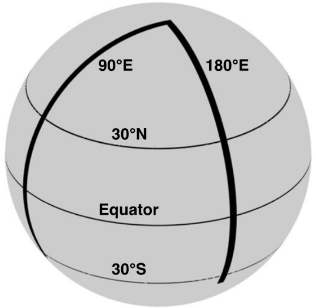
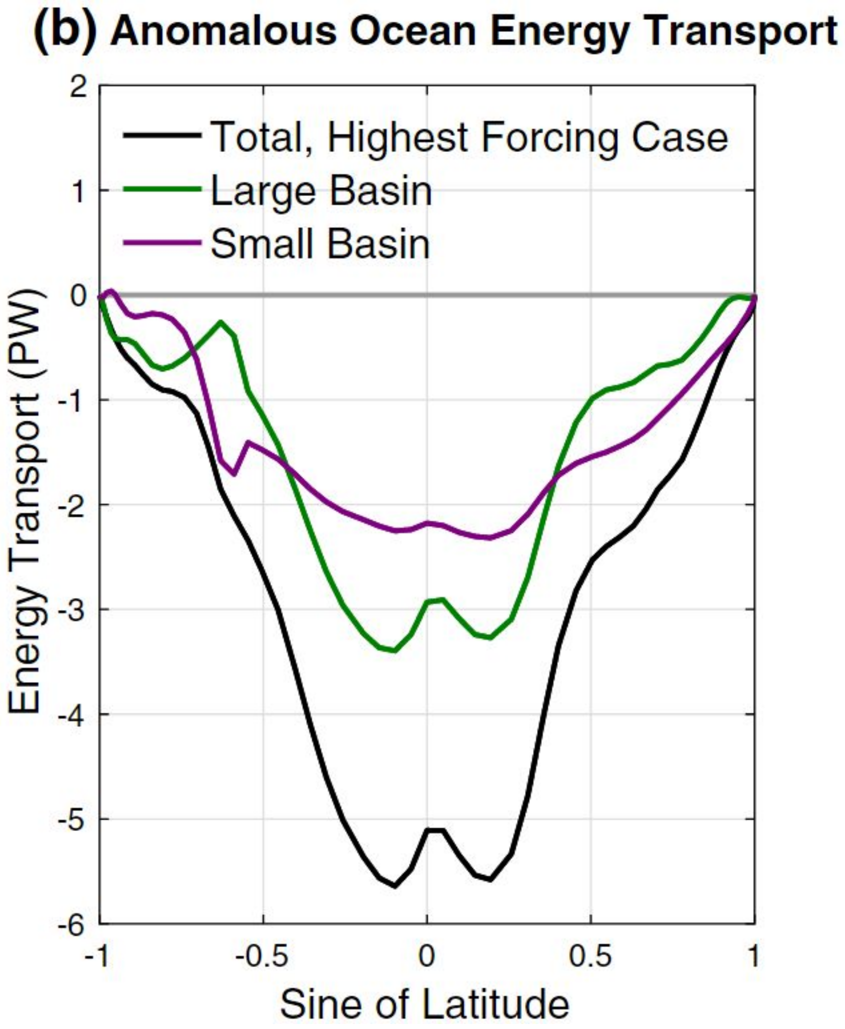
- We construct a hierarchy of ocean models that can be used in CESM1. We applied Arctic sea-ice loss to study the ocean modulation on air-sea coupling.
- In OGCM, AMOC uptake the heat strongly that ITCZ shift is inhibited.
- In EMOM, the frictional Ekman flow amplifies the ITCZ shift. The heat transport is sensitive to the thickness of Ekman layer at the equator.

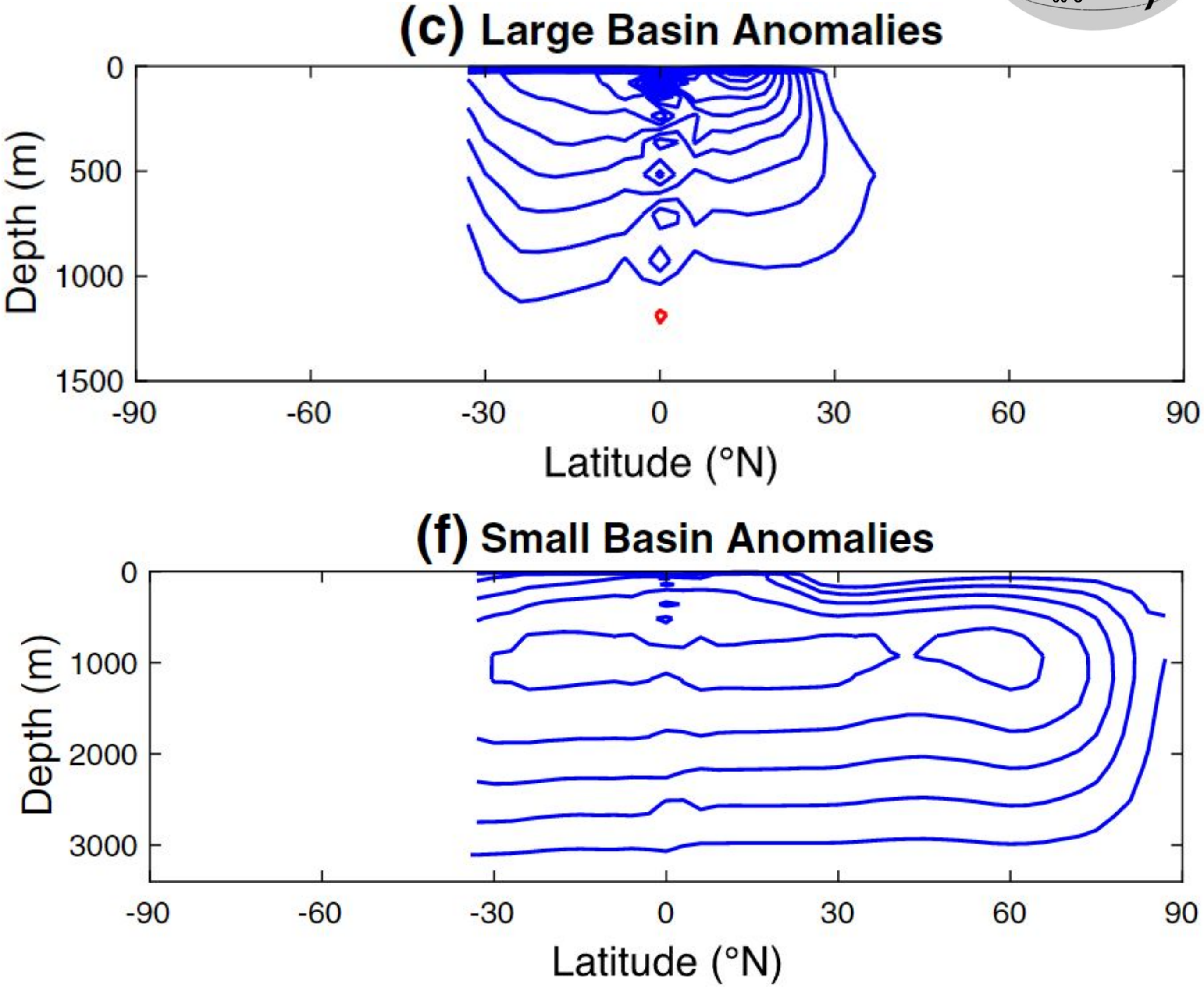




Green & Marshall (2019) Figures 9b and 5c, 5f
Forced with surface albedo
(mitgcm fully coupled, idealized topography)



