Nonlocal and nonlinear climate feedbacks: insights from an aquaplanet

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University of Washington

in collaboration with Gerard Roe

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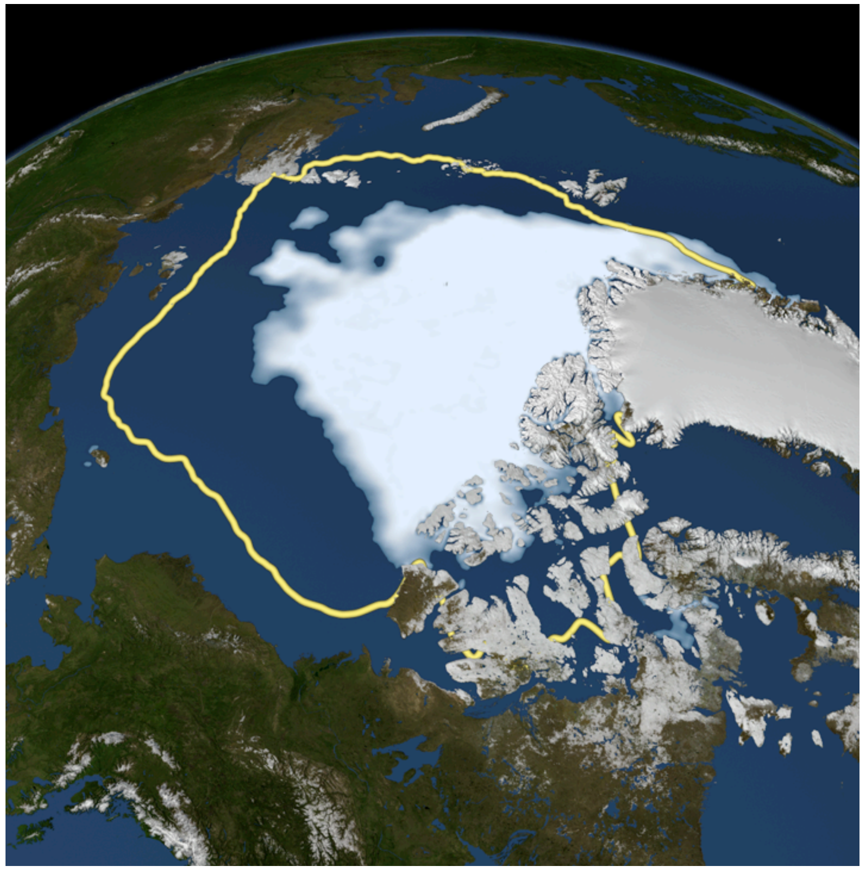
- But trying to understanding global sensitivity through a local lens raises questions:
- Nonlinear: What is the extent to which we can we treat feedbacks as independent of each other, i.e. neglecting interactions between them?
- Nonlocal: How do local and remote processes combine to affect the spatial pattern of warming (e.g. polar amplification)?

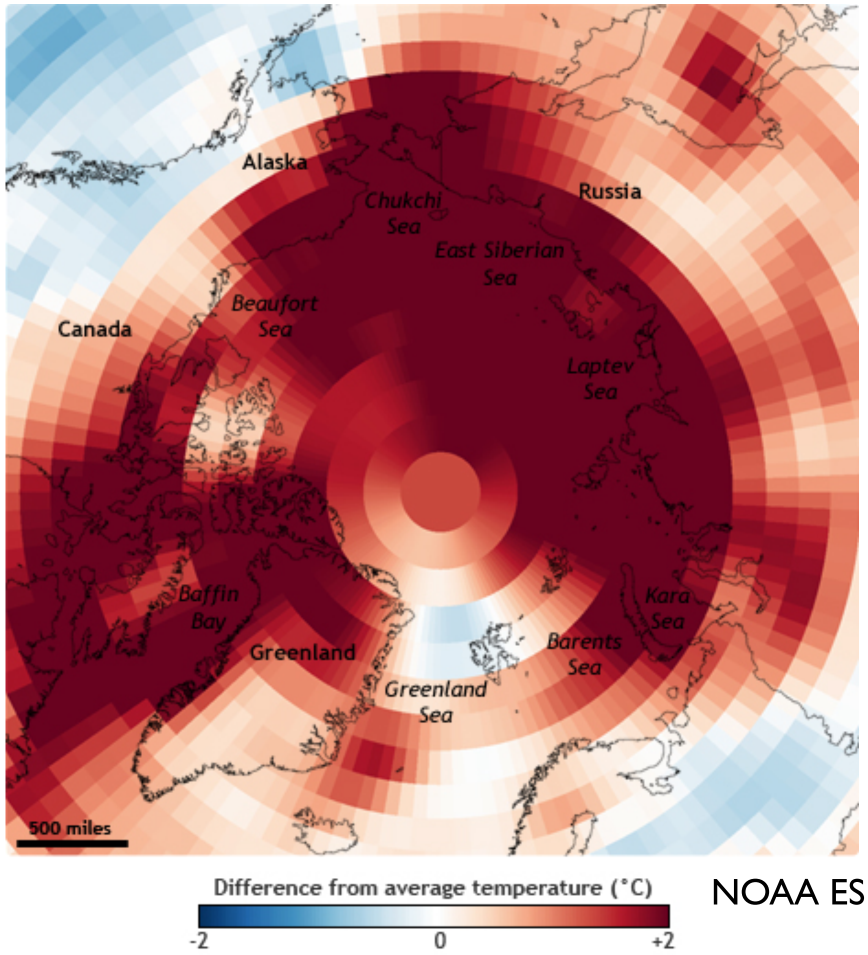
How do local and remote processes combine to affect patterns of warming?

Arctic sea ice extent (Sept 16, 2012)



[yellow line = 1979-2010 average extent of yearly min; NASA GSFC]

Arctic surface warming (2011 minus 1981-2010)

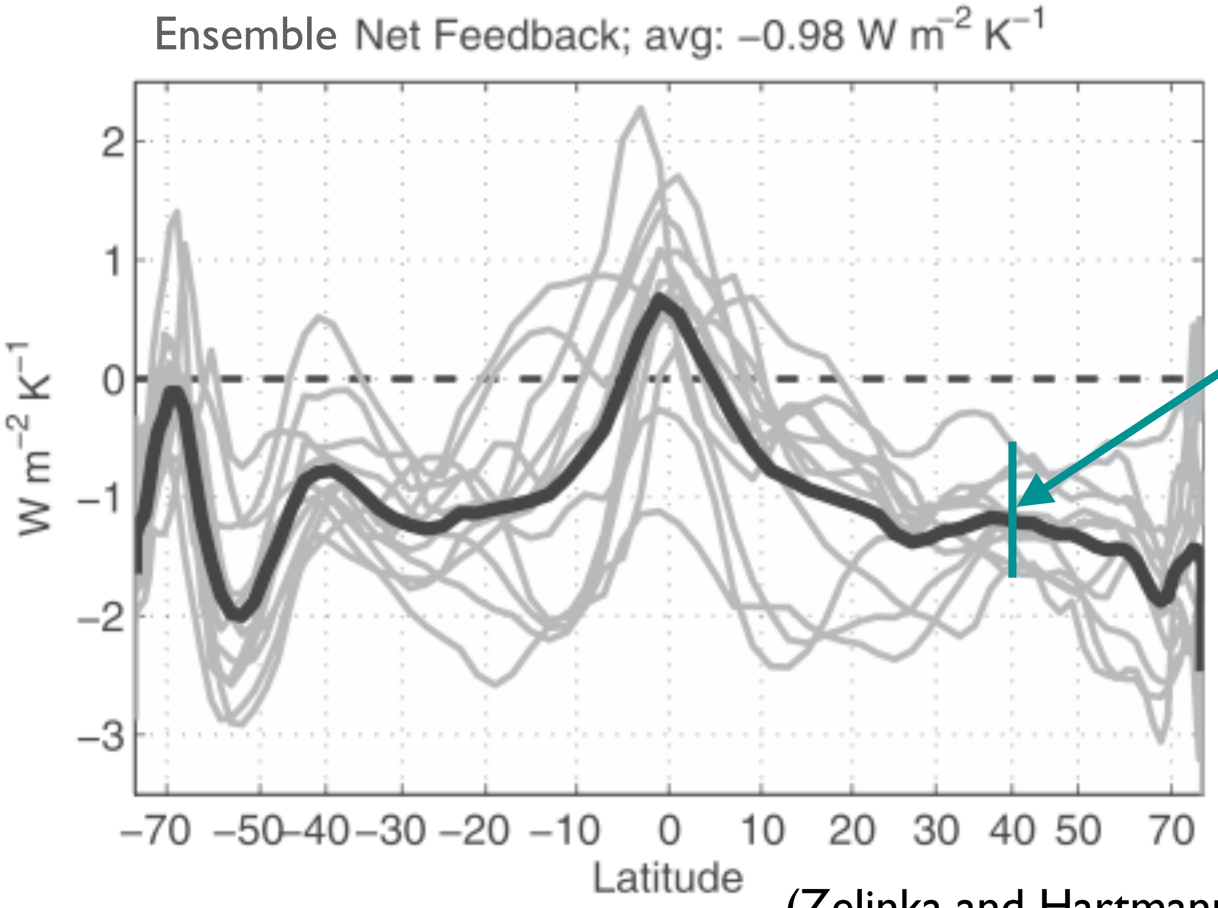


NOAA ESRL

This approach offers a particularly clean set-up and a detailed feedback analysis

Spread in CMIP feedbacks

A challenge for regional climate predictability



at some location

(Zelinka and Hartmann, 2012)

Uncertainty in warming due to uncertainty in:
local feedbacks? feedbacks elsewhere? nonlinearities in feedbacks?

