The relative roles of radiative feedbacks and heat transport in polar amplification

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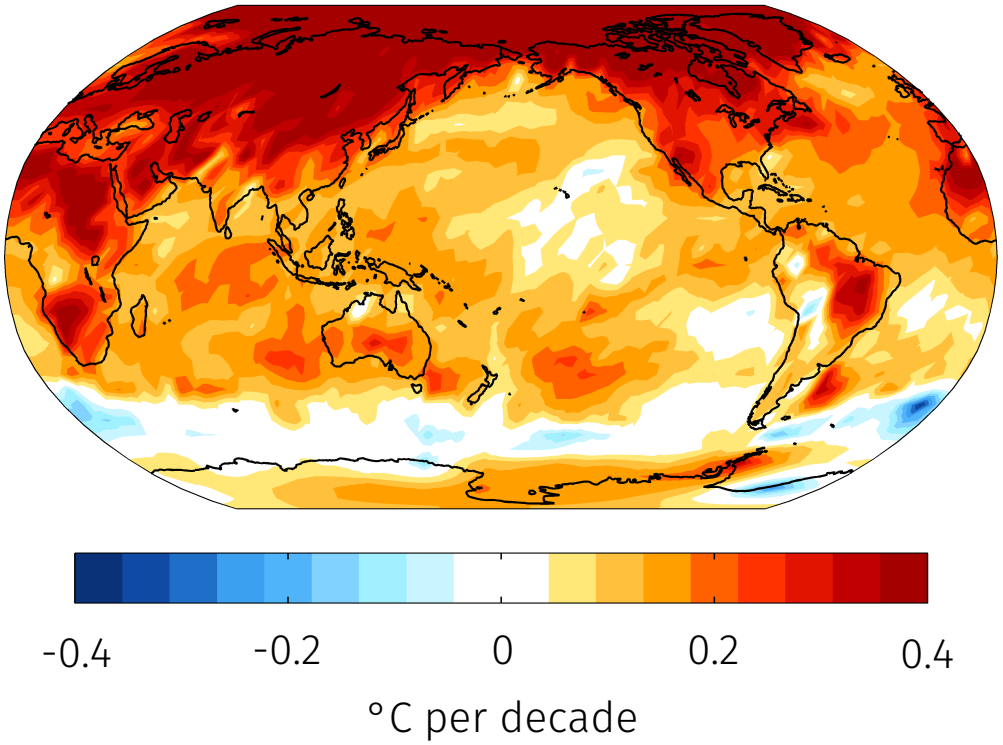
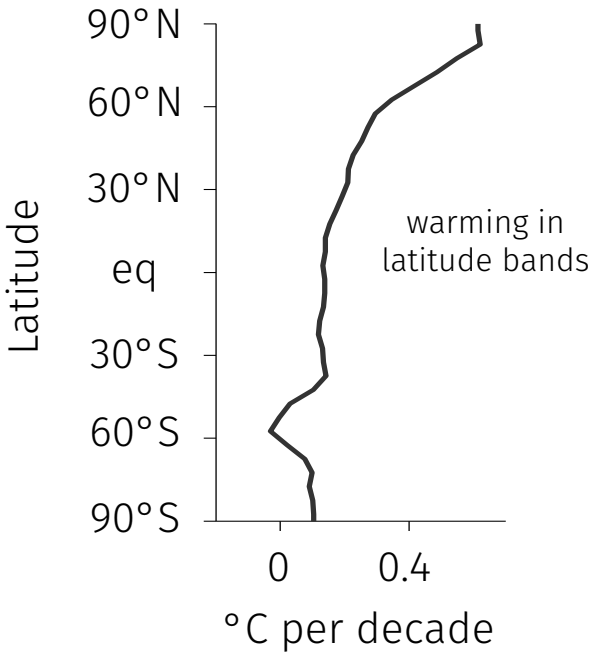
Nicole Feldl (UC Santa Cruz)
Nick Siler (Scripps)

AGCI Polar Amplification Workshop

Observed surface temperature trends

- Annual-mean surface temperature trends over 1965-2015

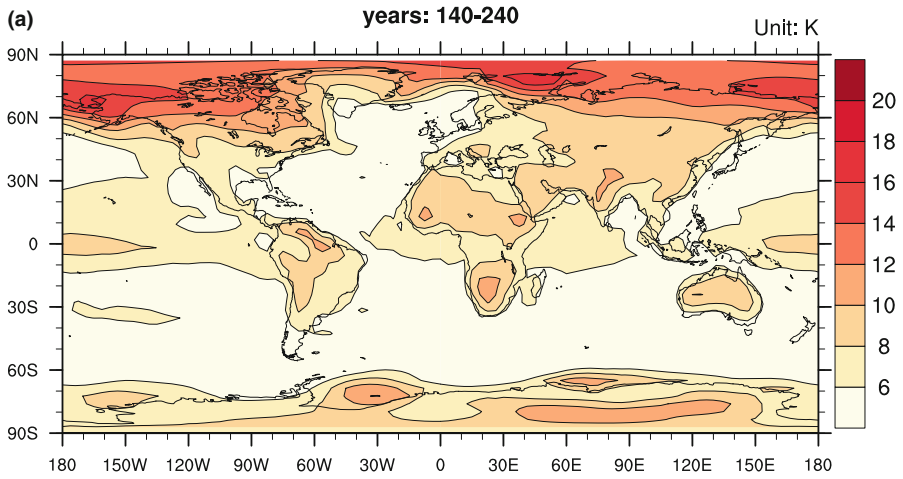




HadCRUT4 near surface temperature dataset

Warming patterns in GCMs

- Warming after 1%/yr ramping to 4×CO_2 in ECHAM5



(Li et al. 2012)

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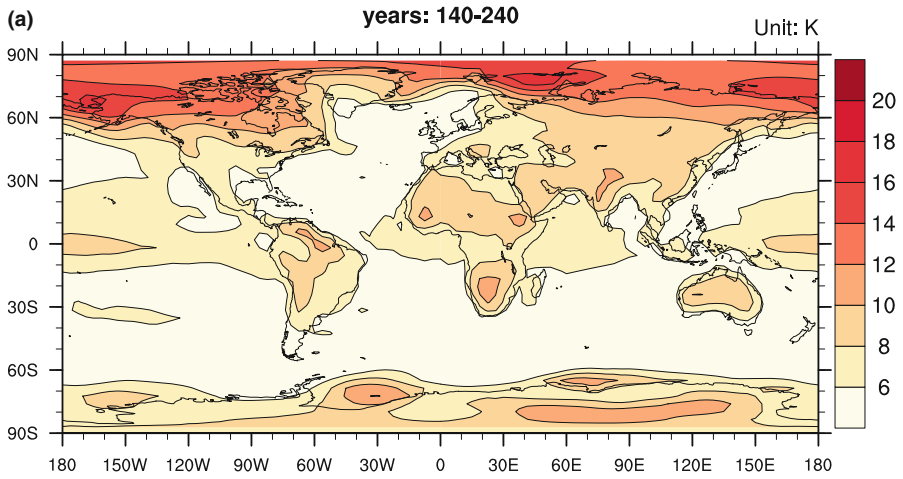

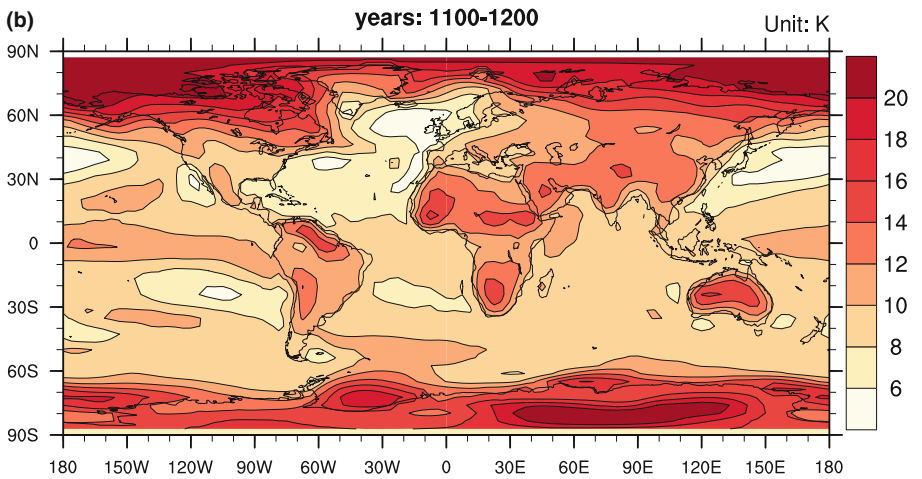

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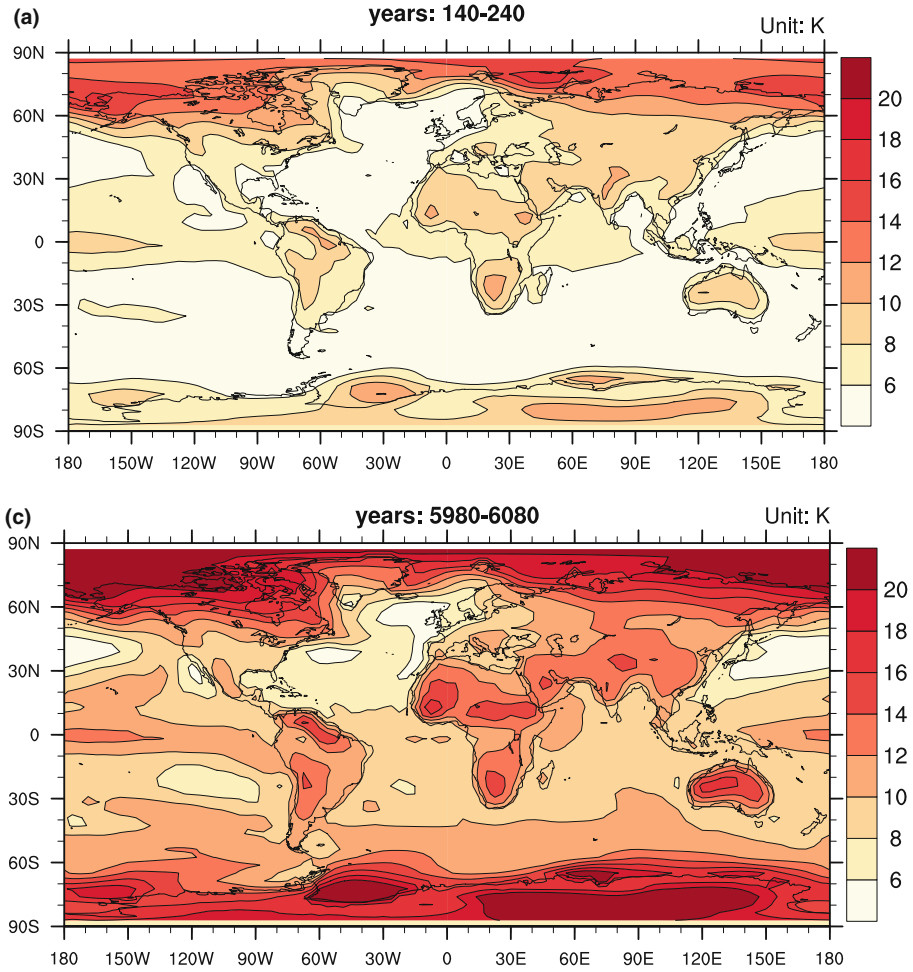

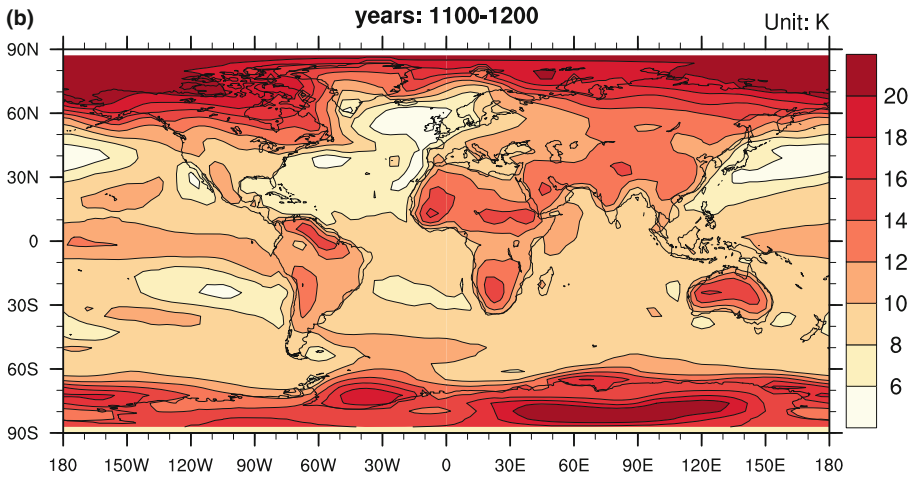

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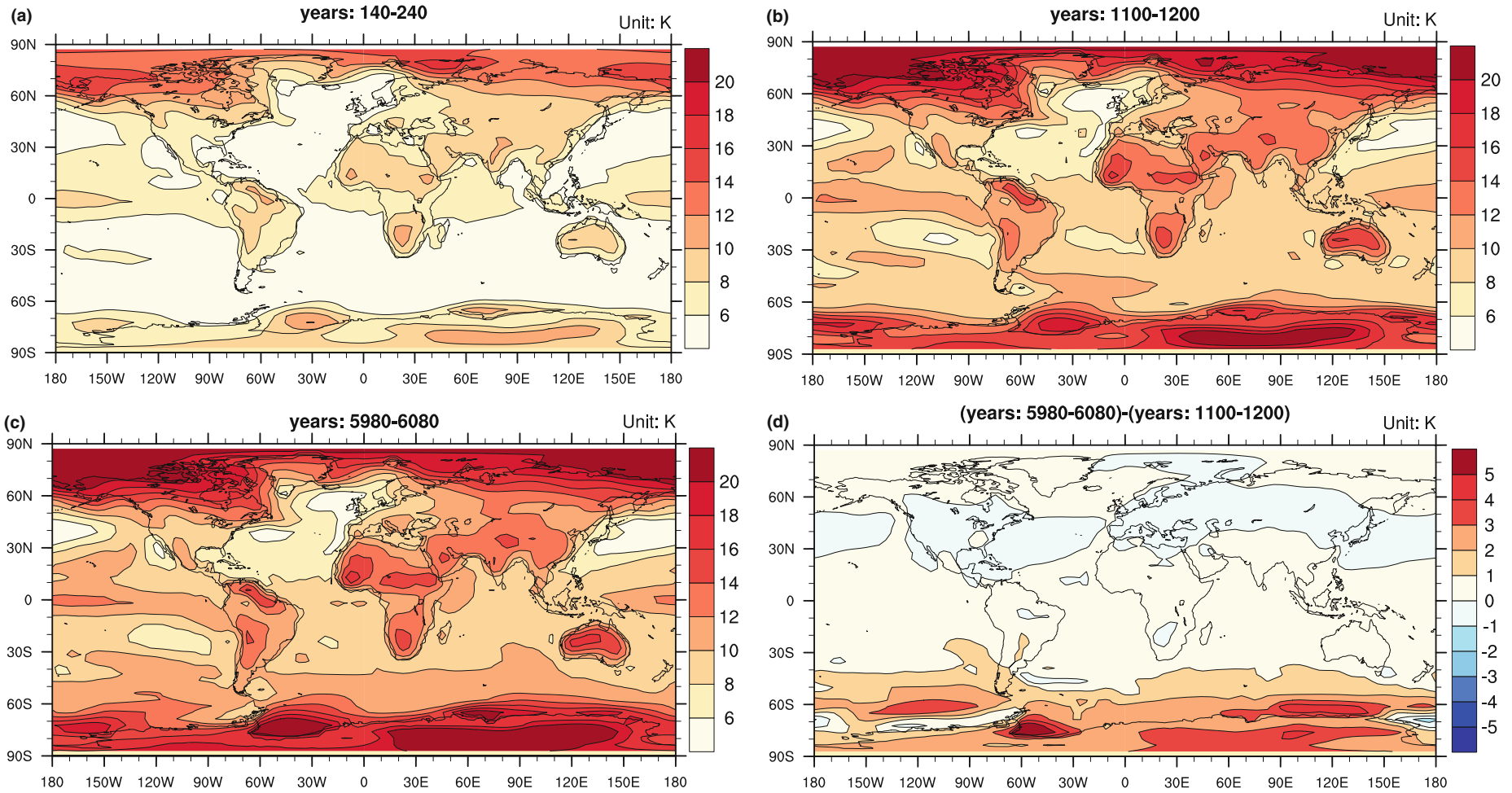
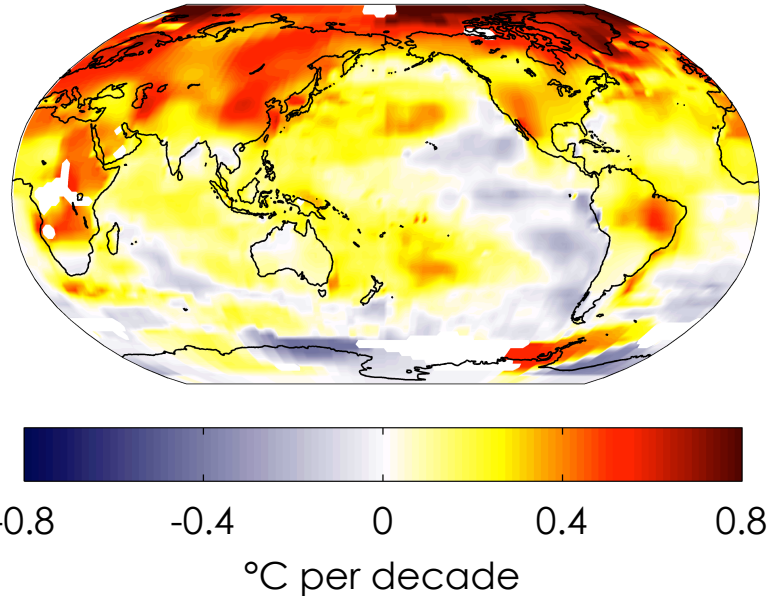


(Li et al. 2012)

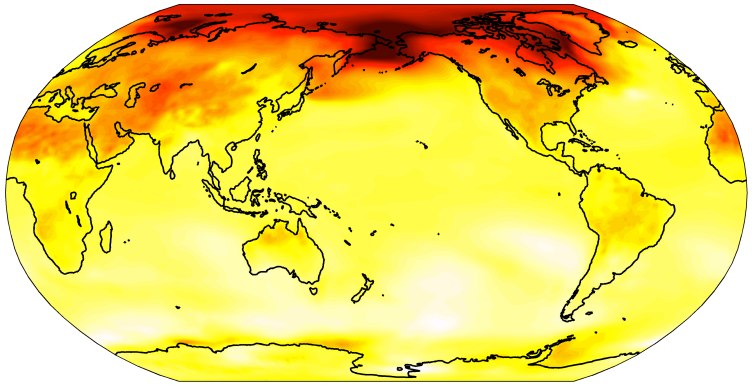
Observed and modeled temperature trends

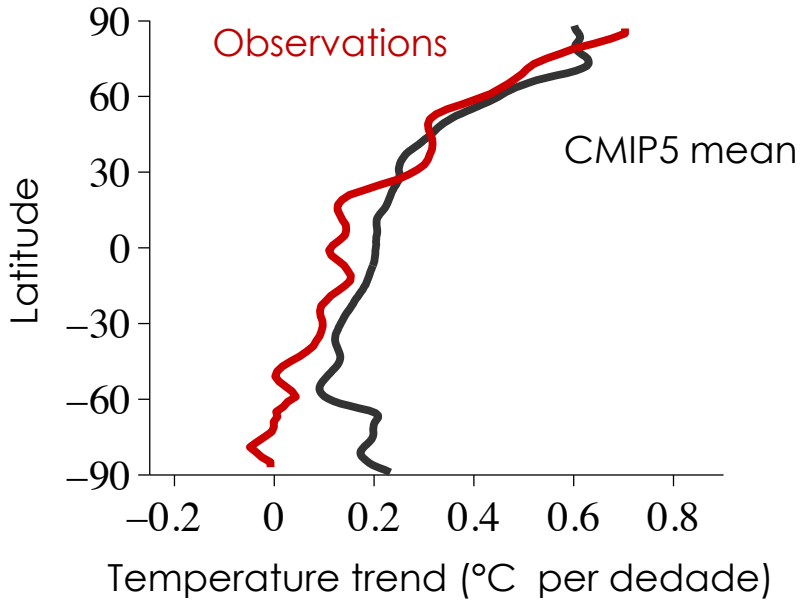
- Annual-mean surface temperature trends over 1979-2005

NASA GISTEMP



CMIP5 mean





Observed surface temperature trends

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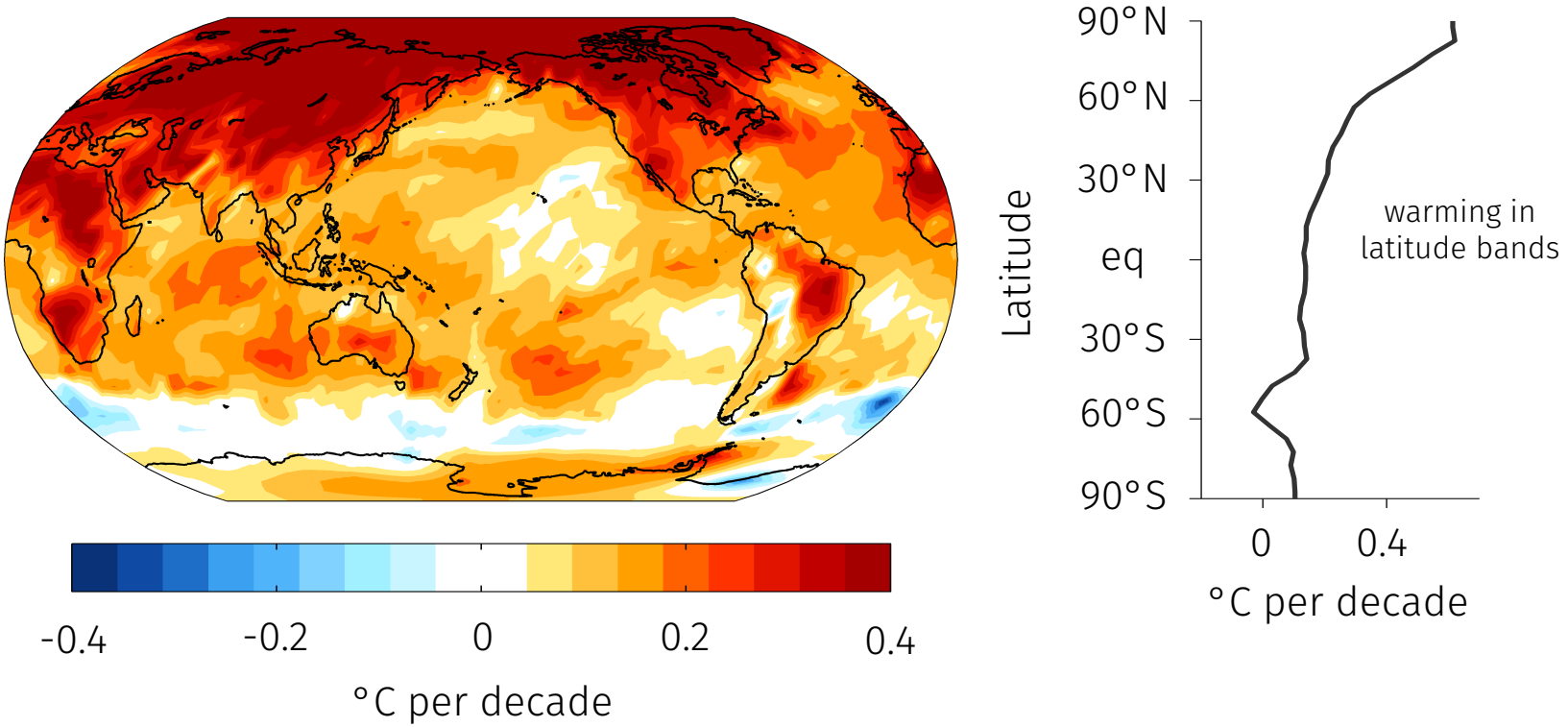

- What mechanisms drive polar amplification?
- Why does polar amplification emerged quickly in the Arctic (decades) but slowly in the Antarctic (centuries to millennia)?

What drives polar amplification?

- Can diagnose the various contributions to warming with a local energy budget analysis (following Crook et al 2011; Feldl and Roe 2013; Armour et al 2013; Pithan and Mauritsen 2014)

$$R(\phi) + \mathrm{OHU}(\phi) + \lambda(\phi)T(\phi) = \nabla \cdot F(\phi)$$

radiative forcing at TOA

ocean heat uptake at surface

local radiative feedbacks

surface temperature anomaly

atmospheric heat flux divergence

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- TOA radiative forcing from CMIP5 abrupt 4×CO_2 w/fixed SST simulations

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- Ocean heat uptake from anomalous net surface heat flux at year 100 of CMIP5 abrupt 4×CO_2

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- Feedbacks calculated from radiative kernels (Shell et al 2008) at year 100 of CMIP5 abrupt 4×CO_2, defined in terms of TOA radiative response per degree of *local* surface warming

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- Near-surface air temperature anomaly at year 100 of CMIP5 abrupt 4×CO_2

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- Atmospheric heat transport / divergence calculated at year 100 of CMIP5 abrupt 4×CO_2

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Warming contribution quantified as:

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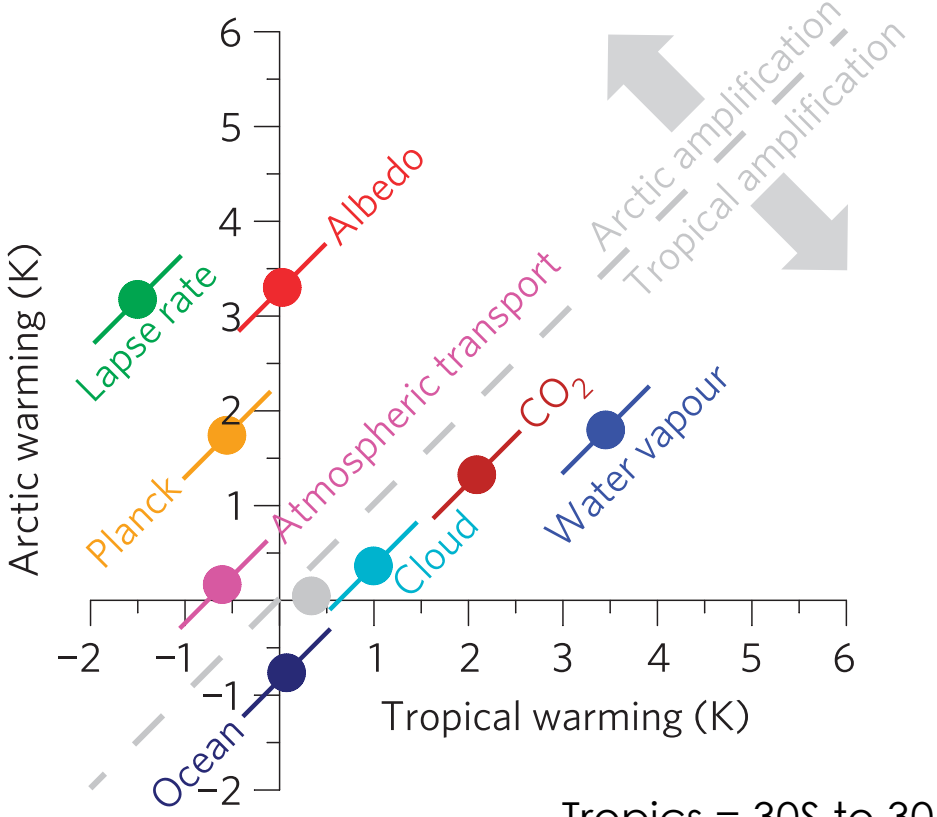

Tropics = 30S to 30N
Arctic = 60N to 90N

Pithan and Mauritsen (2014)

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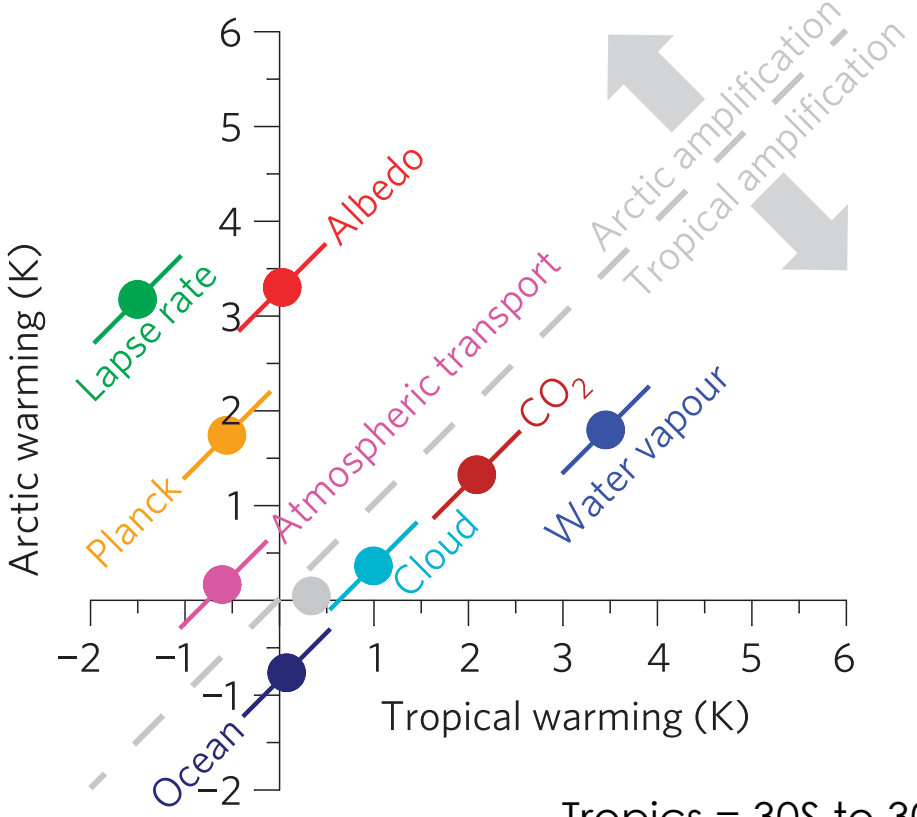

- Lapse rate, albedo and Planck (curvature) feedbacks are the primary drivers of Arctic amplification

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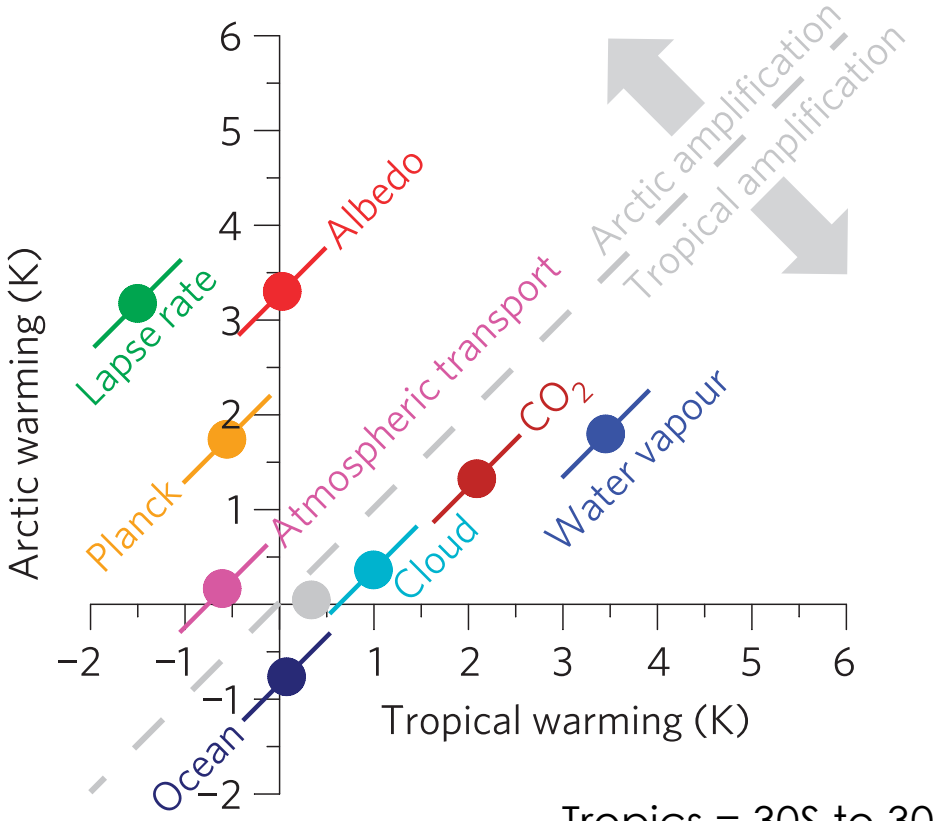