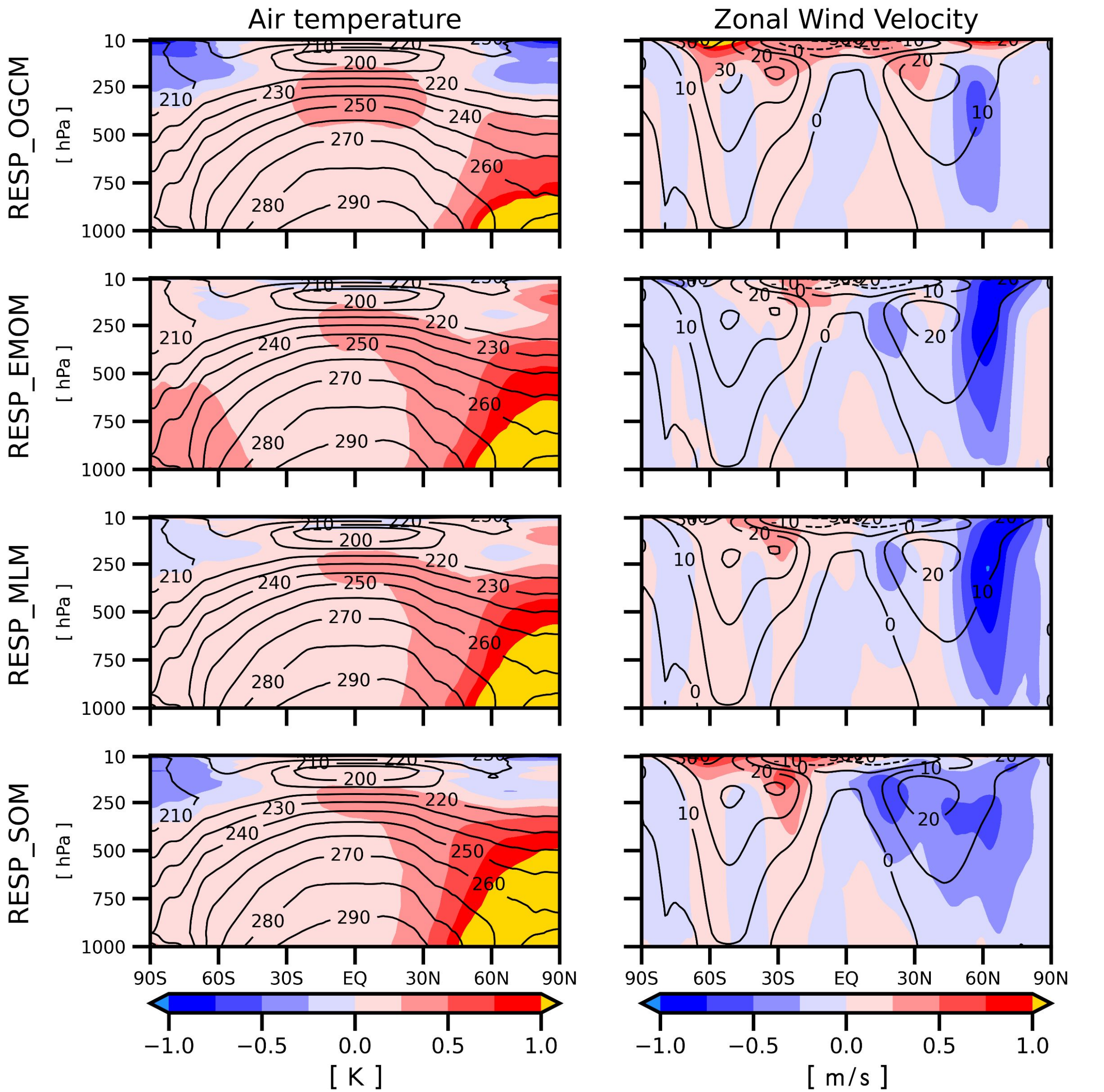




Ocean heat uptake modulates the response of the Jet

Contour: Pre-industrial run

Shading: Response to Arctic sea-ice loss



Southward shift

Southward shift and weakening

Southward shift and weakening

Overall weakening

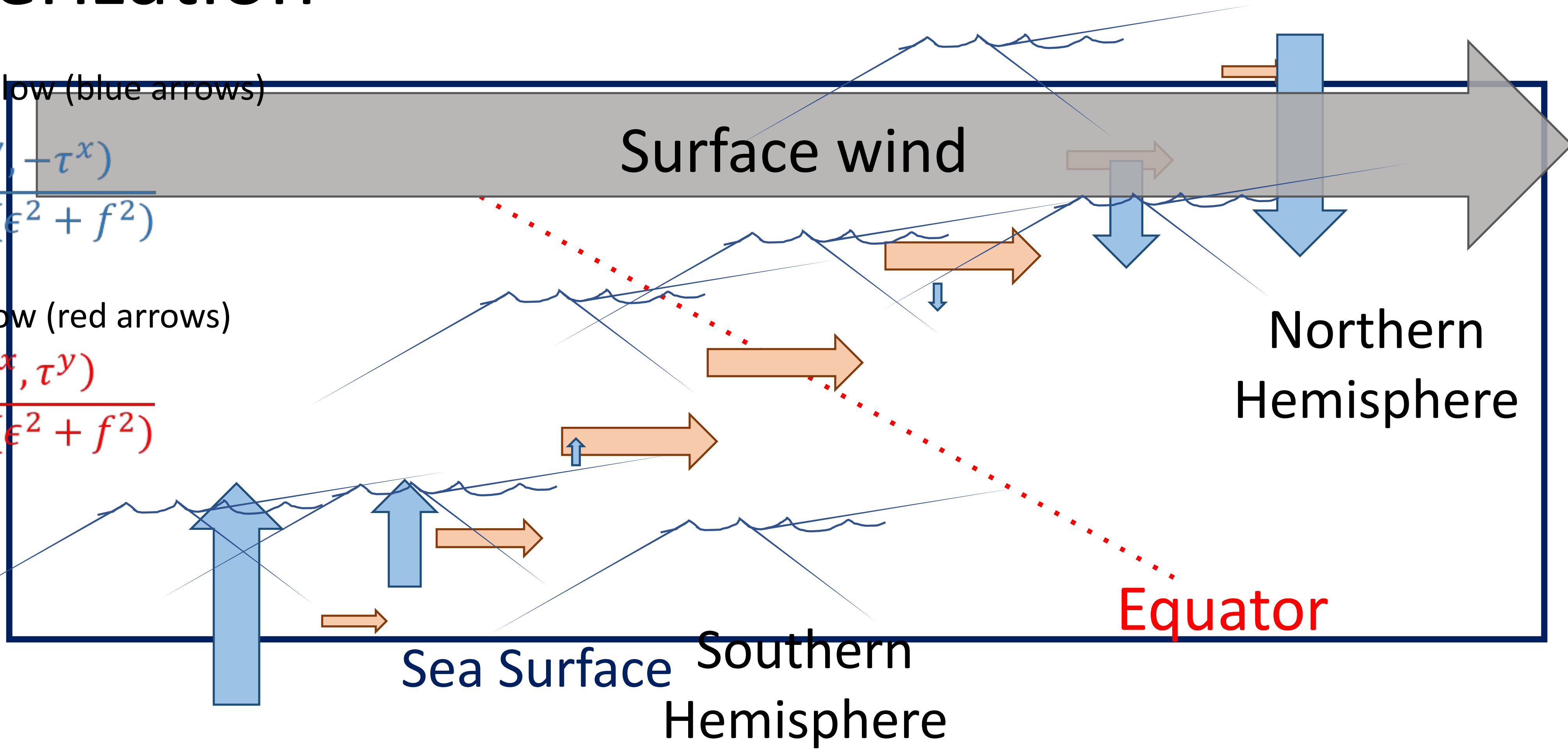
Ekman flow parameterization

Rotational Ekman Flow (blue arrows)

$$\vec{U}_r = \frac{f(\tau^y, -\tau^x)}{\rho\, H_{EK}(\epsilon^2 + f^2)}$$

Frictional Ekman Flow (red arrows)

$$\vec{U}_f = \frac{\epsilon(\tau^x, \tau^y)}{\rho\, H_{EK}(\epsilon^2 + f^2)}$$



Ekman flow parameterization

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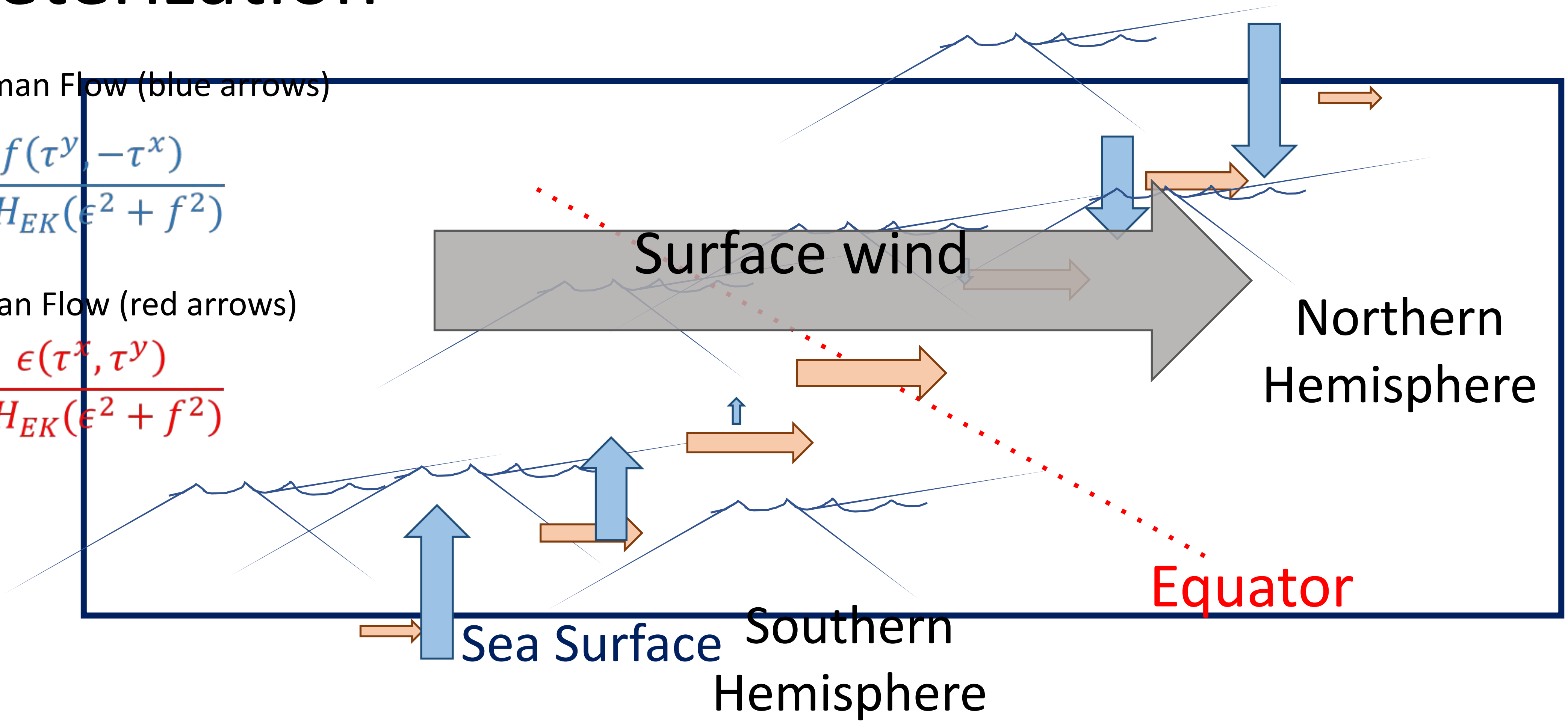


Governing equations of EMOM

Temperature Tendency — Advection — Vertical diffusion (mixed layer) — Horizontal diffusion (mixed layer)

$$\frac{\partial T}{\partial t} + \vec{\mathbf{v}}_H \cdot \nabla_H T + w\frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\left(K_V \frac{\partial T}{\partial z}\right) + \nabla_H \cdot (K_H \nabla_H T)$$

$$-\frac{1}{\rho c_p}\frac{\partial F_T}{\partial z} - \frac{1}{t_R}(T - T_{\text{clim}}) - \frac{\Lambda}{\tau_{\text{FRZ}}}(T - T_{\text{FRZ}}) + \frac{Q_T}{\rho c_p},$$

Surface fluxes — Weak restoring $t_R = 100$ yrs — Latent heat release due to freezing — Missing processes

Diagnose the Rayleigh Friction Coefficient ϵ

- Finding the most likely ϵ to explain the monthly mean vertical velocity at 50m depth between $10°\mathrm{S} - 10°\mathrm{N}$ ocean.