Decompose the energy balance

In equilibrium:

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- CO_2 forcing

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$$\Delta R_f$$

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- Feedbacks (temperature, water vapor, clouds, surface albedo)

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Decompose the energy balance

- CO_2 forcing
- Feedbacks (temperature, water vapor, clouds, surface albedo)
- Changes in divergence horizontal heat flux (“transport”) (nonlocal)
- Nonlinear interactions (typically neglected)
- Goal to close the energy balance, to calculate the nonlinearity as a residual (n.b. clear-sky only)

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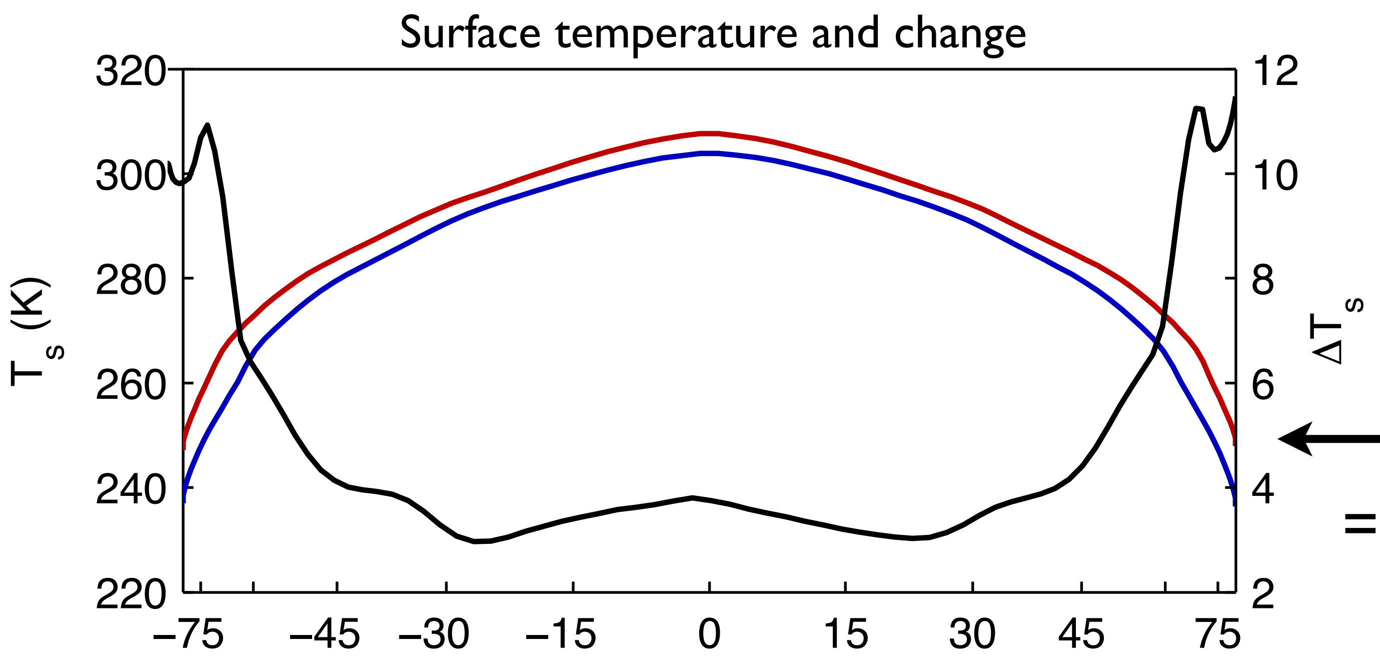
Idealized aquaplanet experiment



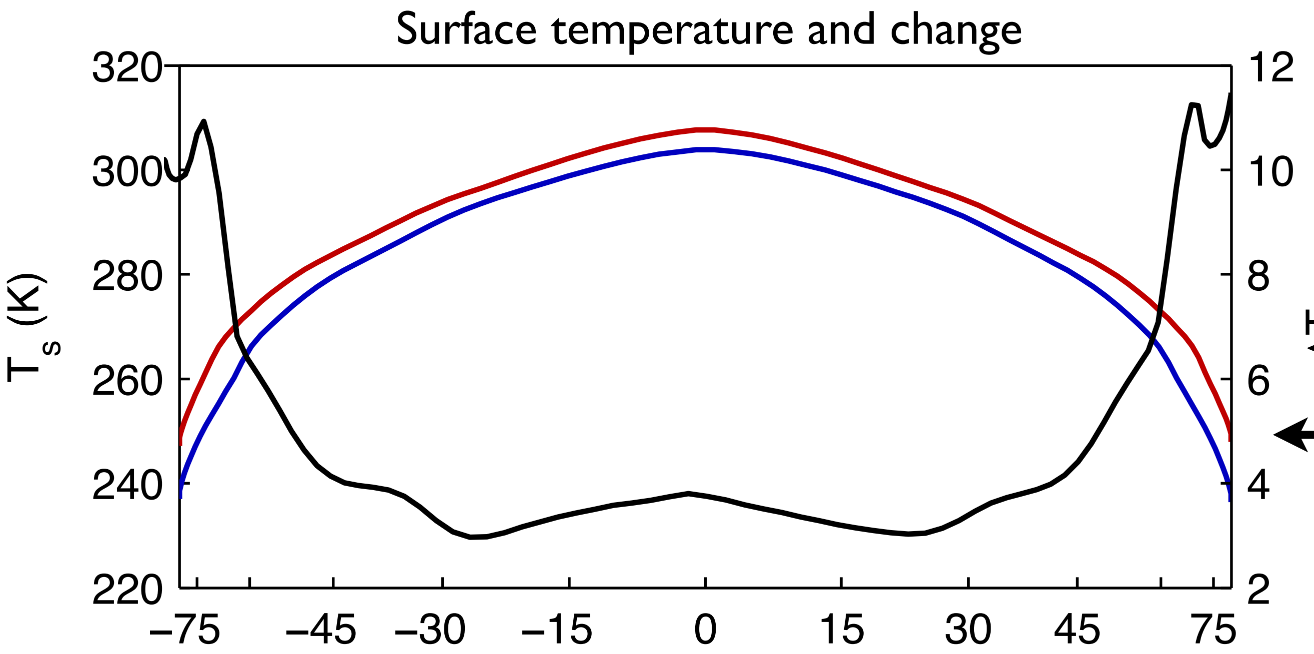
$\Delta\overline{T_s}$

= 4.69 K

Idealized aquaplanet experiment

- Isolate a clear signal, minimize complexities

GFDL AM2
perpetual equinox
no q-flux
no aerosols
no land
20-m mixed layer ocean
infinitesimally thin sea ice
$2\times CO_2$ to equilibrium



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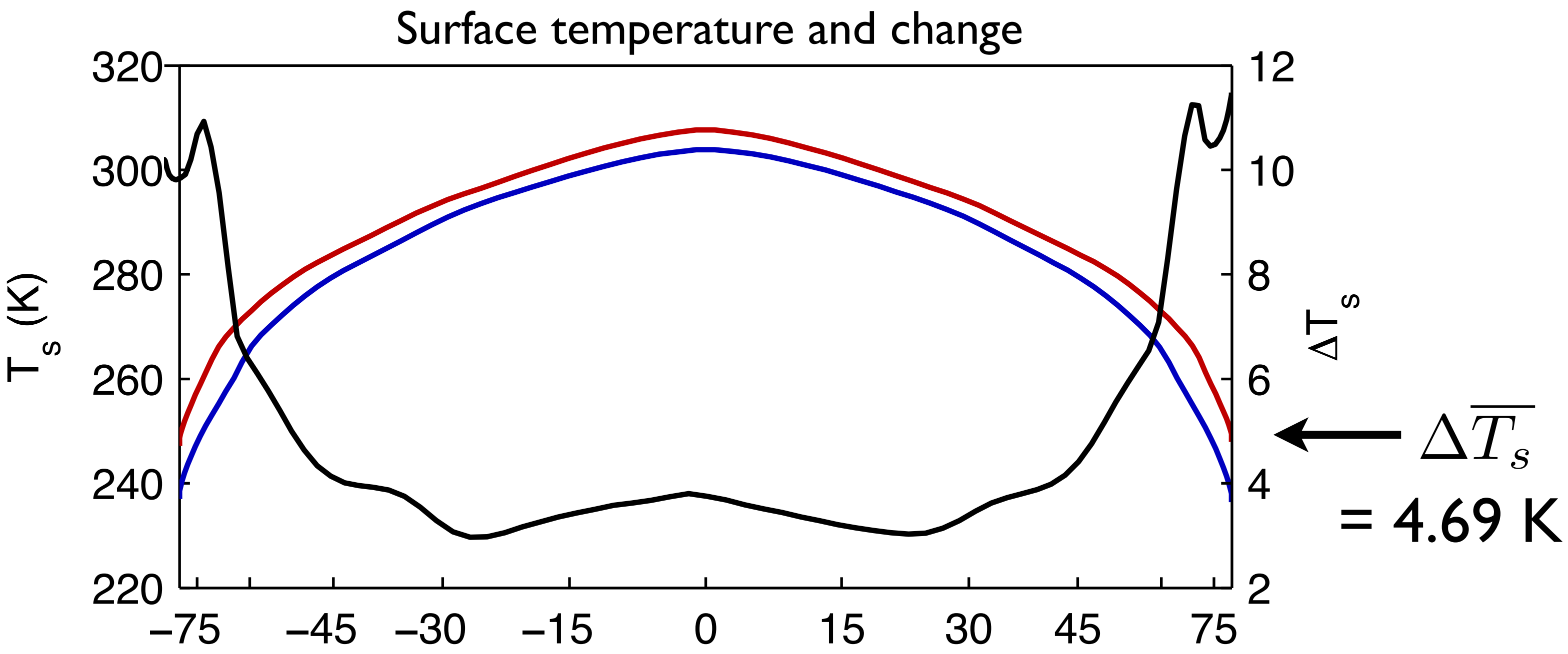

- Future work will relax simplifying assumptions (e.g. ocean heat uptake, aquaplanet intercomparison with Brian Rose, Kyle Armour)