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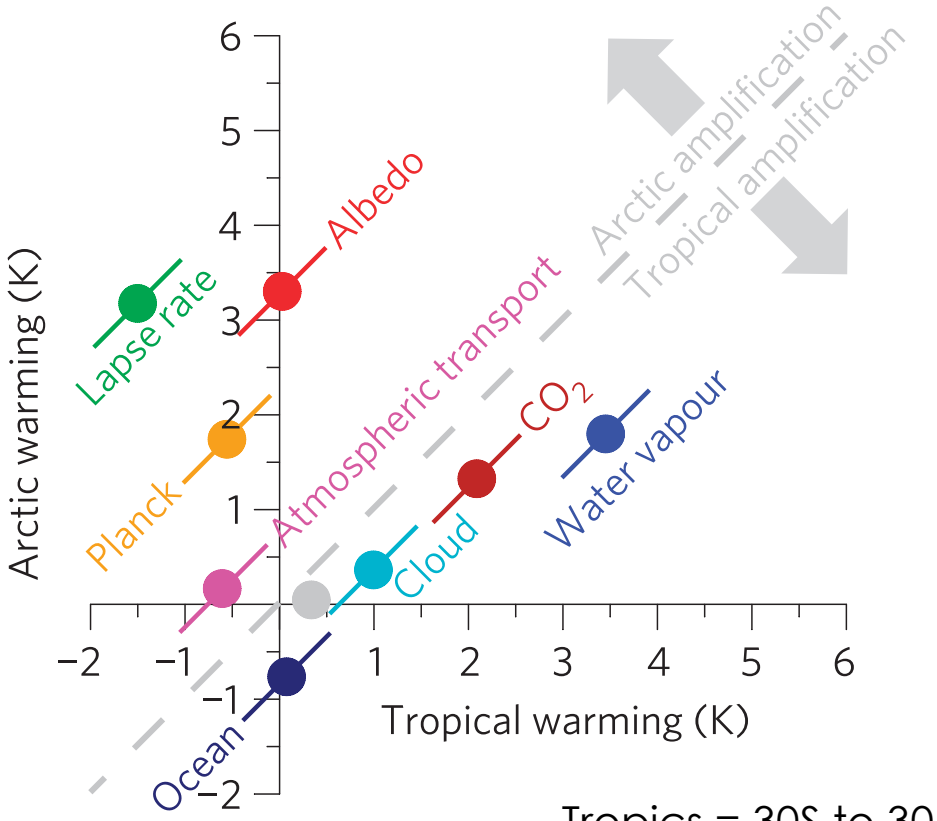

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- Lapse rate, albedo and Planck (curvature) feedbacks are the primary drivers of Arctic amplification
- Water vapor and cloud feedbacks, and CO_2 forcing, amplify tropical warming
- Atmospheric heat transport and ocean heat uptake each play minor roles

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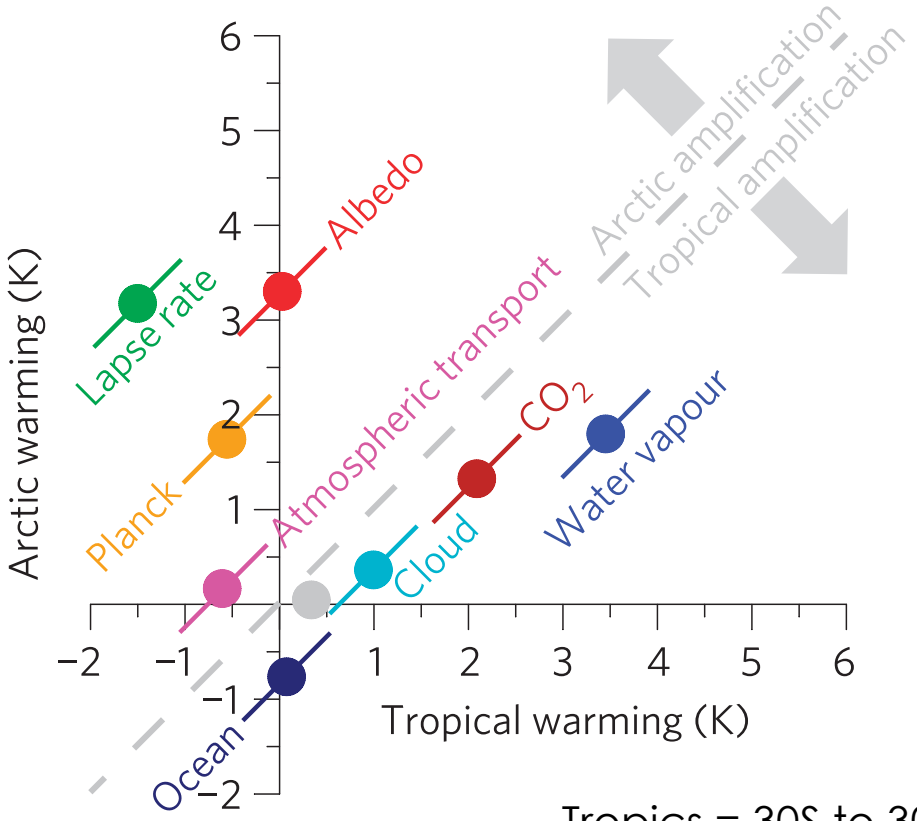

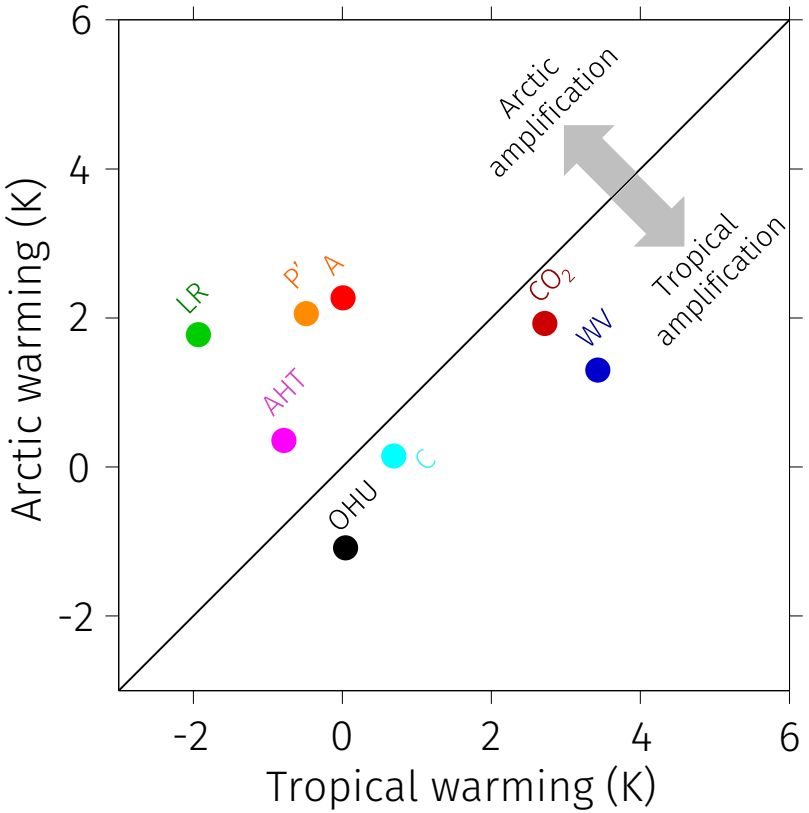

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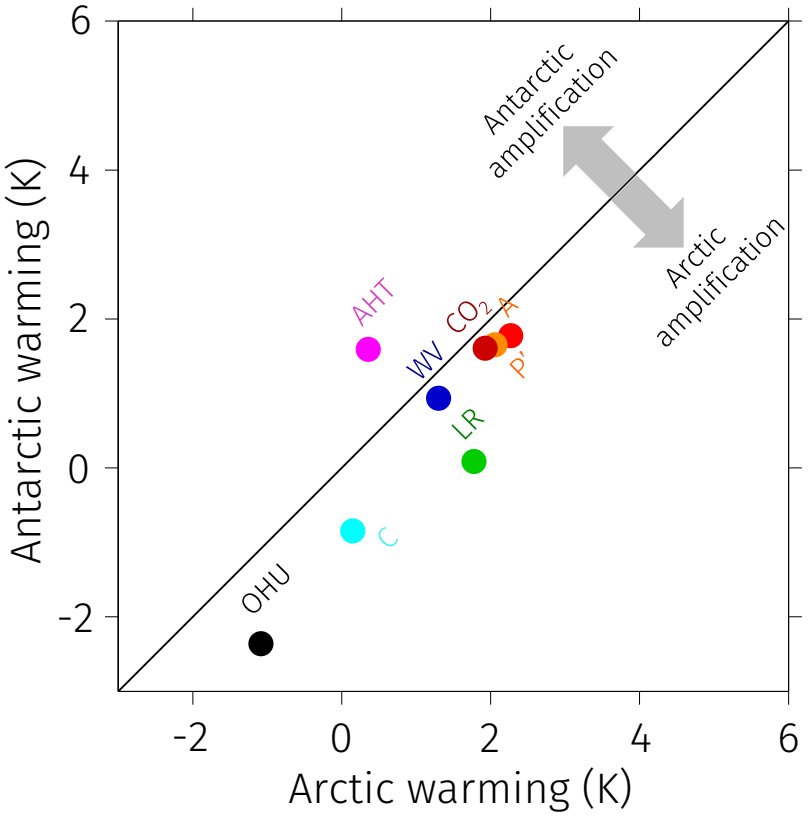

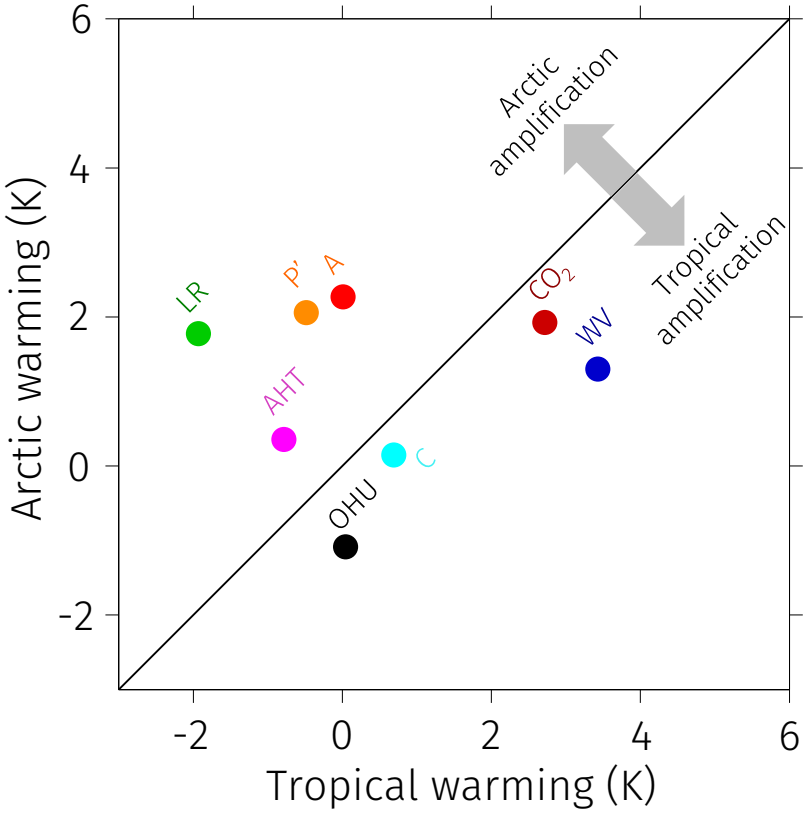

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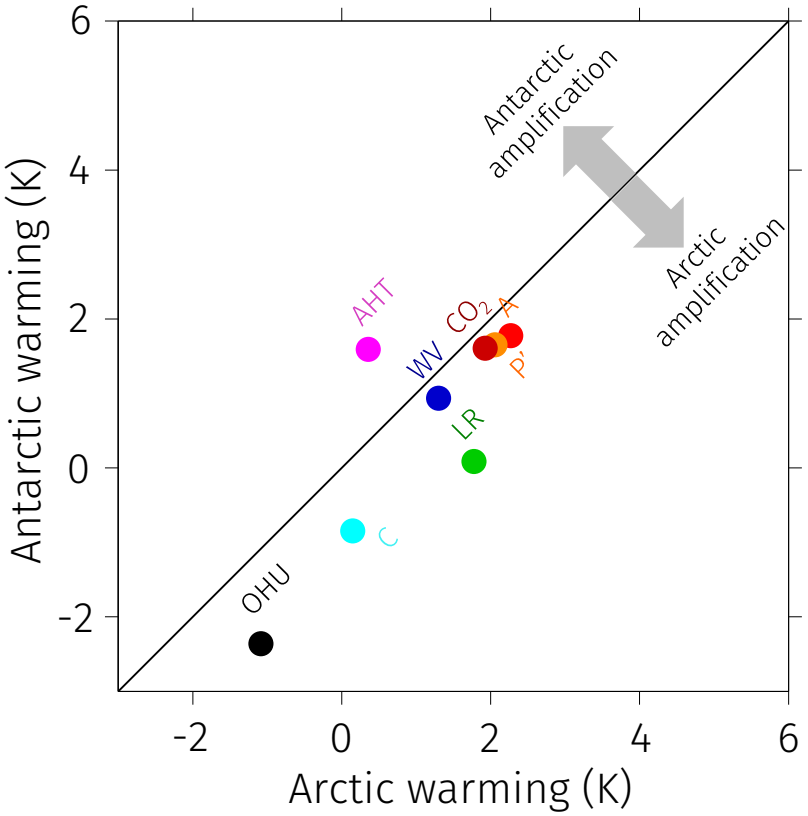

- Most things favor Arctic amplification over Antarctic amplification…
- Lapse rate feedback, cloud feedbacks, and OHU most strongly favor Arctic
- Atmospheric heat transport favors Antarctic amplification

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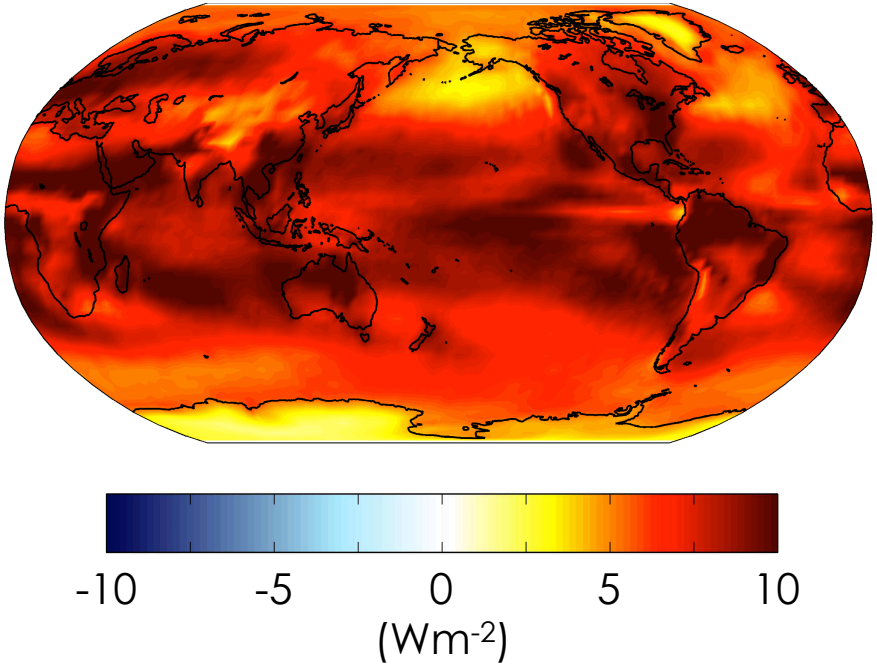
Radiative forcing



- Peaks in the tropics
- Favors tropical warming

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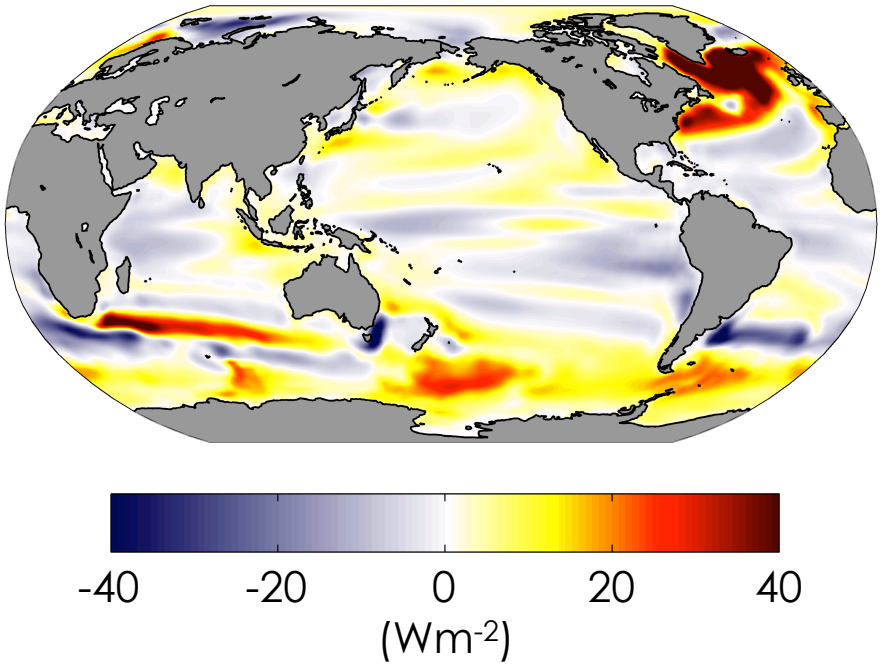
Anomalous heat flux **into ocean**

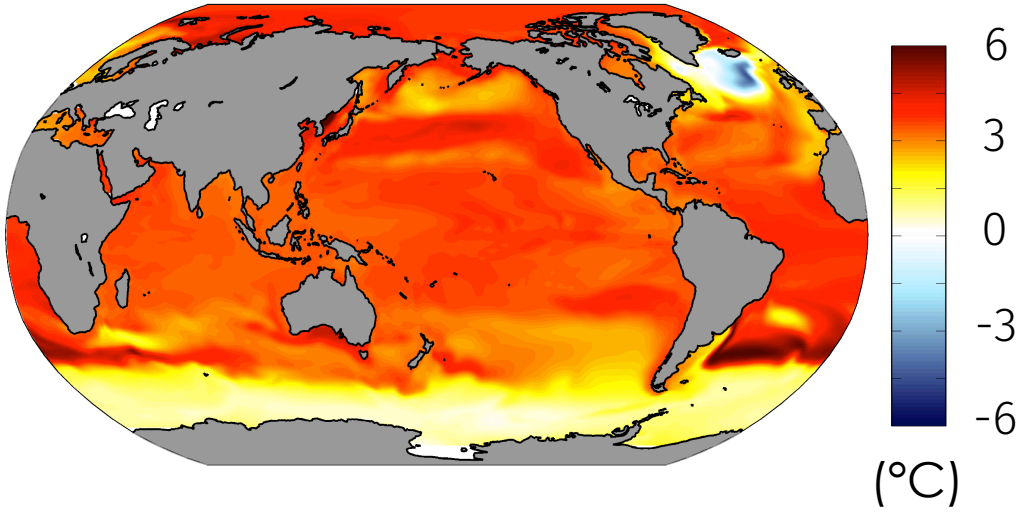


- Peaks in the Southern Ocean and North Atlantic's subpolar gyre

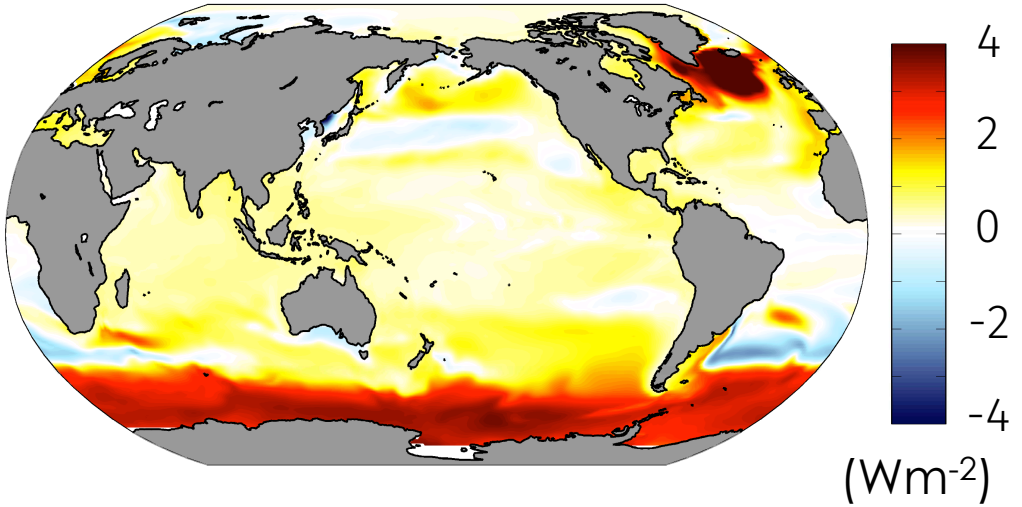
Ocean-only response to radiative forcing

- Ocean-only model response to abrupt uniform radiative forcing, with uniform radiative feedback – no wind or freshwater changes (Marshall et al 2015, Armour et al 2016)

Sea-surface temperature anomaly



Sea-surface heat flux anomaly into ocean



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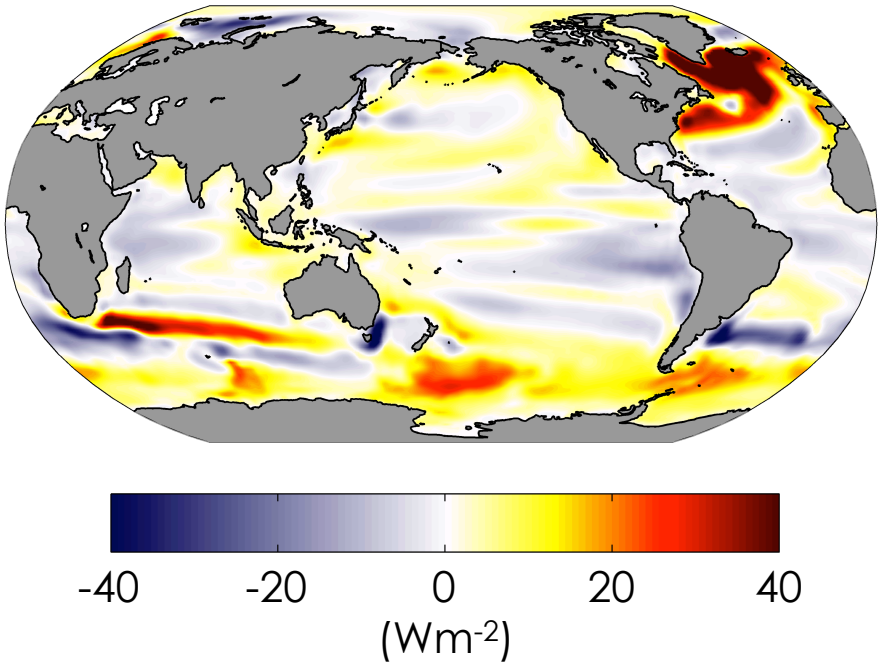

- Peaks in the Southern Ocean and North Atlantic's subpolar gyre
- Pattern set by ocean dynamics:
  - large-scale upwelling in Southern Ocean
  - weakening of AMOC
- Primary reason for very slow emergence of Antarctic amplification

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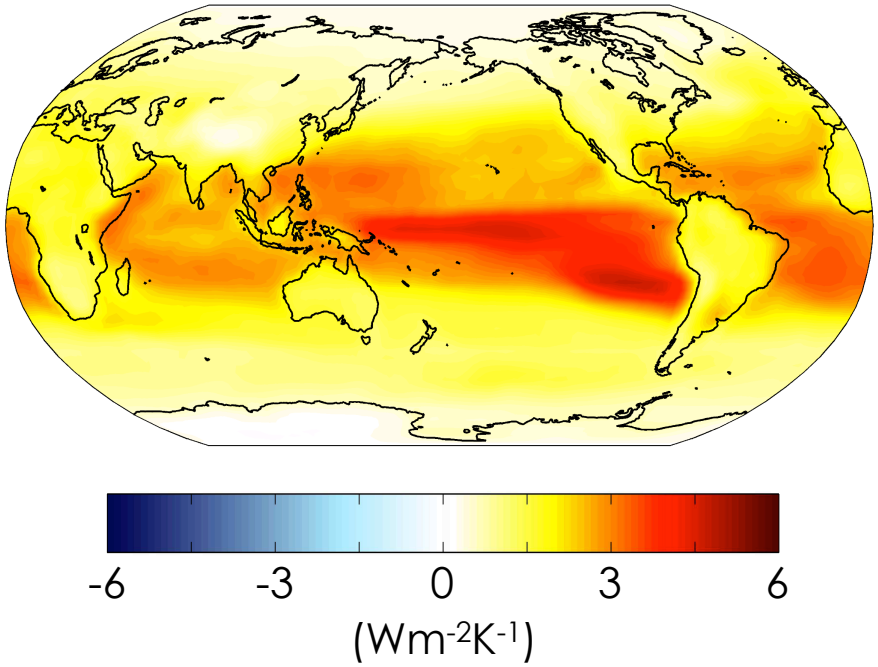
Water vapor feedback (WV)



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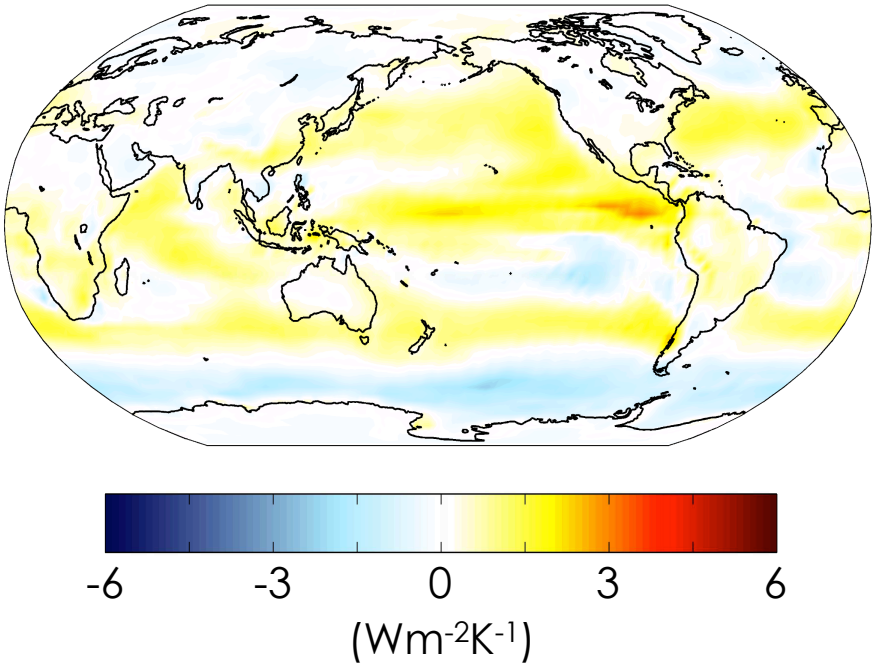
Net cloud feedback (C)



- Generally positive, but weak in Arctic and negative over Southern Ocean
- Favors tropical warming
- Acts to damp Antarctic warming

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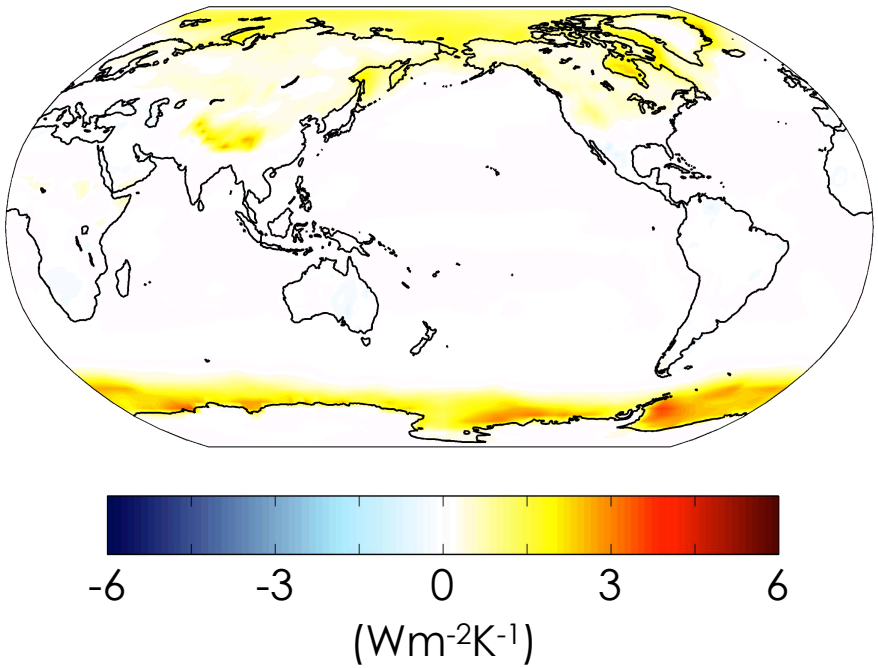
Surface albedo feedback (A)



- Positive at the poles
- Favors polar warming

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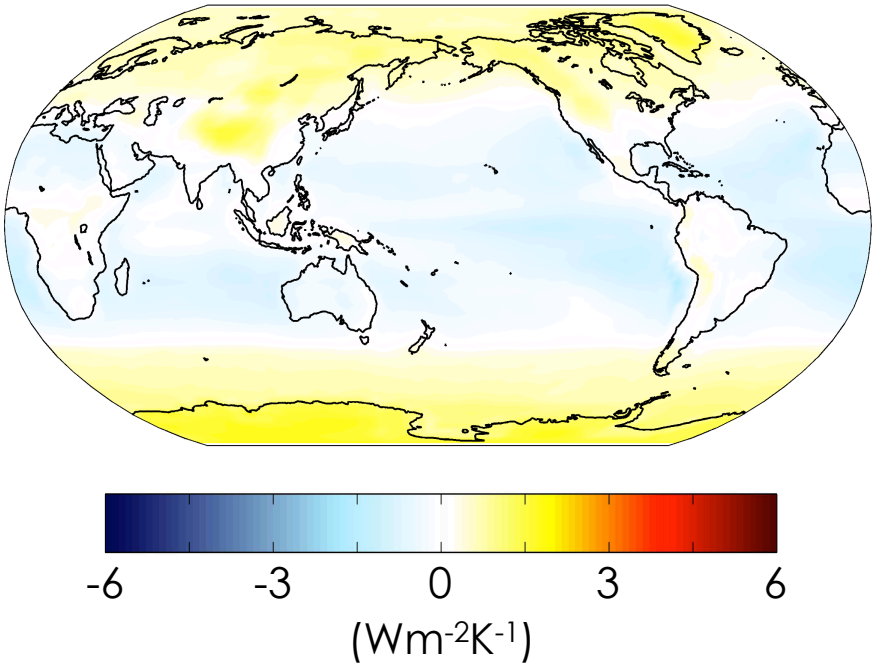
Curvature in Planck feedback (P')



- Positive at the poles, negative in tropics
  - curvature due to temperature nonlinearity in blackbody radiation:

$$\sigma T^4 \approx (4\sigma T^3)\,\Delta T$$

- Favors polar warming

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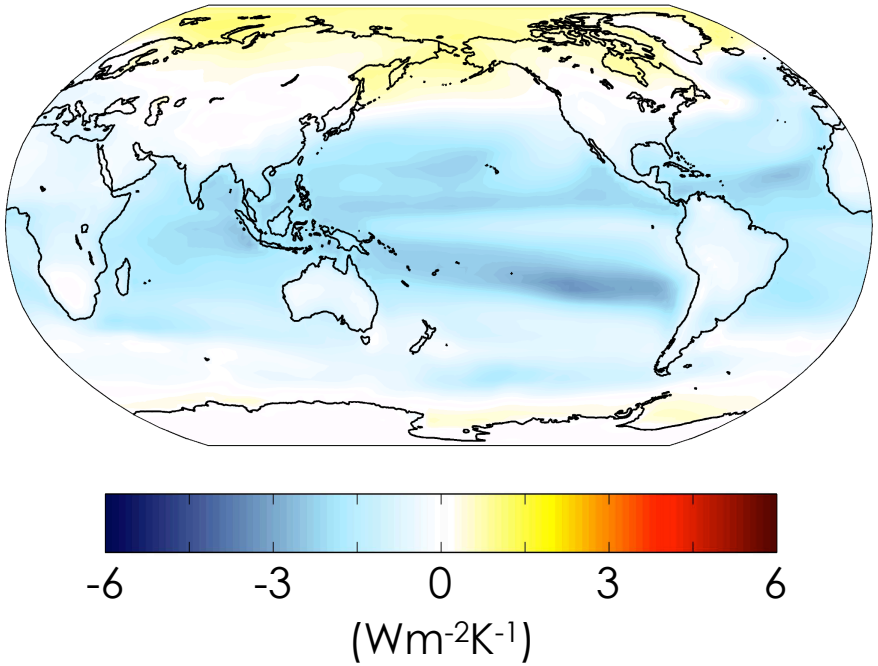
Lapse rate feedback (LR)



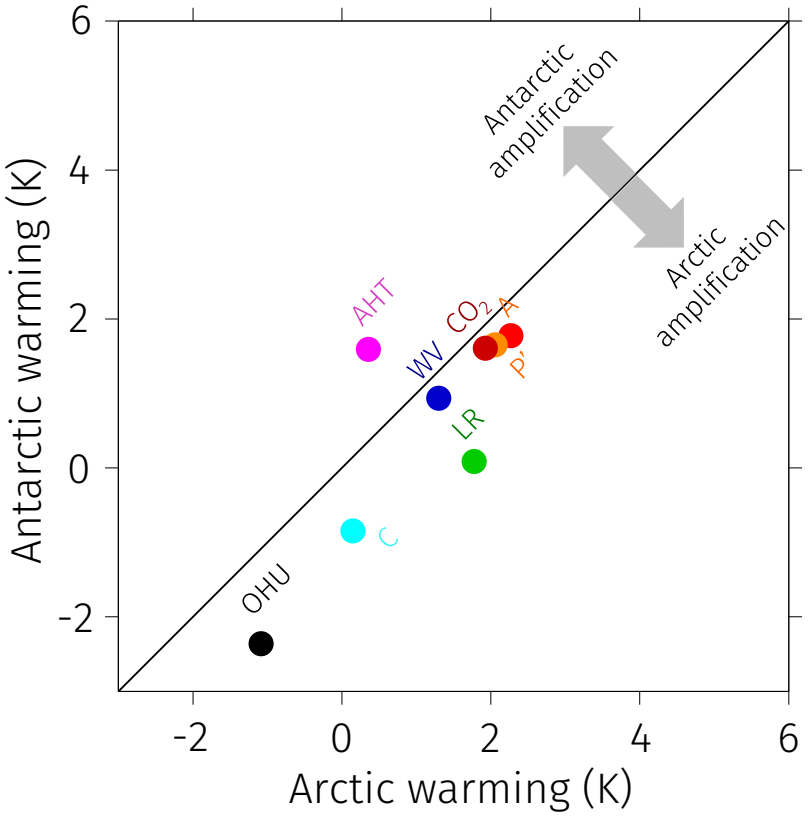
- Negative in tropics where on moist adiabat, positive at the poles where inversions exist
- Favors polar warming, and Arctic warming in particular

What drives polar amplification?