$$R(\epsilon) = \sum_i \left| w^i_{OGCM} - w^i_{EK} \right|^2$$

Estimation

$$w^i_{EK}(\epsilon) = H\nabla \cdot \vec{v}_{EK}(\epsilon)$$

Minimize R →

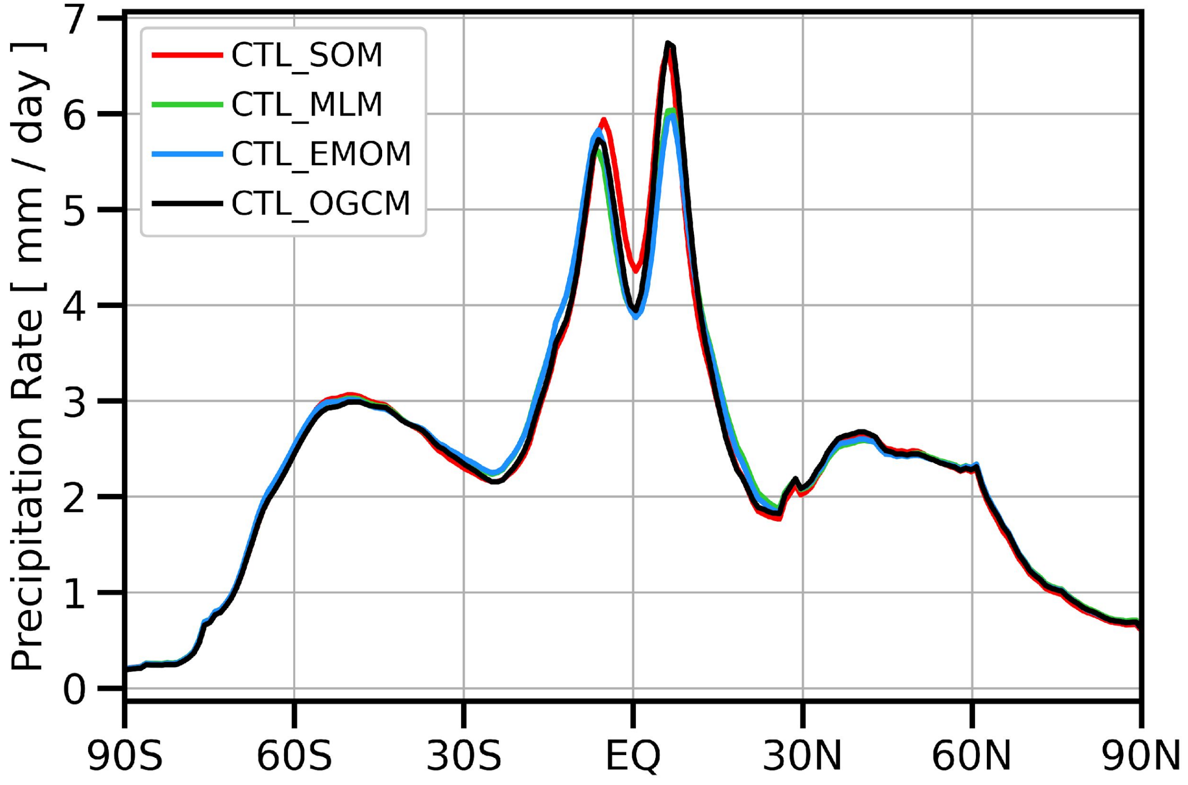
$$\epsilon^{-1} = 0.83 \text{ day}$$

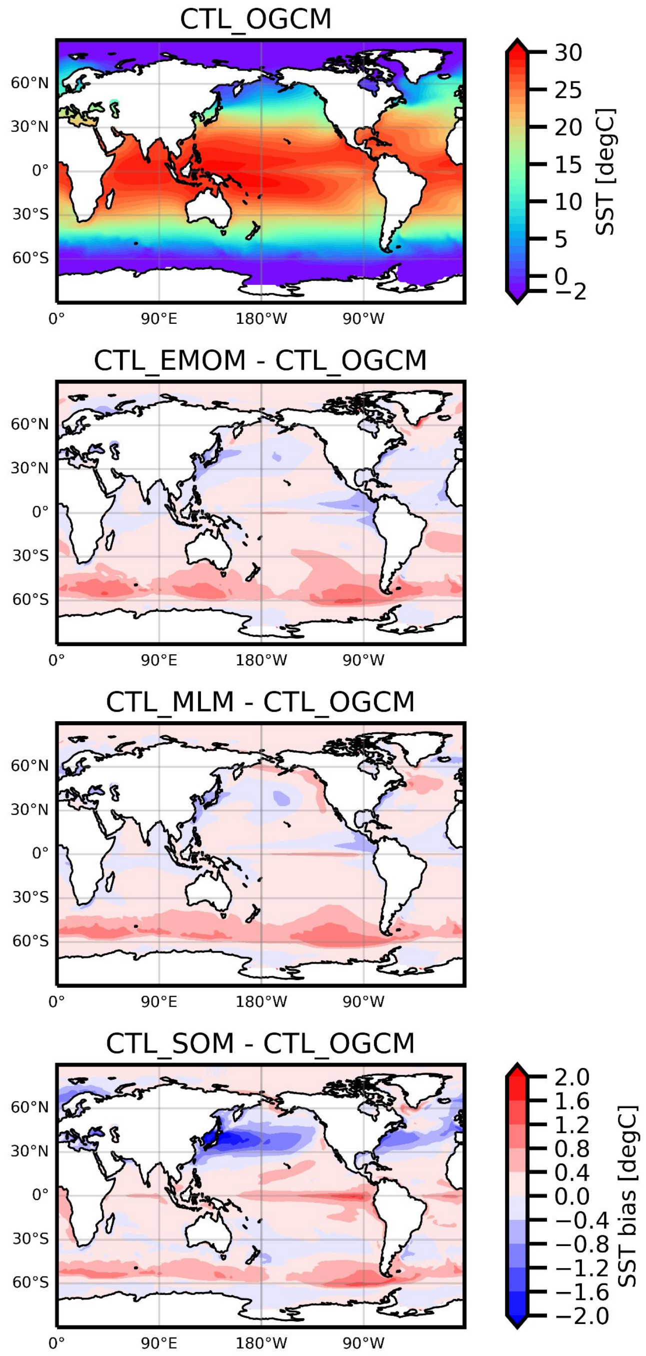
Frictional flow dominates within $5.5°\mathrm{S} \sim 5.5°\mathrm{N}$

Estimated by

$$f = 2\Omega \sin\phi = \epsilon$$

Verification of mean states
(80 years,
CTL = pre-industrial)