QAquMIP

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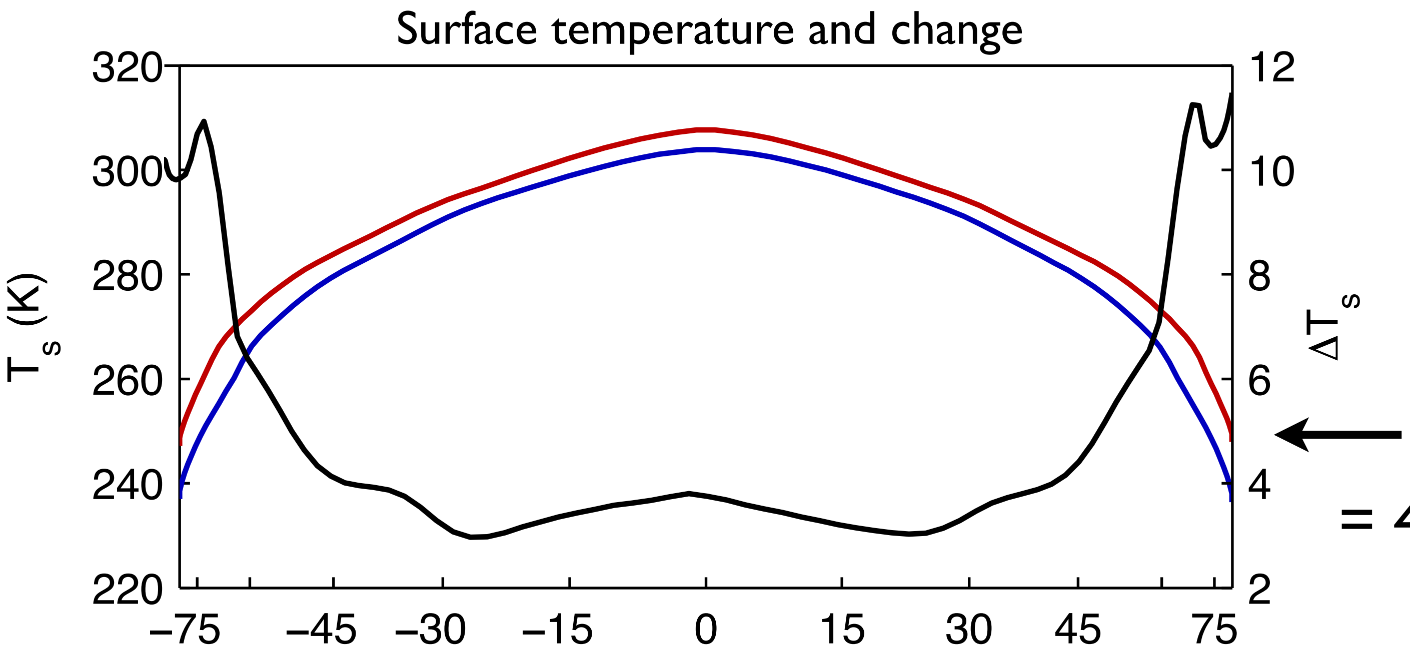

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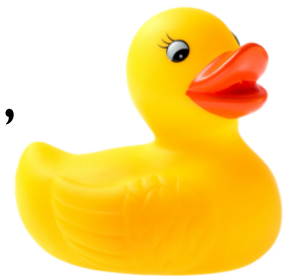
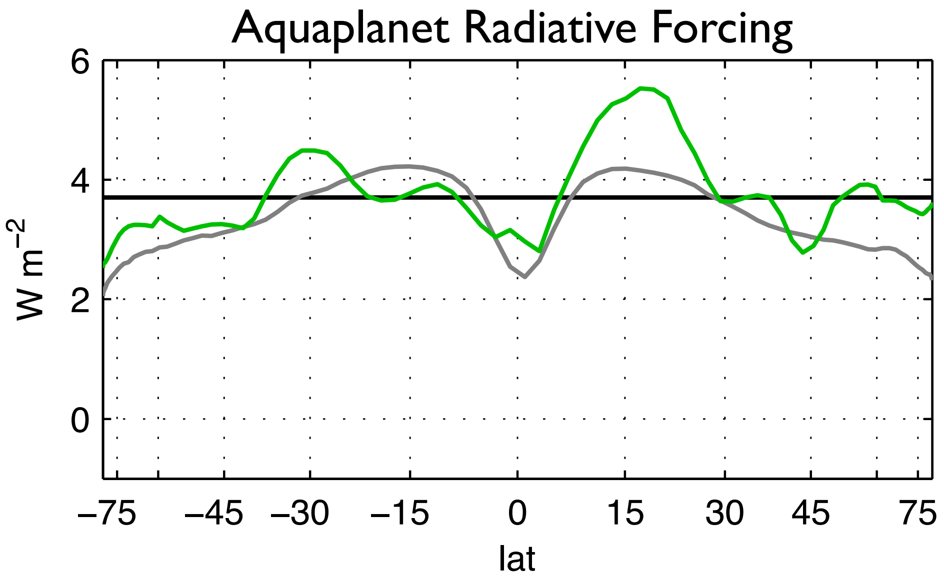


QAquMIP

- Explicitly diagnosed radiative kernels (used to calculate feedbacks) and radiative forcing for this model set-up

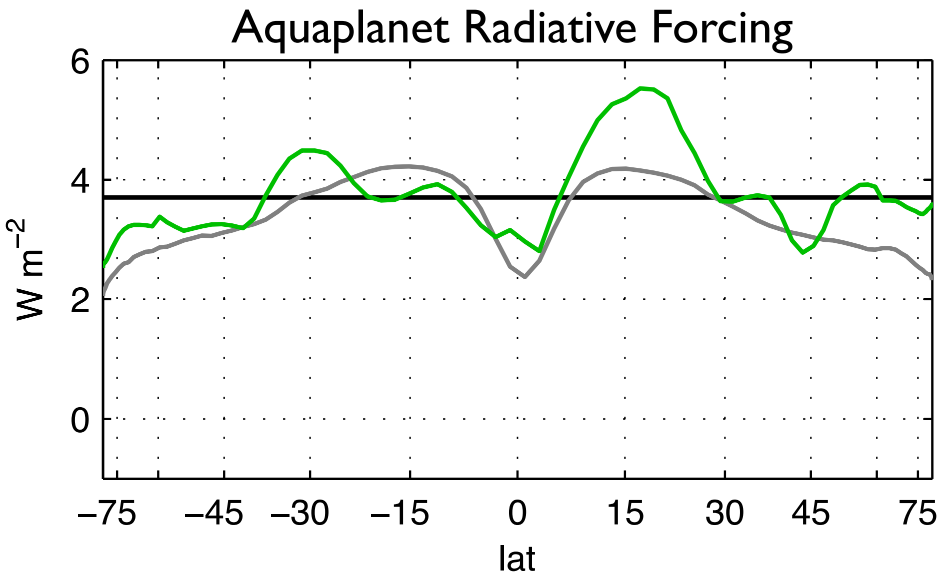
Spatial variability in radiative forcing



Fixed SST 3.8 ± 0.2 W/m^2 (40 year run)
Stratosphere-adjusted 3.4 W/m^2
Uniform 3.7 W/m^2

Spatial variability in radiative forcing

- Two improved methods: stratosphere-adjusted (e.g. IPCC) and fixed-SST



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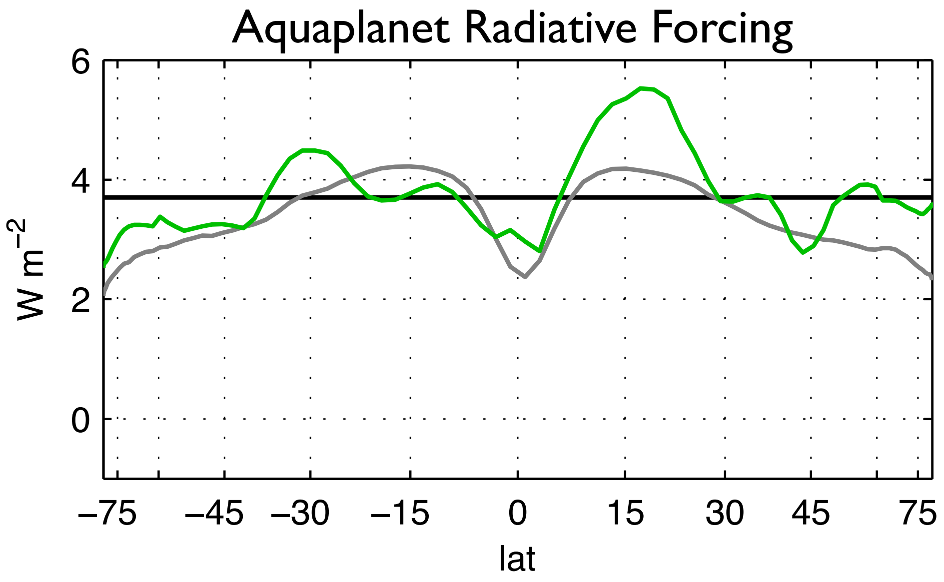