- Can diagnose the various contributions to warming with a local energy budget analysis (following Crook et al 2011; Feldl and Roe 2013; Armour et al 2013; Pithan and Mauritsen 2014)

$$T = -1/\overline{\lambda_P}\,(\lambda'_P T + \lambda_{WV} T + \lambda_C T + \lambda_A T + \lambda_{LR} T + R + \mathrm{OHU} - \nabla \cdot F)$$

- Atmospheric heat transport appears to play a minor role in Arctic warming, greater role in Antarctic warming
- Is this telling us something fundamental about atmospheric dynamics… or is there something else going on here?



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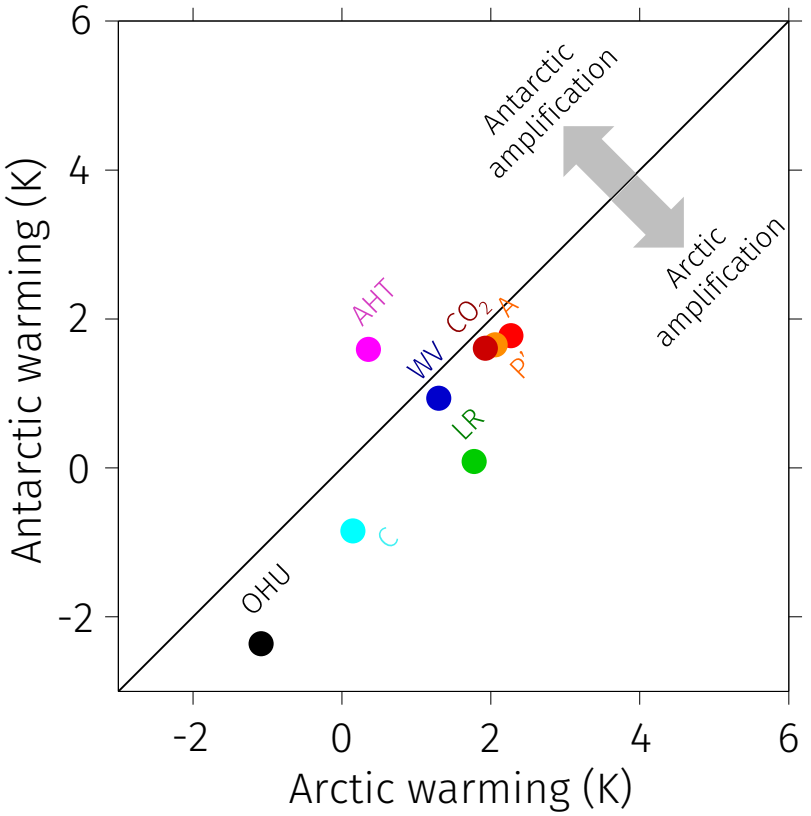
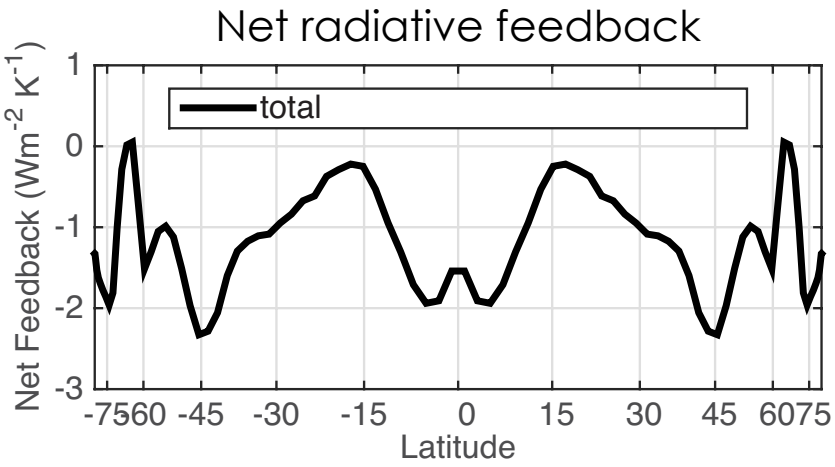
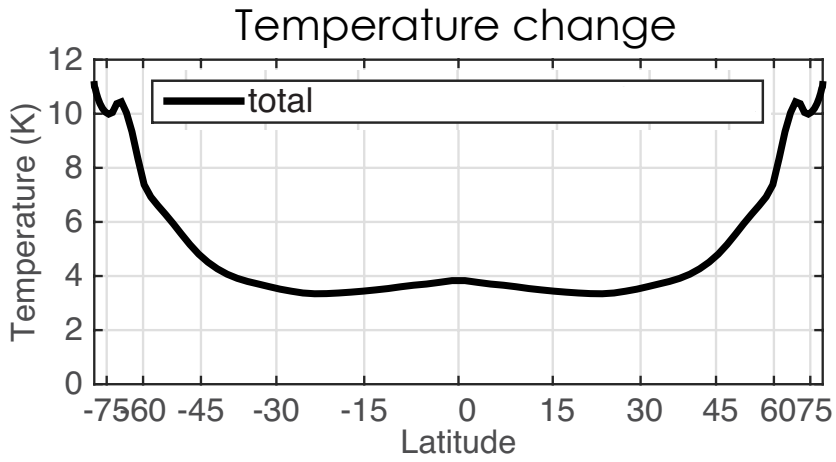
- Atmospheric heat transport appears to play a minor role in Arctic warming, greater role in Antarctic warming
- Is this telling us something fundamental about atmospheric dynamics… or is there something else going on here?
- **We need a deeper understanding of how and why atmospheric heat transport changes**



Understanding atmospheric heat transport

- Look at an idealized aquaplanet slab ocean model (GFDL AM2) response to CO_2 doubling (Roe et al 2015, Feldl and Roe 2013)





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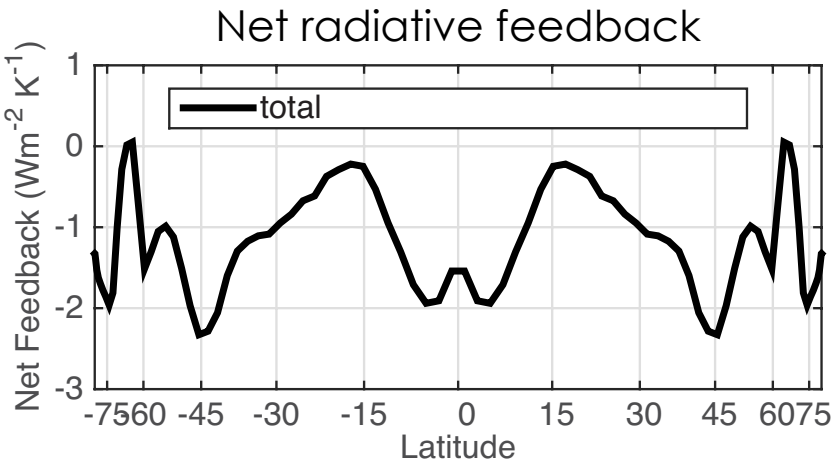

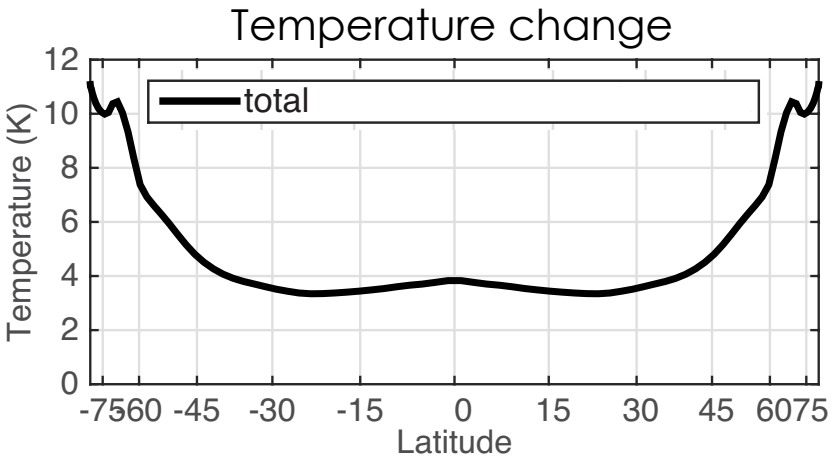

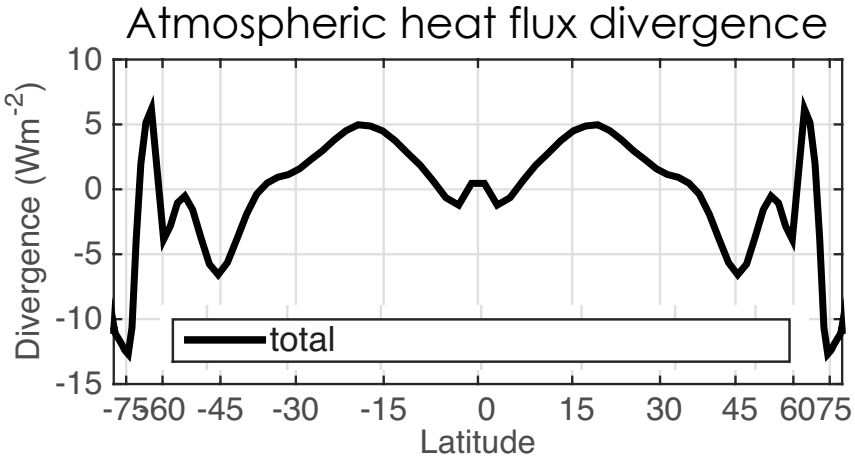

- Atmospheric heat flux divergence change largely mirrors the feedback pattern

Understanding atmospheric heat transport

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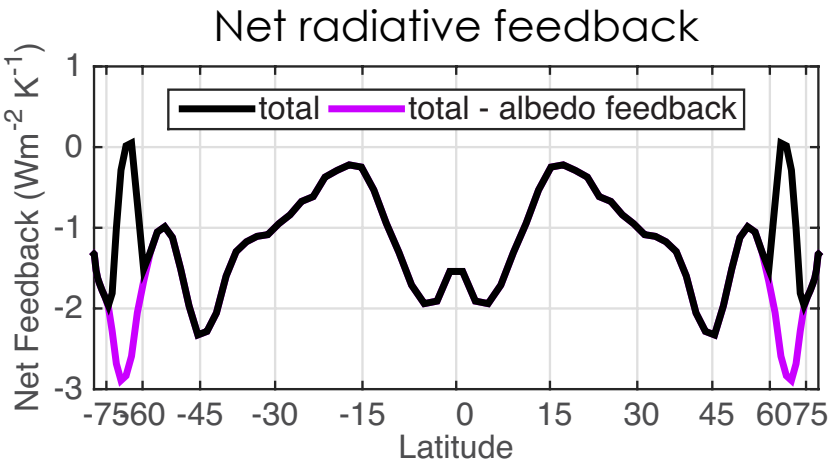

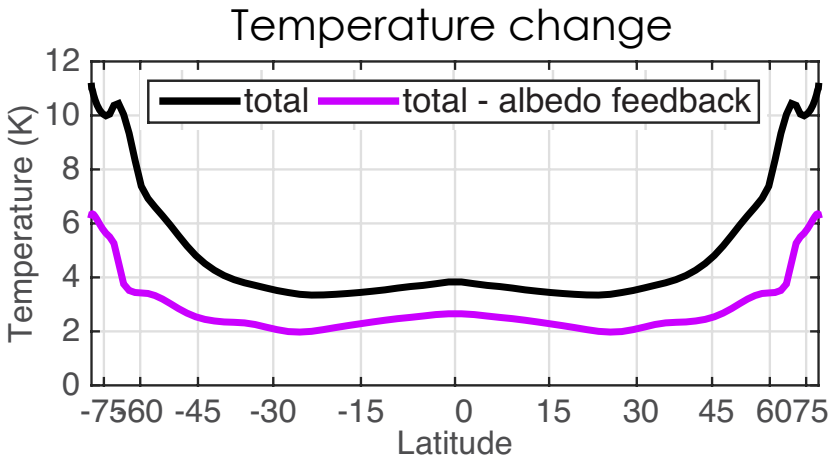

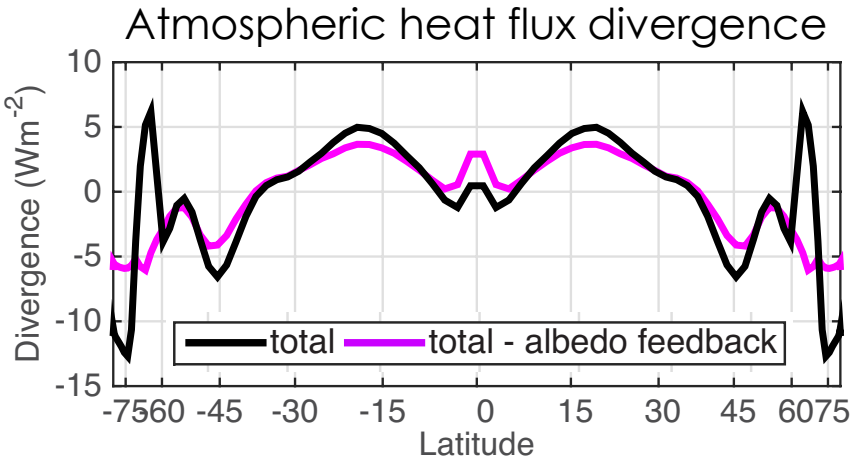

- Atmospheric heat flux divergence change largely mirrors the feedback pattern
- Heat transport dynamically responds to changing feedbacks (Merlis 2015), influencing warming nonlocally

Understanding atmospheric heat transport

- You can parameterize atmospheric heat transport in terms of a diffusion of near-surface **moist-static energy**:

$$\nabla \cdot F = -D\nabla^2 m$$

↑ *constant* diffusivity

$$m(\phi) = c_p T(\phi) + Lq(\phi)$$

energy associated with temperature

energy associated with moisture

- Mimics the stirring of temperature and moisture by atmospheric eddies, which act to transport moist-static energy down gradient: $F = -D\nabla m$

Hwang and Frierson (2010); Hwang et al (2011)

Understanding atmospheric heat transport

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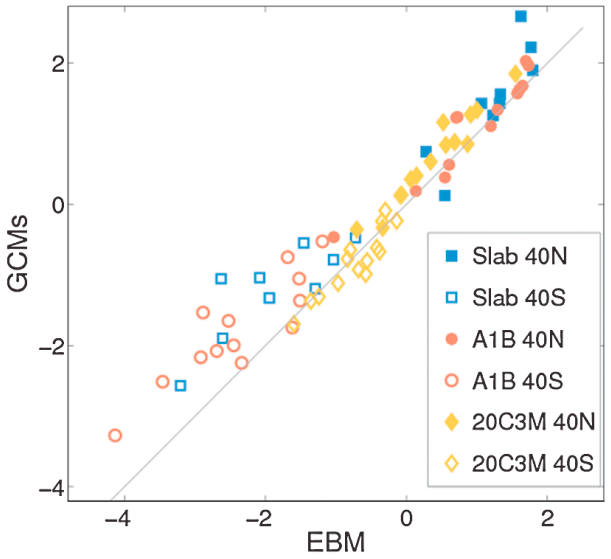

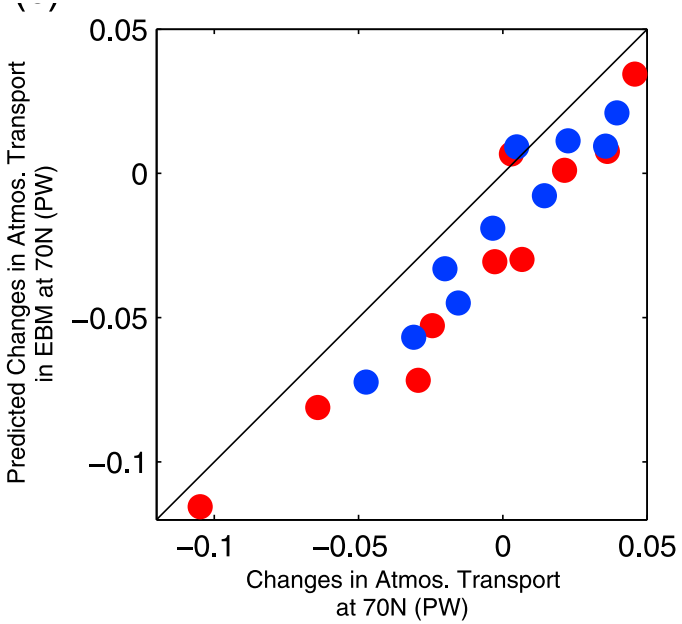

- Captures anomalous heat transport in CMIP models pretty well (Hwang and Frierson)

Hwang and Frierson (2010); Hwang et al (2011)

Understanding atmospheric heat transport

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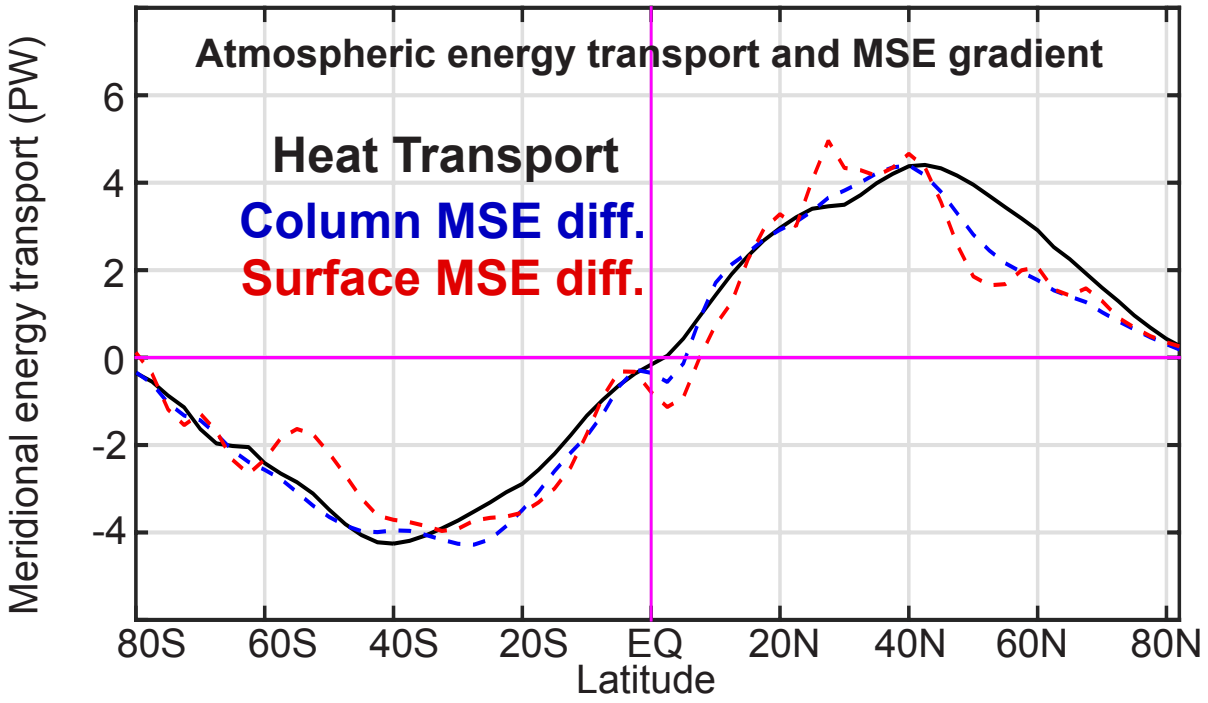


- Captures climatological heat transport in atmospheric reanalyses pretty well (Aaron Donohoe)

Understanding atmospheric heat transport

- You can parameterize atmospheric heat transport in terms of a diffusion of near-surface **moist-static energy**:

$$\nabla \cdot F = -D\nabla^2 m$$

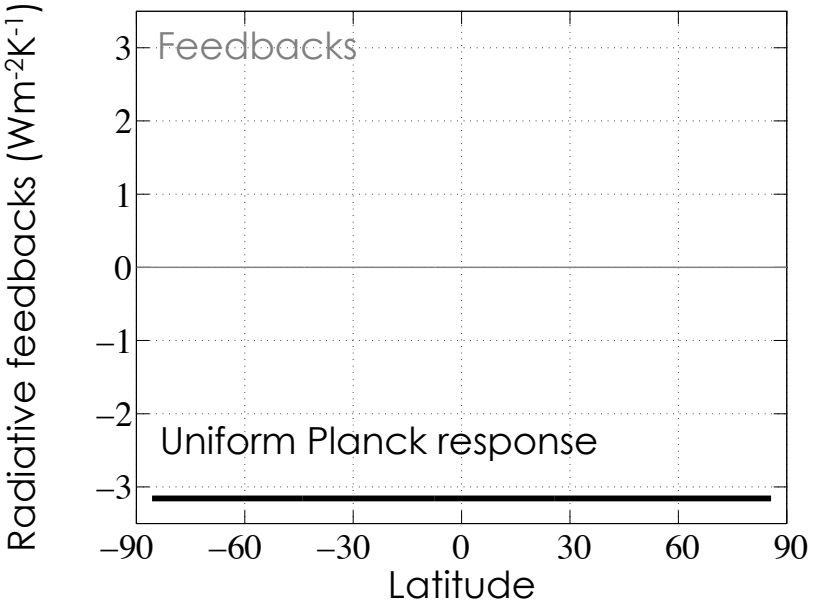
↑ *constant* diffusivity

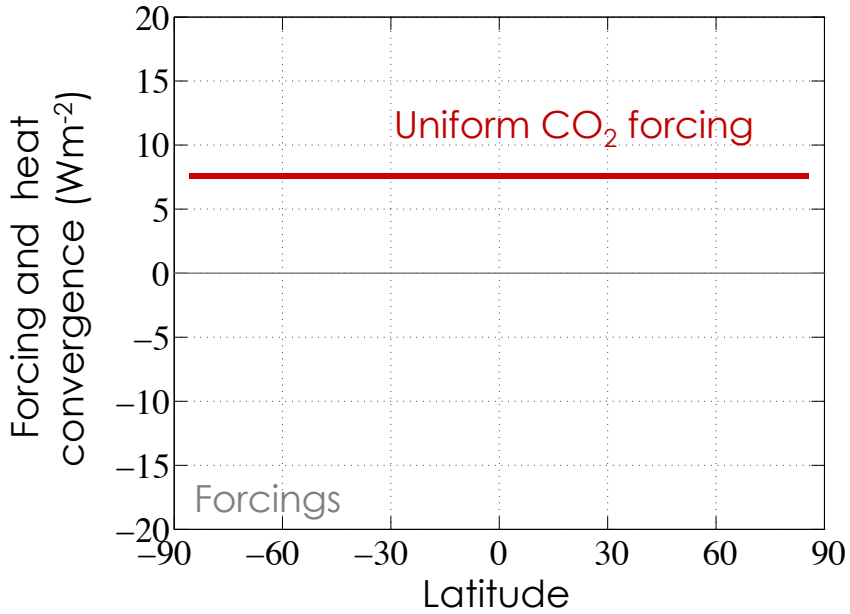
$$m(\phi) = \underbrace{c_p T(\phi)}_{\text{energy associated with temperature}} + \underbrace{Lq(\phi)}_{\text{energy associated with moisture}}$$

- Rose et al (2014) and Roe et al (2015) used this parameterization to create a prognostic energy balance model (EBM): given patterns of forcing and feedbacks, model predicts atmospheric heat transport, surface warming and net TOA radiation fluxes simultaneously

$$R(\phi) + \mathrm{OHU}(\phi) + \lambda(\phi)T(\phi) = \nabla \cdot F(\phi)$$

Uniform forcing and radiative response





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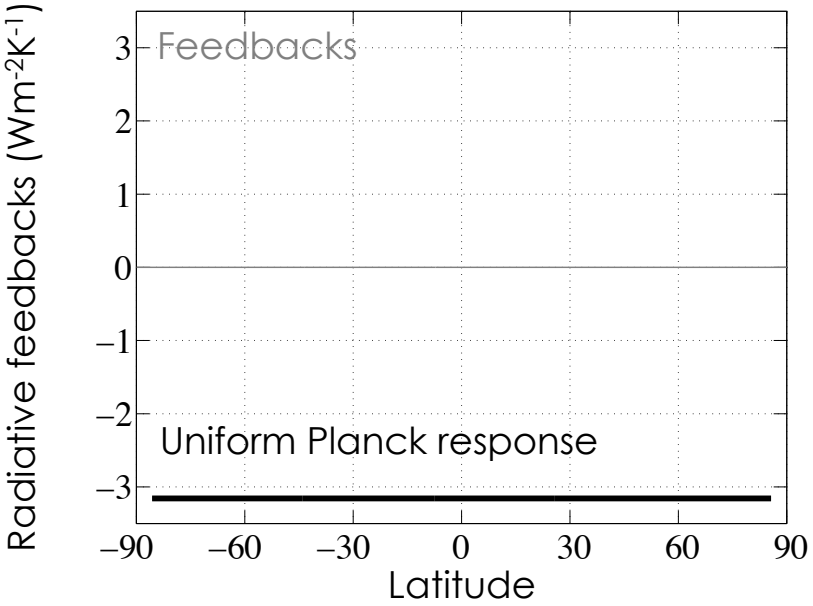

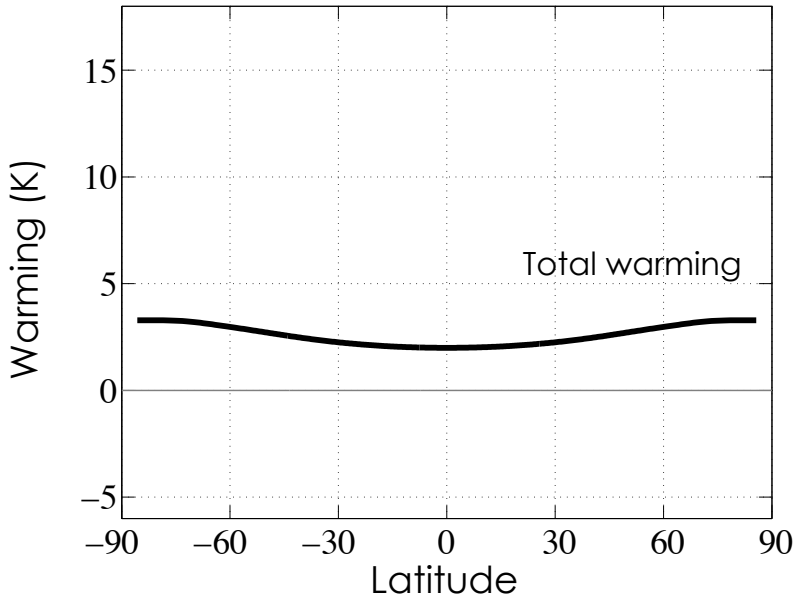

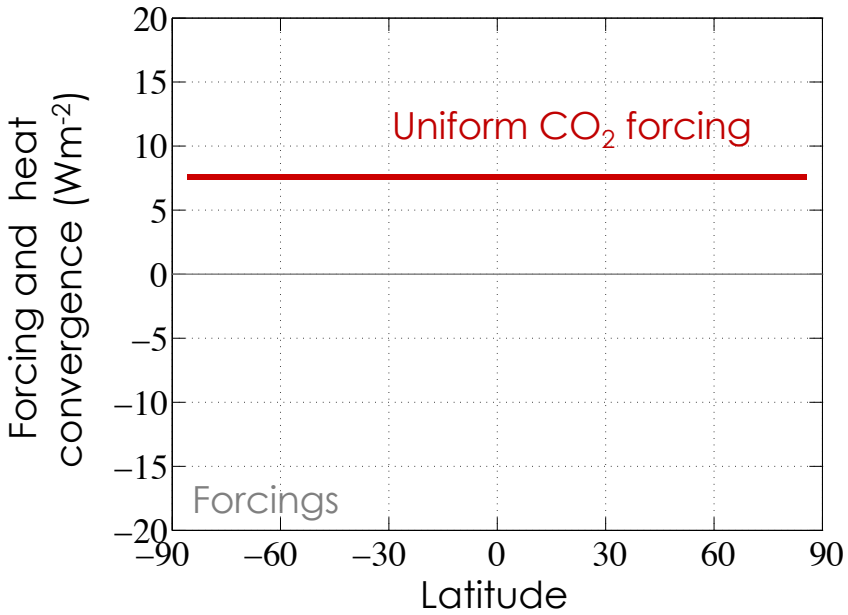

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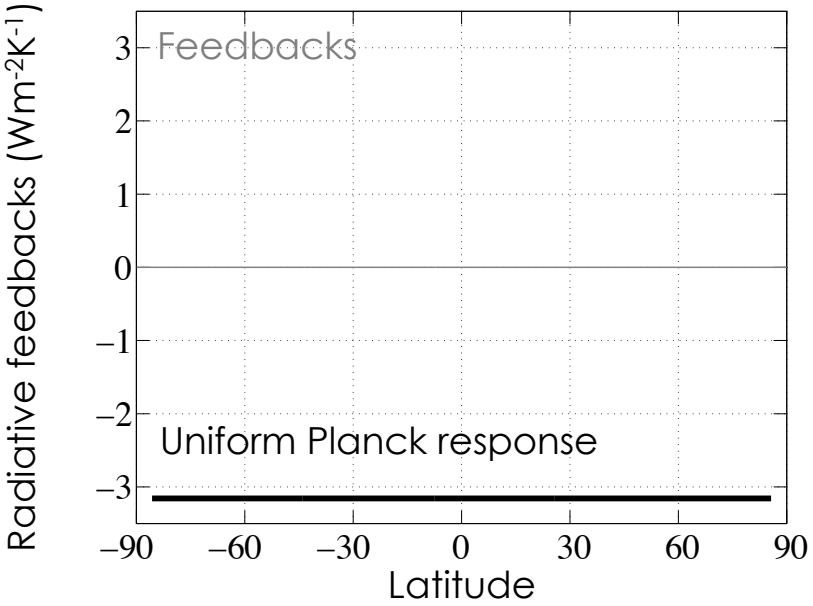