Verification of mean states

(80 years,
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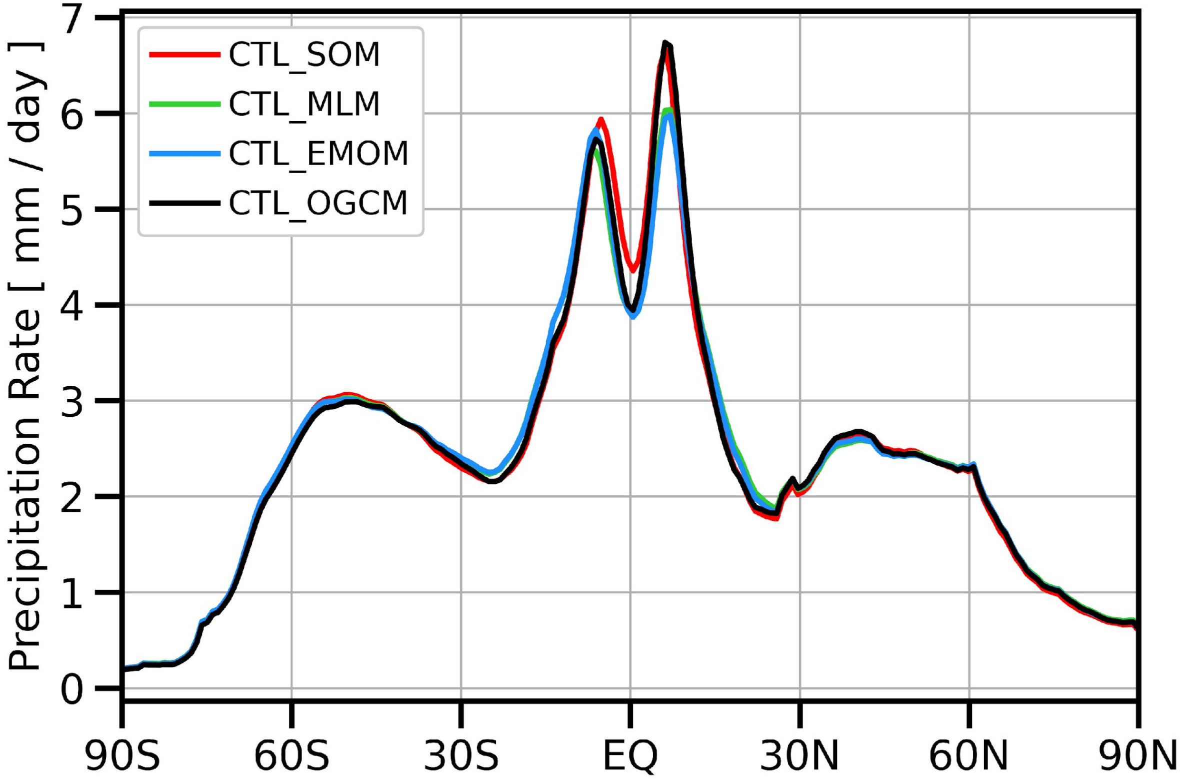
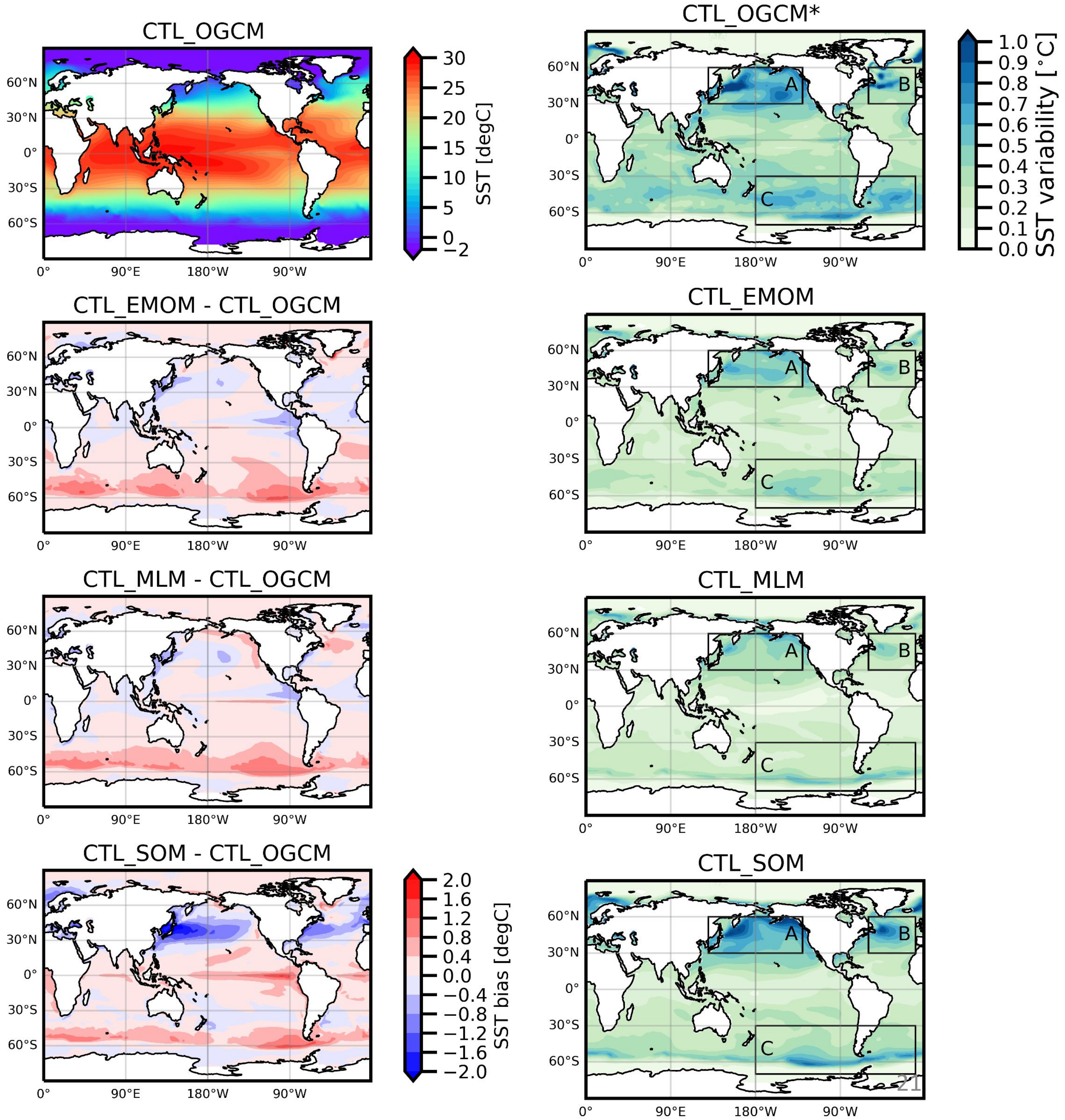
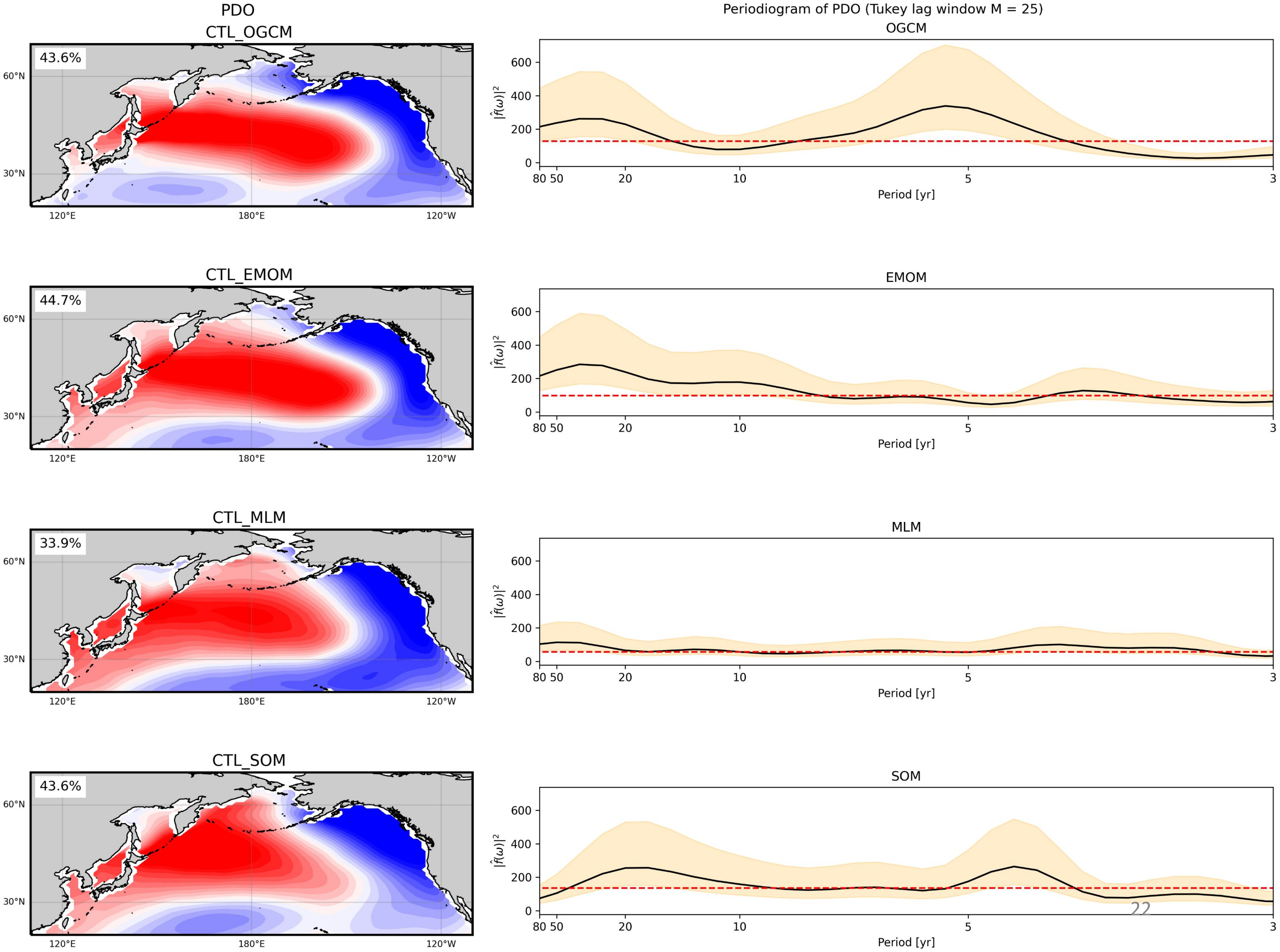
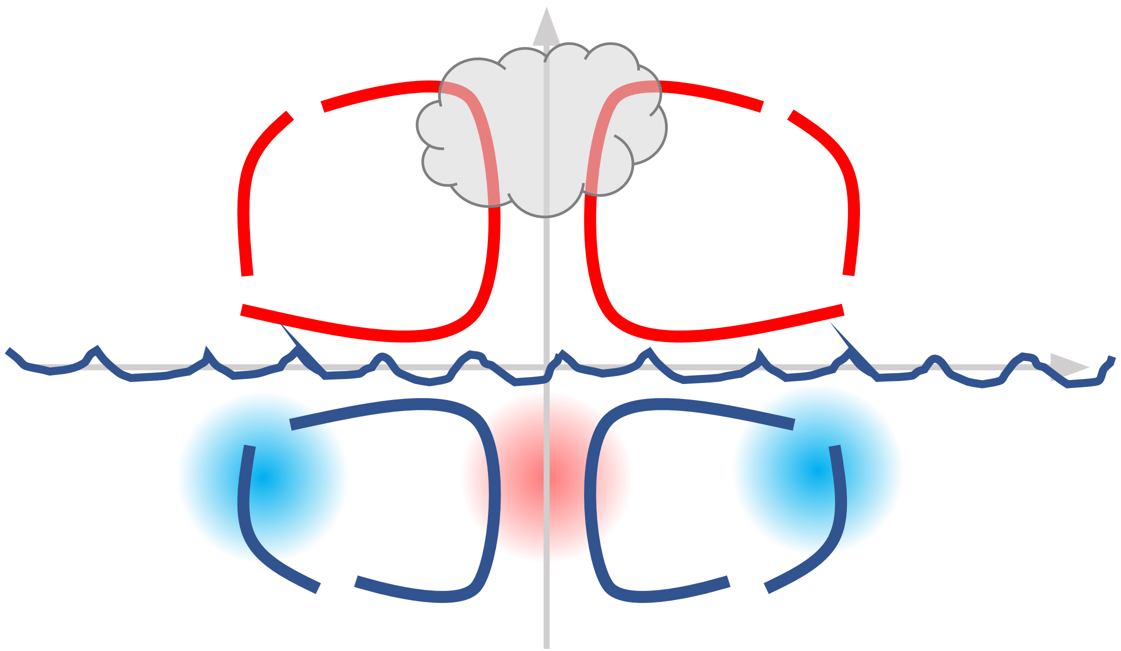