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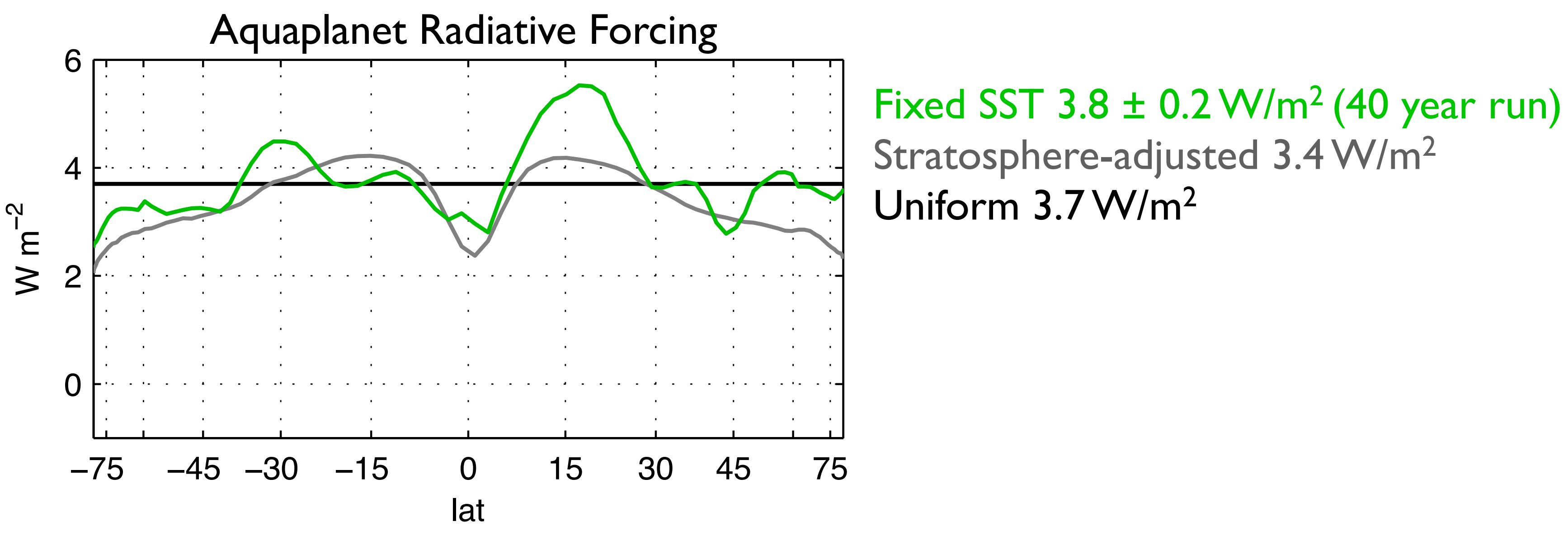
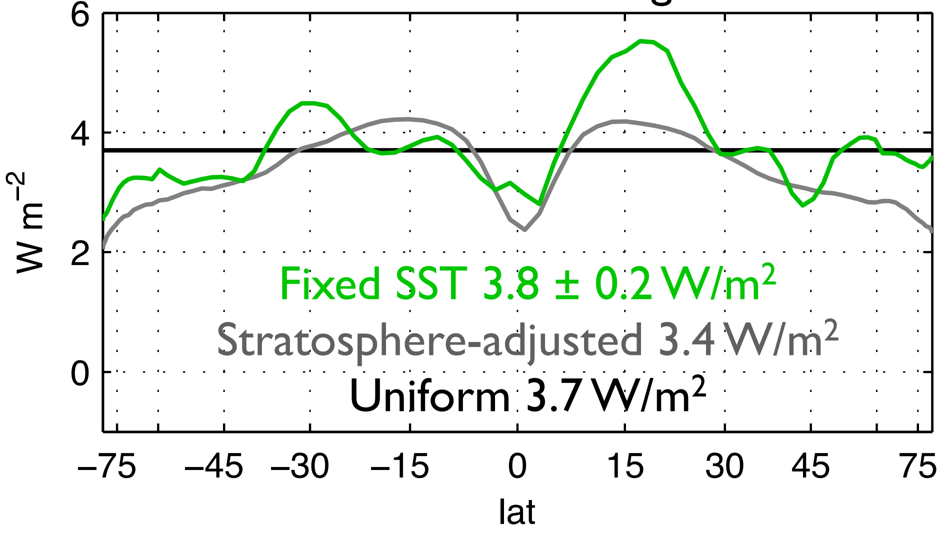
- Recent work demonstrates narrowing of intermodel spread in cloud feedback when rapid troposphere adjustments are binned with forcing rather than feedback (Andrews and Forster, 2008)

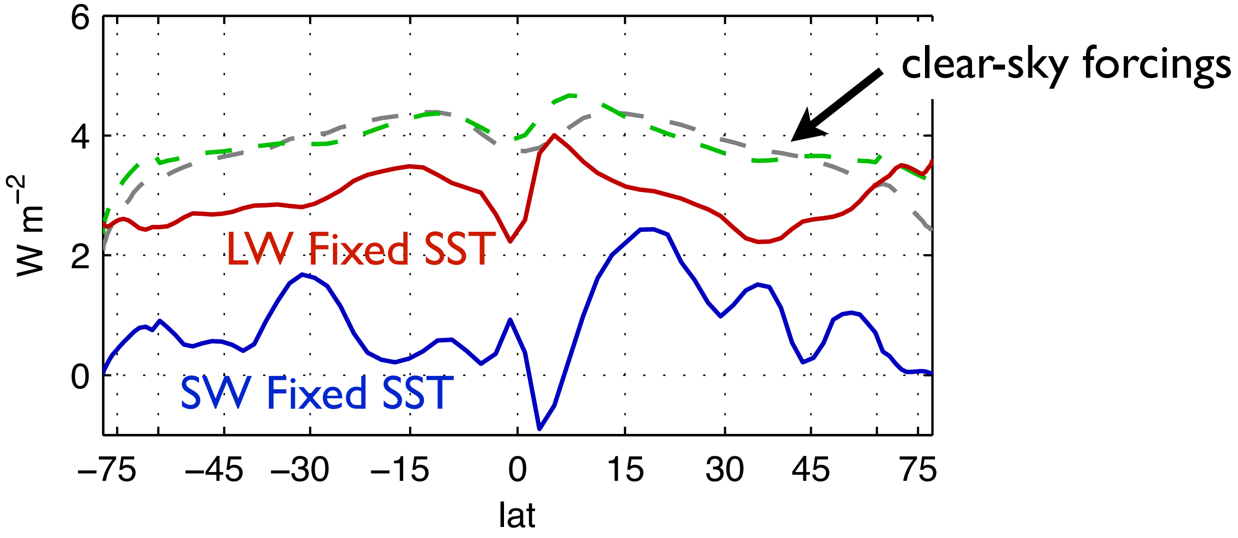


Asymmetries are absent from the clear-sky forcing

- Attributed to the shortwave response of clouds *directly* to CO_2 (analogous to effect of aerosols on cloudiness)
- Rapid cloud adjustment also noted in other studies (Colman and McAveney, 2011; Watanabe et al., 2011; Wyant et al., 2012)