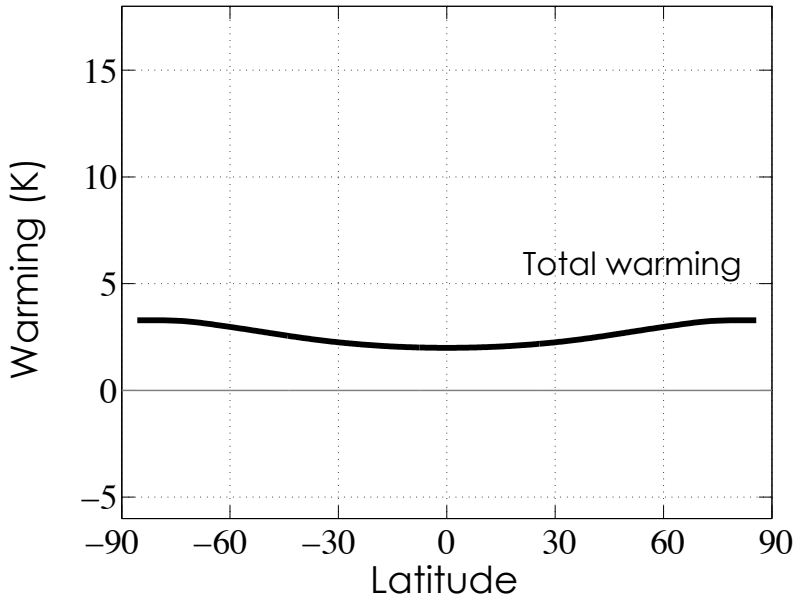

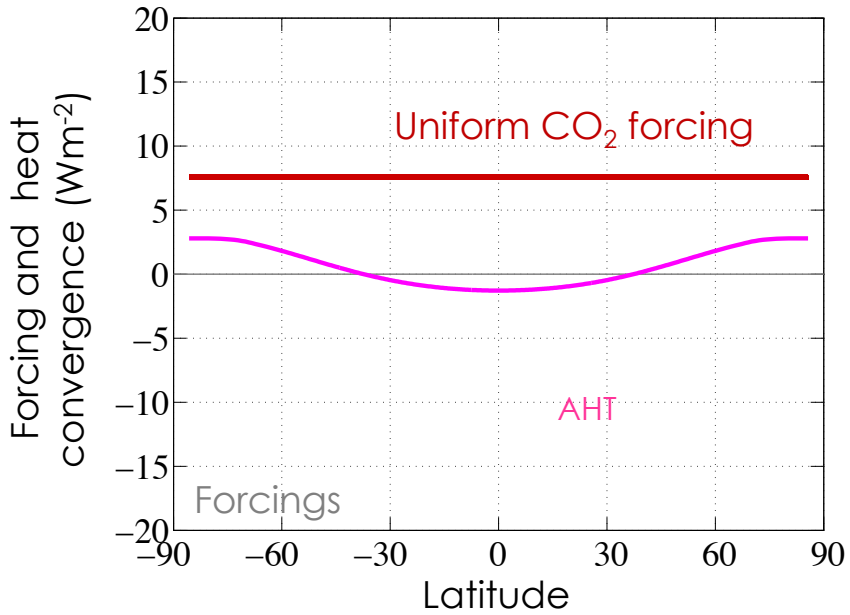

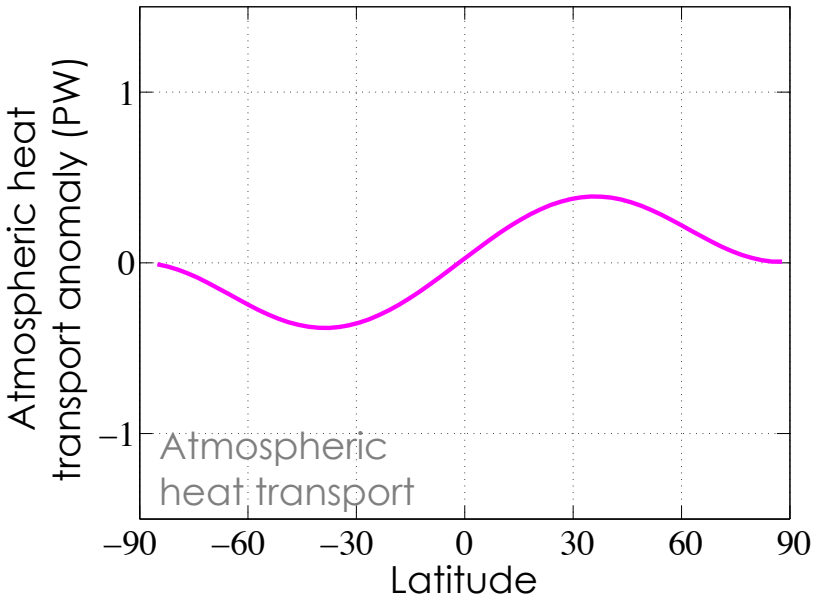

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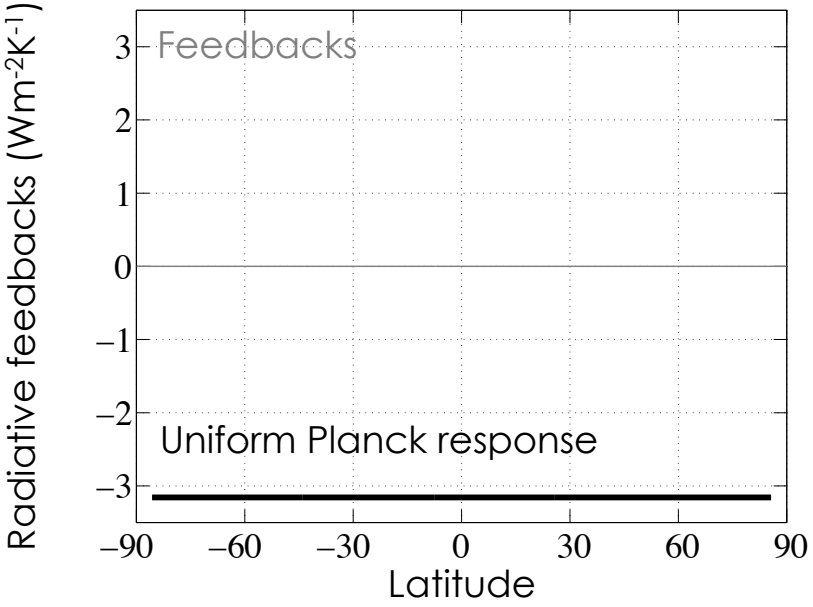

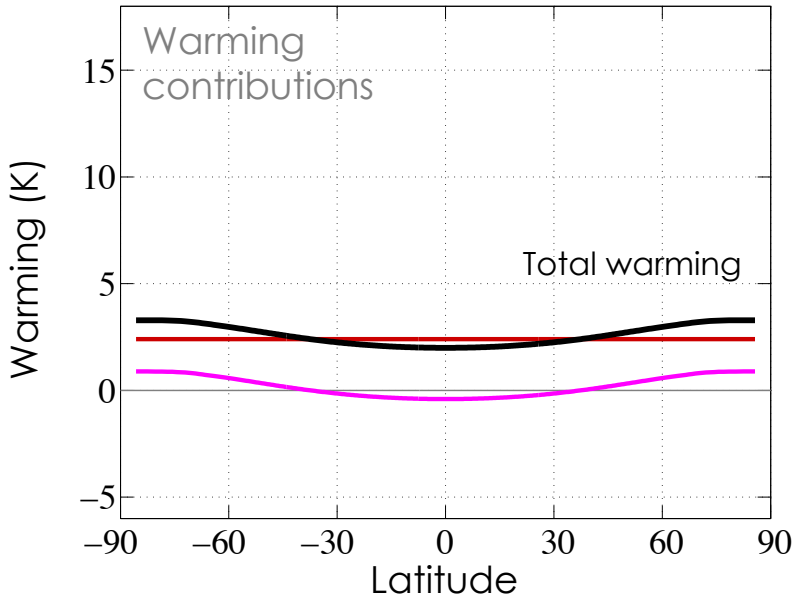

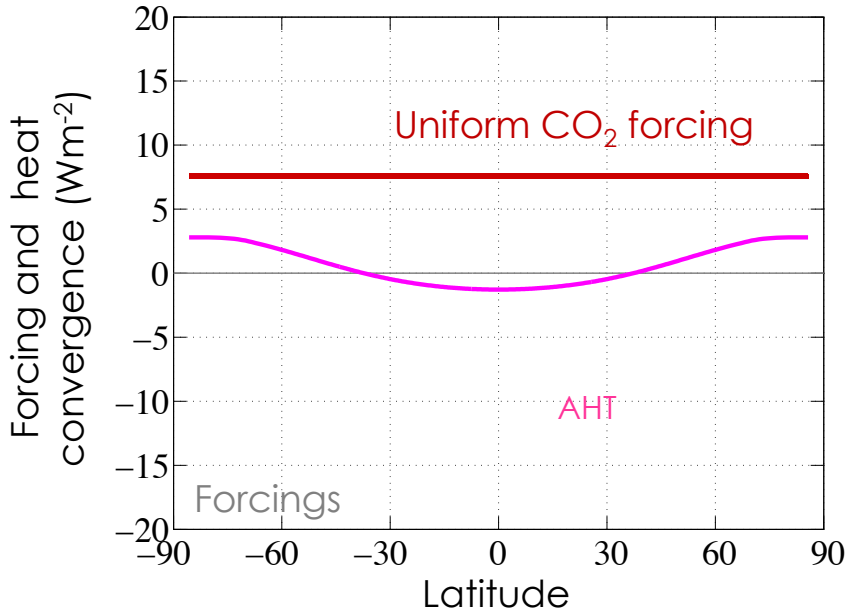

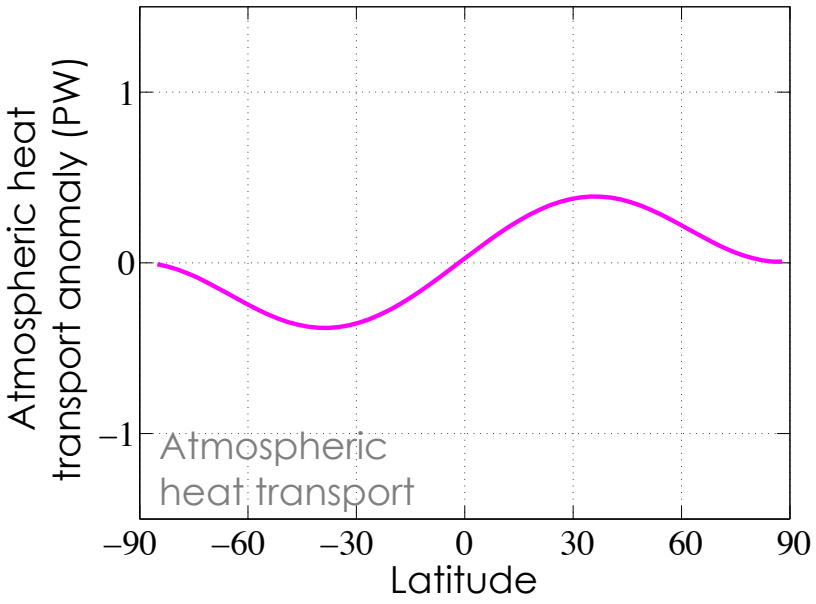

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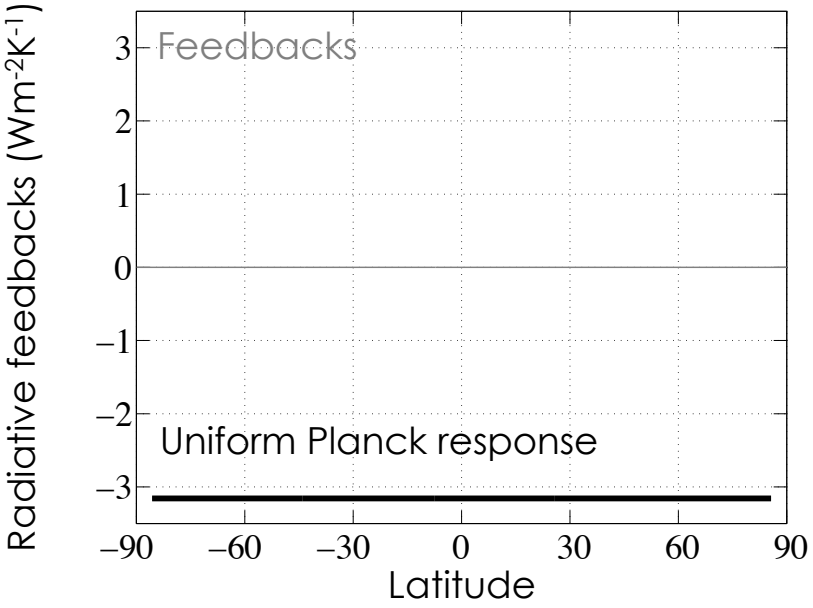
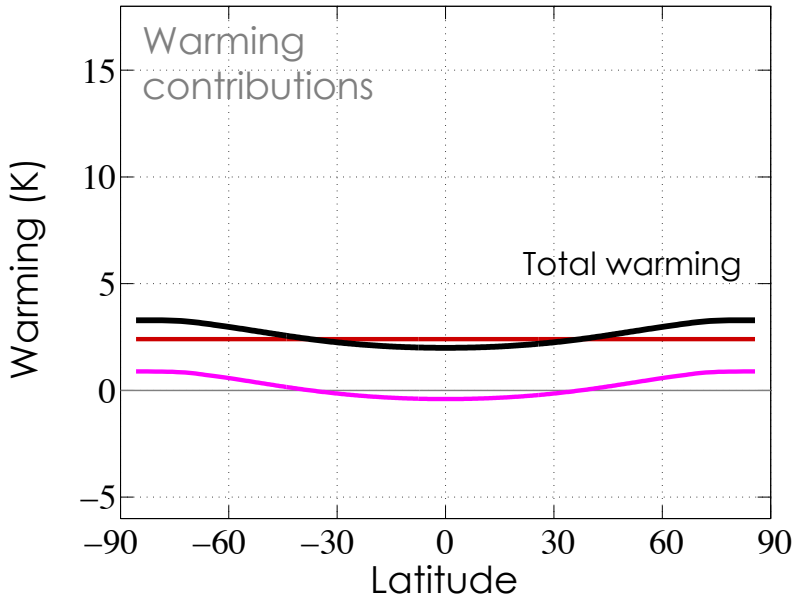
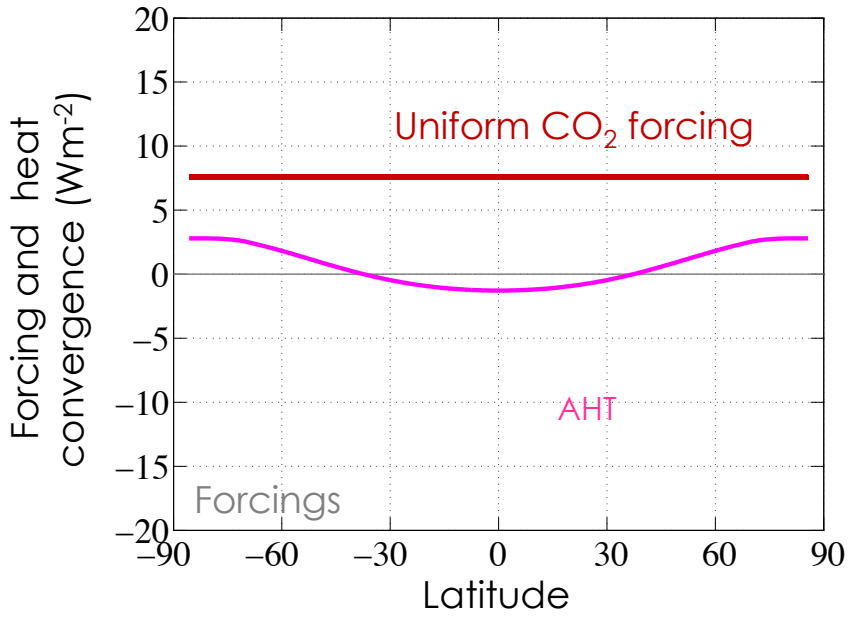
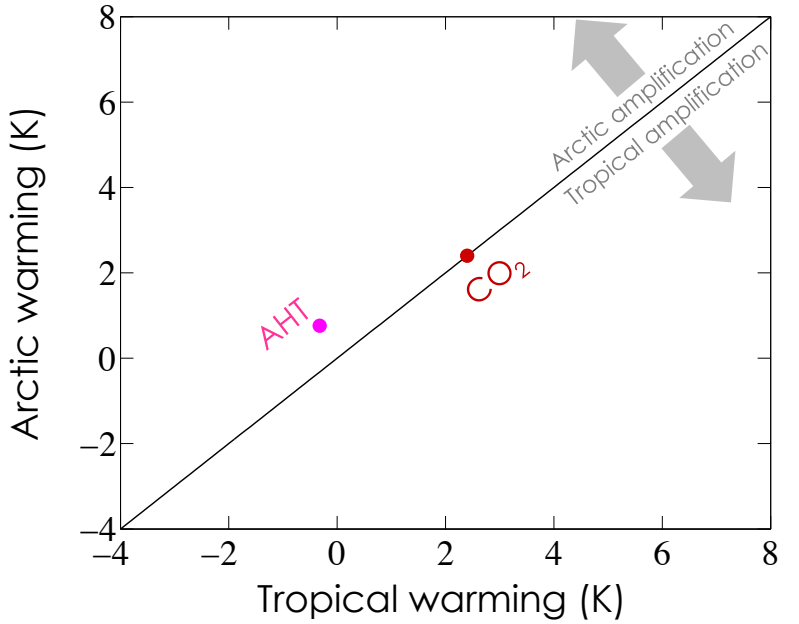
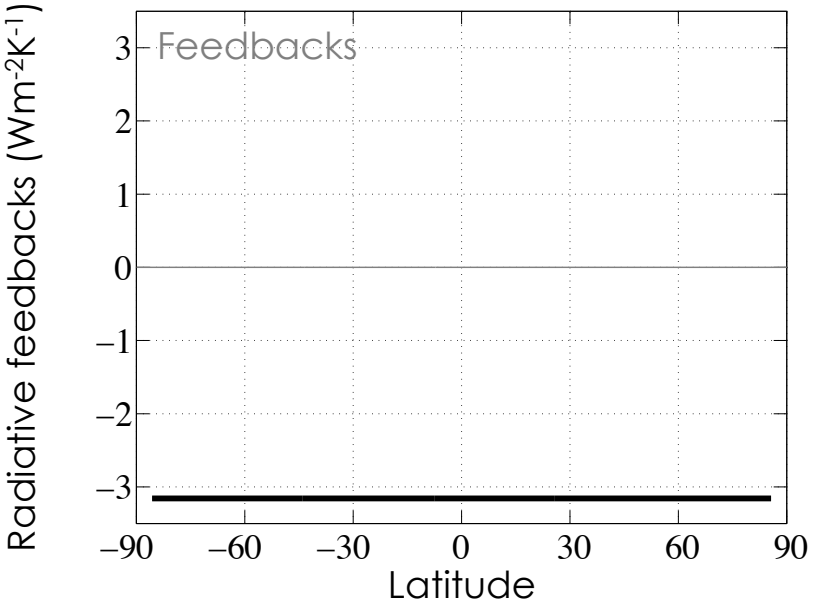