Pacific Decadal Oscillation in the Hierarchy

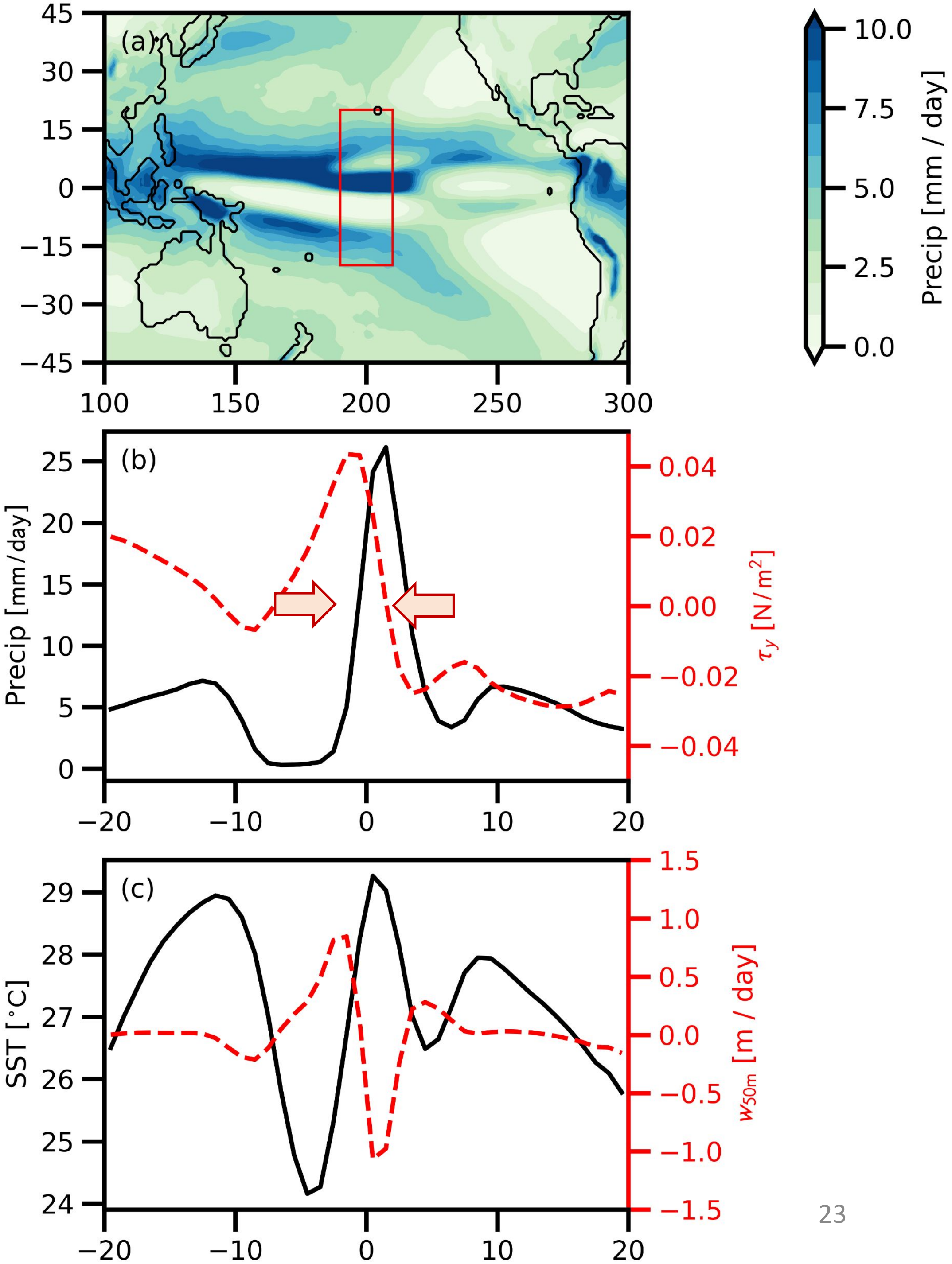


Coupled mode involving Frictional Ekman Flow



Solution: Enhanced horizontal diffusivity near the equator

$$K_H = K_0 + (K_1 - K_0)\exp\left(-\frac{\phi^2}{2\sigma_K^2}\right)\exp\left(\frac{z}{H_K}\right)$$



Deriving flux corrections (a.k.a. Q-flux)

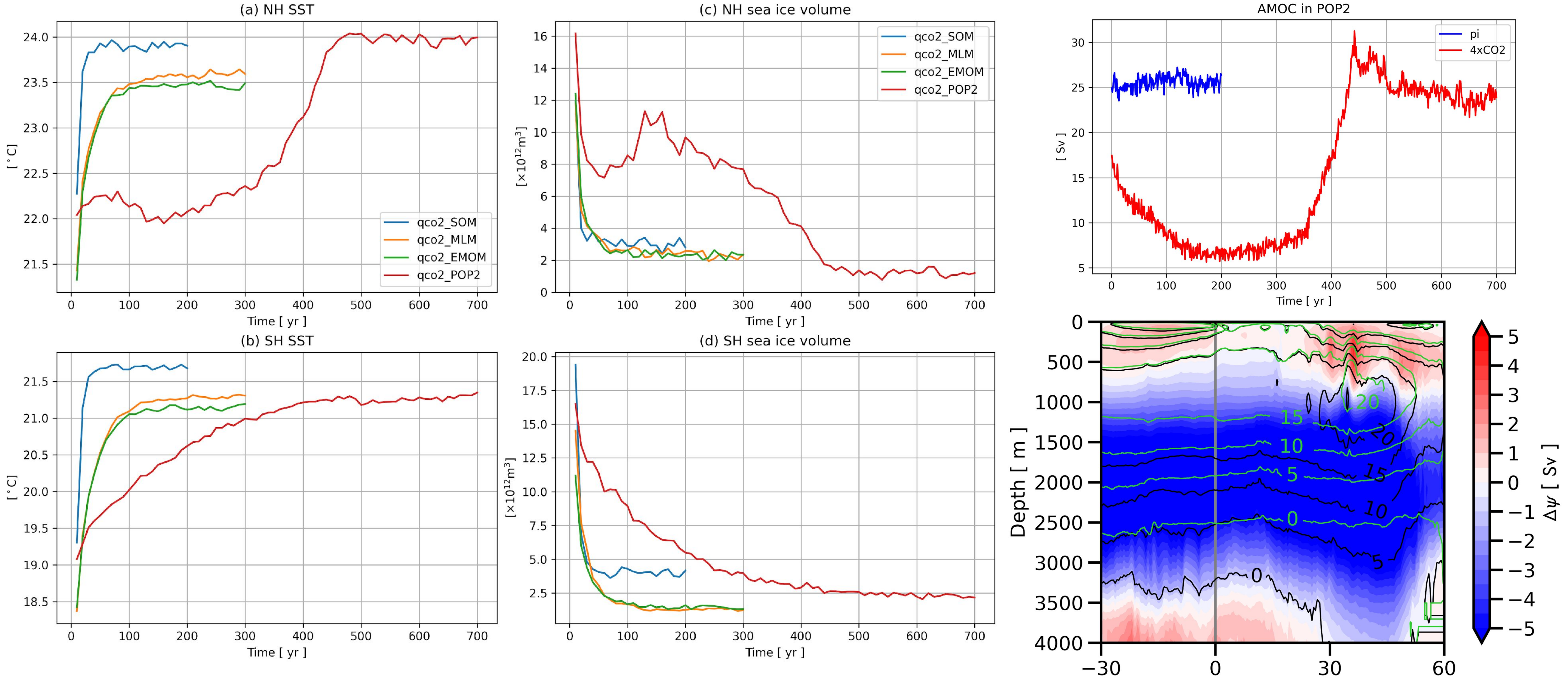
$$\frac{\partial T}{\partial t} + \vec{\mathbf{v}}_H \cdot \nabla_H T + w\frac{\partial T}{\partial z} = \frac{\partial}{\partial z}\left(K_V \frac{\partial T}{\partial z}\right) + \nabla_H \cdot (K_H \nabla_H T)$$

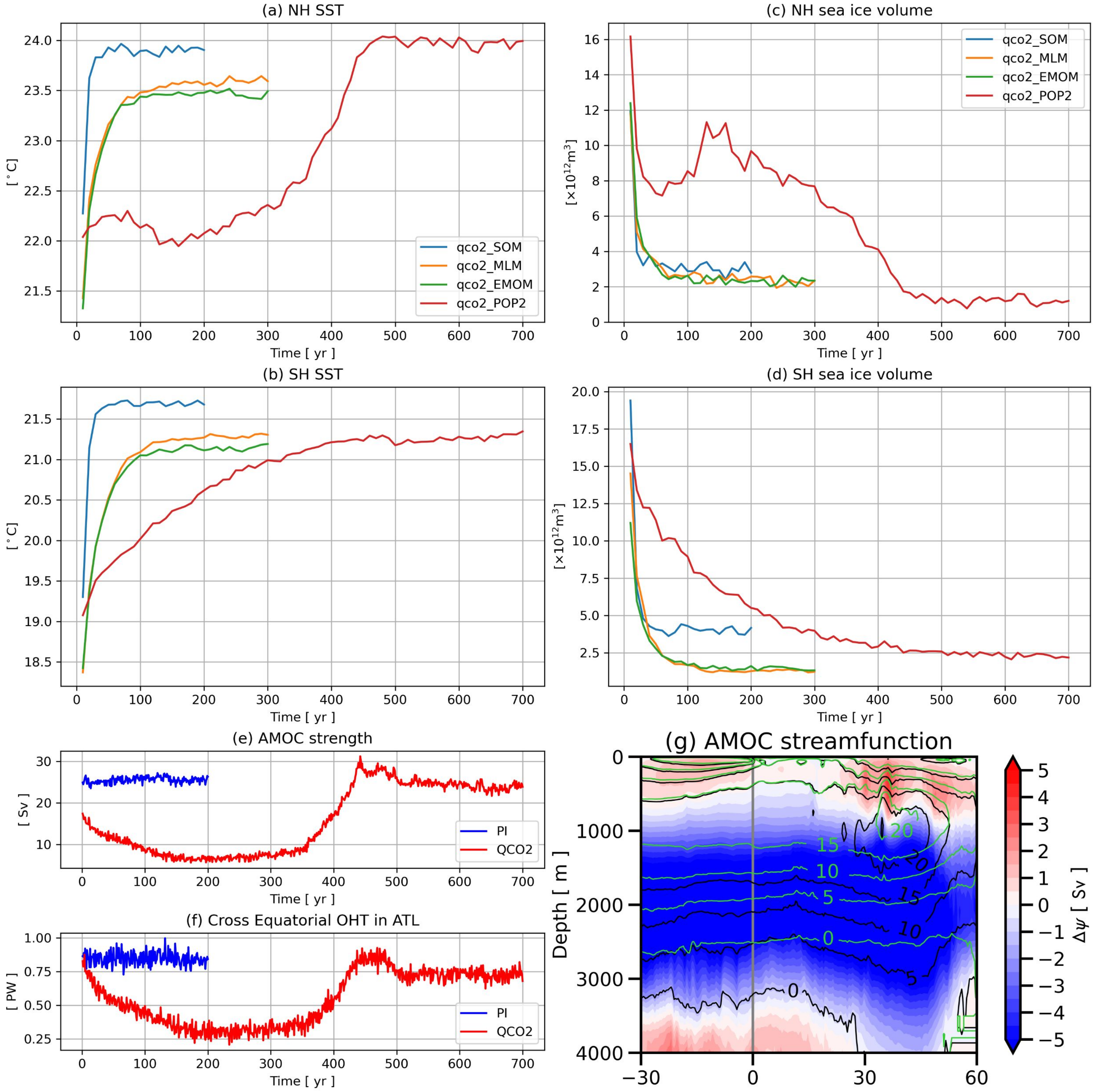
$$-\frac{1}{\rho c_p}\frac{\partial F_T}{\partial z} - \frac{1}{t_R}(T - T_{\text{clim}}) - \frac{\Lambda}{\tau_{\text{FRZ}}}(T - T_{\text{FRZ}}) + \boxed{\frac{Q_T}{\rho c_p},}$$

- Set $t_R = 15$ days, $Q_T = 0$. Run for 30 years and record the value of the relaxation term to a pre-derived climatology from the fully-coupled model.
- The recorded value of relaxation term will assign to Q_T in the normal run.