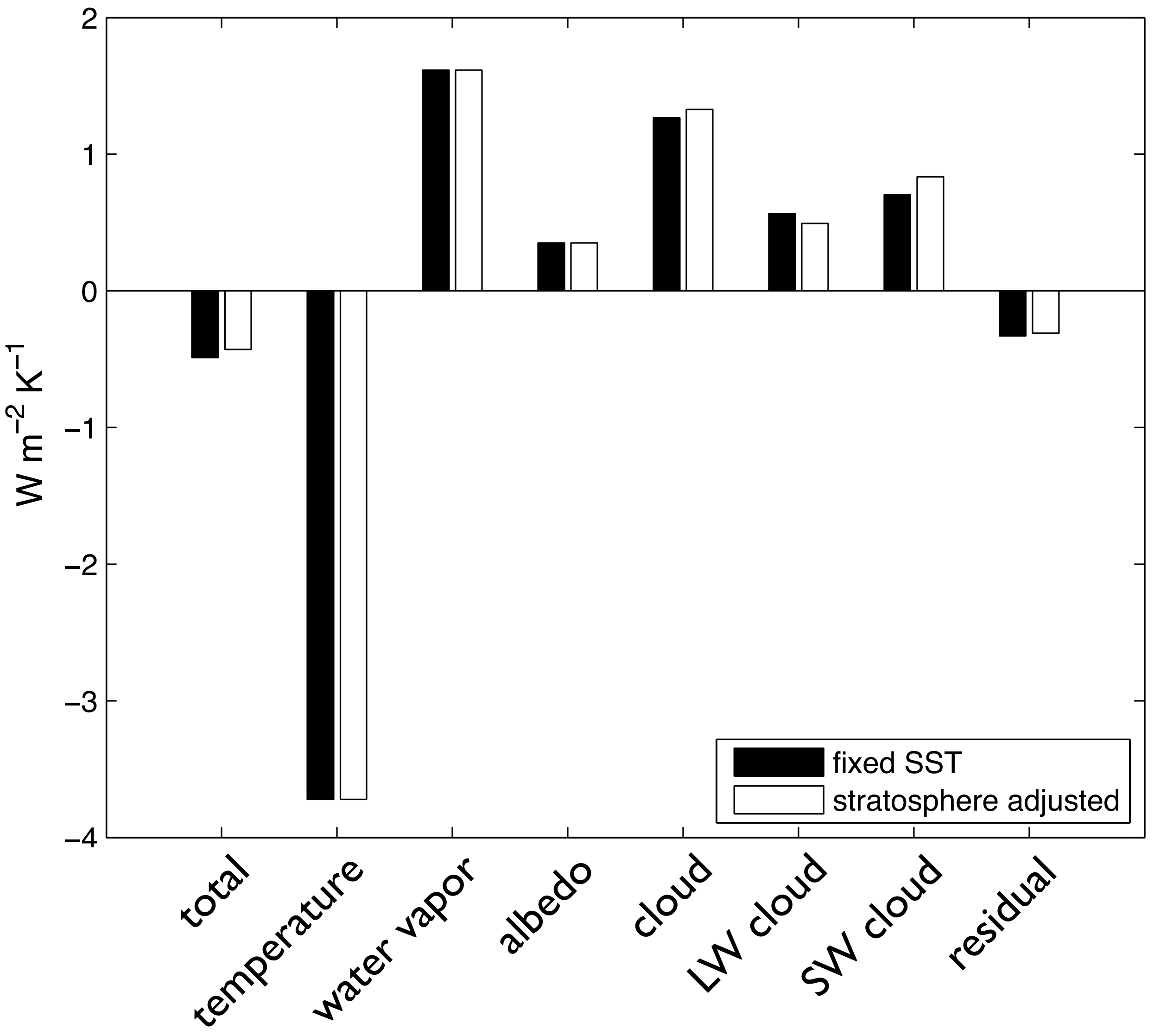


Radiative forcing



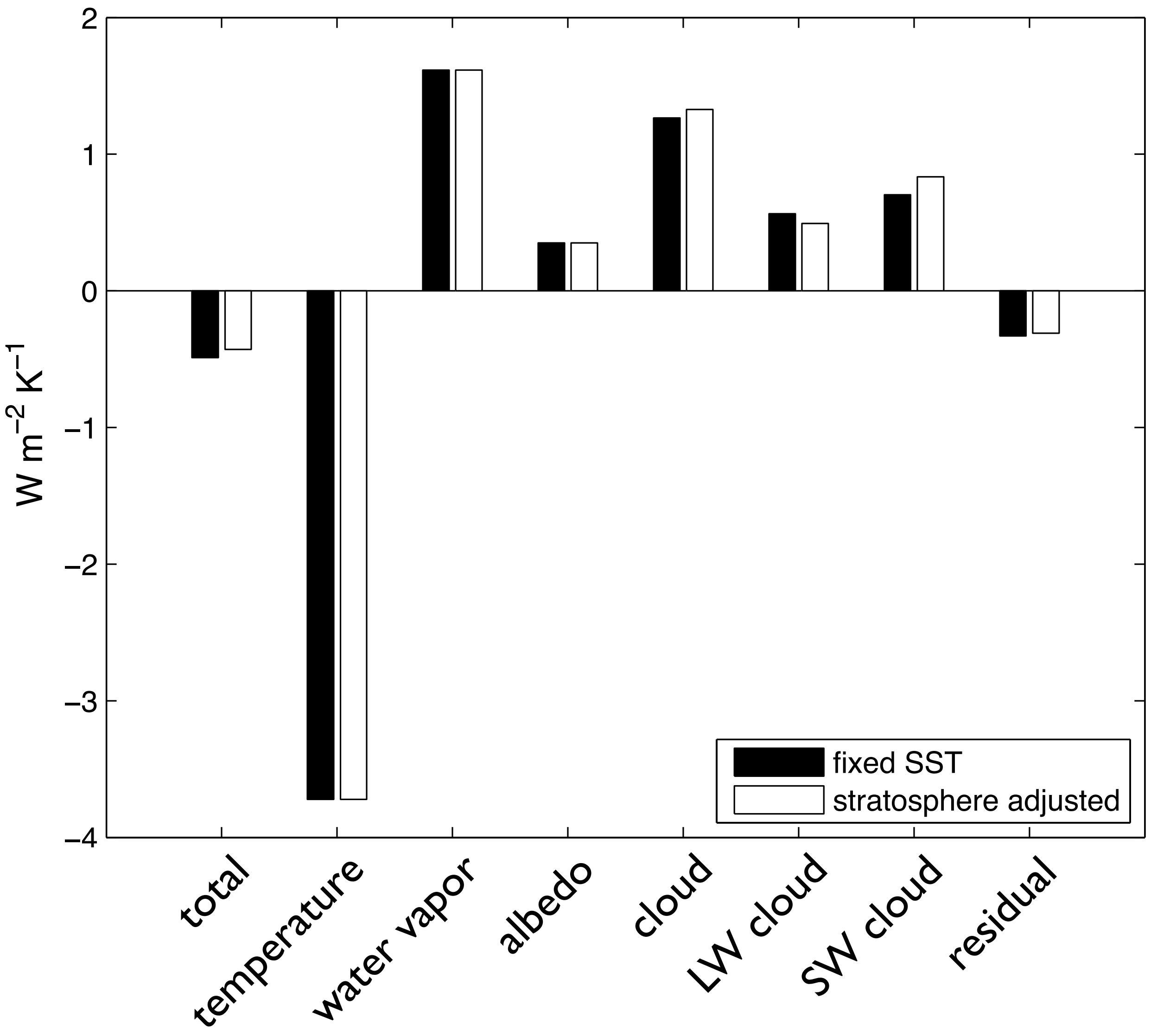
Components of radiative forcing

Global mean feedbacks



Nonlinearities compensate total linear feedback.

Global mean feedbacks



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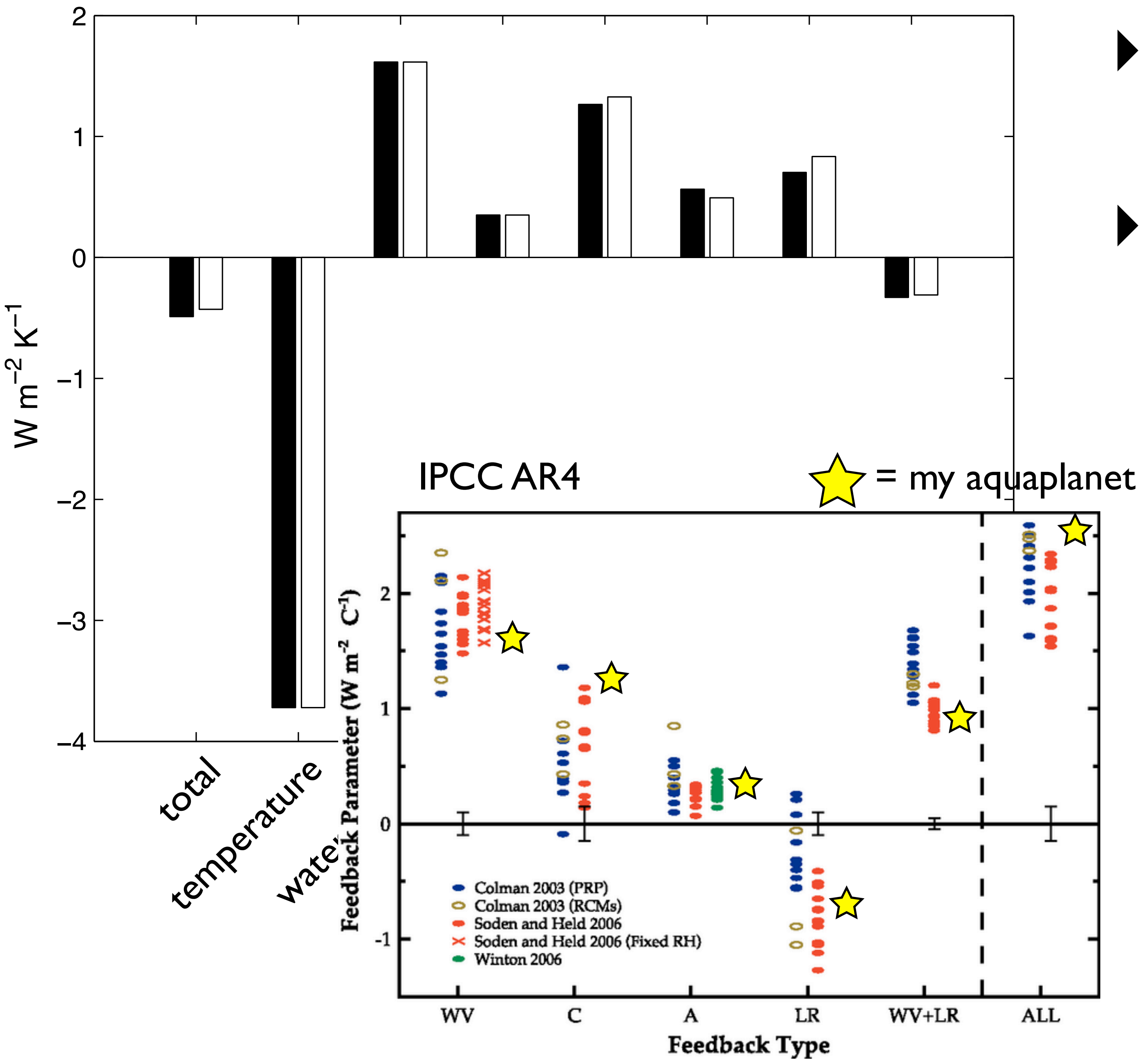

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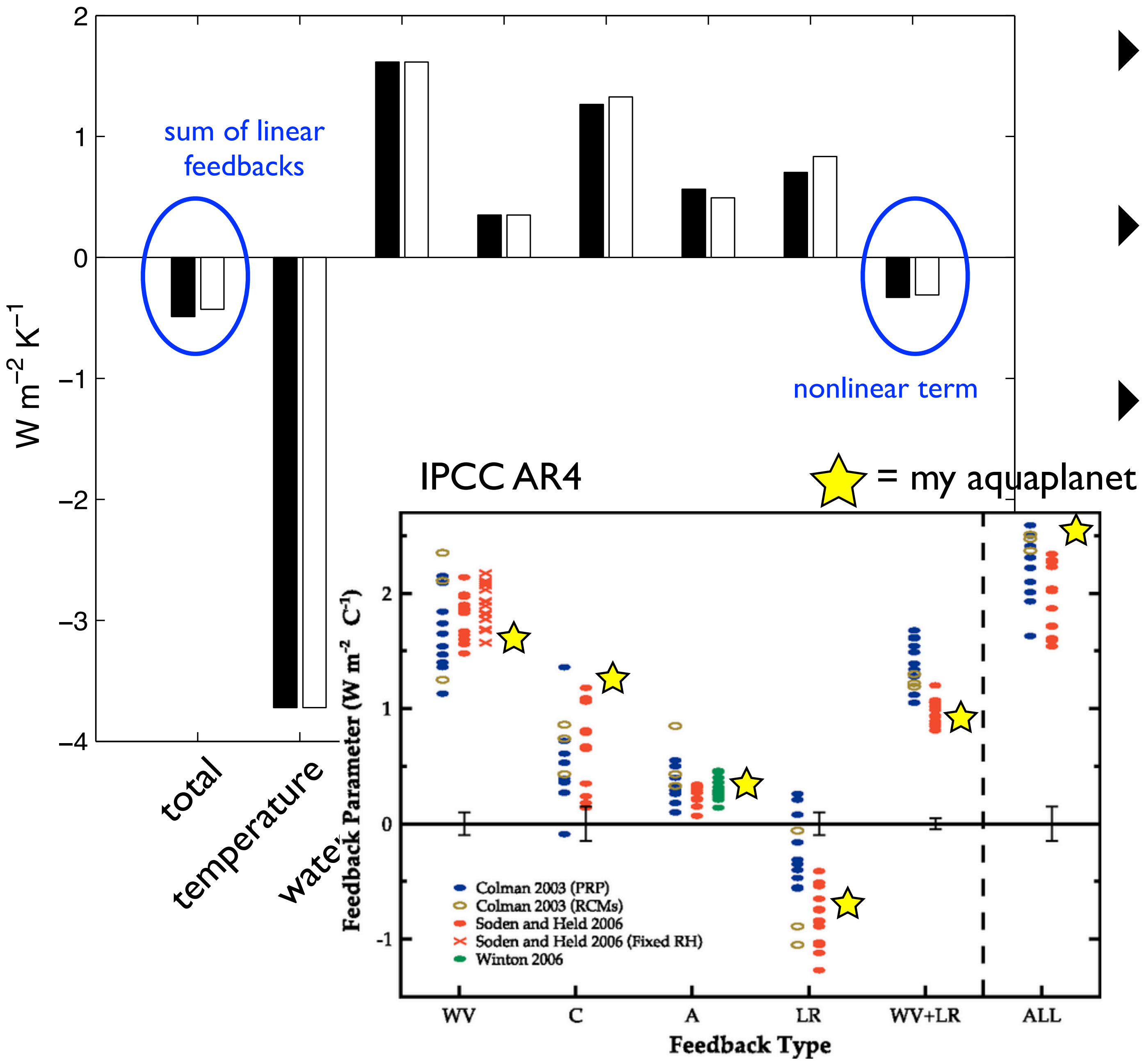