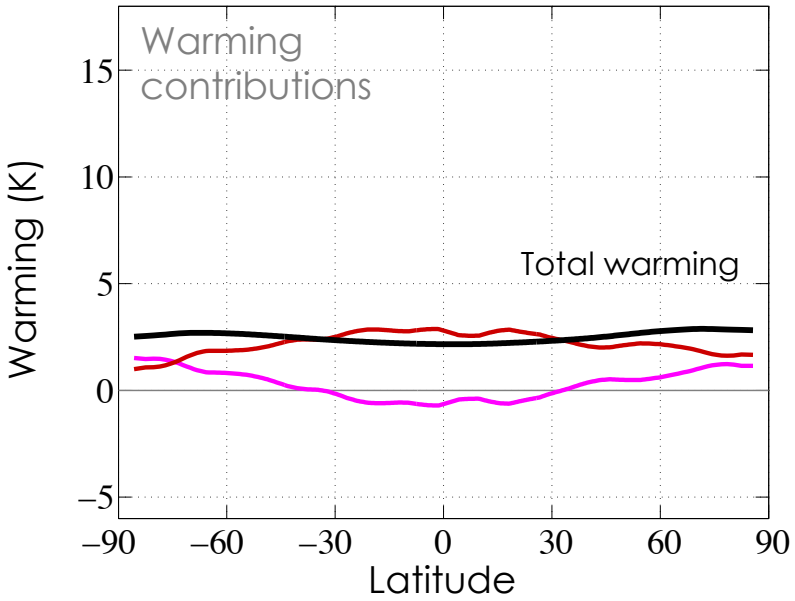


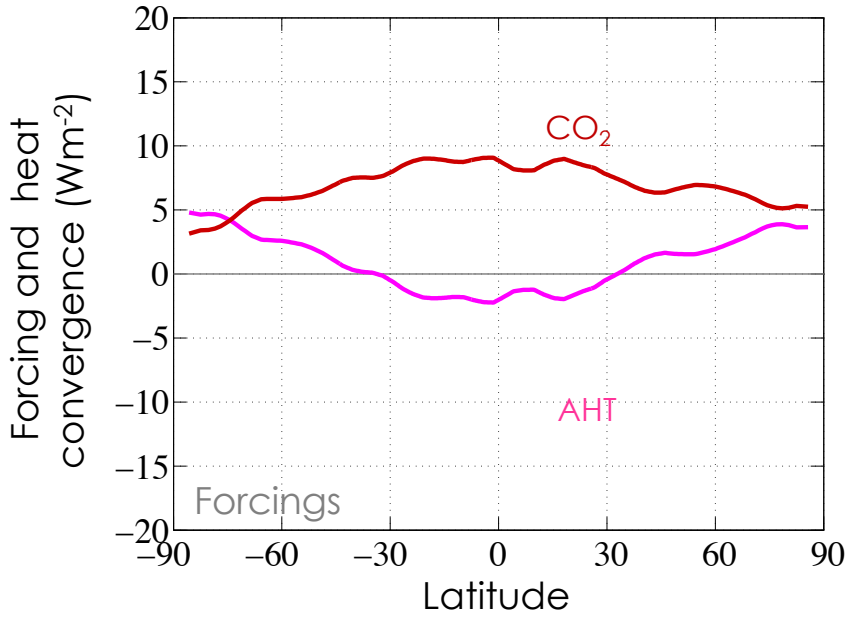


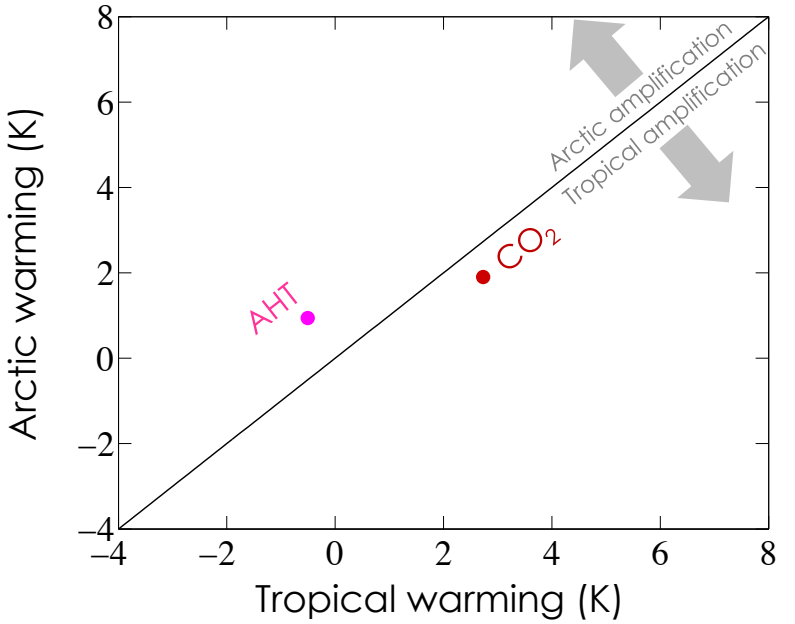


Add spatial structure in CO_2 forcing

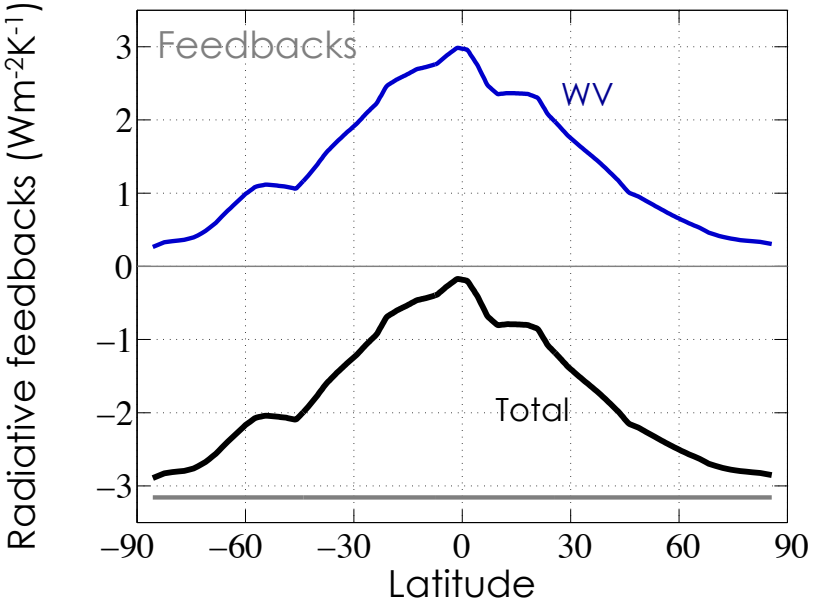


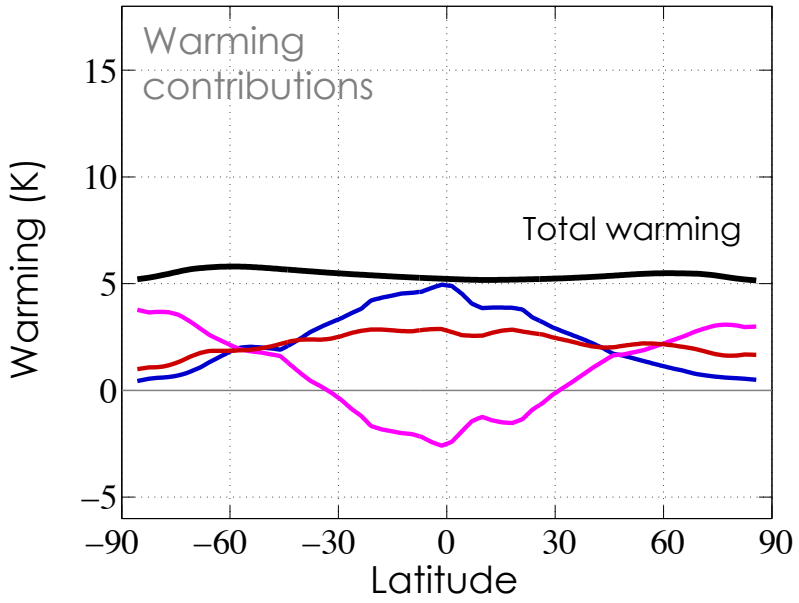


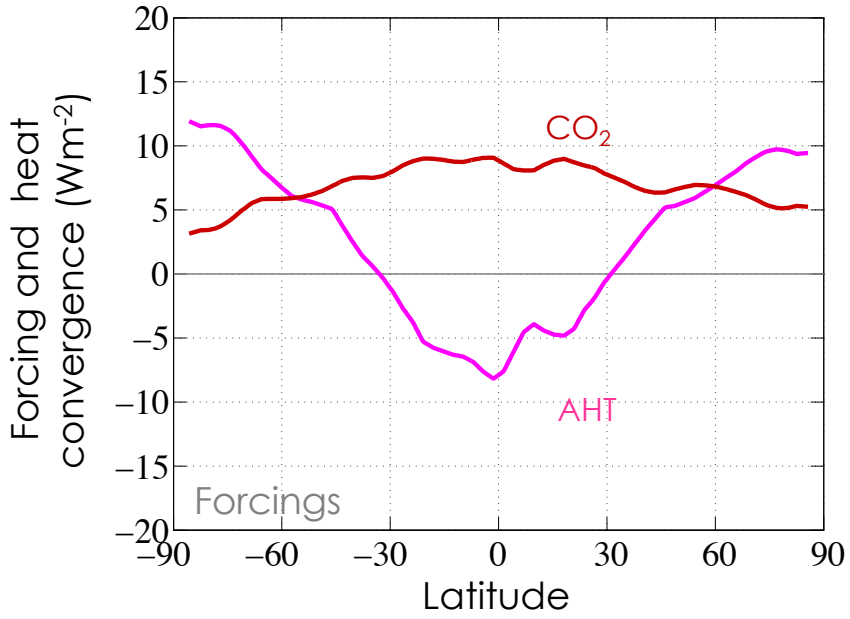


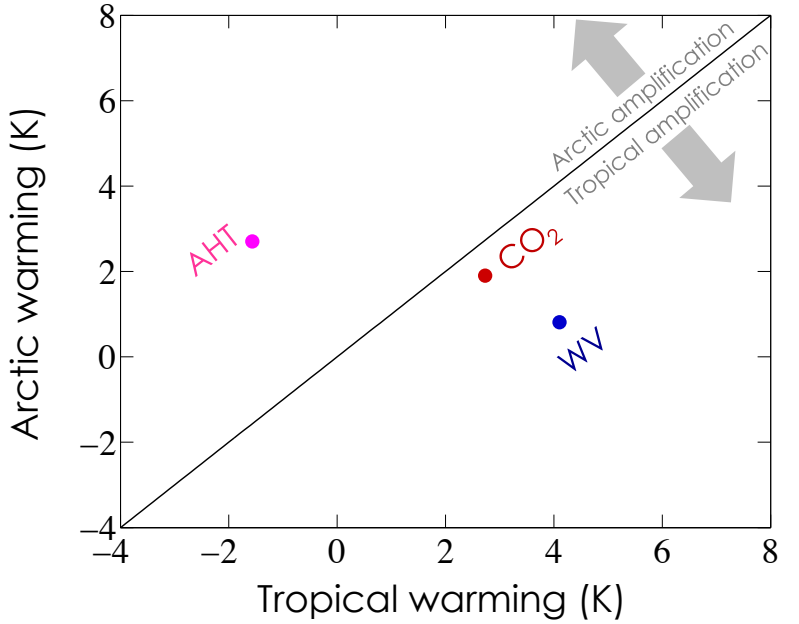


Add water vapor feedback

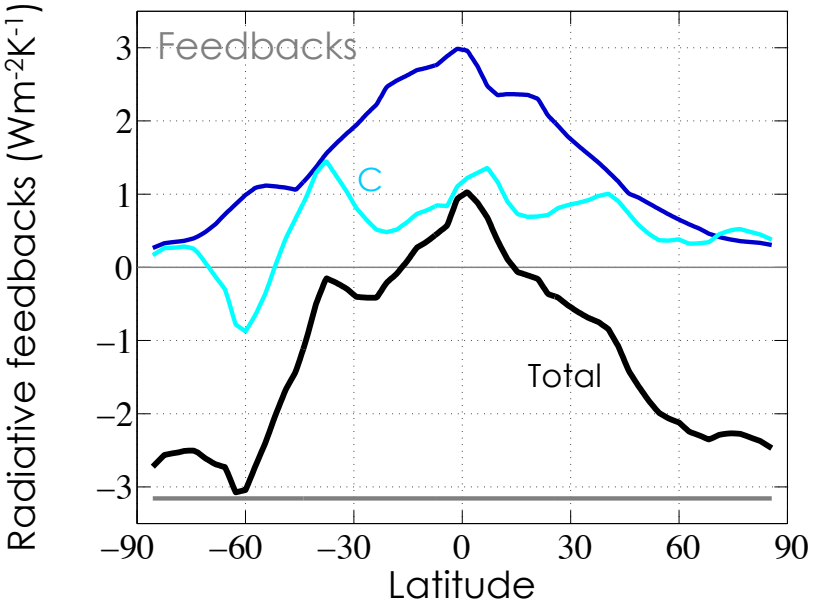


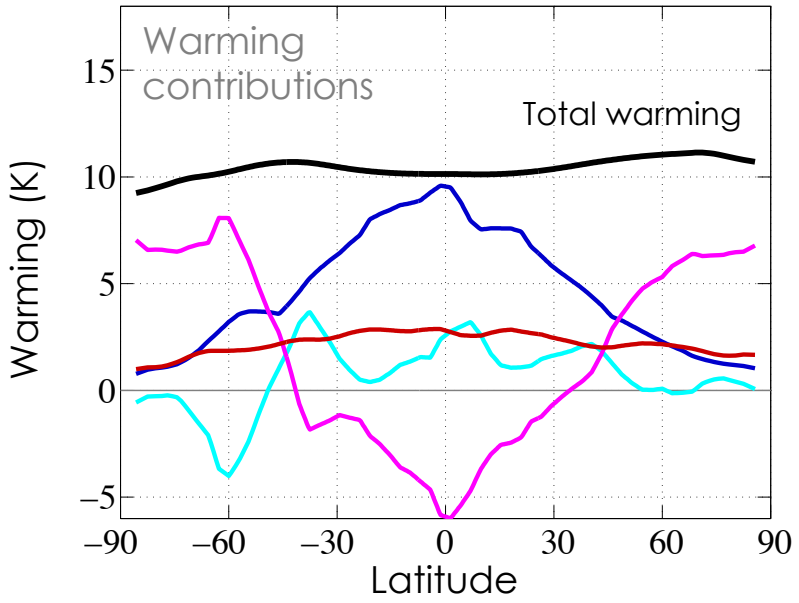


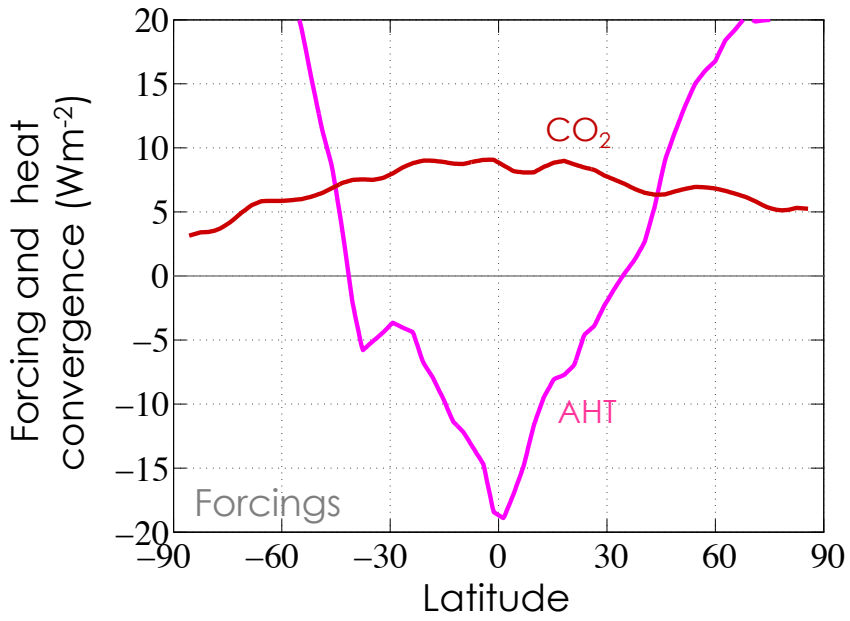


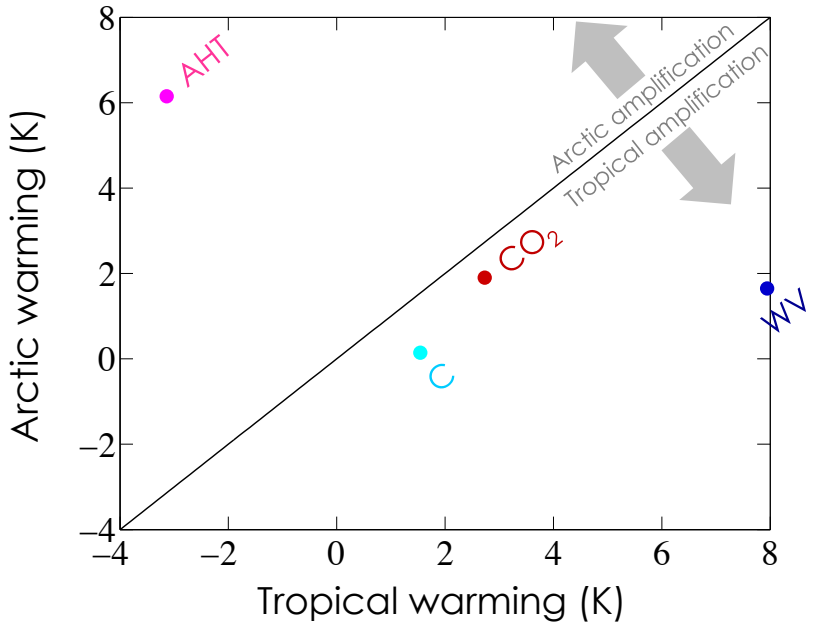


Add cloud (SW+LW) feedback

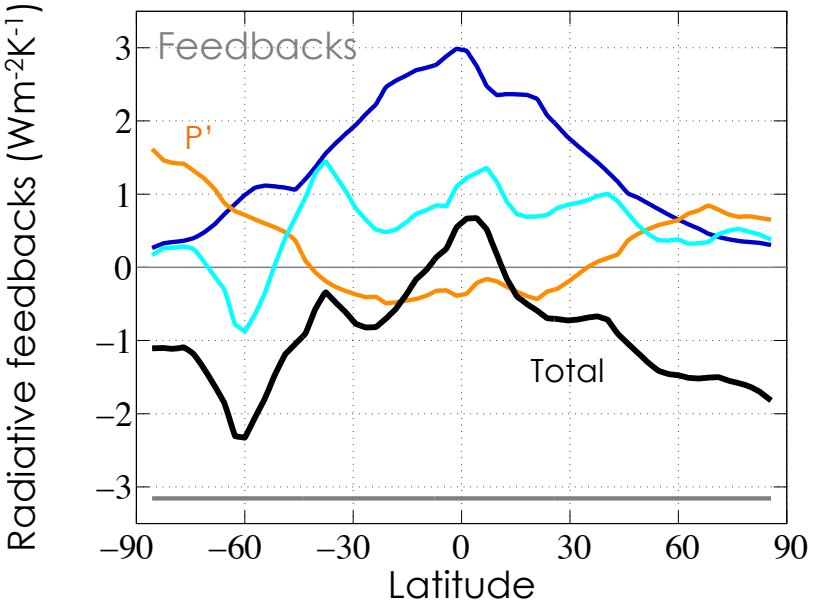


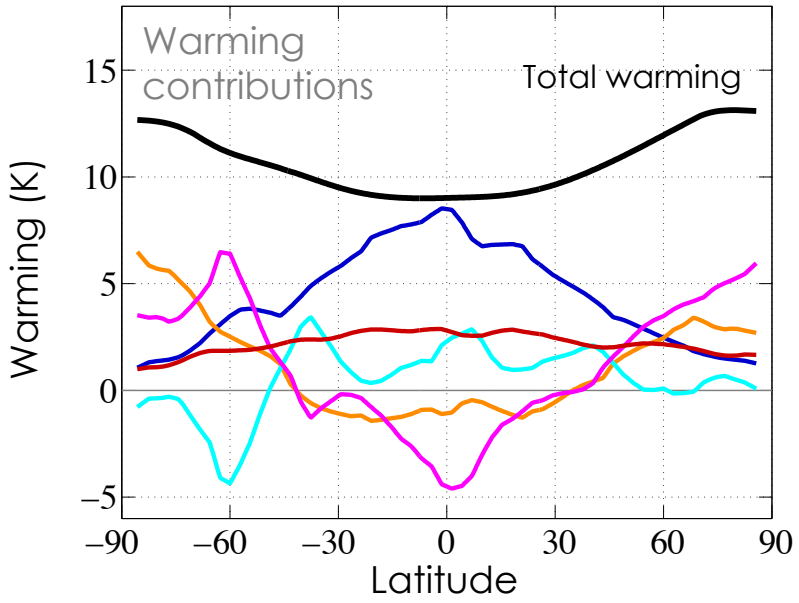


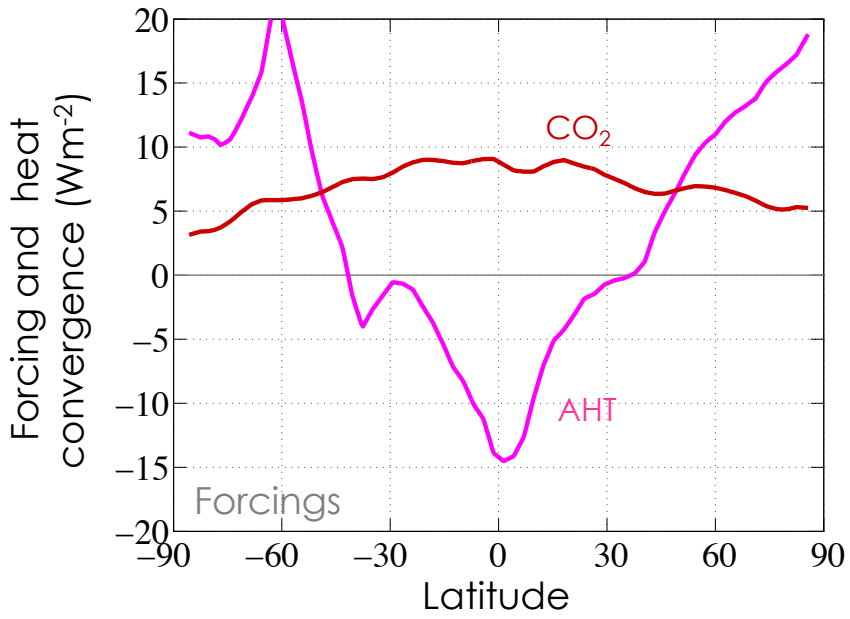


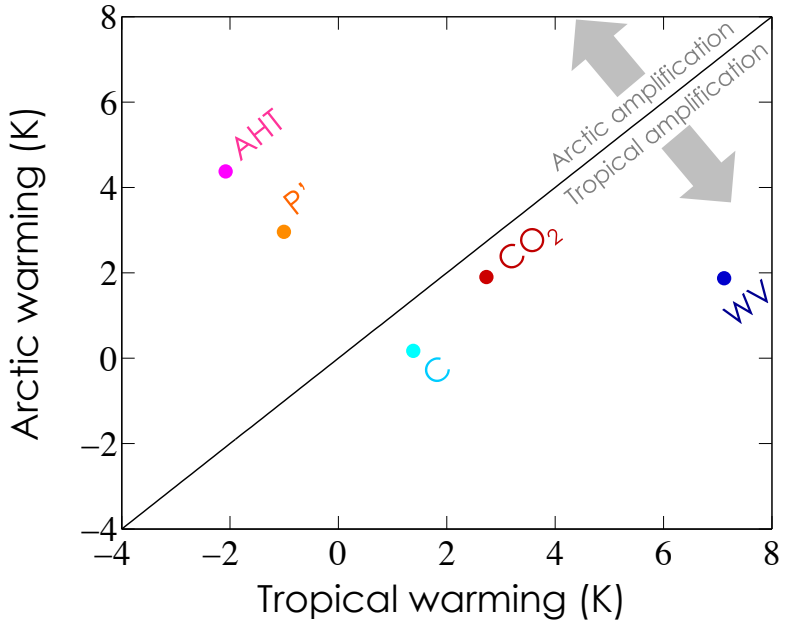


Add curvature in Planck feedback

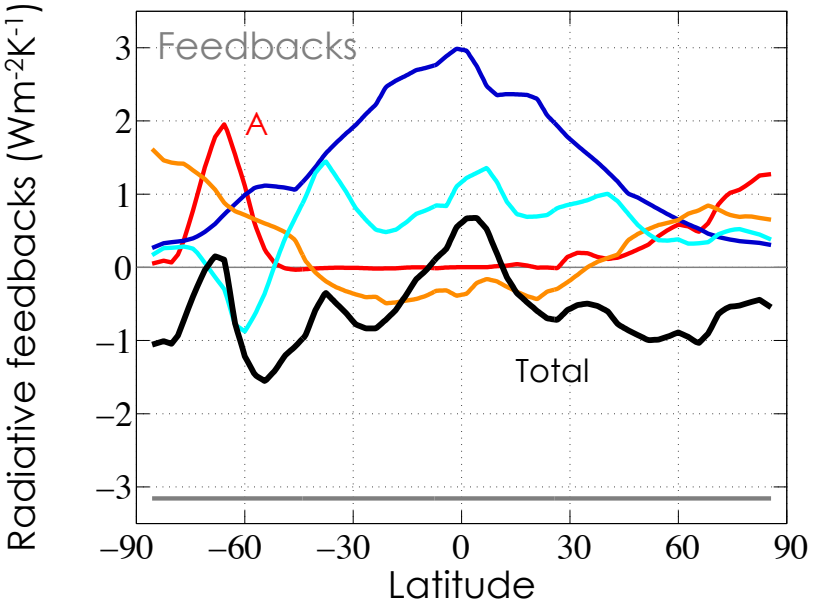


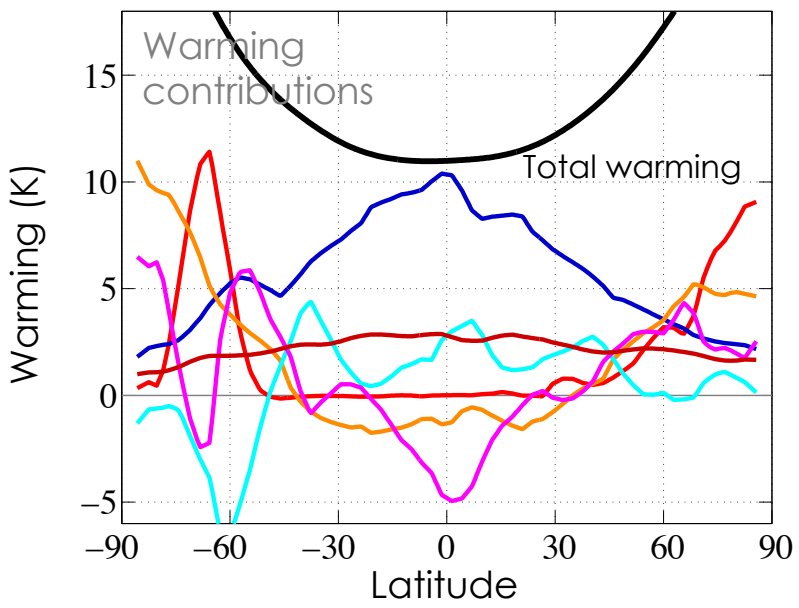


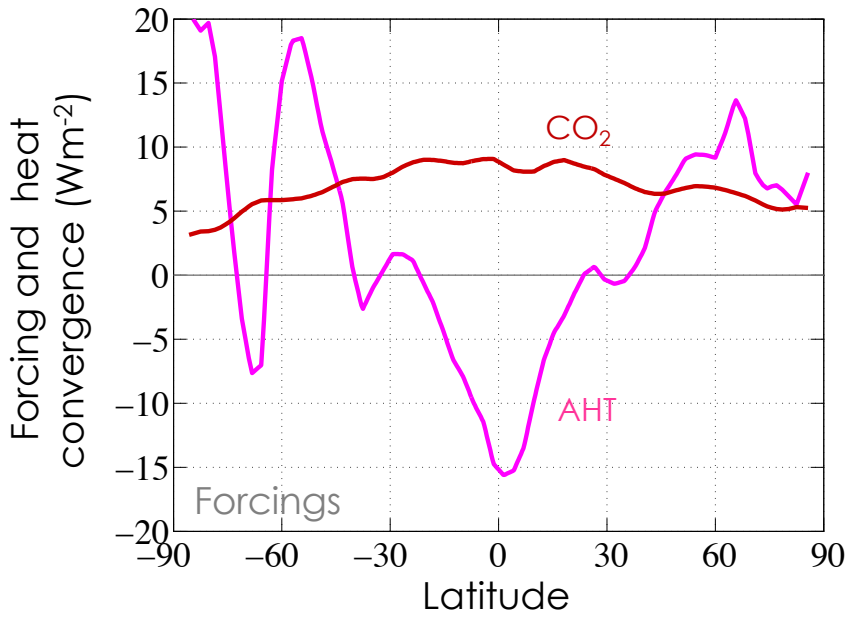


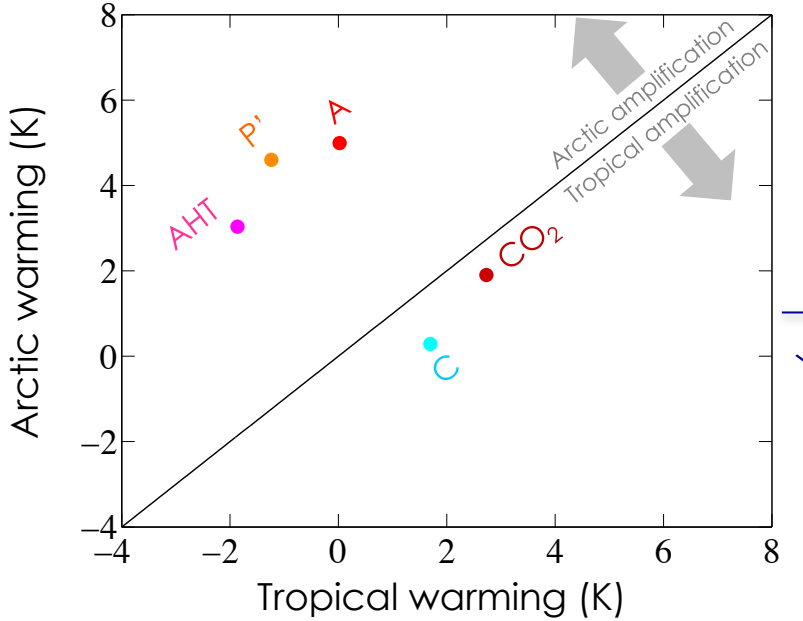


Add ice albedo feedback

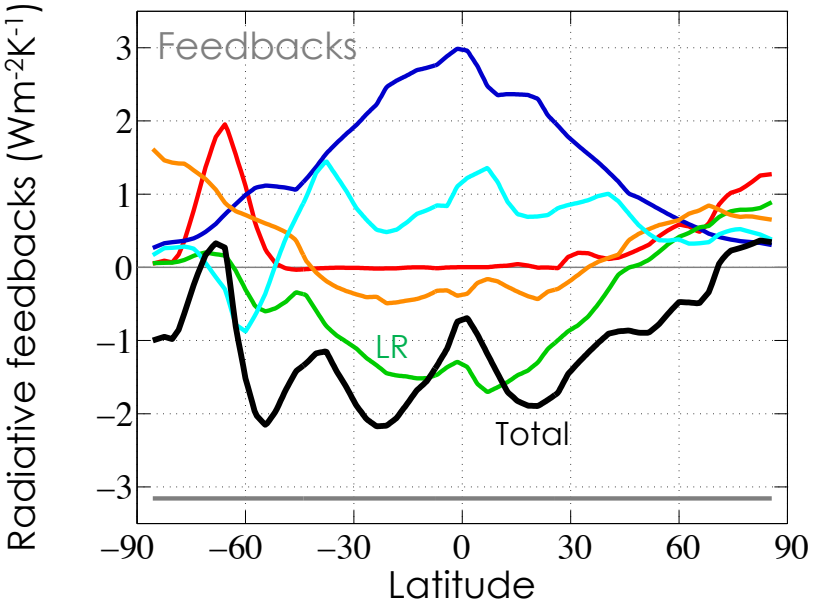


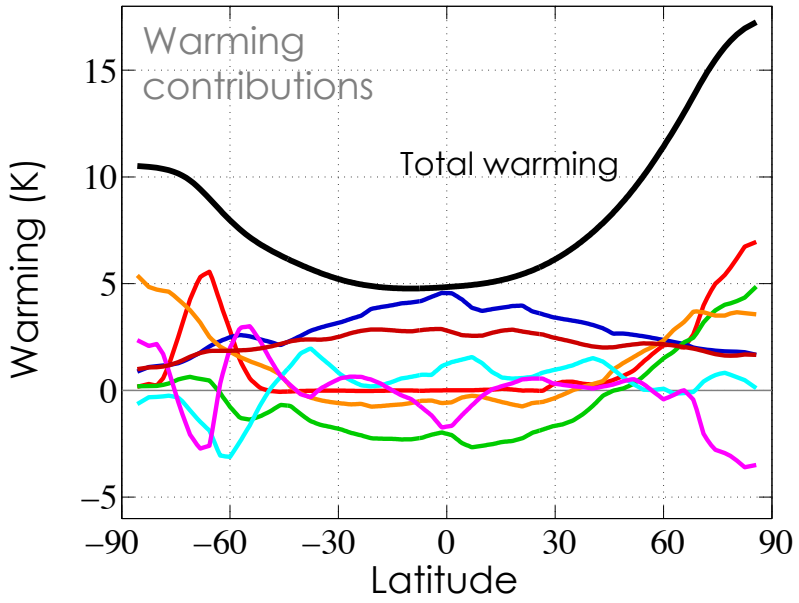


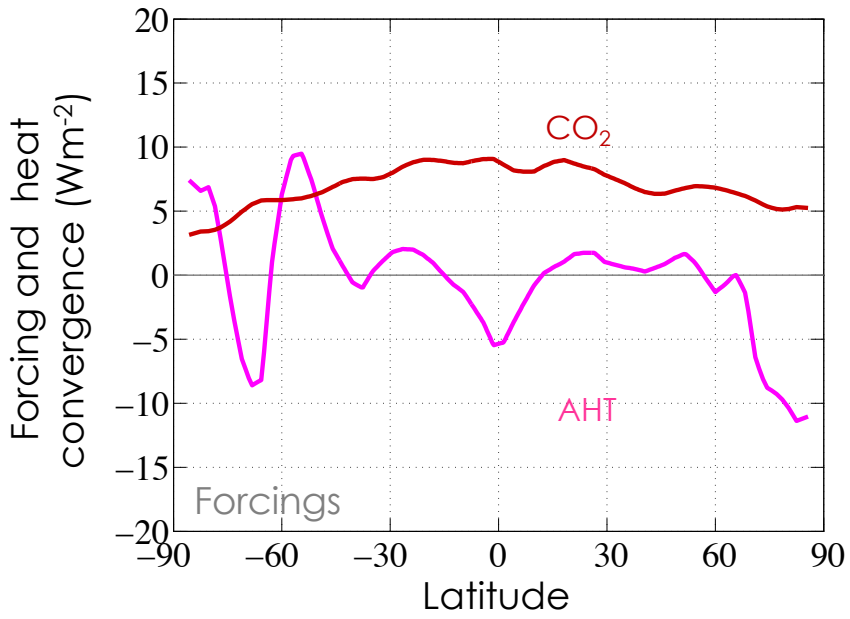


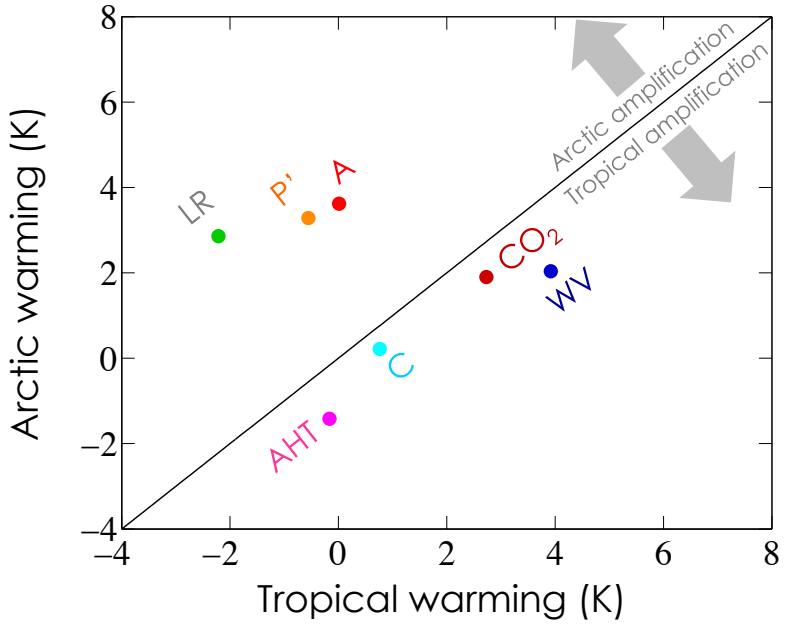


Add lapse rate feedback

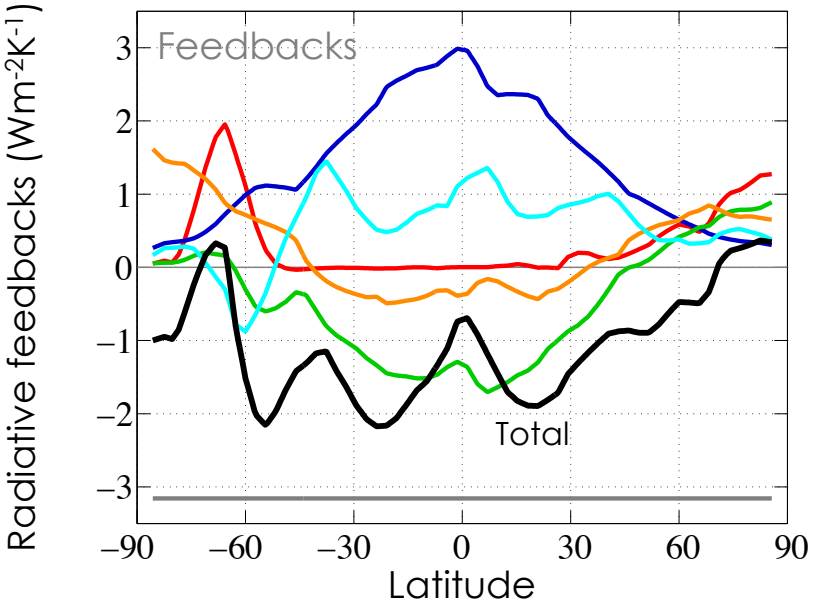


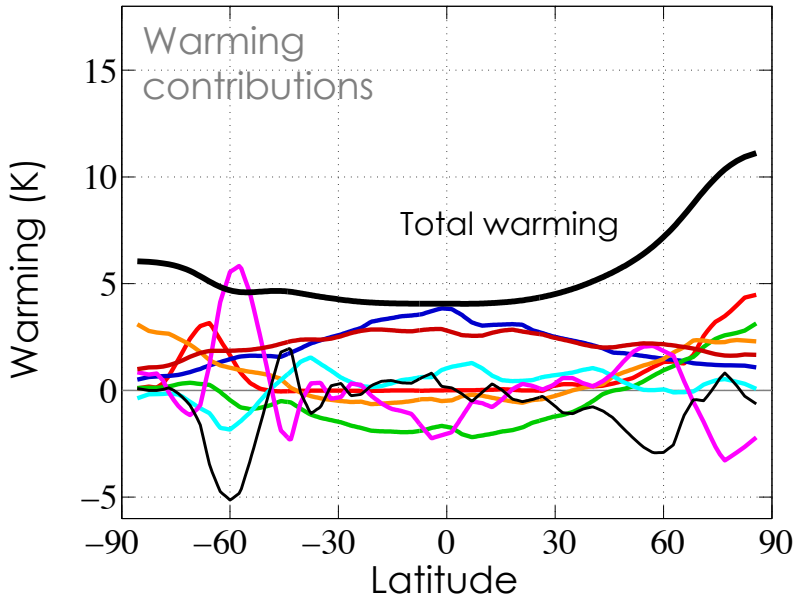


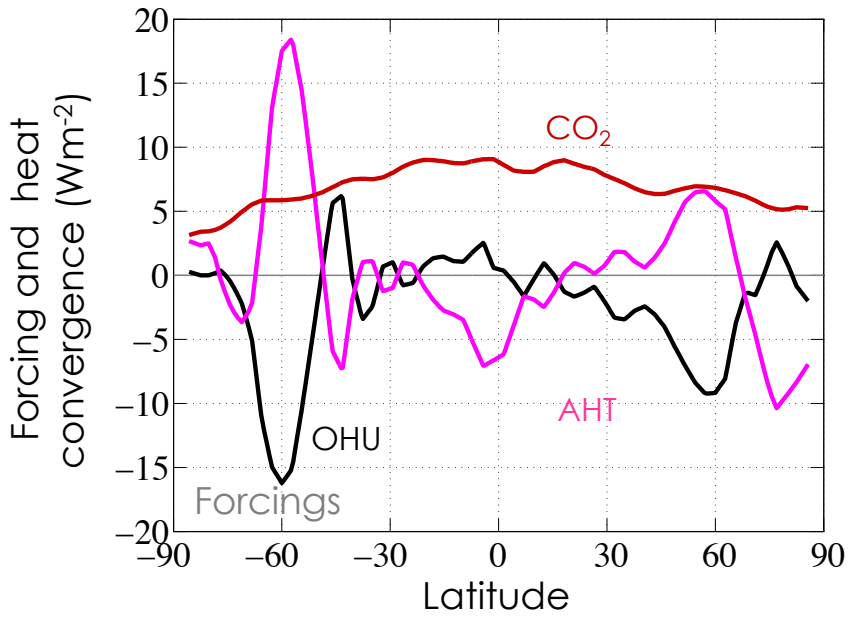


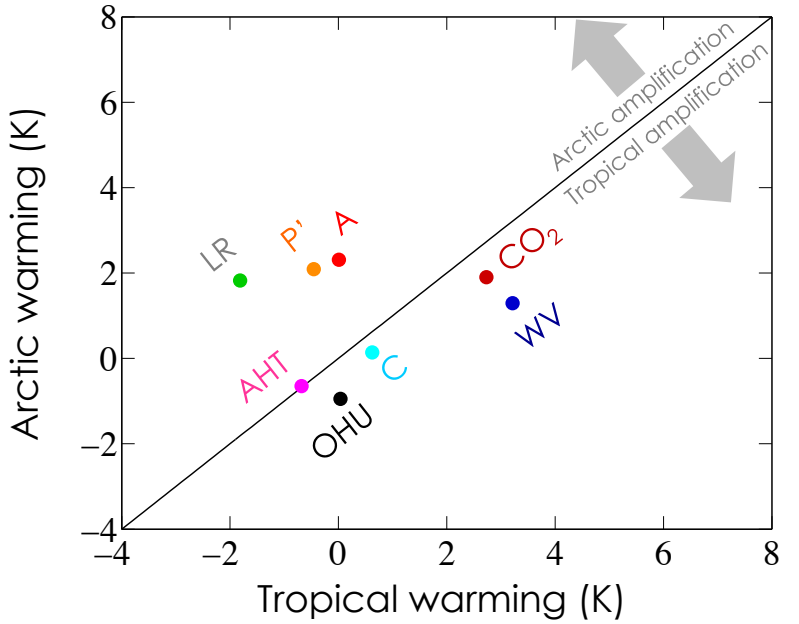


Add ocean heat uptake

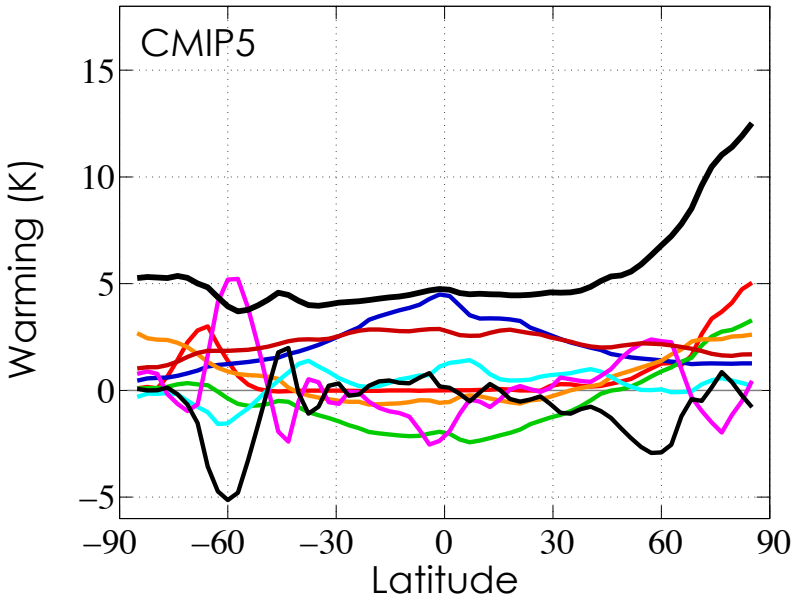


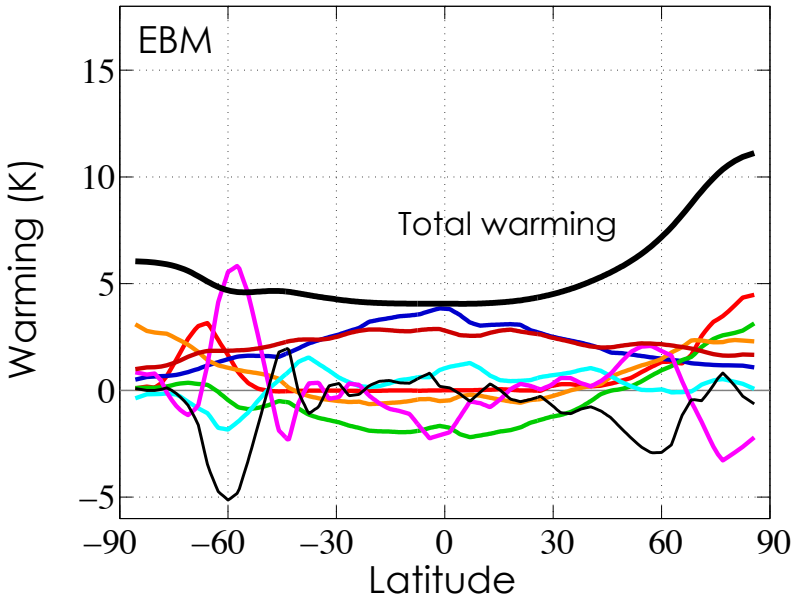


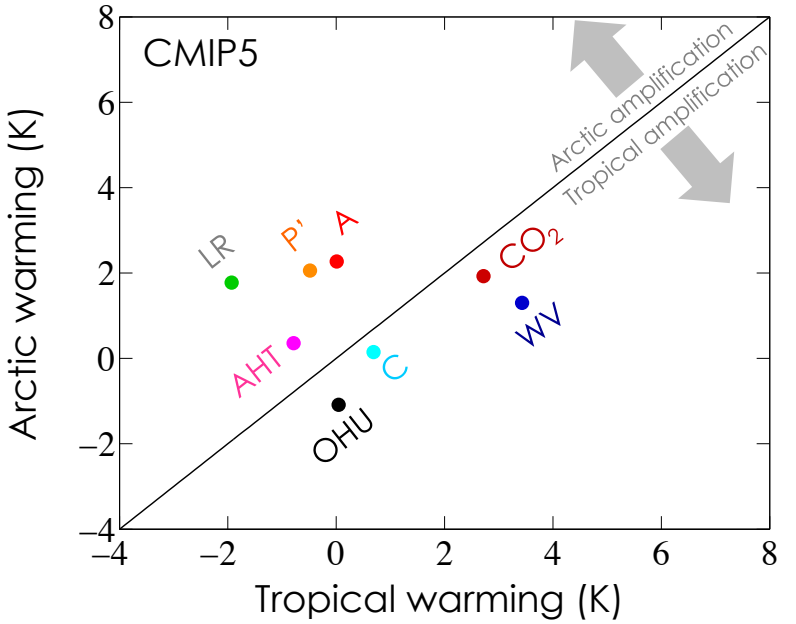


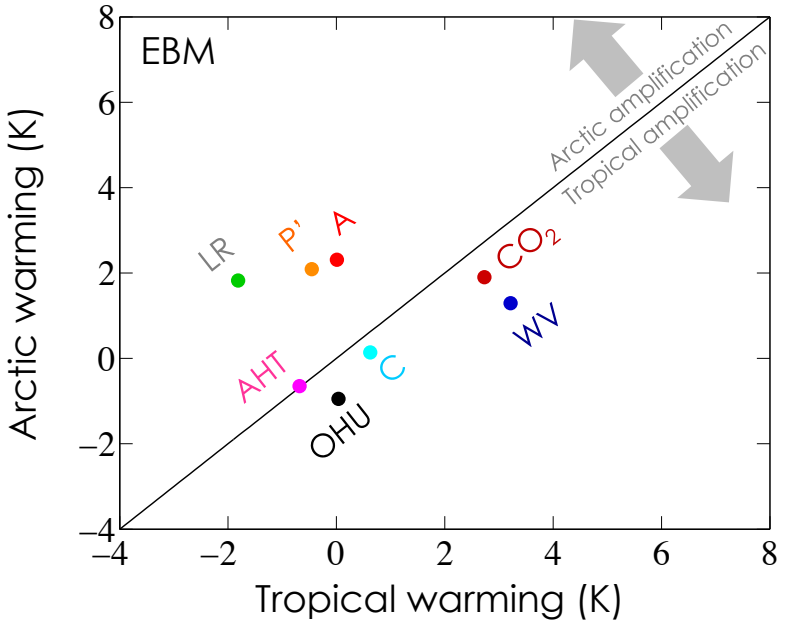


CMIP5 vs Energy Balance Model



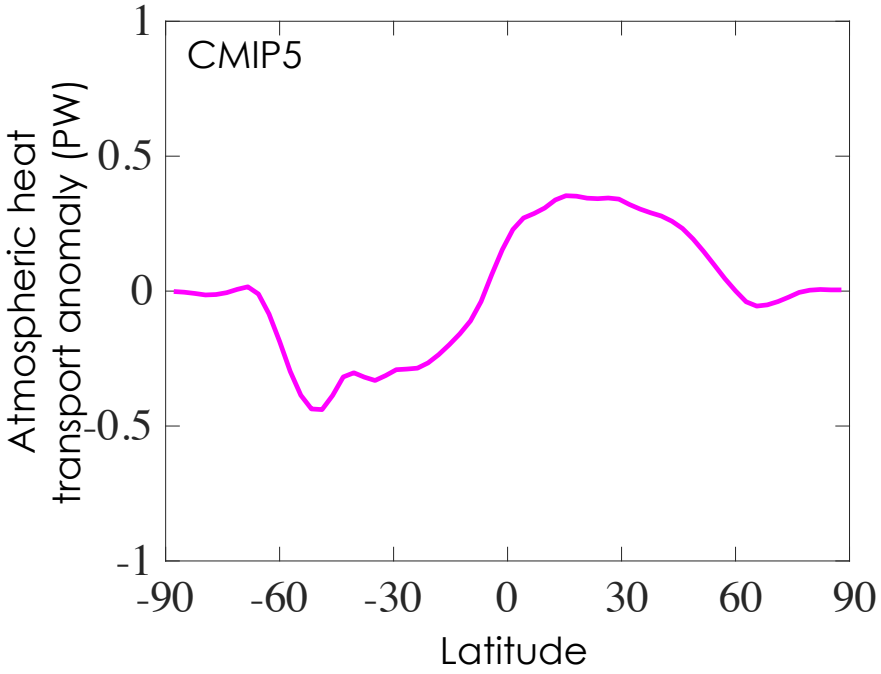


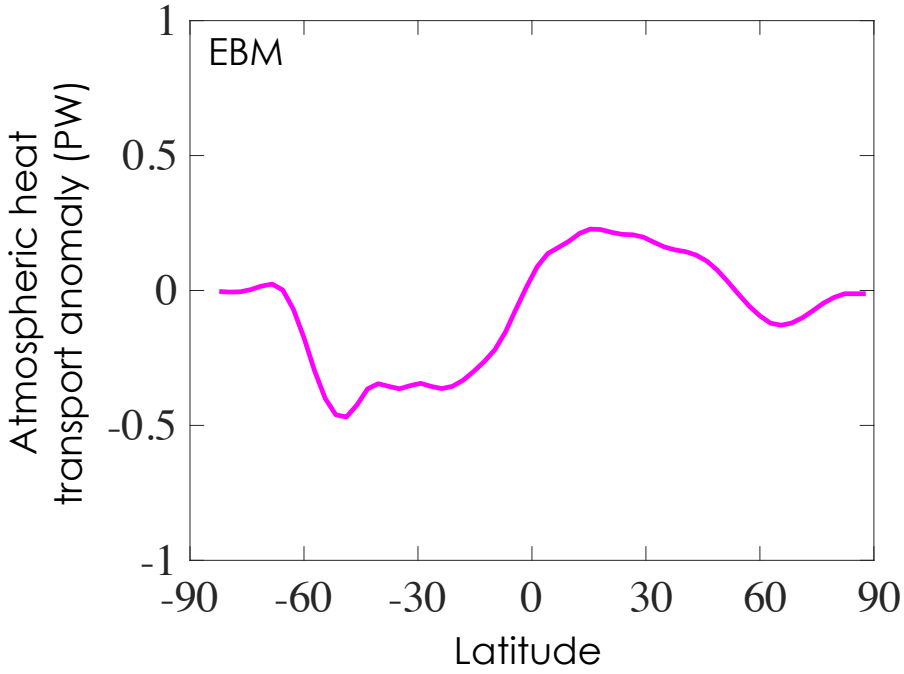




CMIP5 vs Energy Balance Model

- Success of the EBM rests fundamentally on capturing the relationship between heat transport, surface temperature, and TOA radiation





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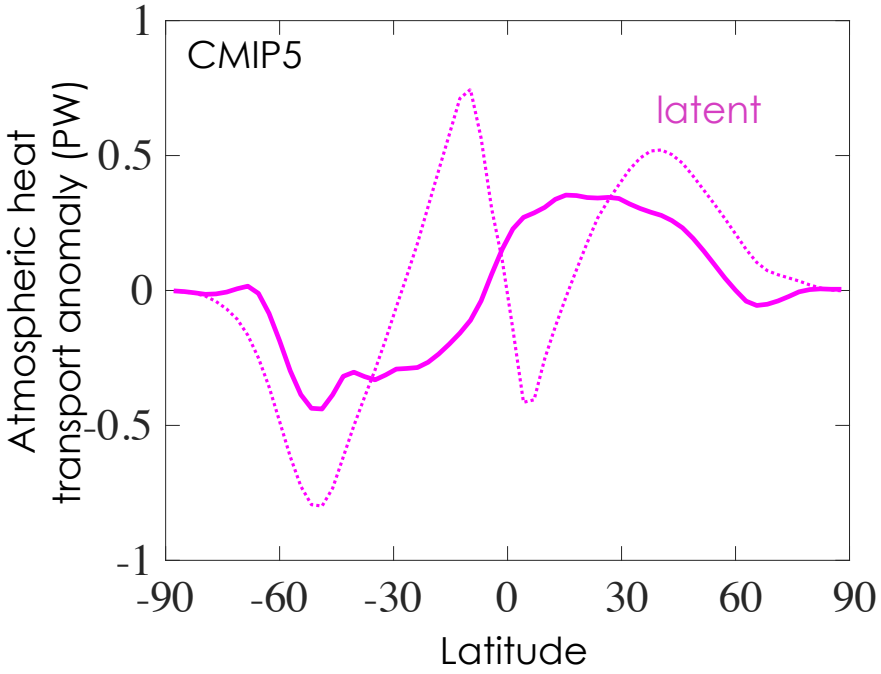

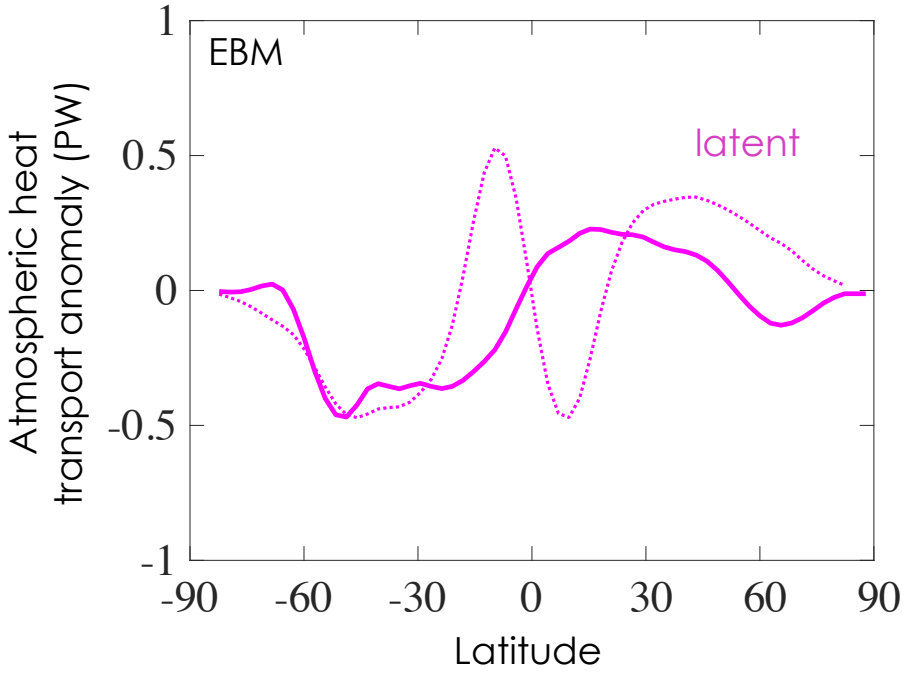

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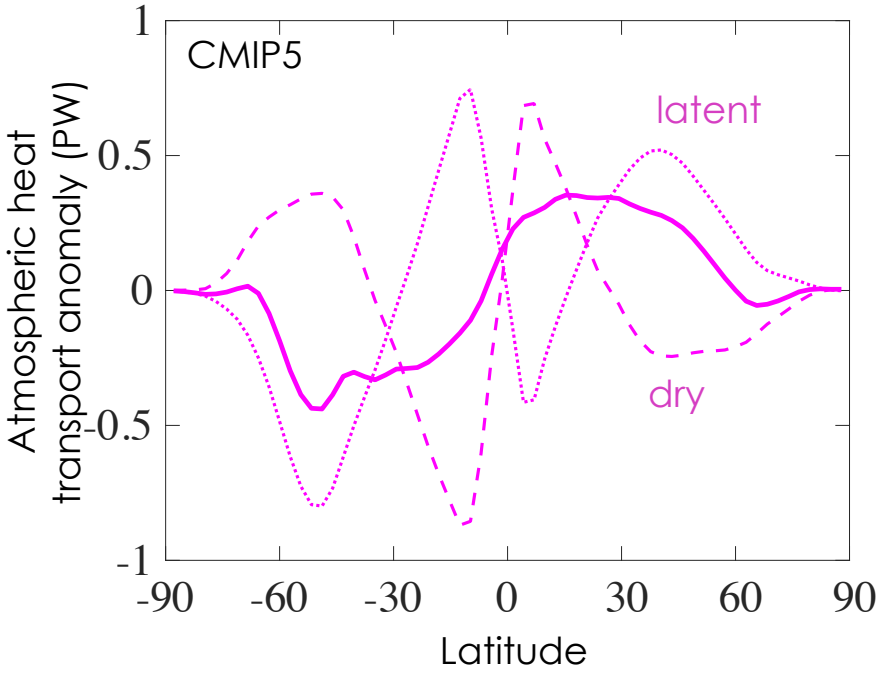
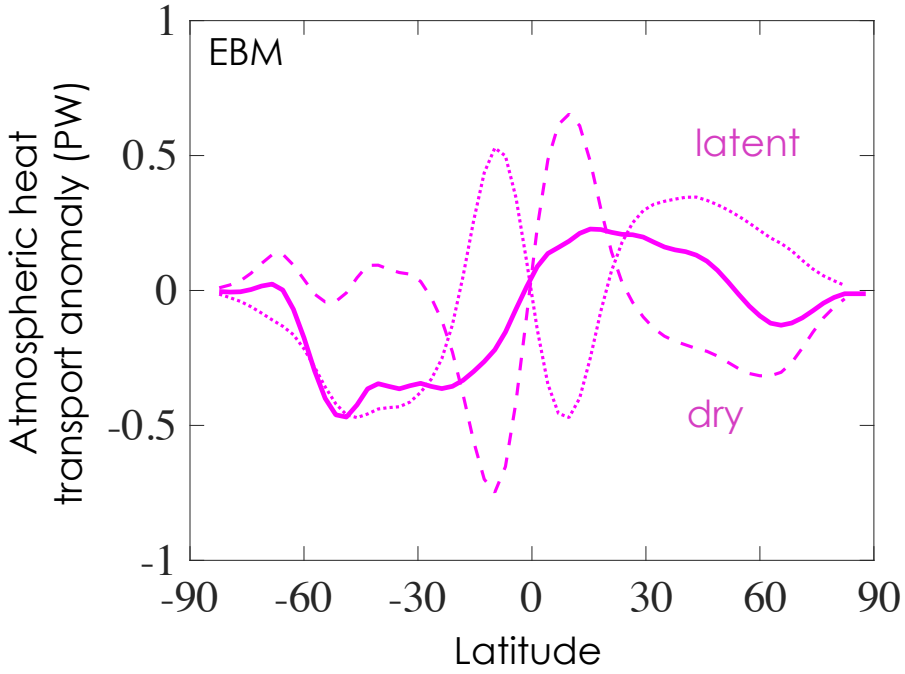
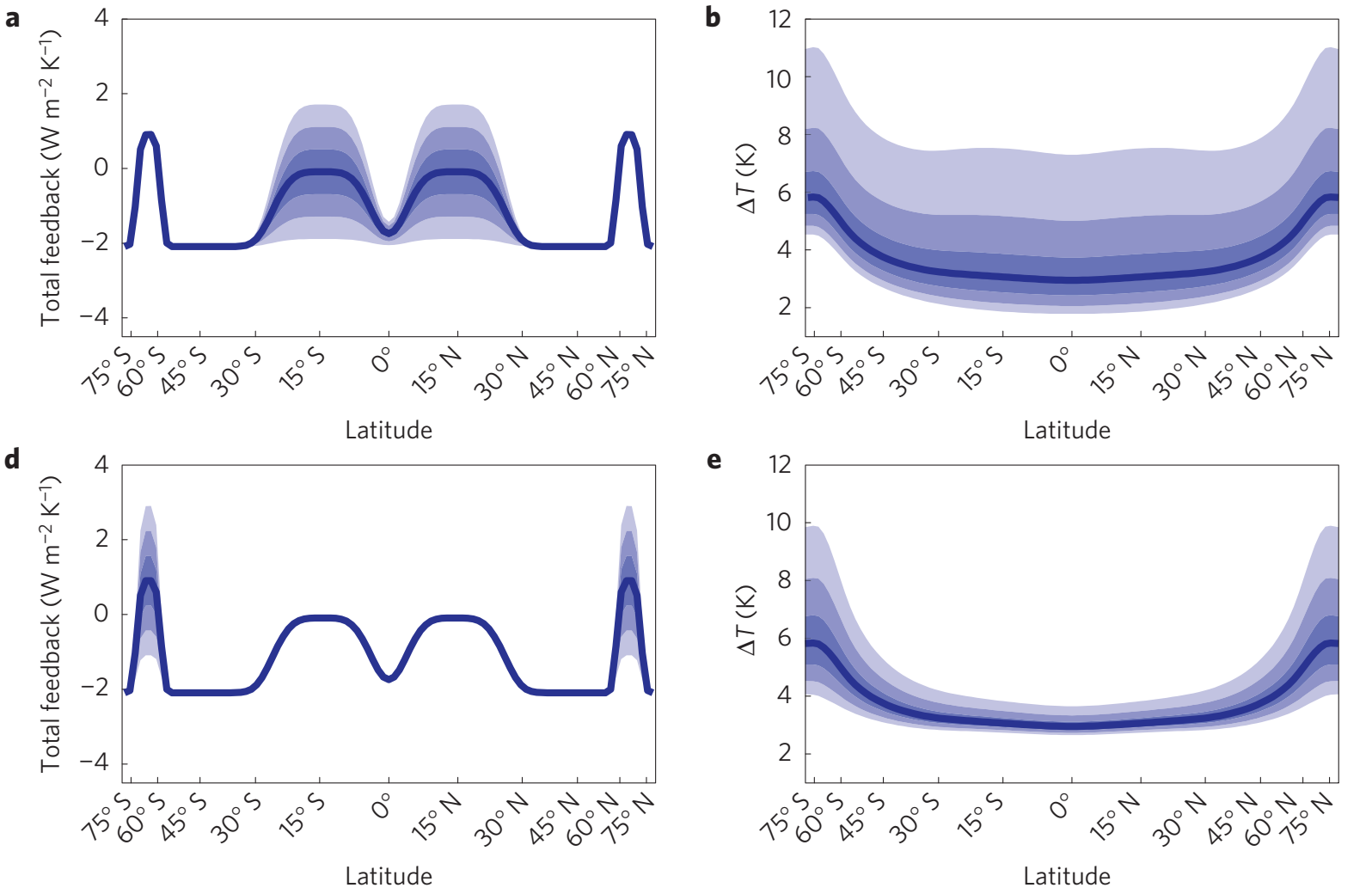


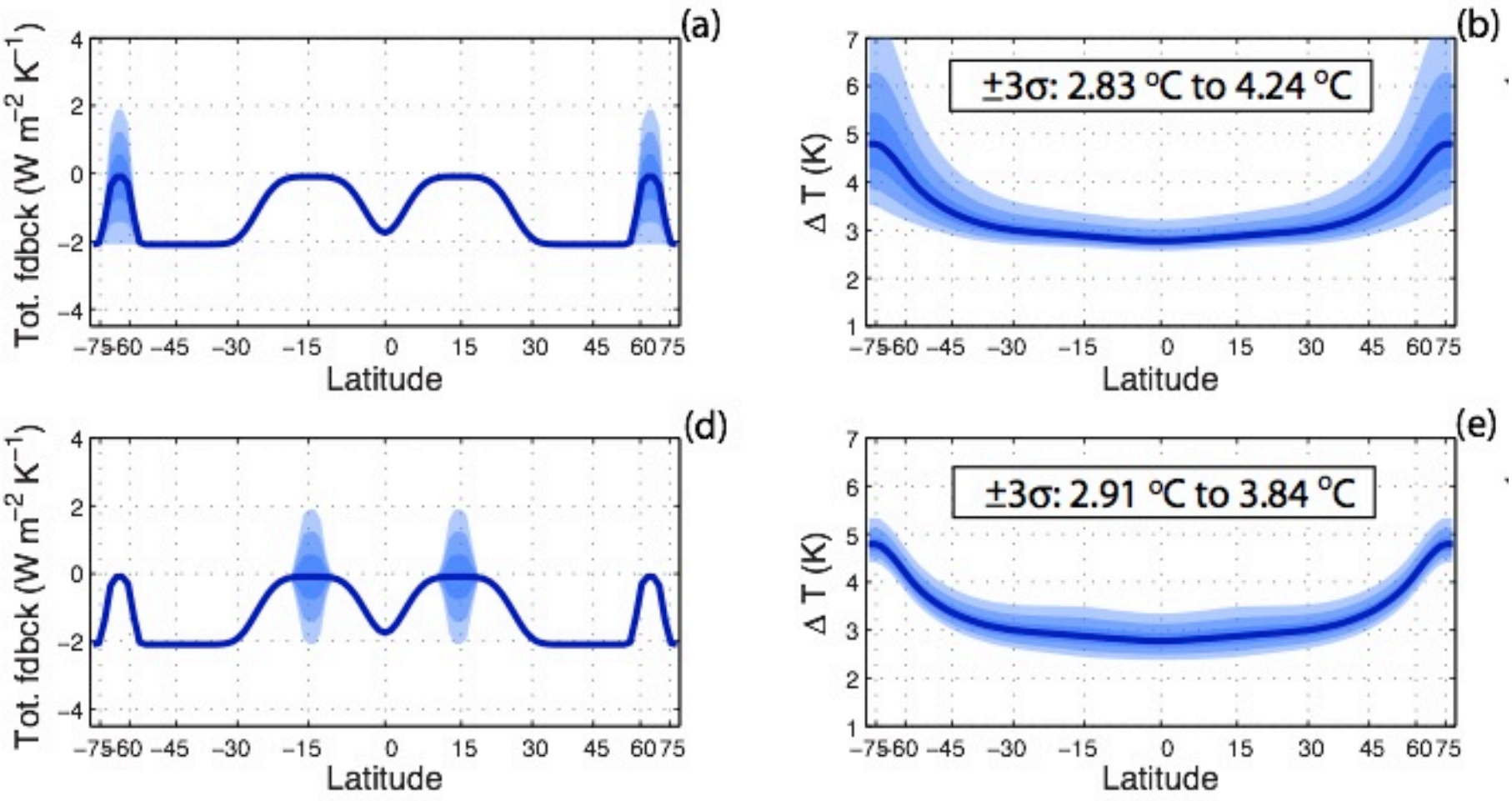


Uncertainty propagates poleward



Roe et al (2015)

Arctic feedbacks have largest impact on global warming



Roe et al (2015)

Parting thoughts