Informative discussion with Dr. Young-Oh Kwon

Perturbation exp: Quadruple CO_2 (287 ppm => 1148 ppm)

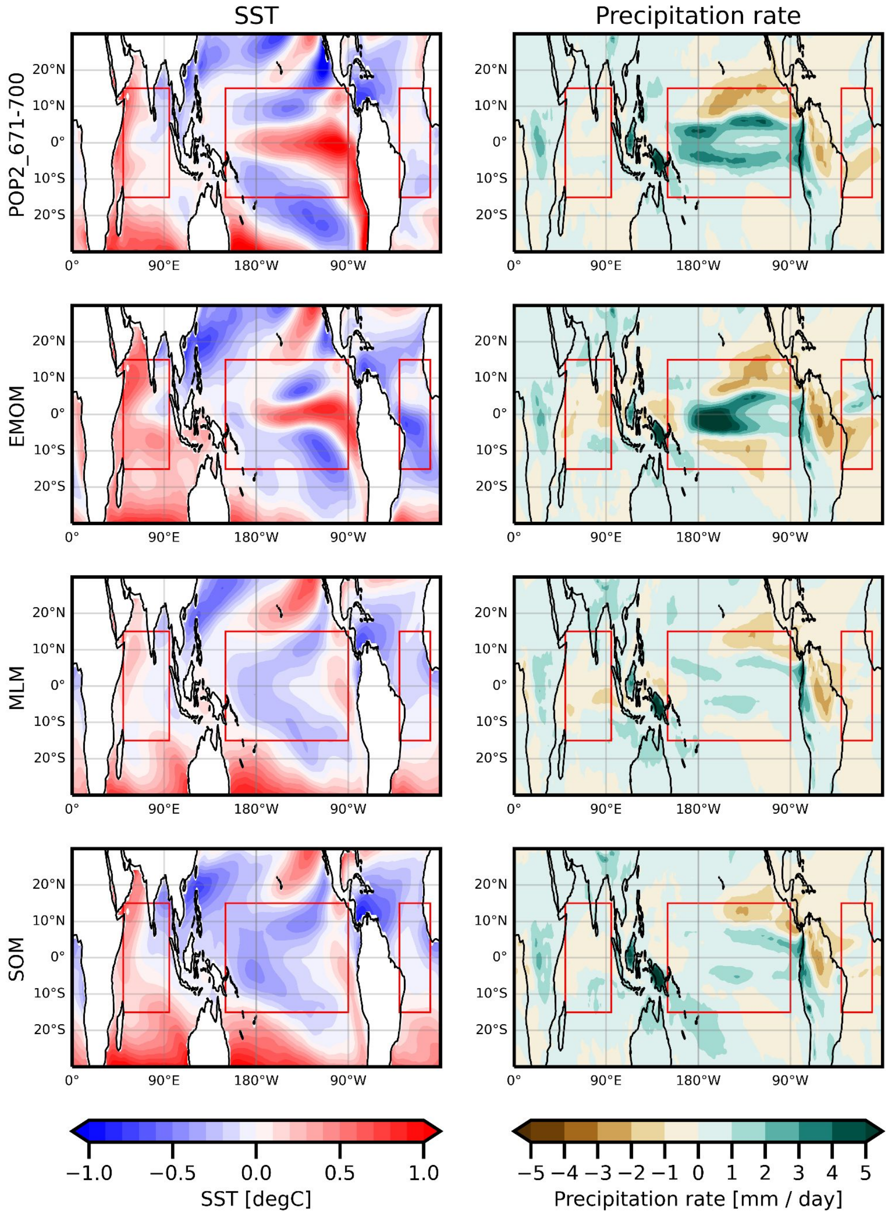


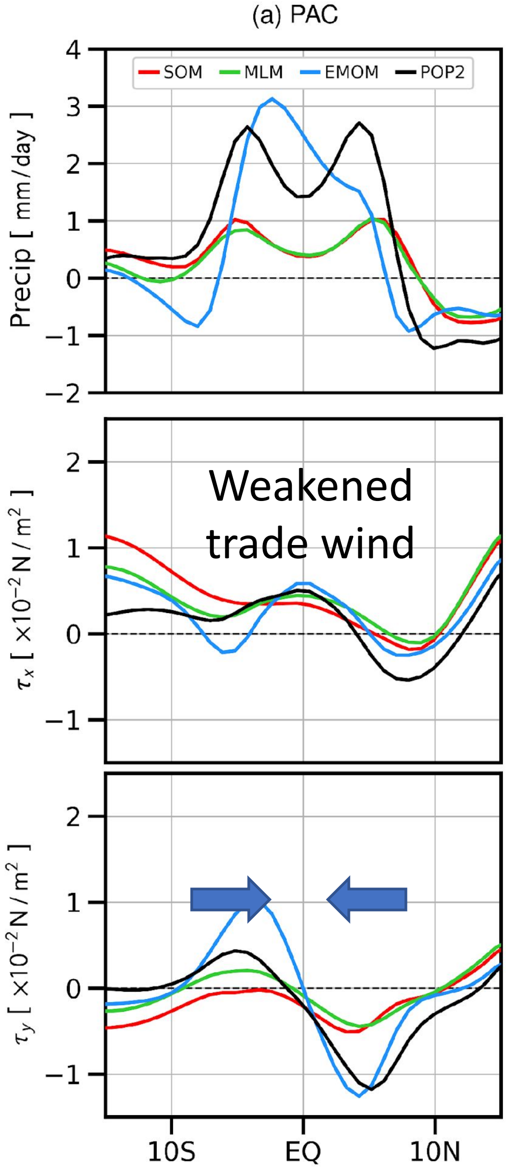


(a) NH SST
[°C]
Time [yr]
qco2_SOM
qco2_MLM
qco2_EMOM
qco2_POP2
(c) NH sea ice volume
[×10^12 m^3]
Time [yr]
(b) SH SST
[°C]
Time [yr]
(d) SH sea ice volume
[×10^12 m^3]
Time [yr]
(e) AMOC strength
[Sv]
PI
QCO2
Time [yr]
(f) Cross Equatorial OHT in ATL
[PW]
PI
QCO2
Time [yr]
(g) AMOC streamfunction
Depth [m]
Δψ [Sv]

Anomalous

Anomalous





Anomalous precipitation

Anomalous zonal wind

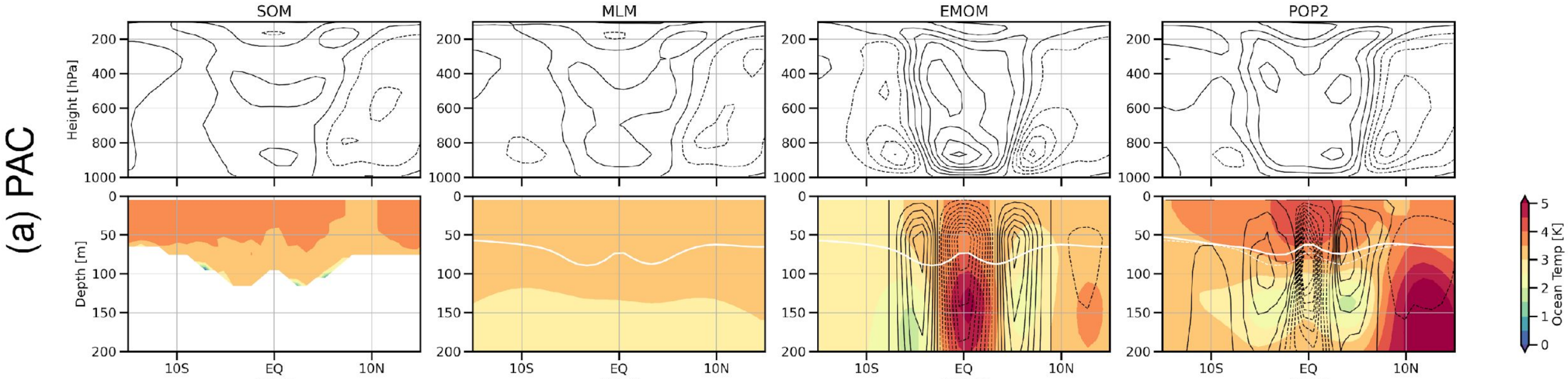
Anomalous meridional wind

Upper panel:

- Contour = anomalous vertical velocity

Lower panel:

- Black Contour = anomalous vertical velocity
- White contour = Mixed layer in CTL (solid) and 4xCO_2 (dashed)
- Shading = anomalous ocean temperature



Upper panel:

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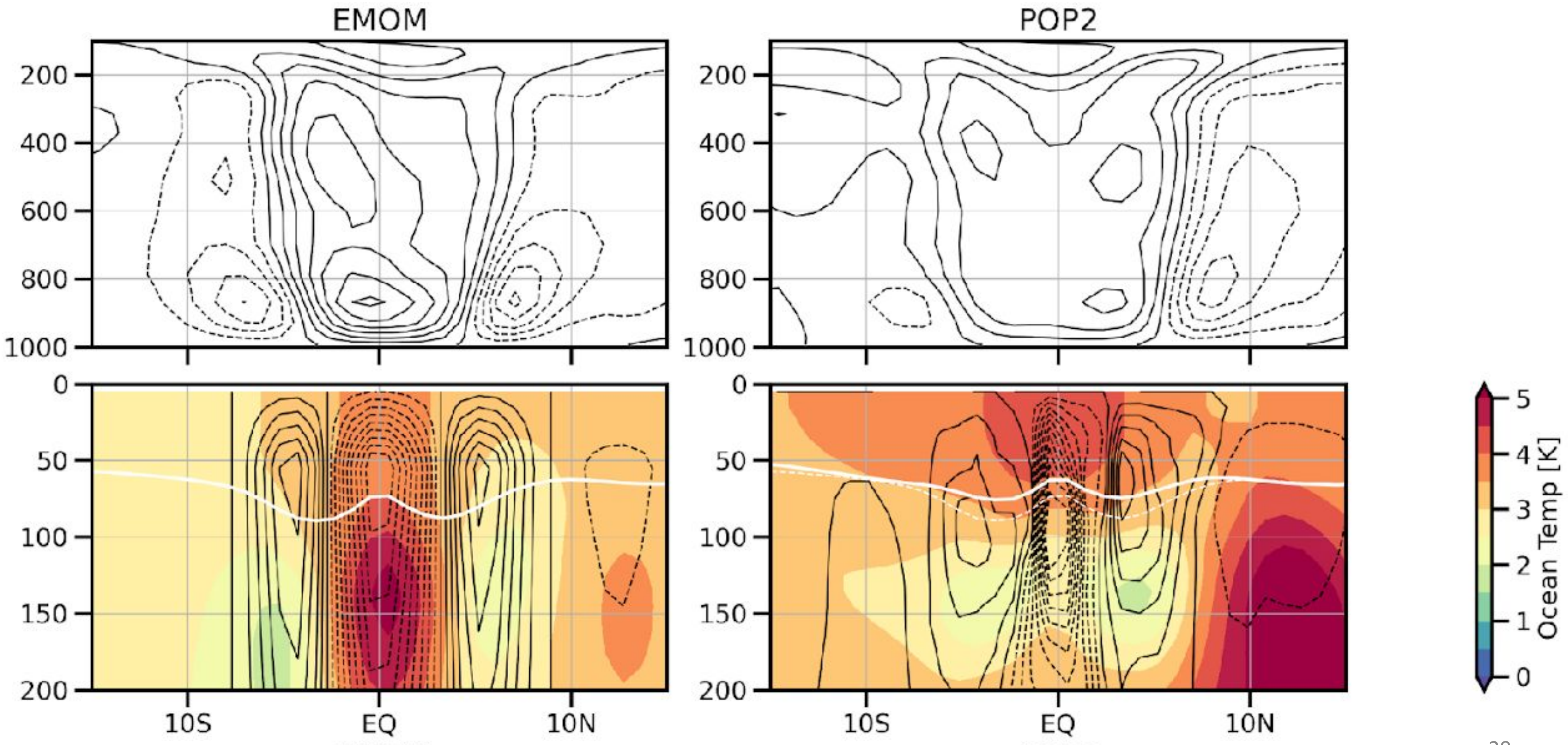
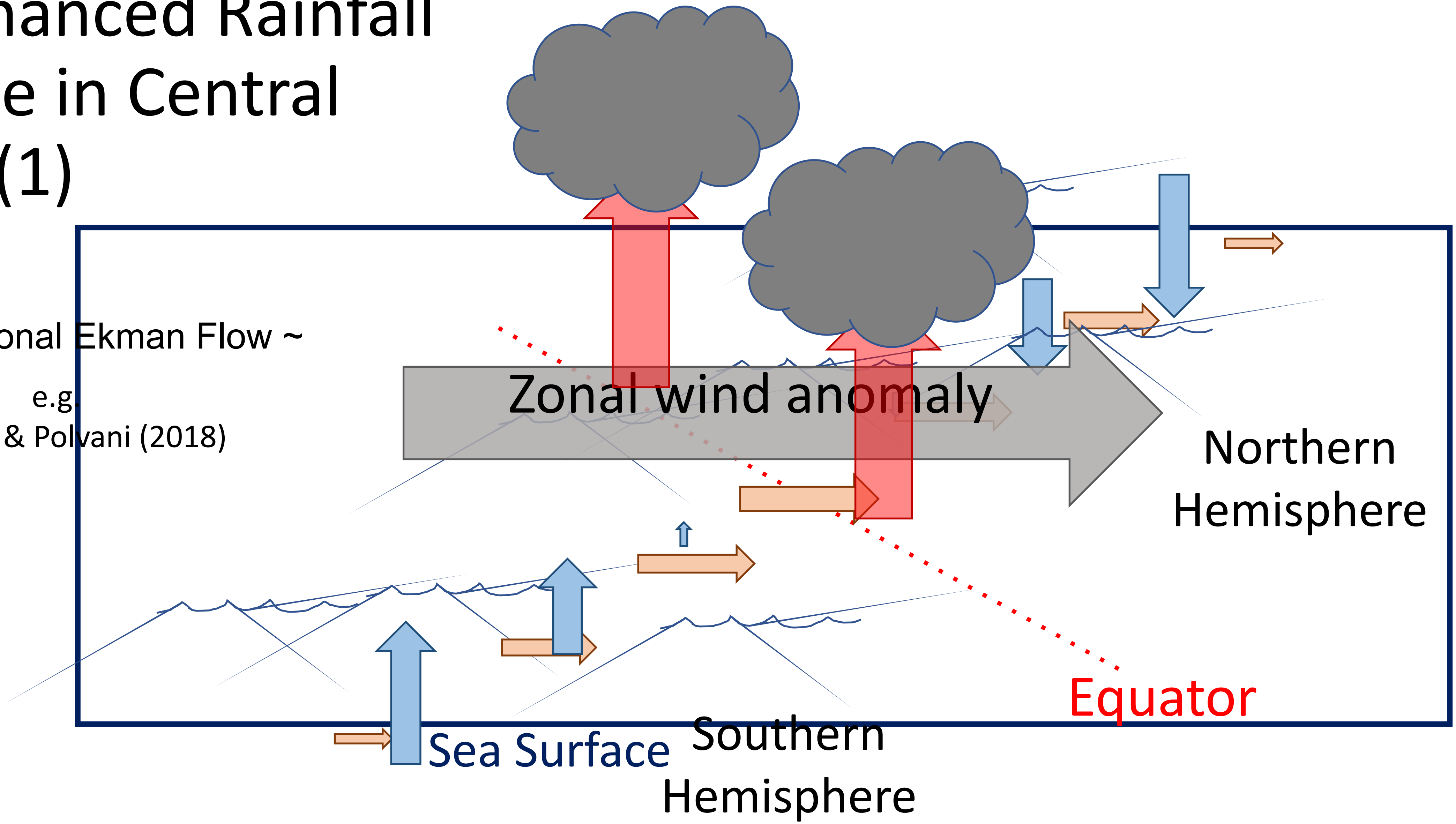


Why Enhanced Rainfall Response in Central Pacific? (1)

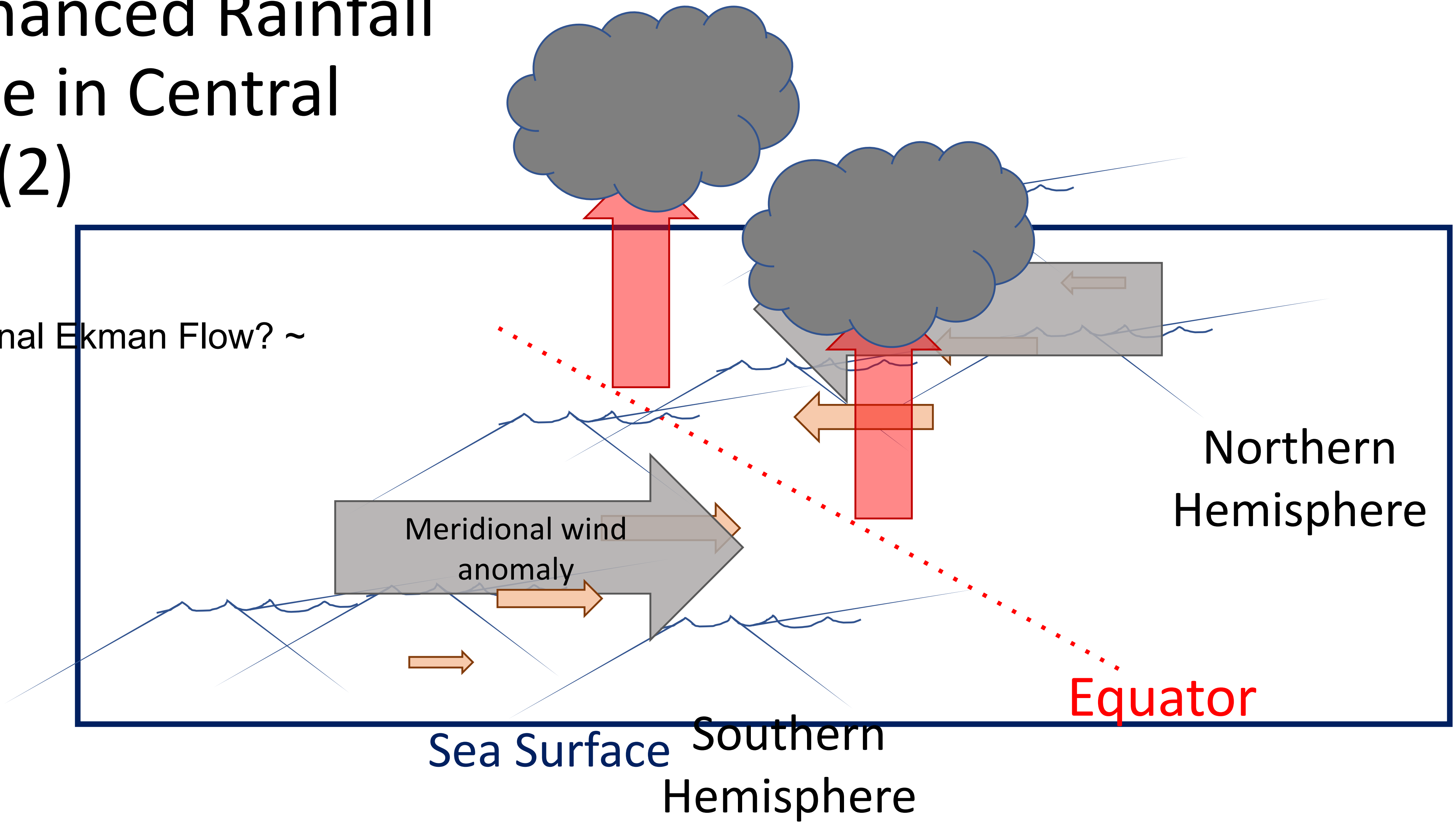
~ Rotational Ekman Flow ~

e.g.
Chemke & Polvani (2018)