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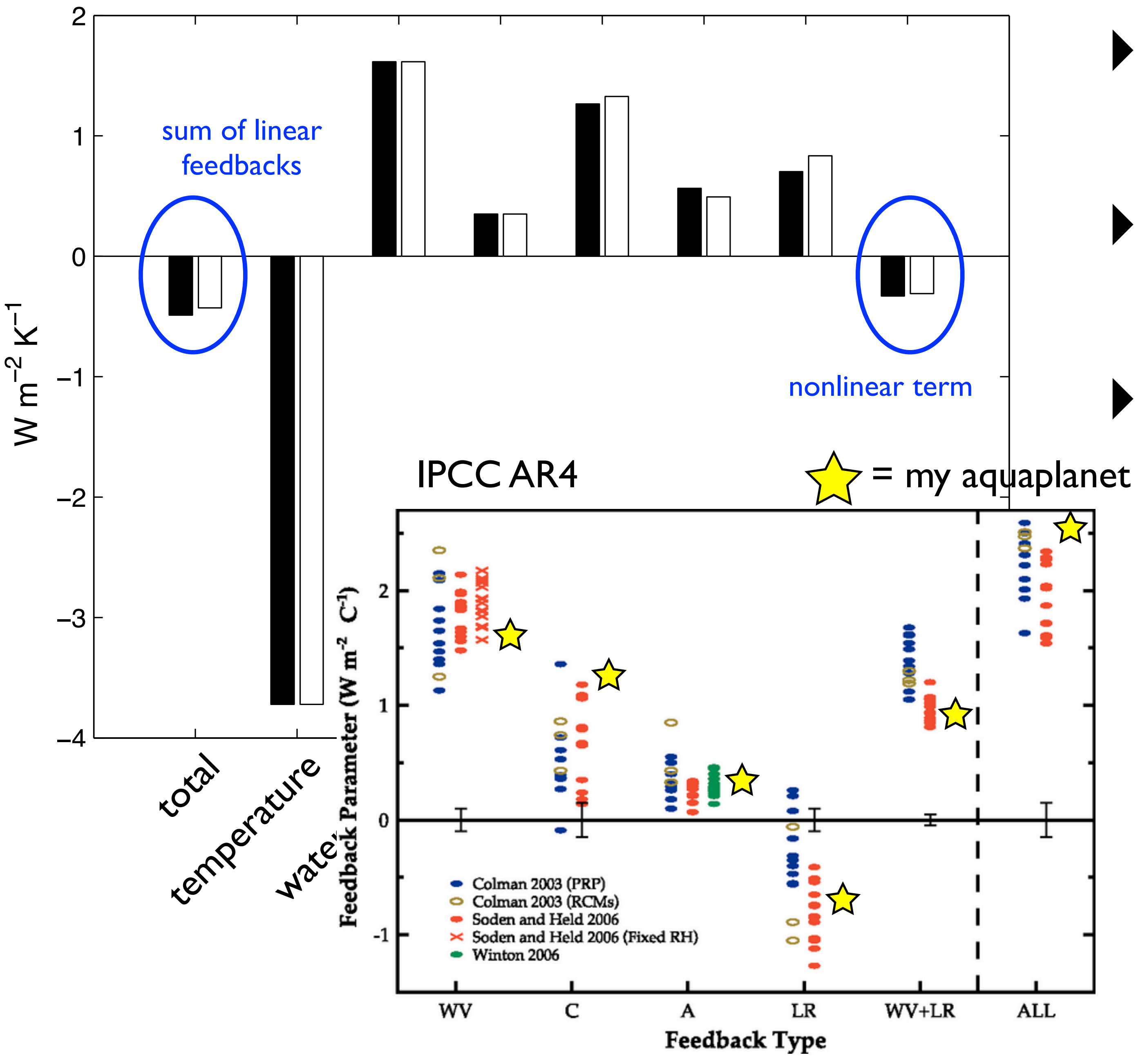

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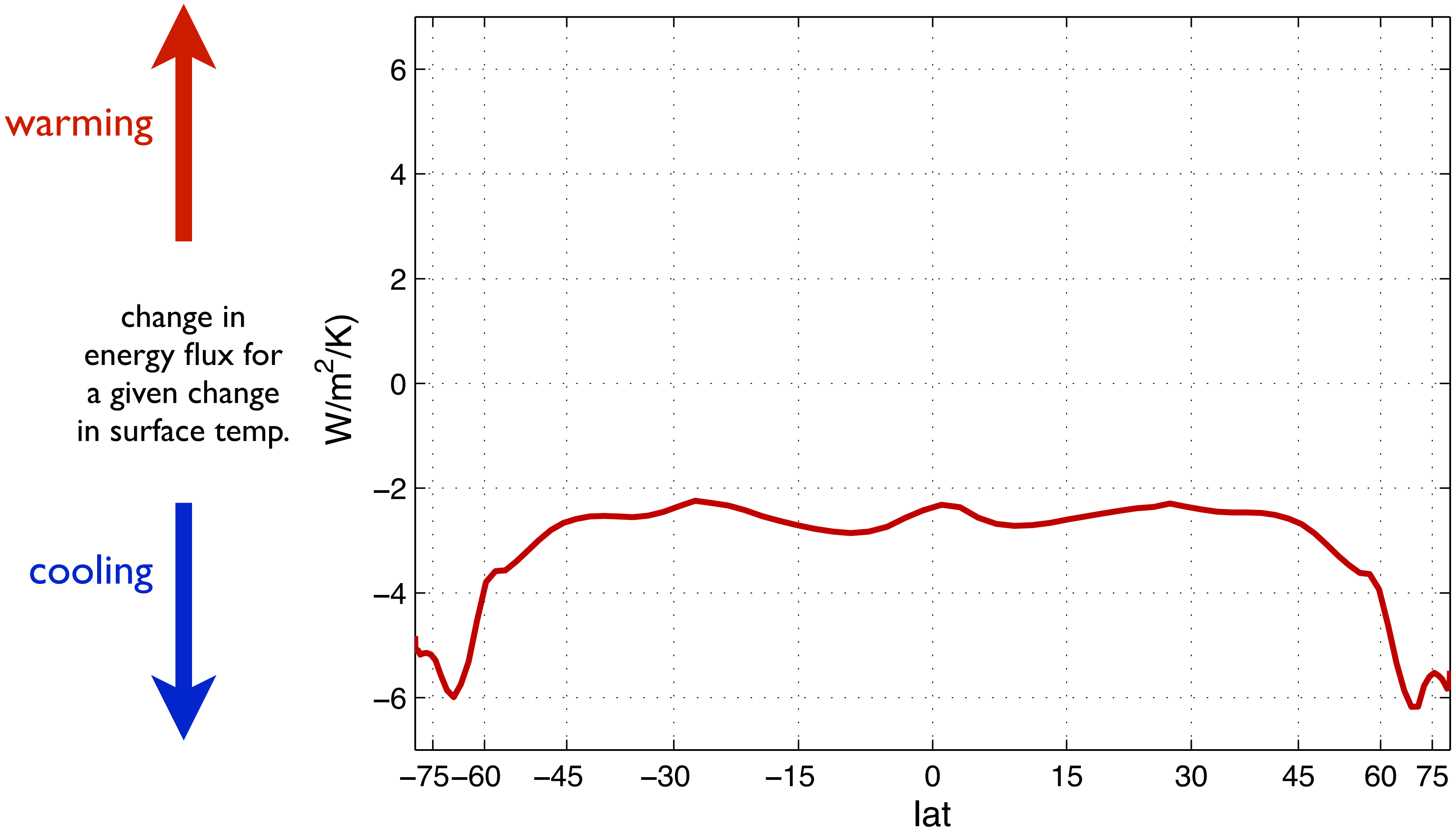
If assumed linearity, would calculate sensitivity as ...

$$\Delta\overline{T}_s = \Delta\widetilde{\overline{R}}_f / \overline{\sum_x \lambda_x} = 7.7K$$

rather than actual 4.69 K

Nonlinearities compensate total linear feedback.

Spatial pattern of aquaplanet feedbacks



change in energy flux for a given change in surface temp.