- Atmospheric heat transport changes can be understood as satisfying (i) down-gradient transport of MSE (with *constant diffusivity*) and (ii) energetic constraints set by radiative forcing and feedbacks
  - Why does this work so well? Is there a role for atmospheric circulation changes?
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- Uncertainty in polar warming isn't just due to uncertainty in polar feedbacks, it's due to uncertainty in tropical feedbacks as well; uncertainty in polar feedbacks have outsized affect on global warming

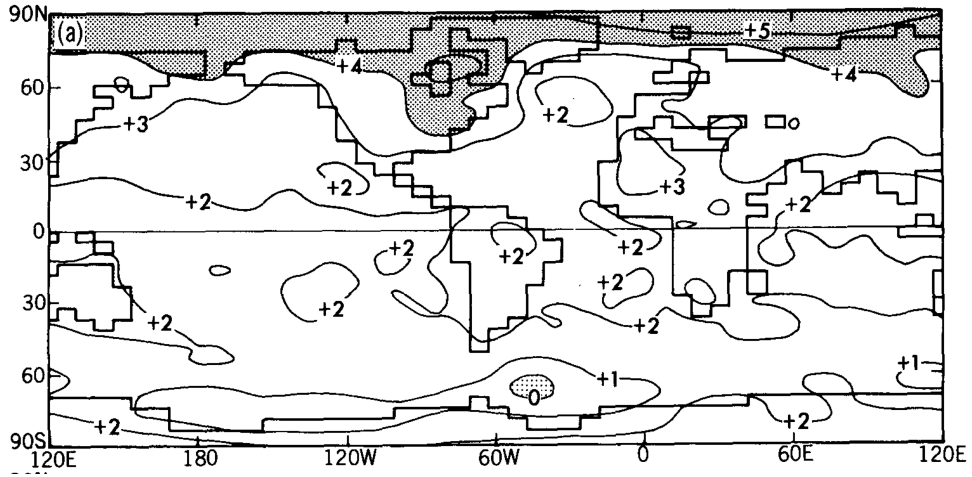
Our papers related to this

- Roe, Feldl, Armour, Hwang and Frierson (2015) The remote impacts of climate feedbacks on regional predictability, *Nature Geoscience*
- Armour, Marshall, Scott, Donohoe and Newsom (2016) Southern Ocean warming delayed by circumpolar upwelling and equatorward transport, *Nature Geoscience*
- Marshall, Scott, Armour, Campin, Kelly and Romanou (2015) The ocean's role in the transient response of climate to abrupt greenhouse gas forcing, *Climate Dynamics*
- Rose, Armour, Battisti, Feldl and Koll (2014) The dependence of transient climate sensitivity and radiative feedbacks on the spatial pattern of ocean heat uptake, *Geophysical Research Letters*
- Armour, Bitz and Roe (2013) Time-varying climate sensitivity from regional feedbacks, Journal of Climate
- Feld and Roe (2013) The nonlinear and nonlocal nature of climate feedbacks, Journal of Climate

… *several more on the way*

Warming patterns in GCMs

Warming under 1%/yr ramping to 2×CO_2
in coupled atmos-ocean GCM (year 70)



(Manabe et al 1991)

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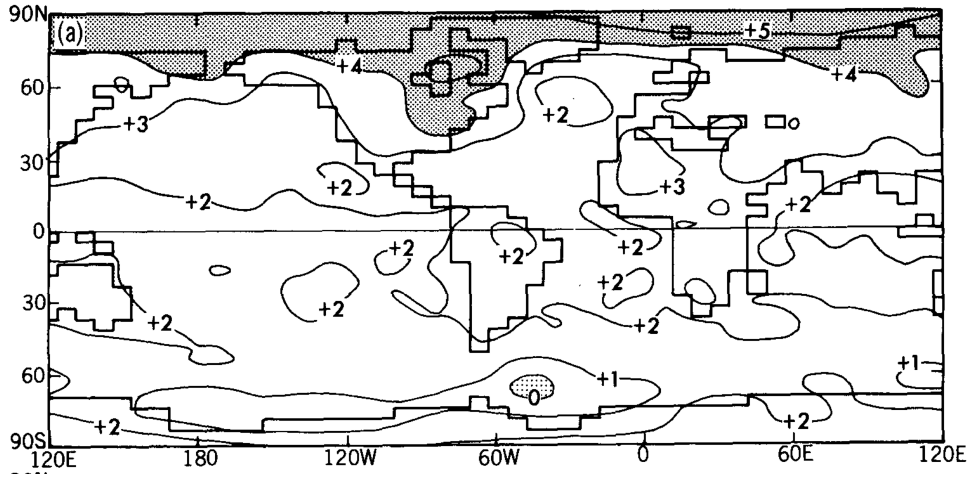
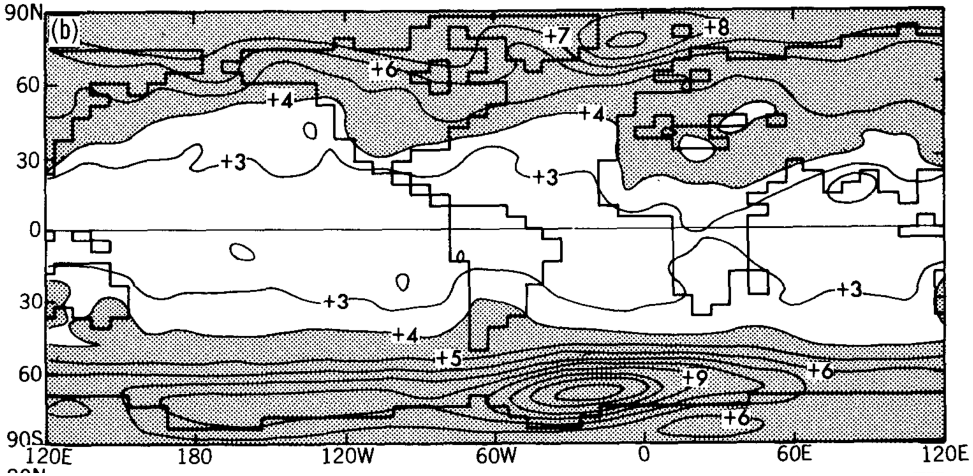


Warming under 2×CO_2 in atmospheric GCM with a slab ocean (equilibrium)



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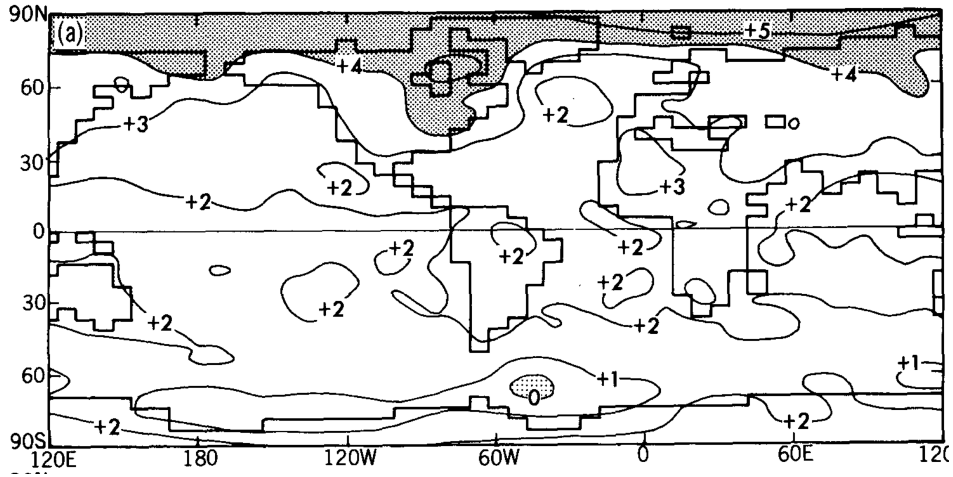

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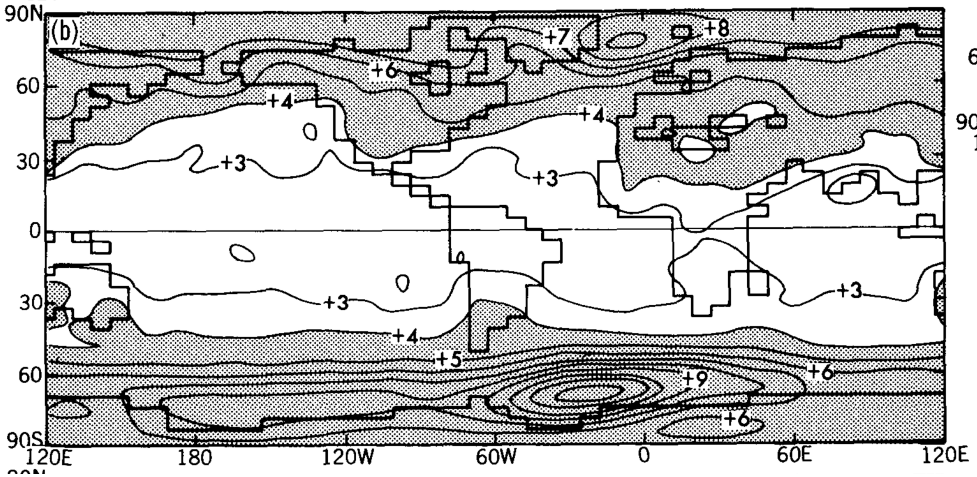
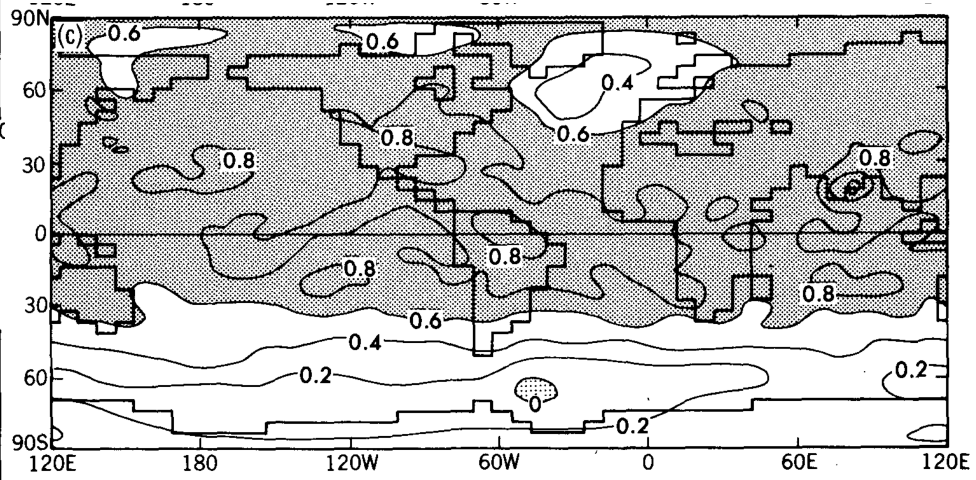
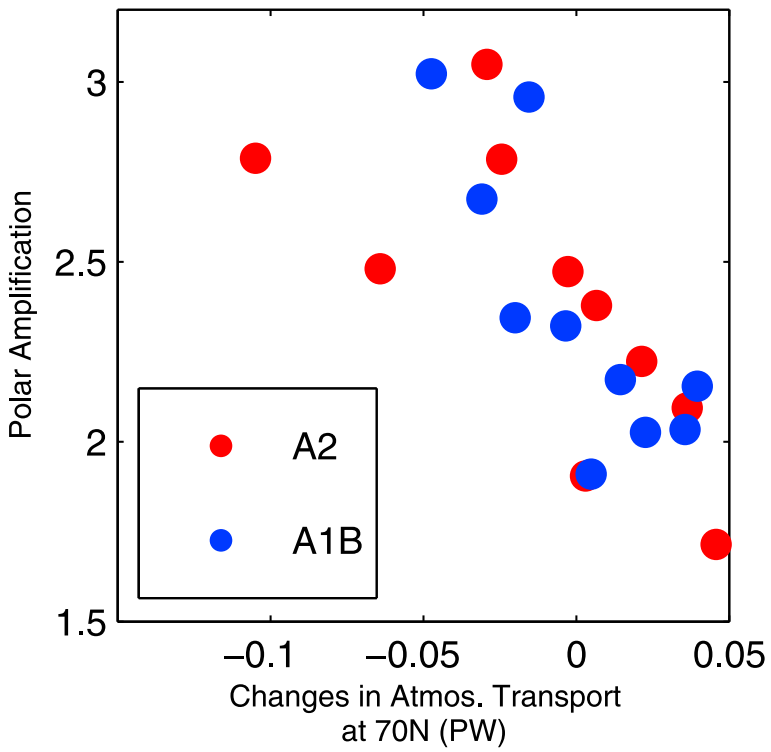


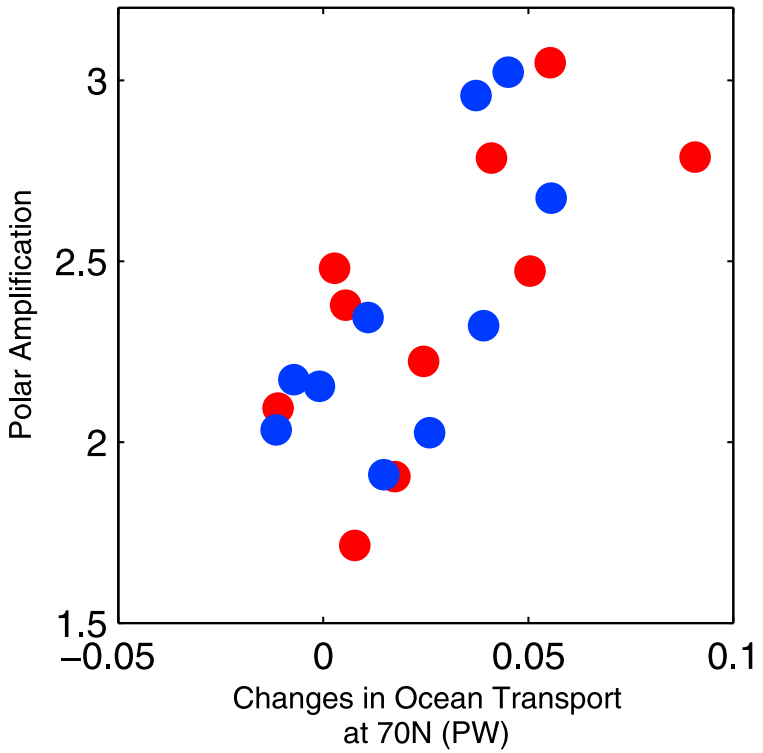
Ratio of transient to equilibrium warming



(Manabe et al 1991)

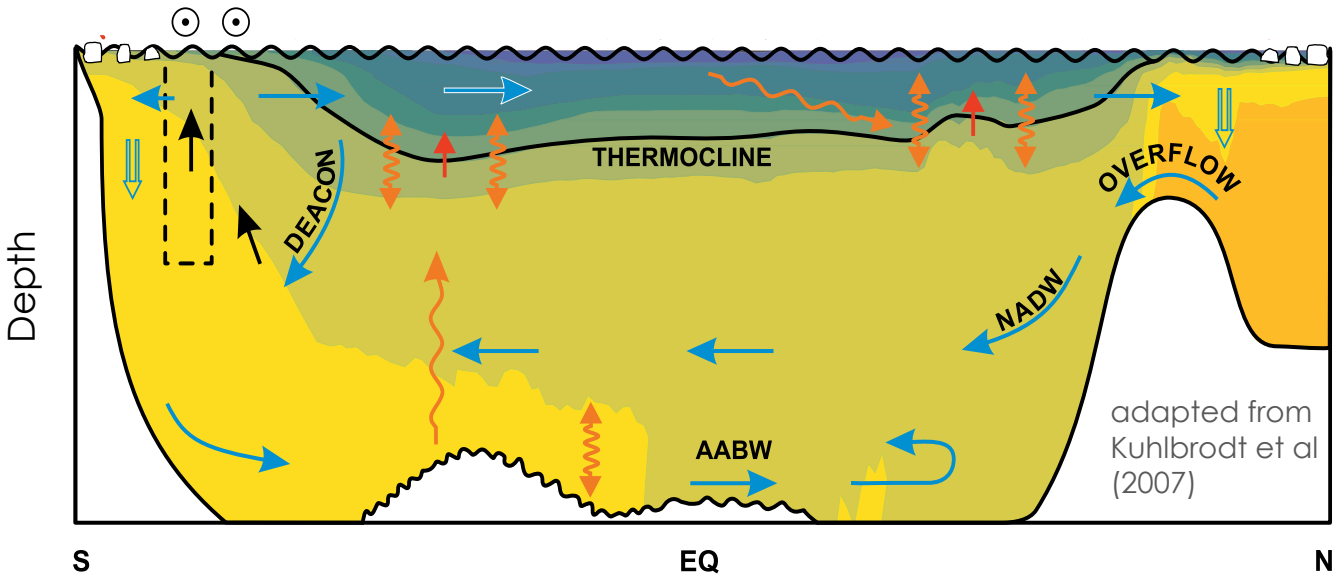
Does the increase in heat transport into the Arctic matter?