Why Enhanced Rainfall Response in Central Pacific? (2)

~ Frictional Ekman Flow? ~



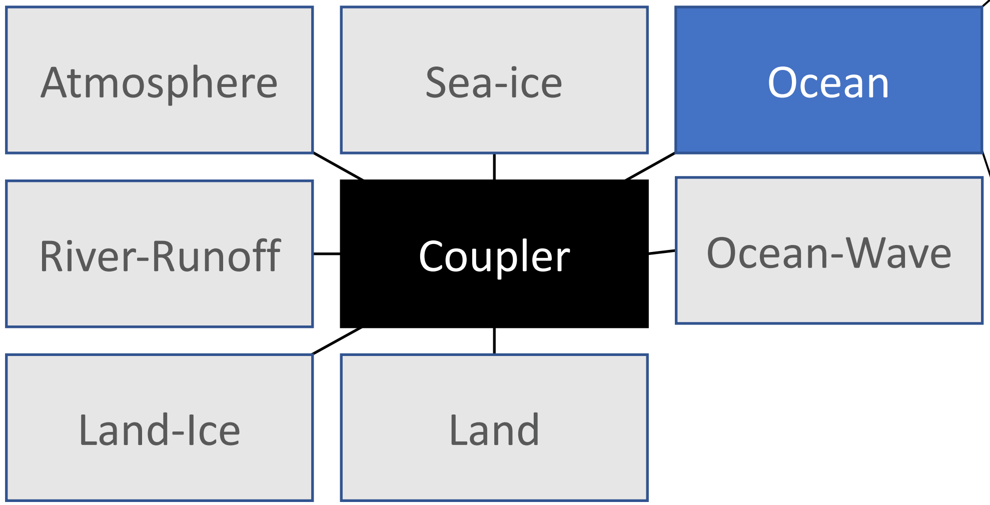
Take home message

- The EMOM hierarchy can capture tropical large-scale features to quadrupling $\mathrm{CO_2}$ once the effect of AMOC dissipates.

- The Ekman coupling amplifies the tropical rainfall response. Both the rotational and frictional Ekman flow contribute.

- The modulation of Ekman flow is sensitive to the vertical location of upwelling and the subsurface horizontal diffusivity of temperature.

Architecture of CESM1



(Fortran)

DOCN (docn_comp_mod.F90)

Slab ocean model snippet (less than 40 lines)

```
   case('SOM')
      lsize = mct_avect_lsize(o2x)
      do n = 1,SDOCN%nstreams
         call shr_dmodel_translateAV(SDOCN%avs(n),avstrm,avifld,avofld,rearr)
      enddo
      if (firstcall) then
         do n = 1,lsize
            if (.not. read_restart) then
               somtp(n) = o2x%rAttr(kt,n) + TkFrz
            endif
            o2x%rAttr(kt,n) = somtp(n)
            o2x%rAttr(kq,n) = 0.0_r8
         enddo
      else   ! firstcall
         do n = 1,lsize
         if (imask(n) /= 0) then
            !--- pull out h from av for resuse below ---
            hn = avstrm%rAttr(kh,n)
            !--- compute new temp ---
            o2x%rAttr(kt,n) = somtp(n) + &
               (x2o%rAttr(kswnet,n) + &  ! shortwave
                x2o%rAttr(klwup ,n) + &  ! longwave
                x2o%rAttr(klwdn ,n) + &  ! longwave
                x2o%rAttr(ksen  ,n) + &  ! sensible
                x2o%rAttr(klat  ,n) + &  ! latent
                x2o%rAttr(kmelth,n) - &  ! ice melt
                avstrm%rAttr(kqbot ,n) - &  ! flux at bottom
                (x2o%rAttr(ksnow,n)+x2o%rAttr(kioff,n))*latice) * &  ! latent by prec and roff
                dt/(cpsw*rhosw*hn)
             !--- compute ice formed or melt potential ---
            o2x%rAttr(kq,n) = (TkFrzSw - o2x%rAttr(kt,n))*(cpsw*rhosw*hn)/dt  ! ice formed q>0
            o2x%rAttr(kt,n) = max(TkFrzSw,o2x%rAttr(kt,n))                    ! reset temp
            somtp(n) = o2x%rAttr(kt,n)                                        ! save temp
         endif
         enddo
      endif   ! firstcall

   end select
```

Reading stream files (ex: q-flux)

Initialize

Mixed-layer depth

SST

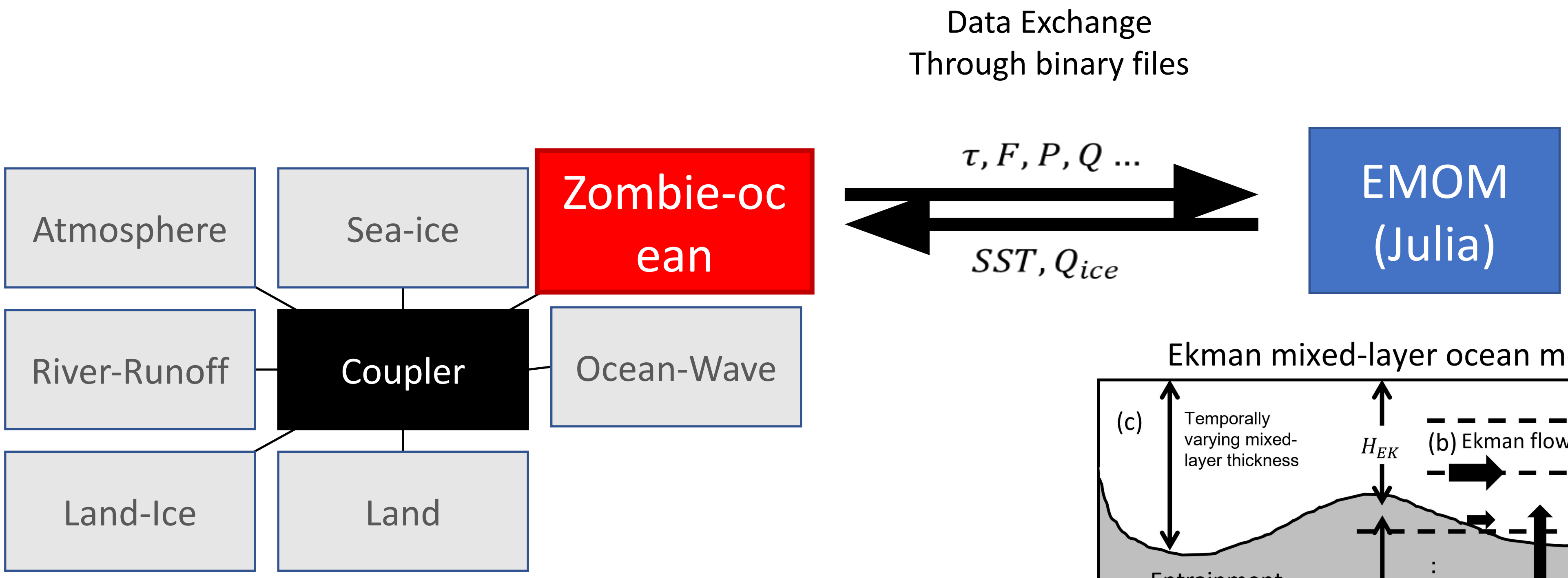
Q-flux

$$c_p h \rho \frac{\partial T}{\partial t} = F + Q$$

Freezing "Q"

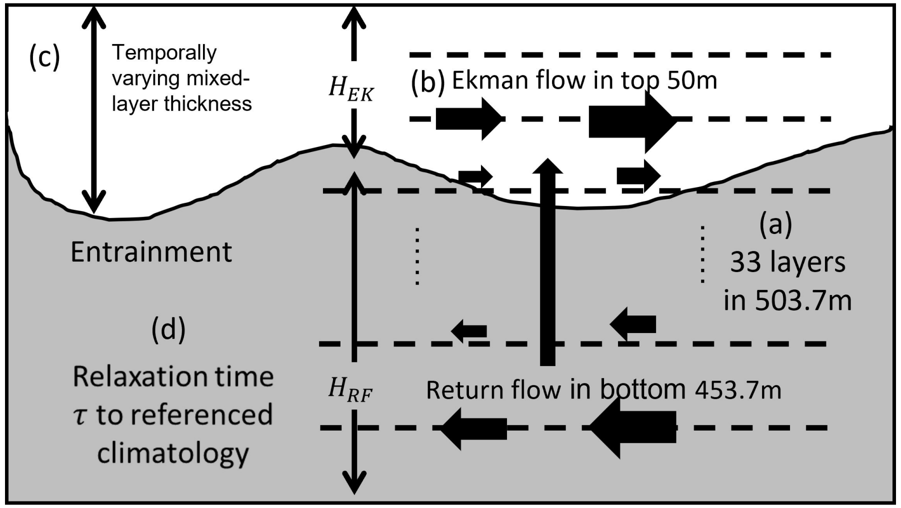
Key: As long as we can provide Freezing "Q" and SST then CESM is happy.

Architecture of CESM1-EMOM



(Fortran)

Ekman mixed-layer ocean model (EMOM)



https://github.com/meteorologytoday/EMOM