Total is characterized by strongly positive feedback in subtropics and negative feedback in the extratropics

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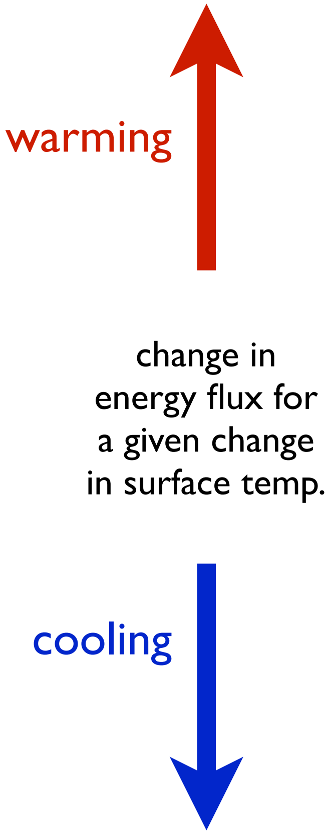

warming

change in
energy flux for
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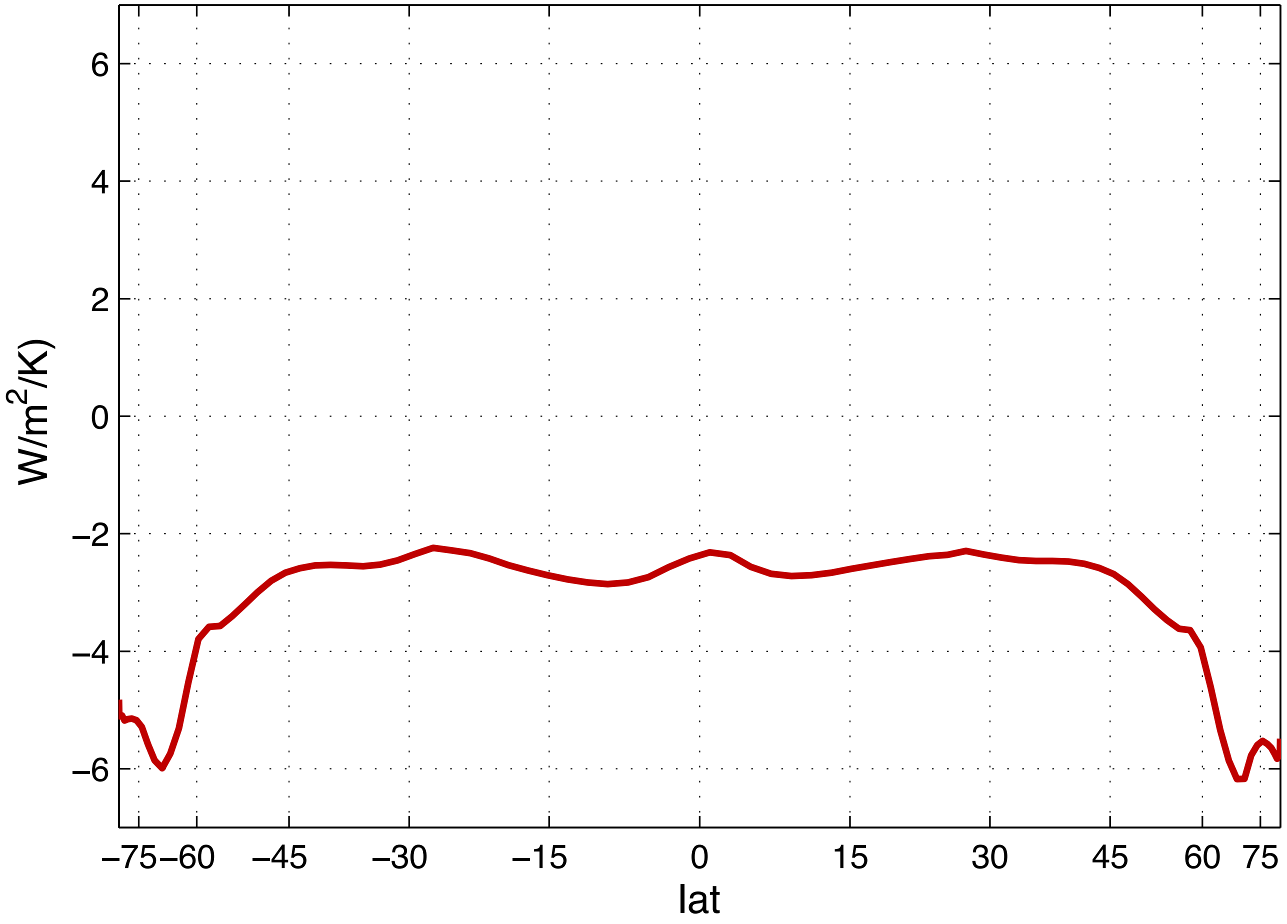
cooling



Planck

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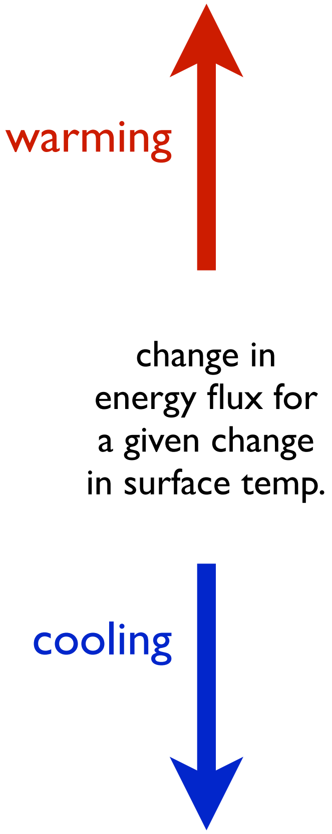

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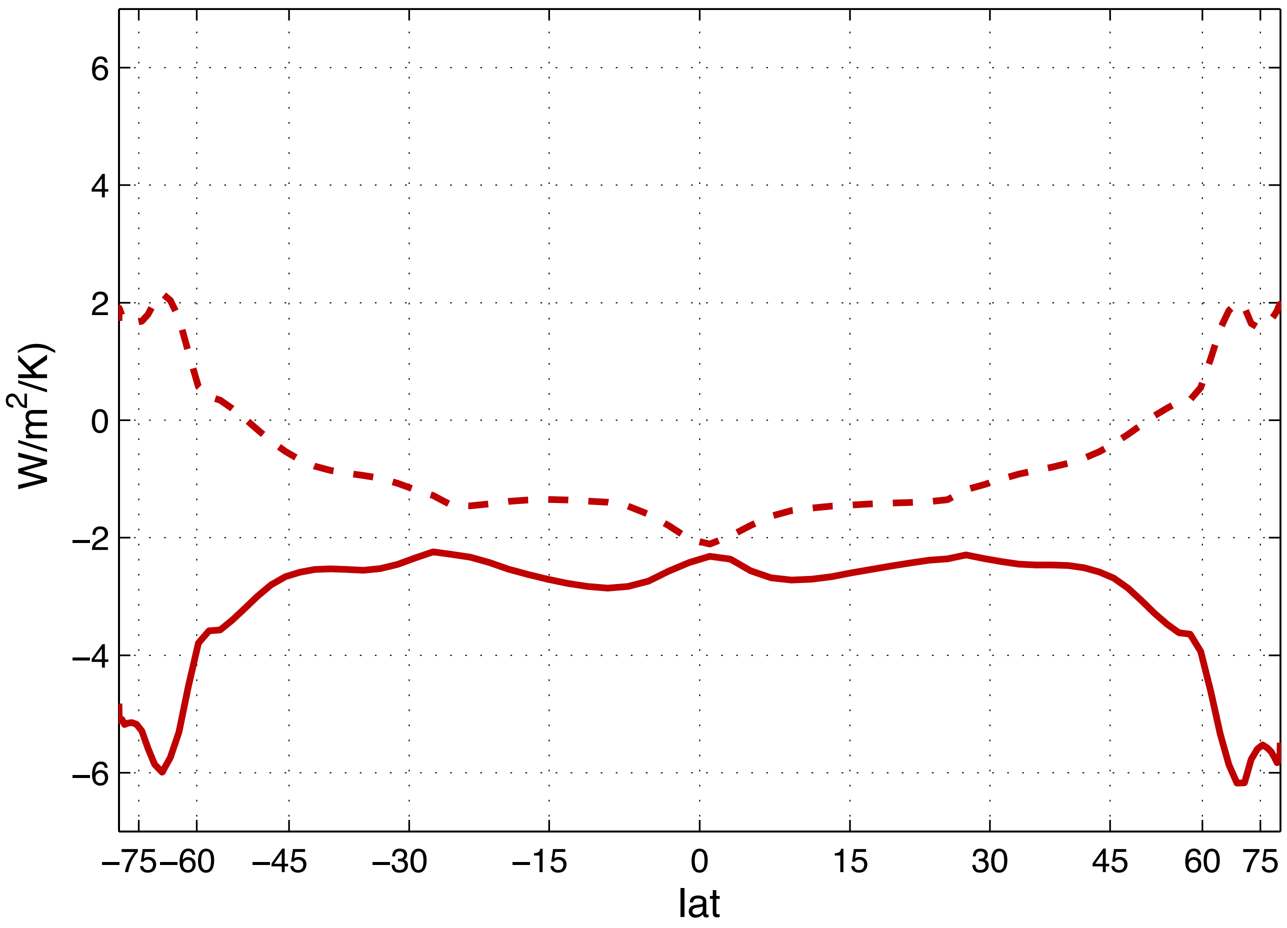