Hwang et al (2011)

Ocean circulation drives pattern of warming and surface heat fluxes



Isolating the ocean's role in climate response to forcing

- Ocean-only simulation with the MITgcm
  - global ocean with realistic land geometry, 1° resolution
  - no atmosphere

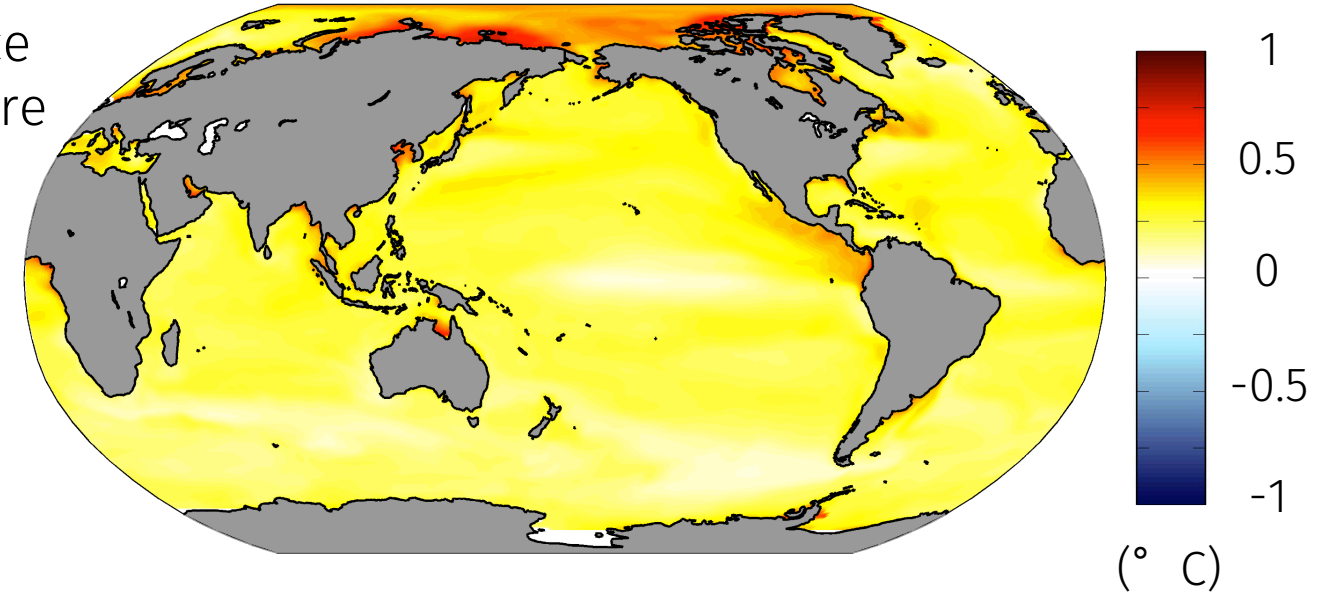
- Model run to equilibrium with air-sea fluxes prescribed through bulk formulae -- CORE protocol of Griffies et al (2009), with an annually repeating cycle

- *Passive tracer* experiment:
  - Abrupt, uniform surface flux of an "orange dye"
  - Uniform damping at the surface (in proportion to surface dye concentration)

→ *Any spatial structure must arise from background (climatological) ocean circulation*

Ocean-only MITgcm: yr 1 response to *passive tracer* forcing

Sea-surface temperature



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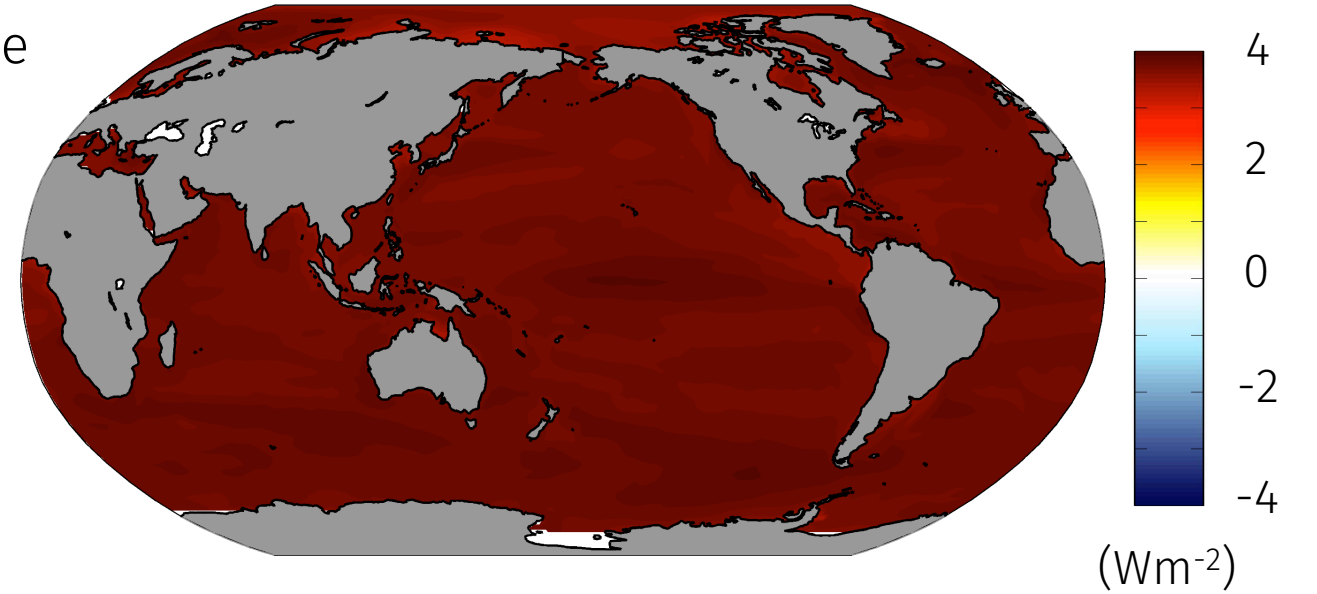
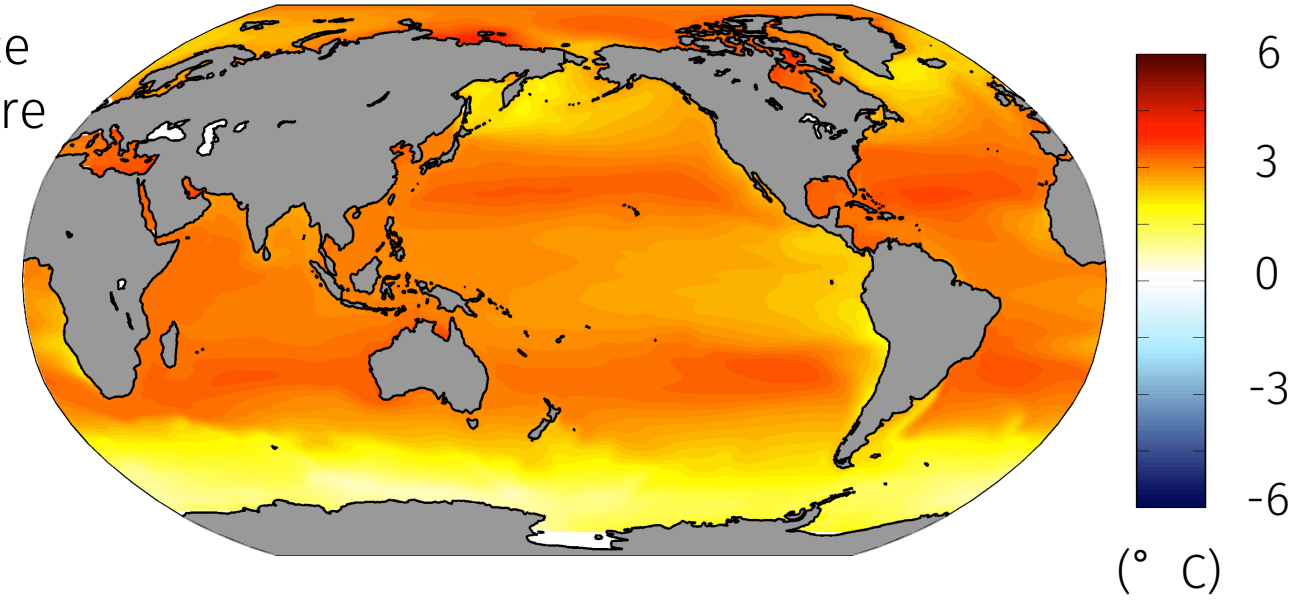
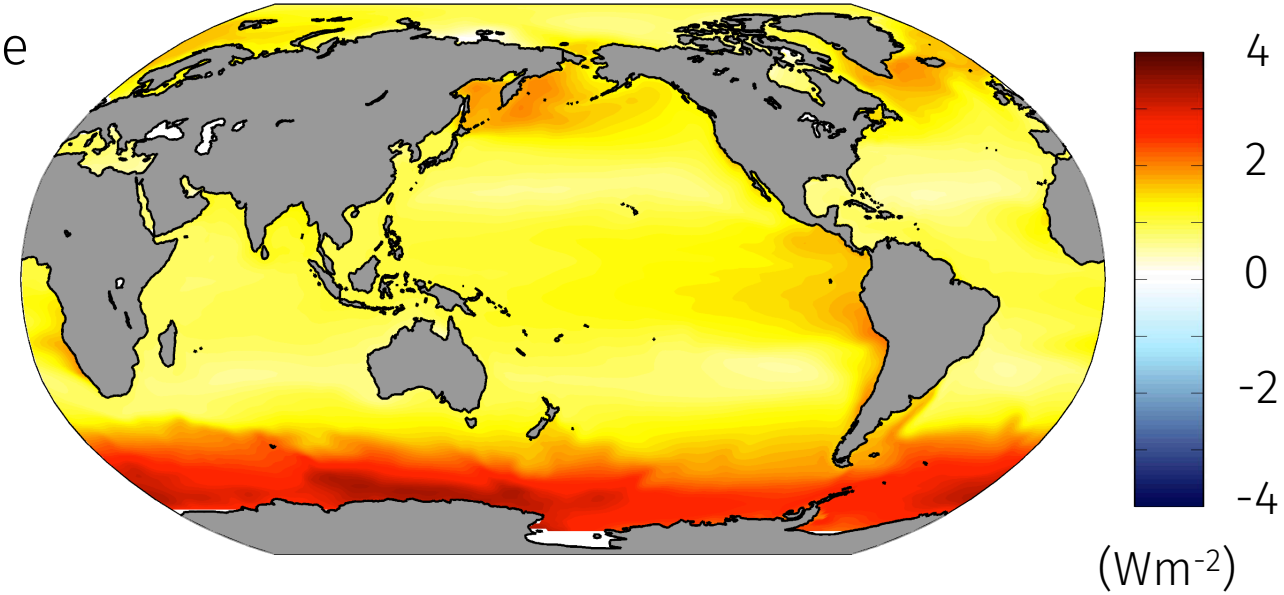


Ocean-only MITgcm: yr 100 response to *passive tracer* forcing

Sea-surface temperature



Sea-surface heat flux



Ocean-only MITgcm: yr 100 response to *passive tracer* forcing

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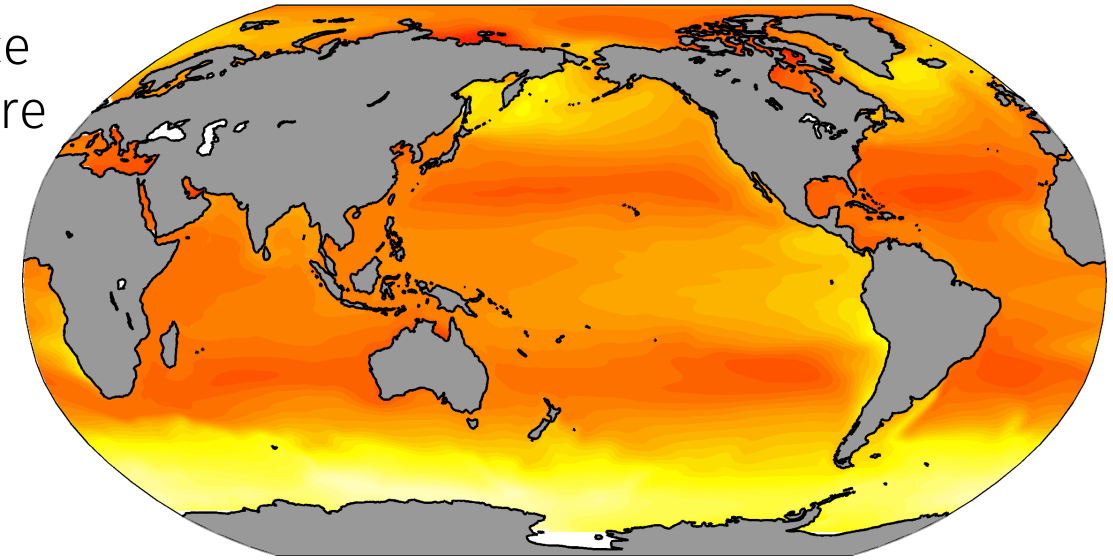

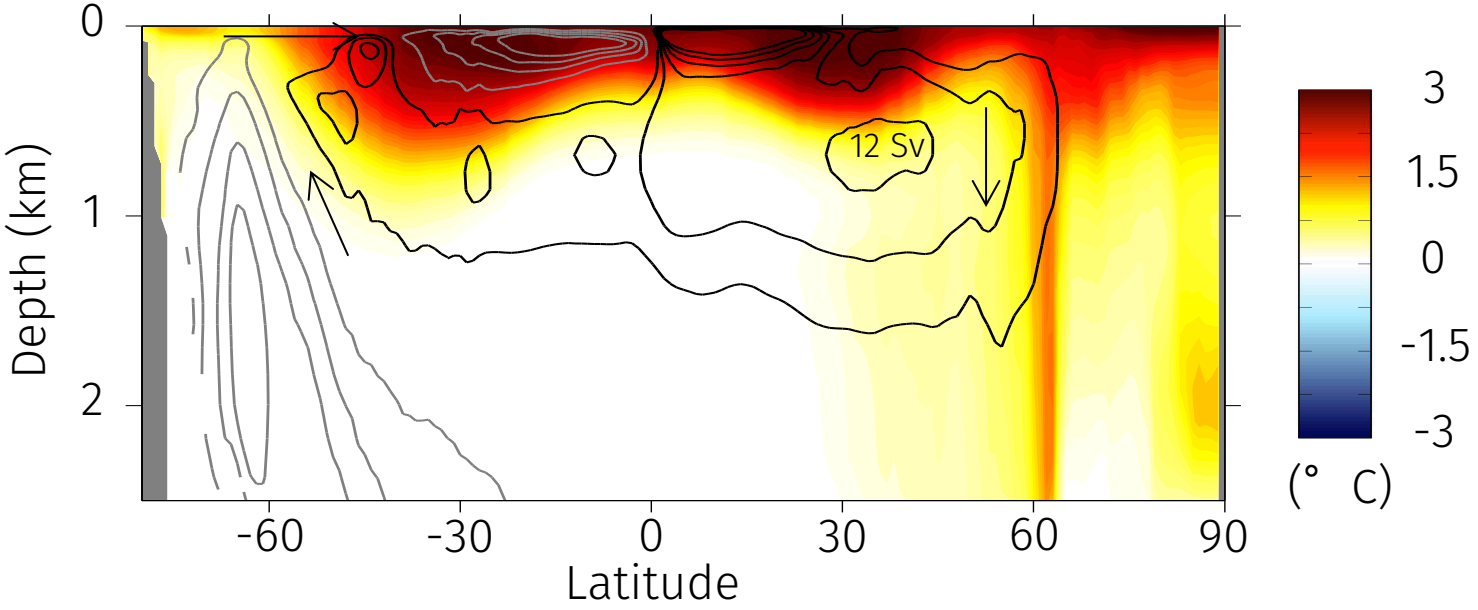

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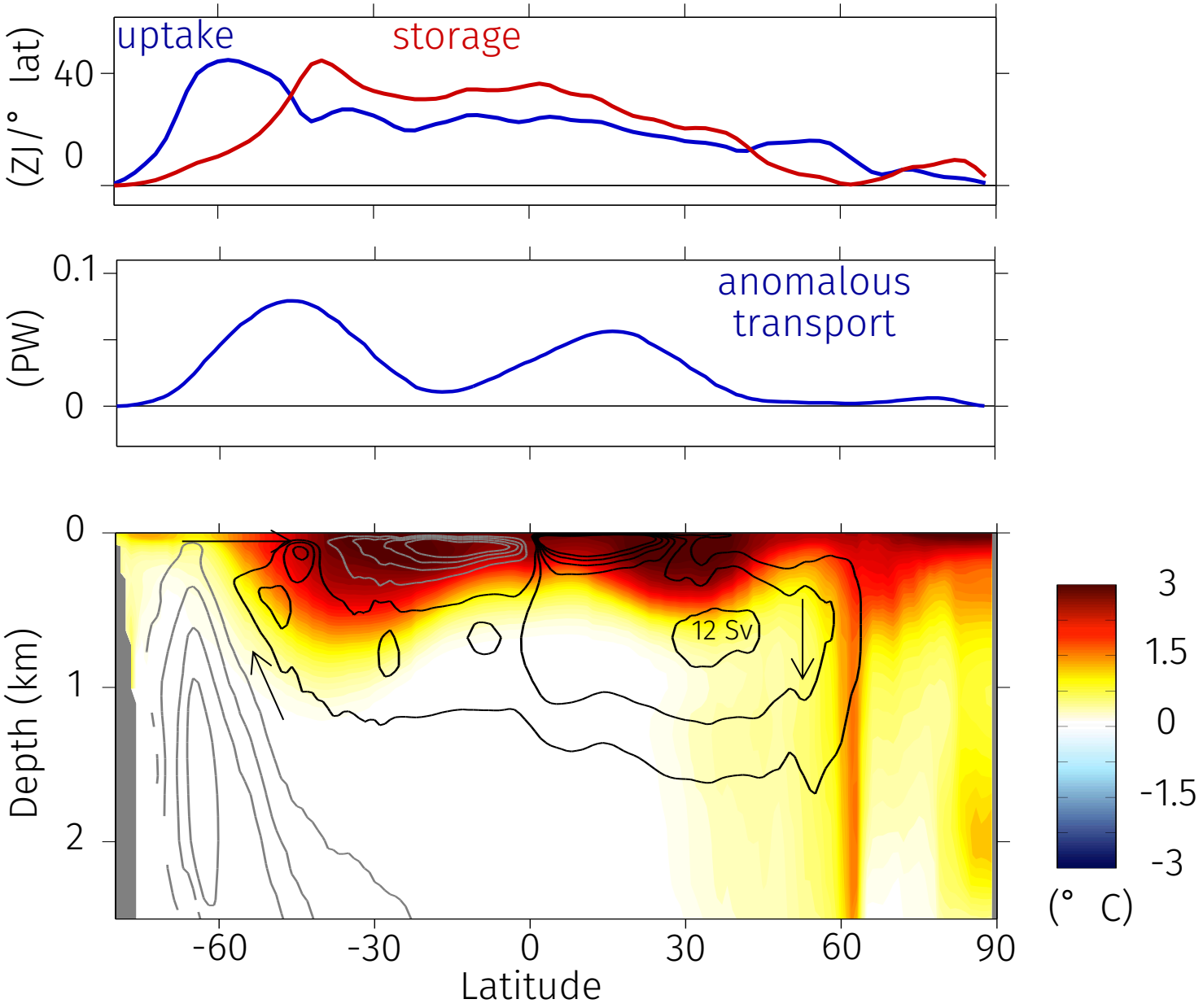

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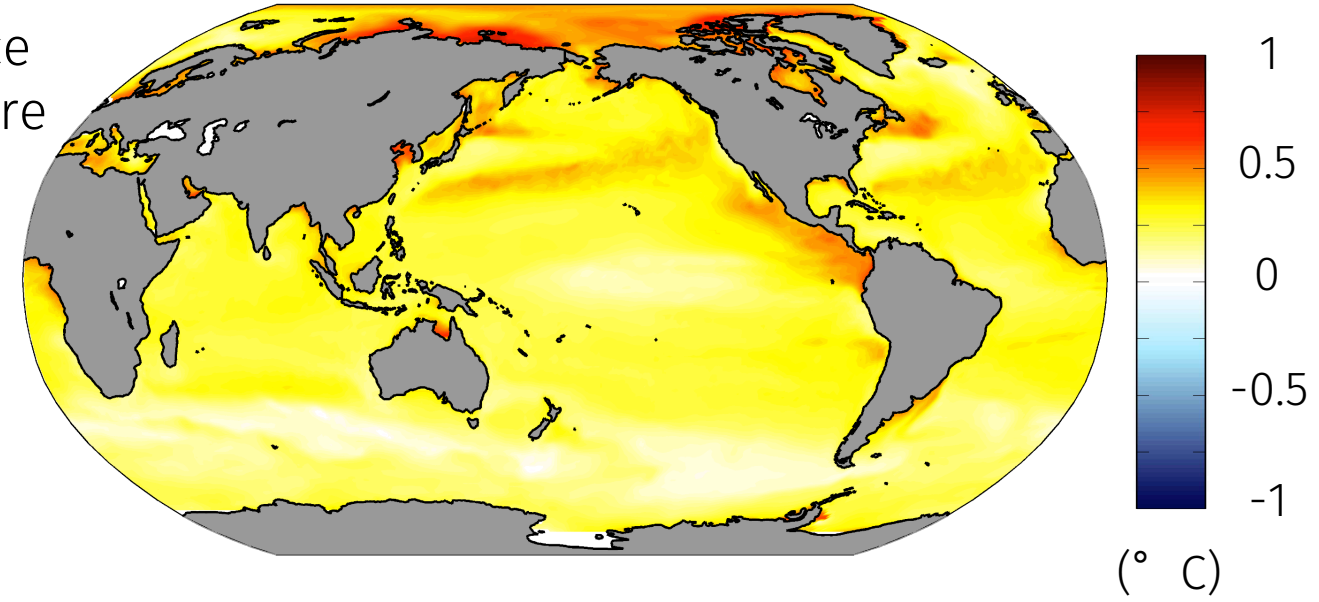
- Greenhouse gas forcing experiment:
  - Abrupt, uniform surface forcing of R = 4 Wm^{-2}
  - Uniform radiative feedback of equal to -1 $Wm^{-2}K^{-1}$
  - No other surface flux changes (wind, fresh water, etc)

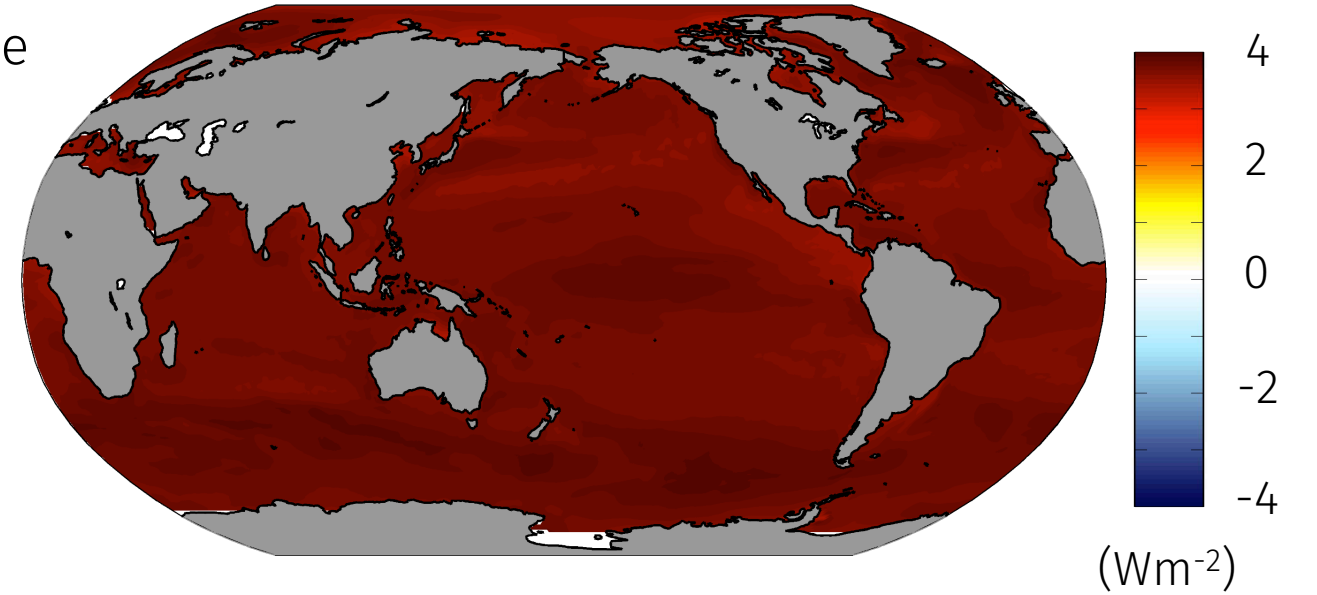
→ *Any spatial structure in warming must arise from ocean circulation*

Ocean-only MITgcm: yr 1 response to abrupt radiative forcing

Sea-surface temperature

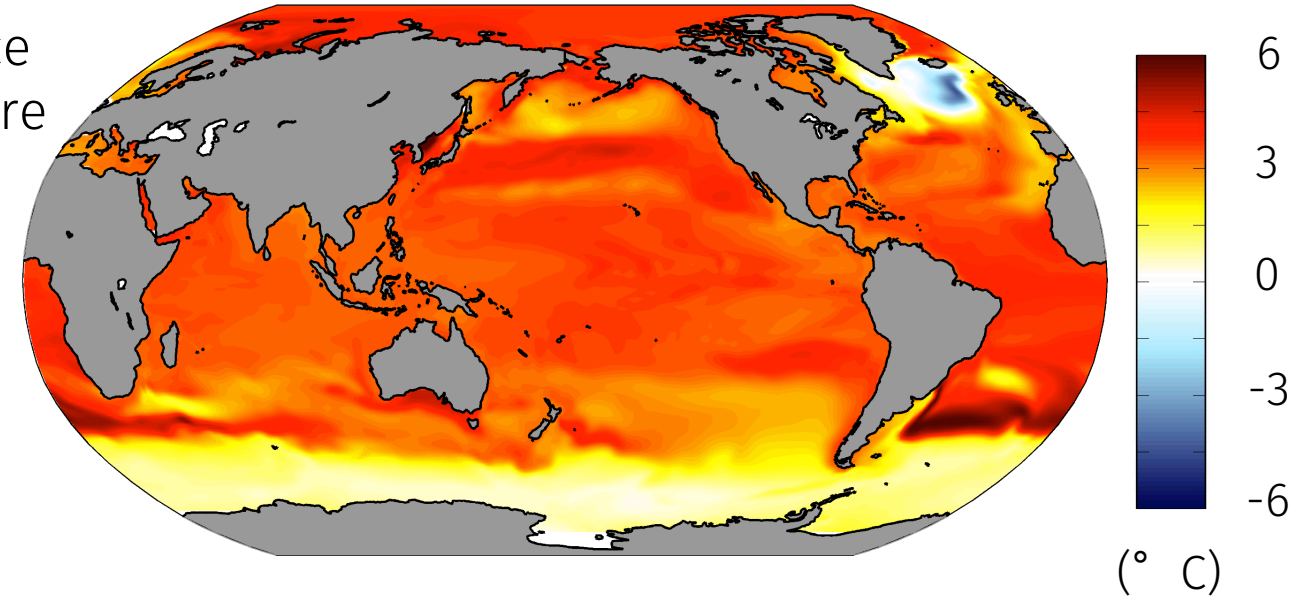


Sea-surface heat flux



Ocean-only MITgcm: yr 100 response to abrupt radiative forcing

Sea-surface temperature



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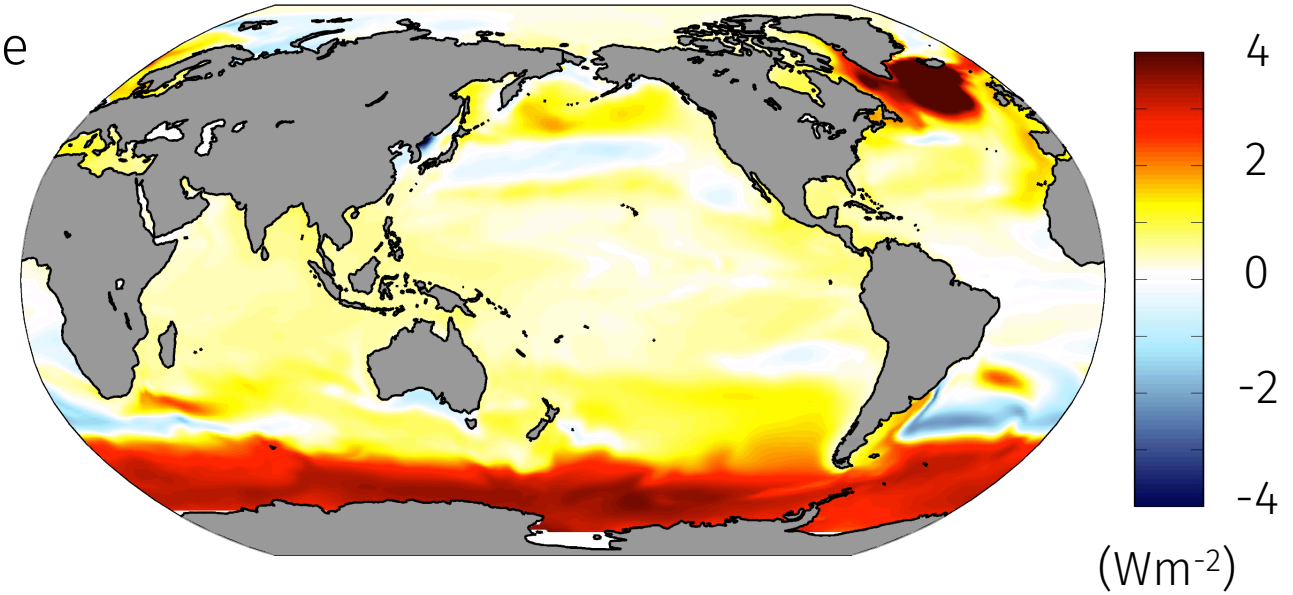

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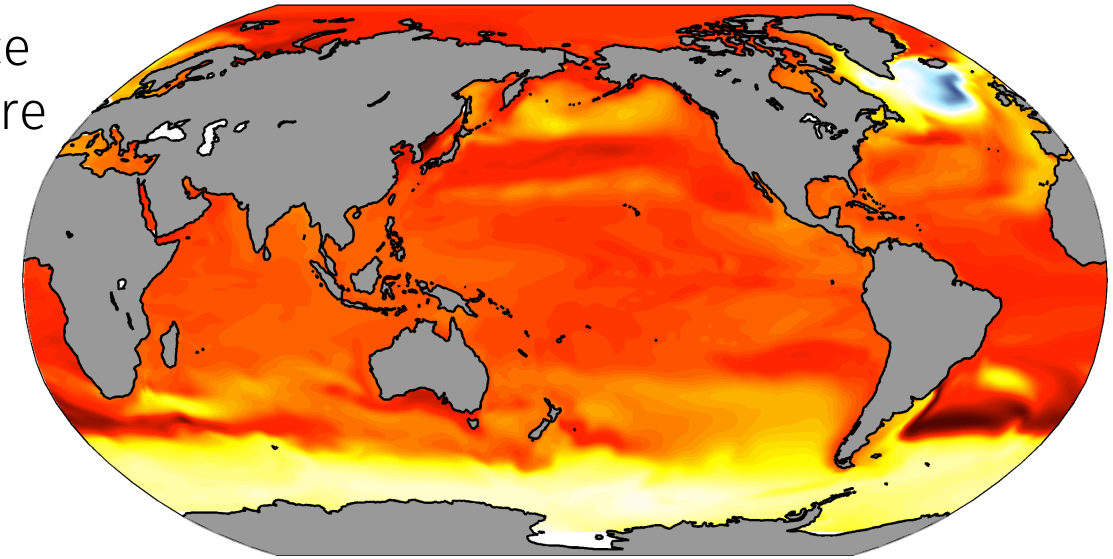

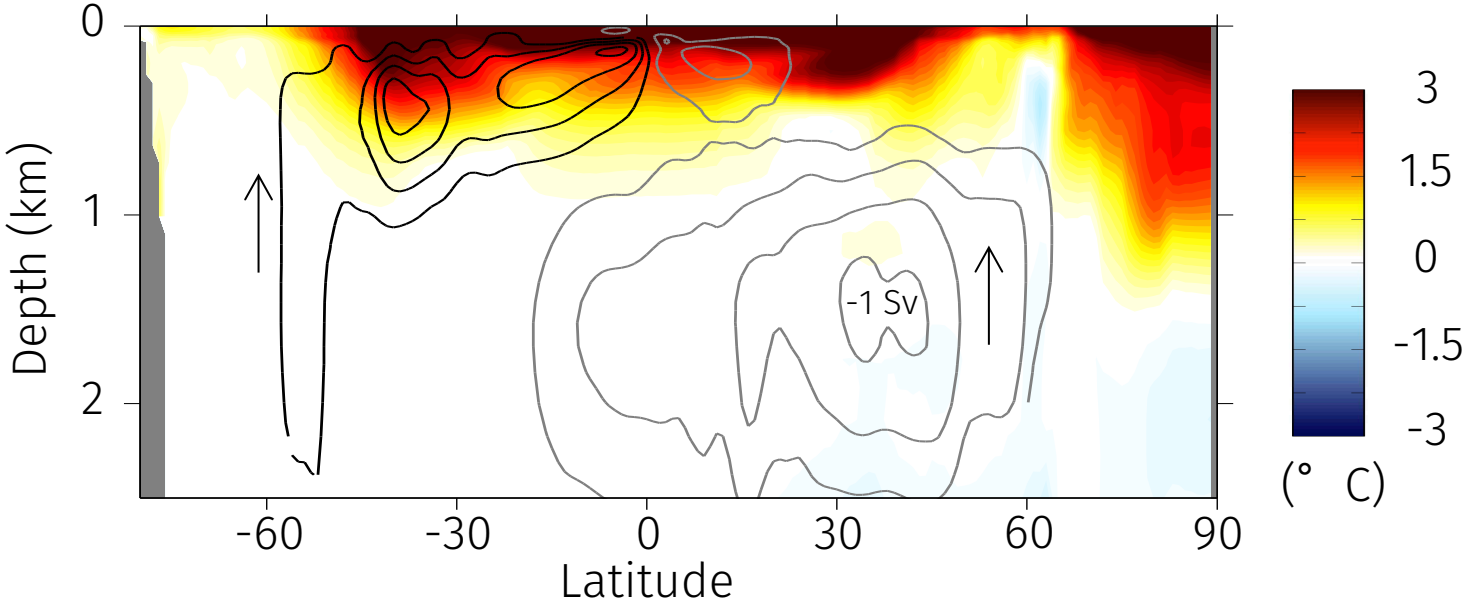

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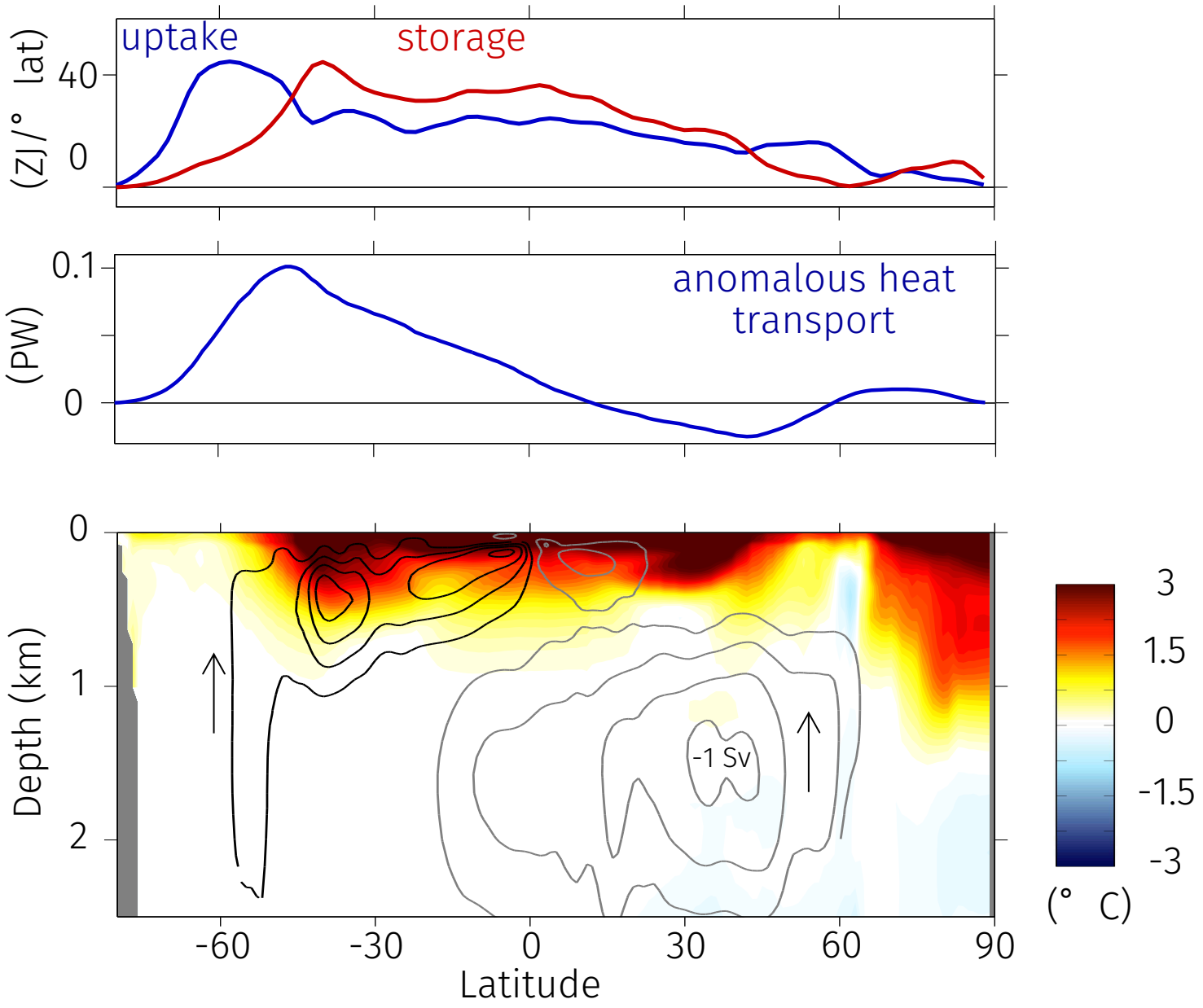
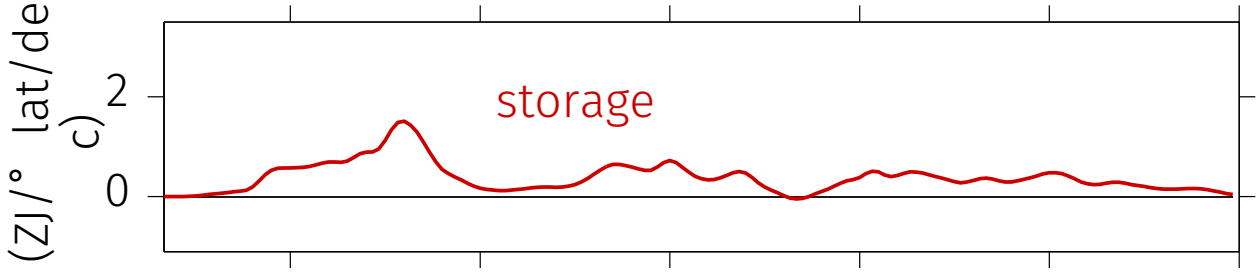
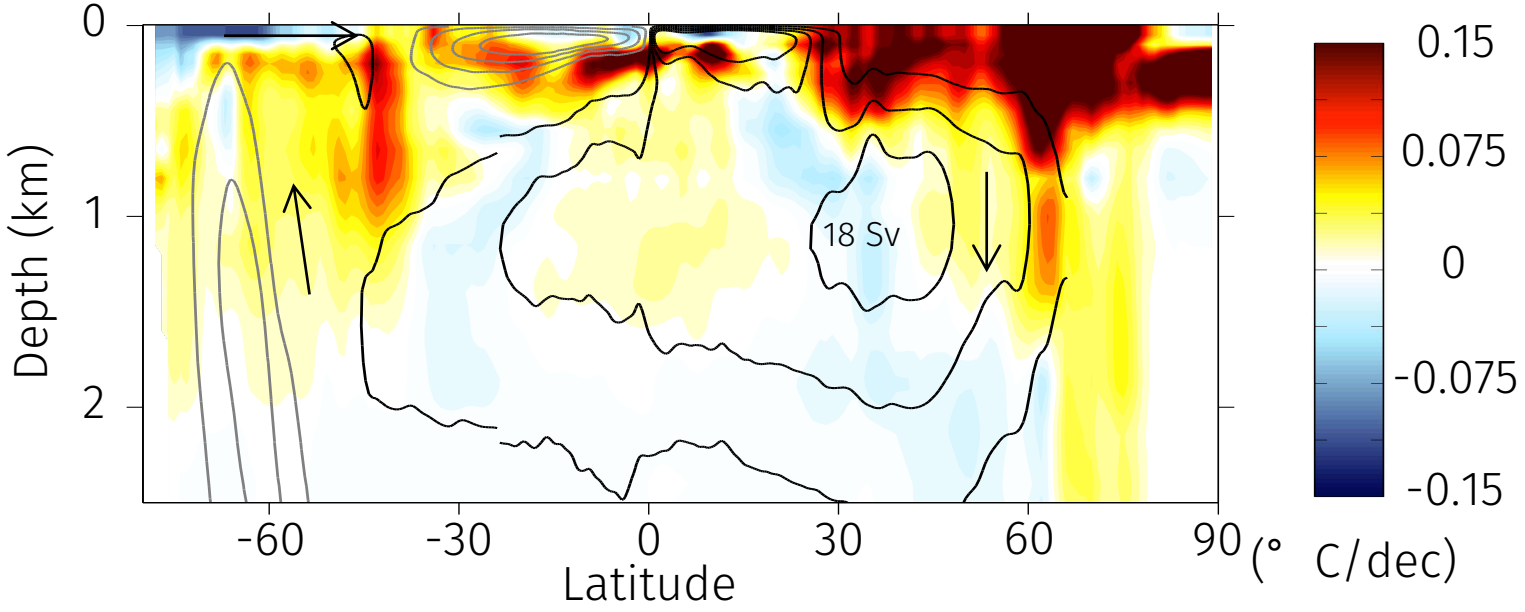
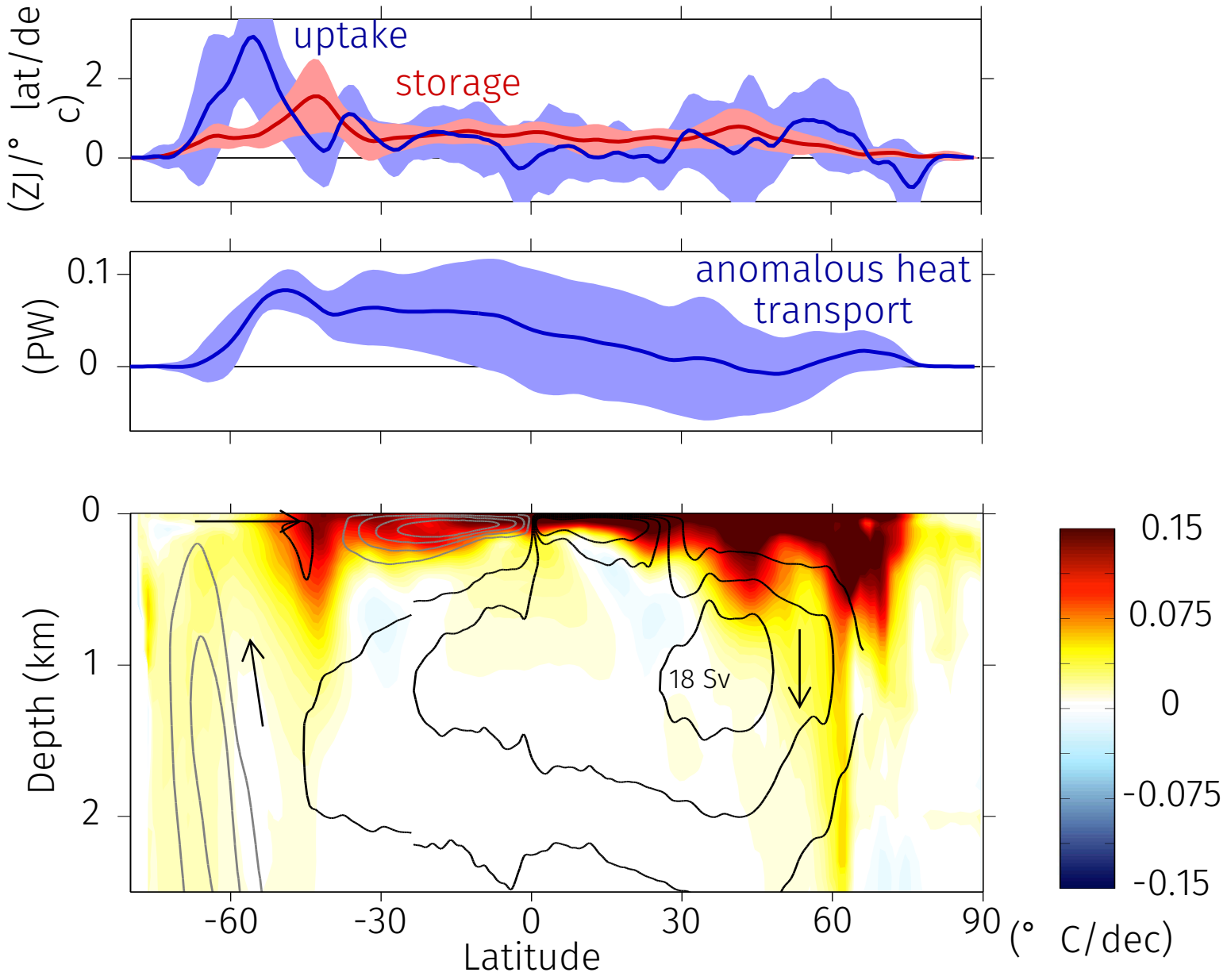


Observed ocean warming over 1982-2012

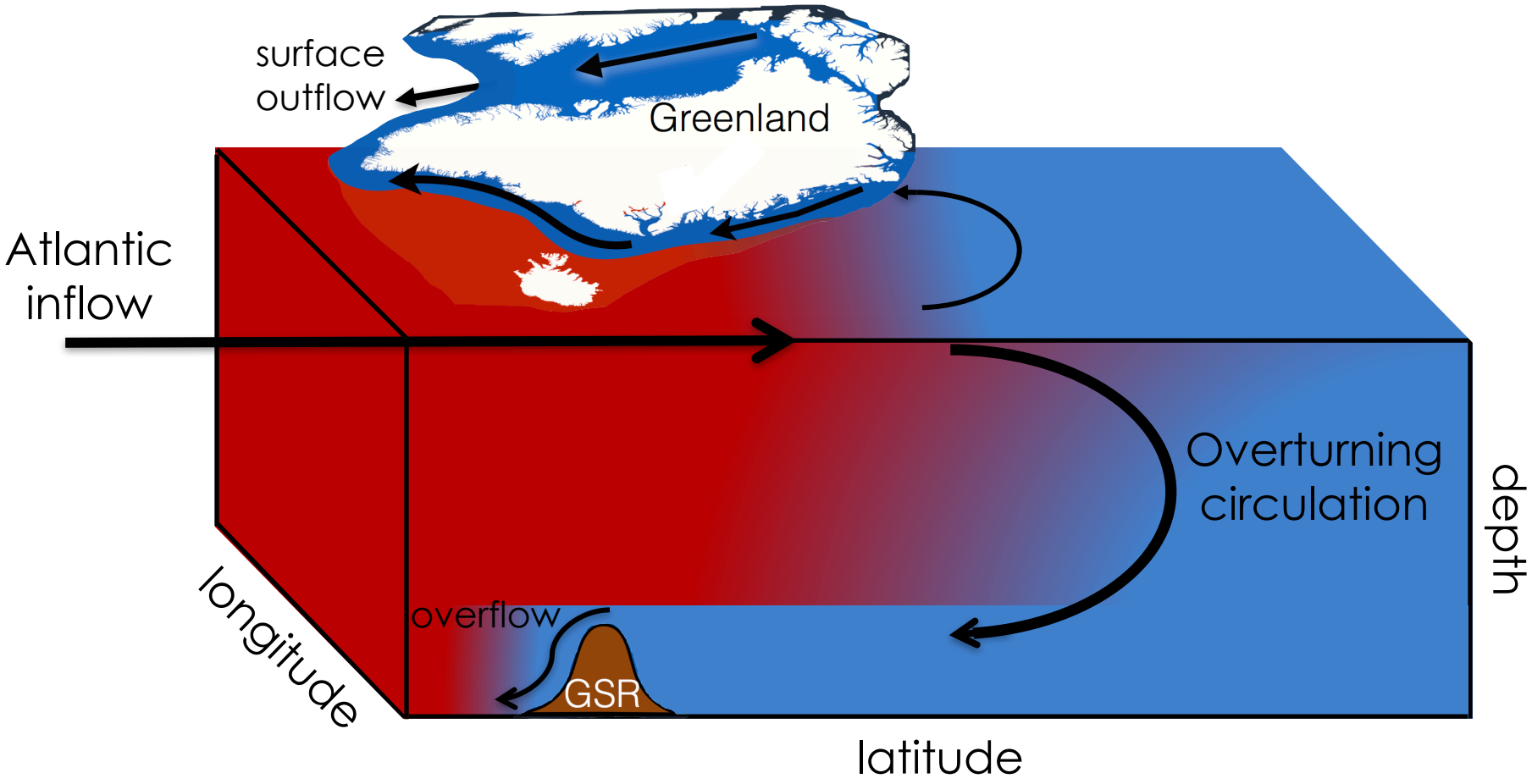




CMIP5-mean historical ocean warming over 1982-2012

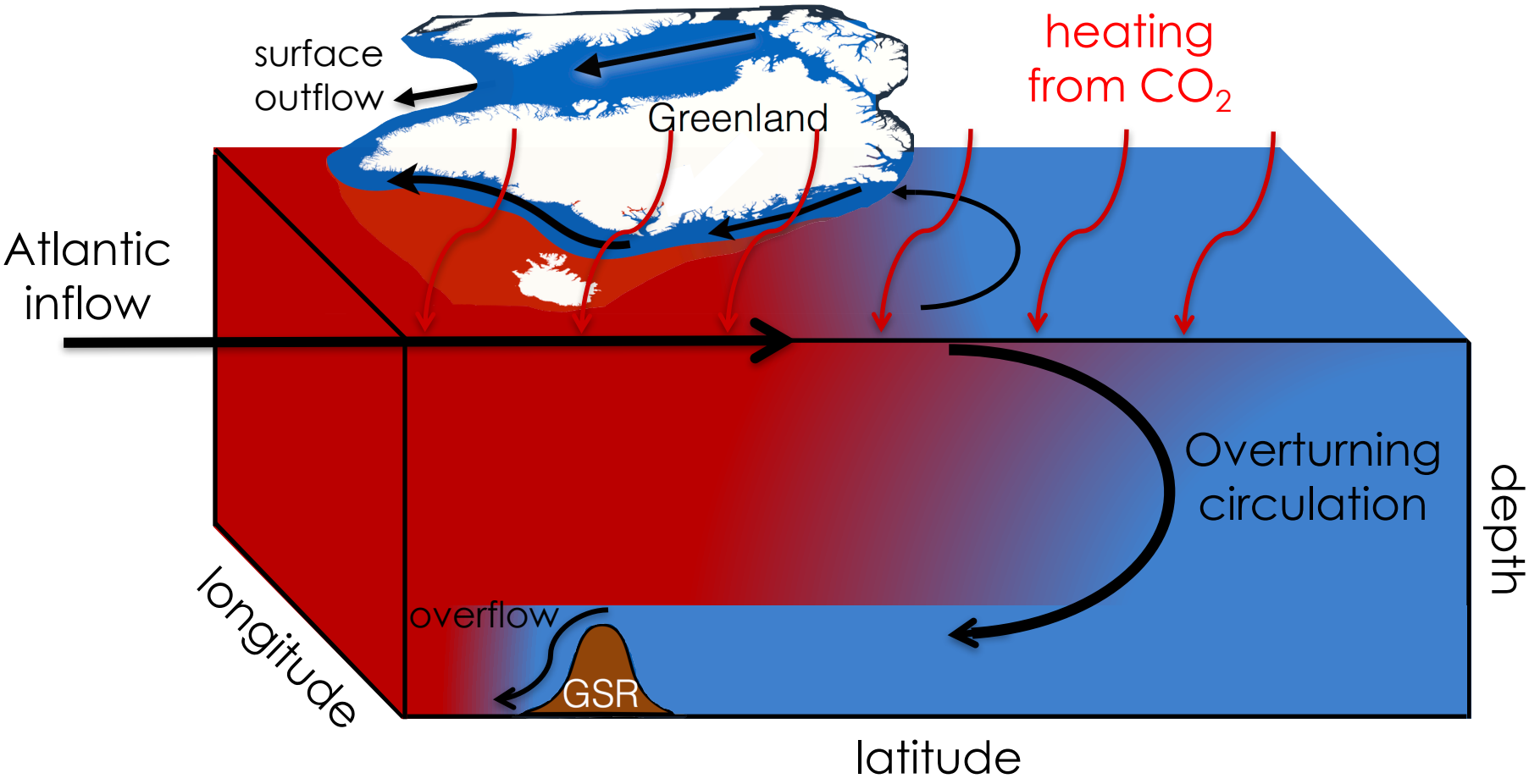


Arctic Ocean



adapted from Nick Beaird

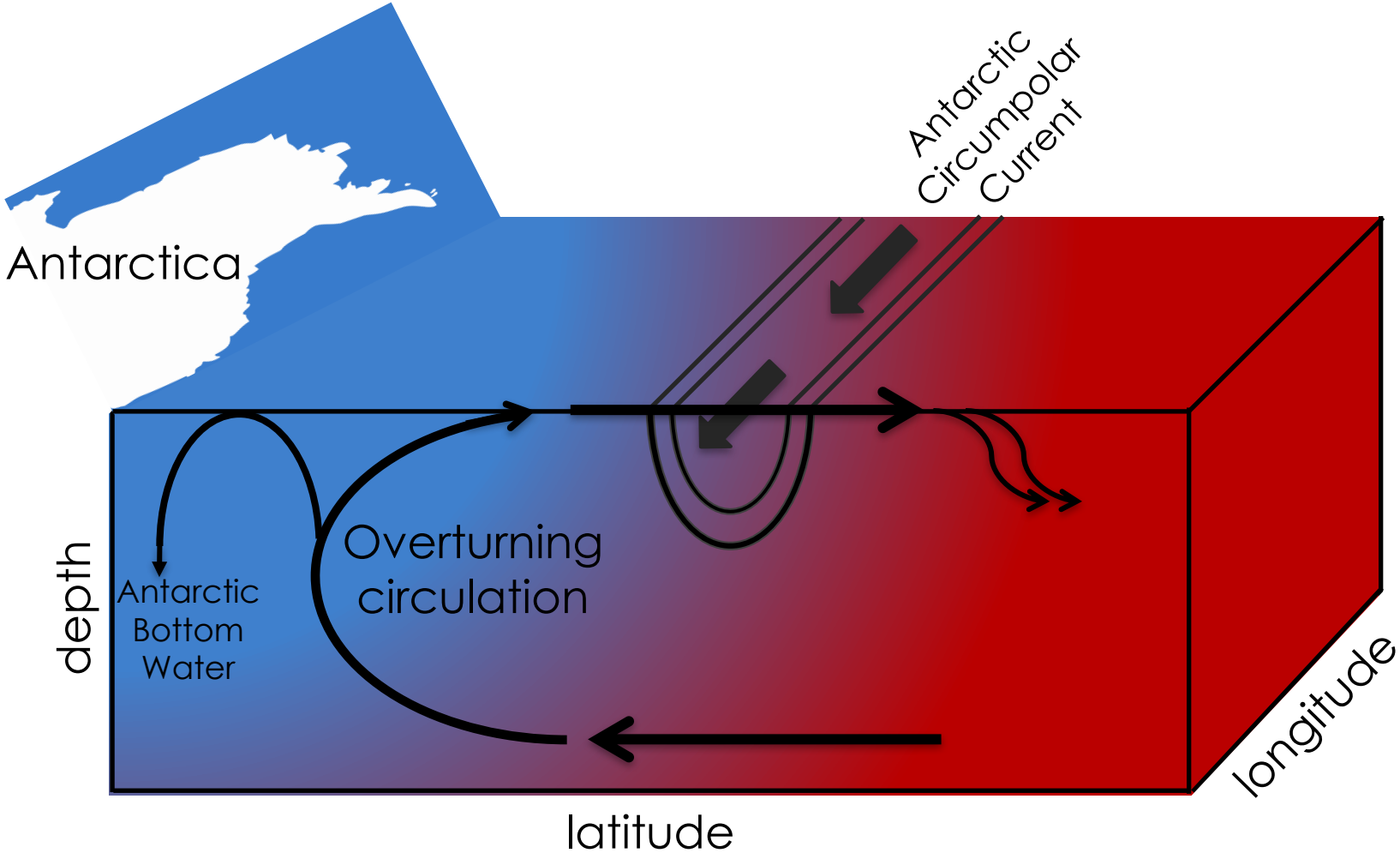
Arctic Ocean



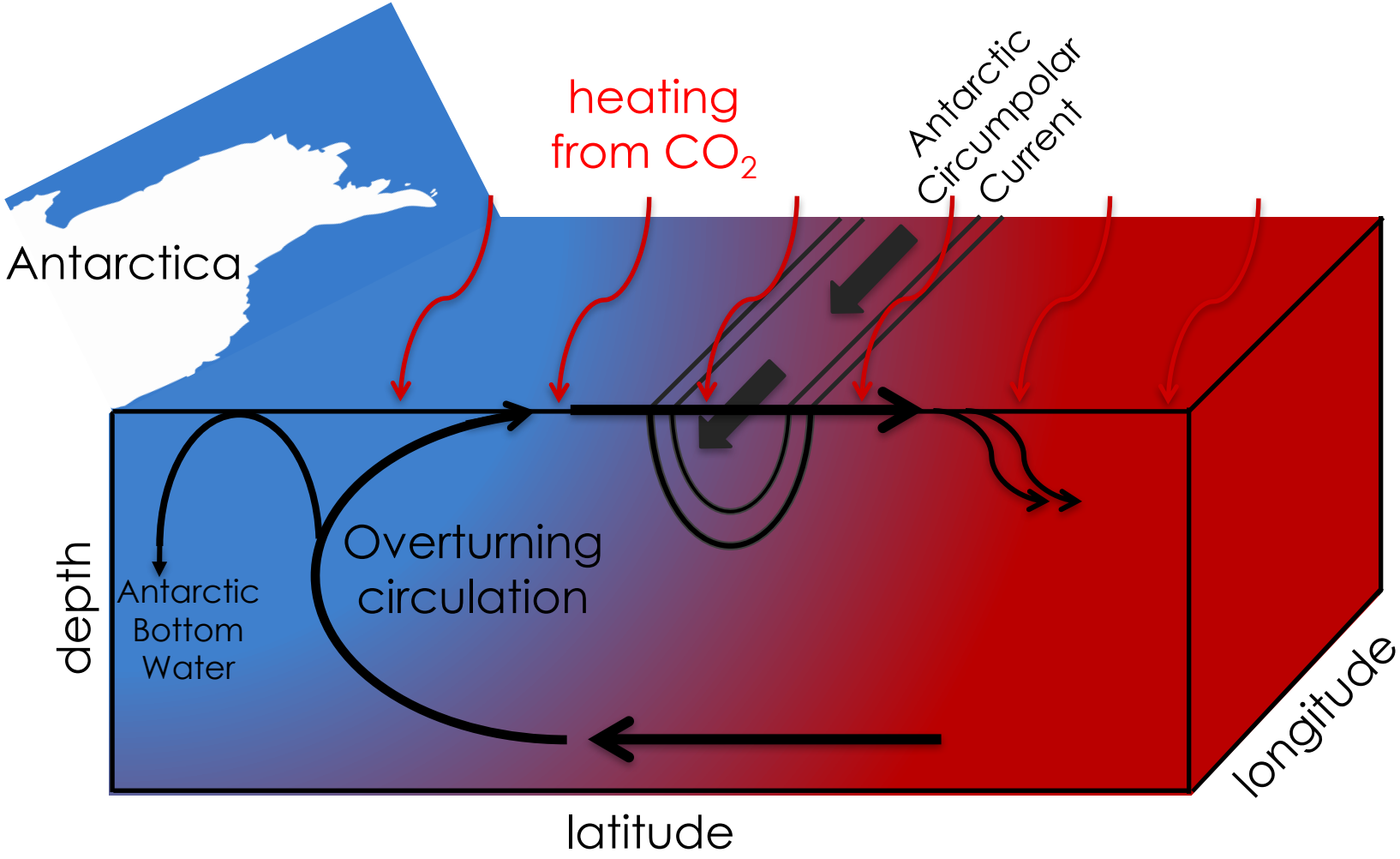
- Heat from CO_2 is carried northward by ocean surface currents, **accelerating Arctic warming**

adapted from Nick Beaird

Southern Ocean



Southern Ocean



- Heat from CO_2 is carried northward by ocean surface currents, **slowing warming around Antarctica**