Planck
Lapse rate --

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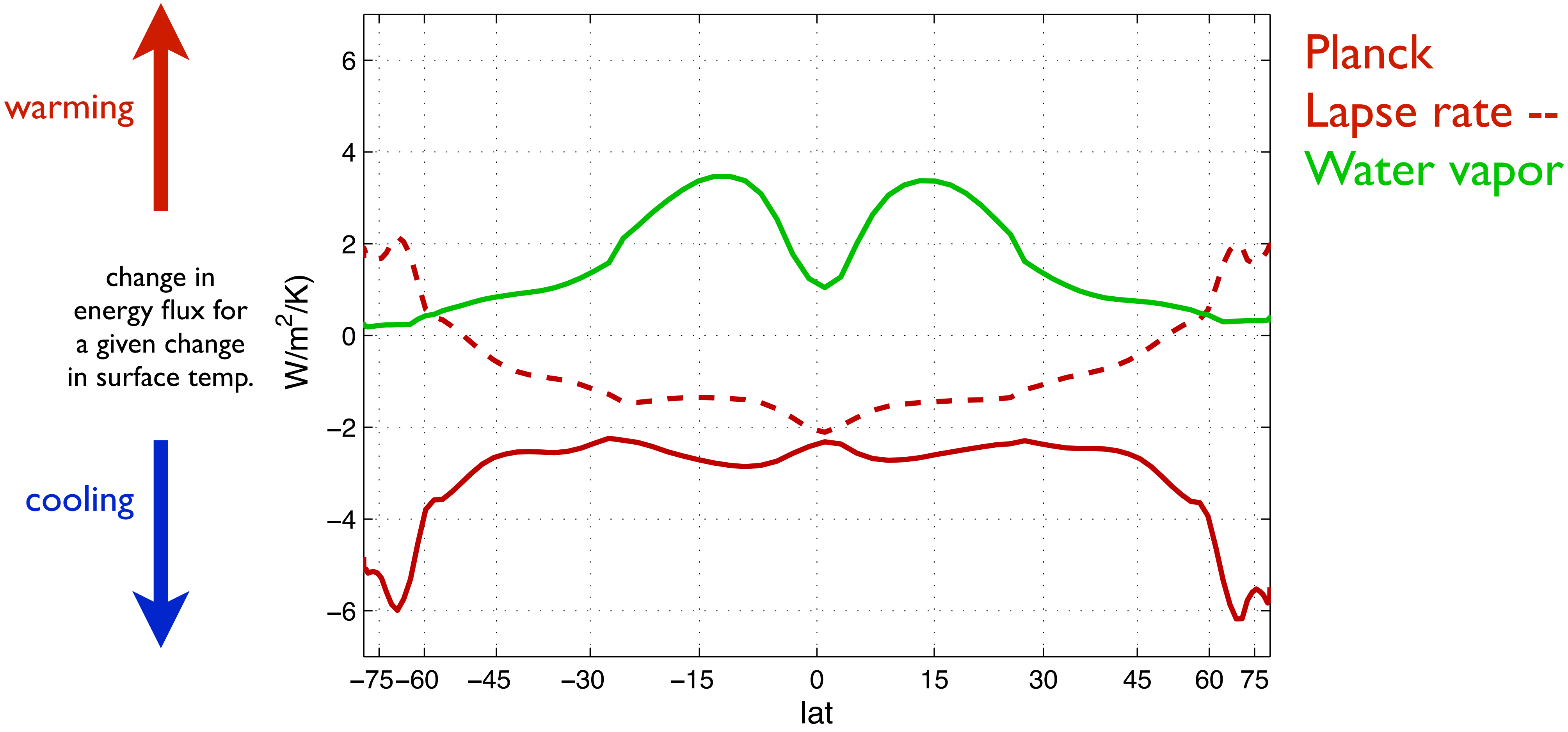
Spatial pattern of aquaplanet feedbacks



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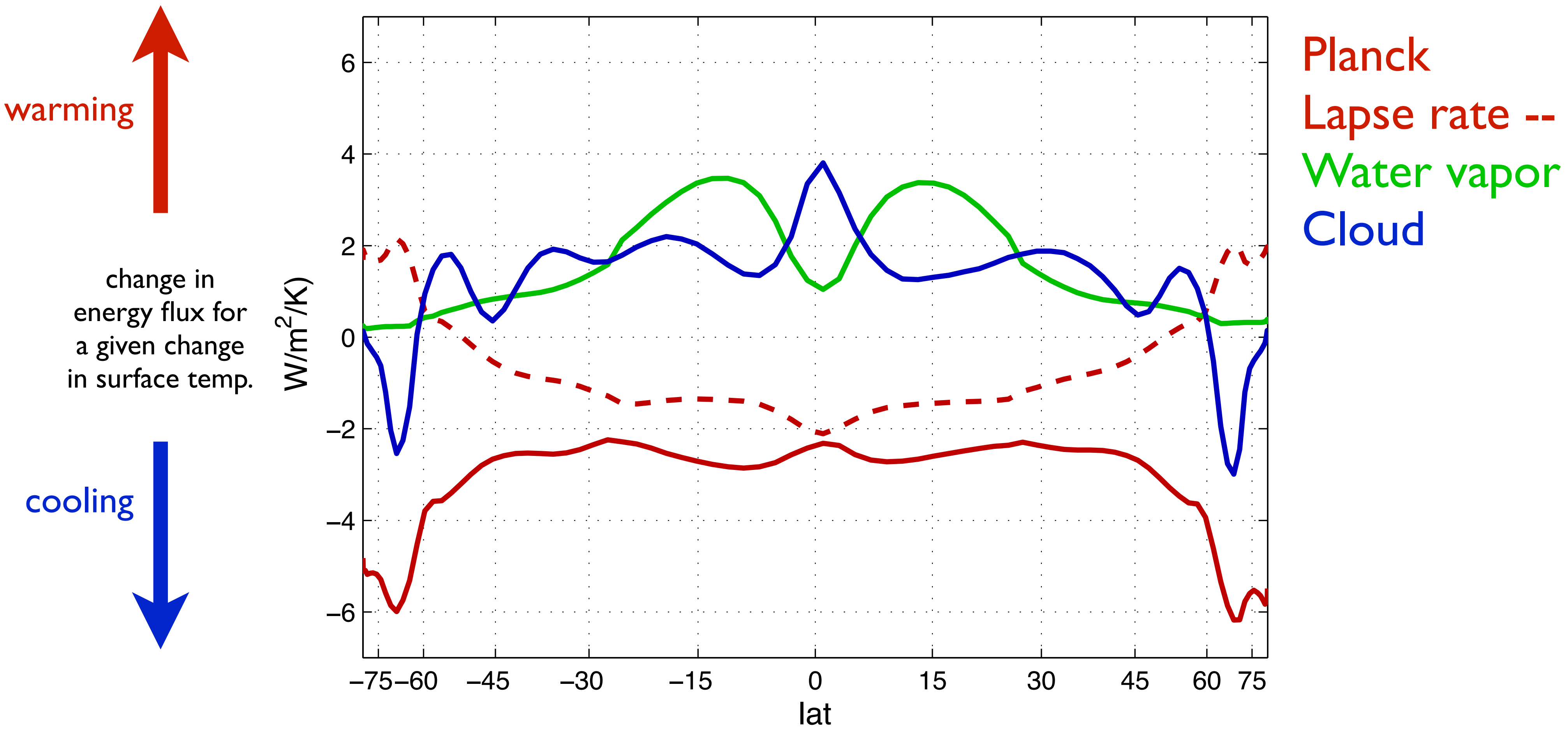

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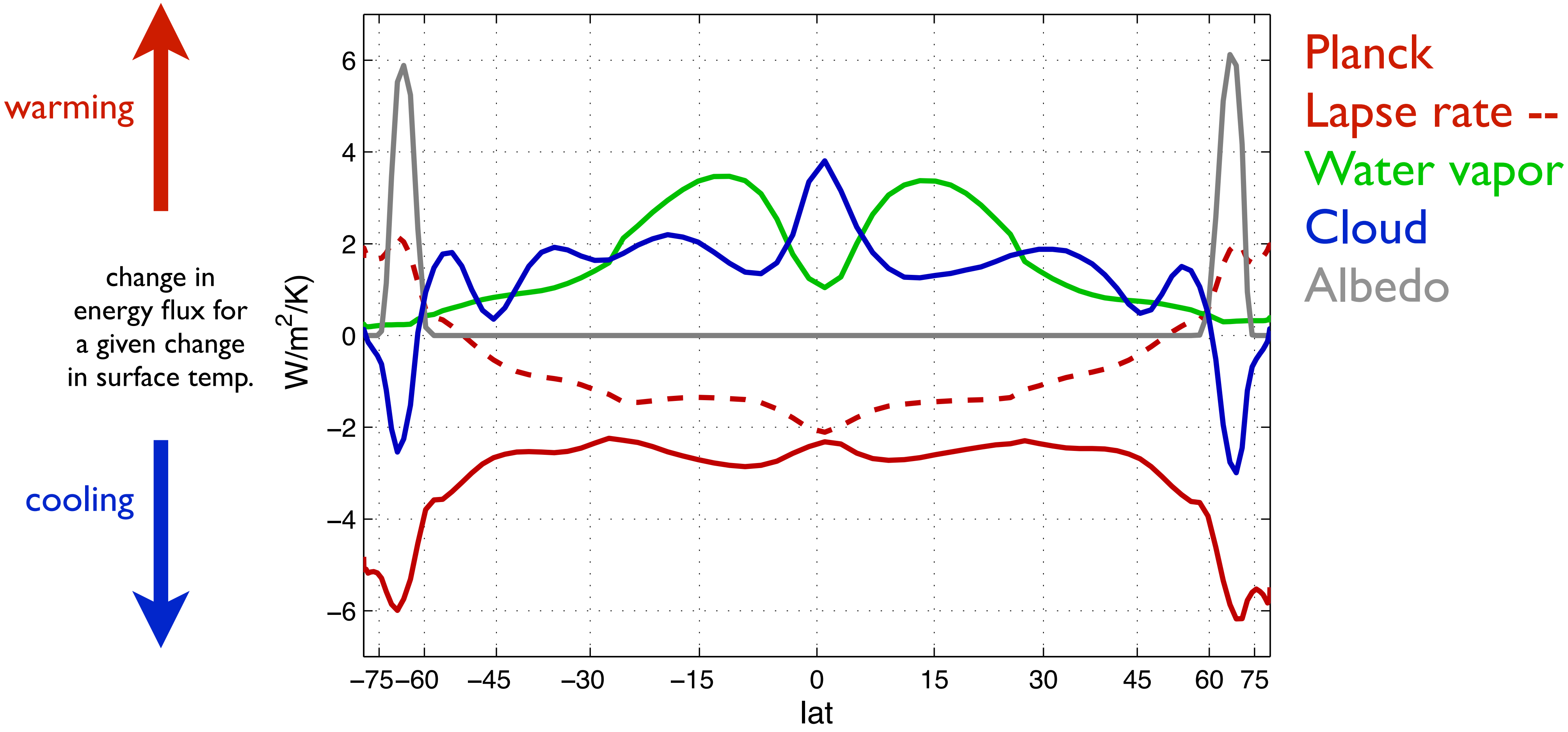

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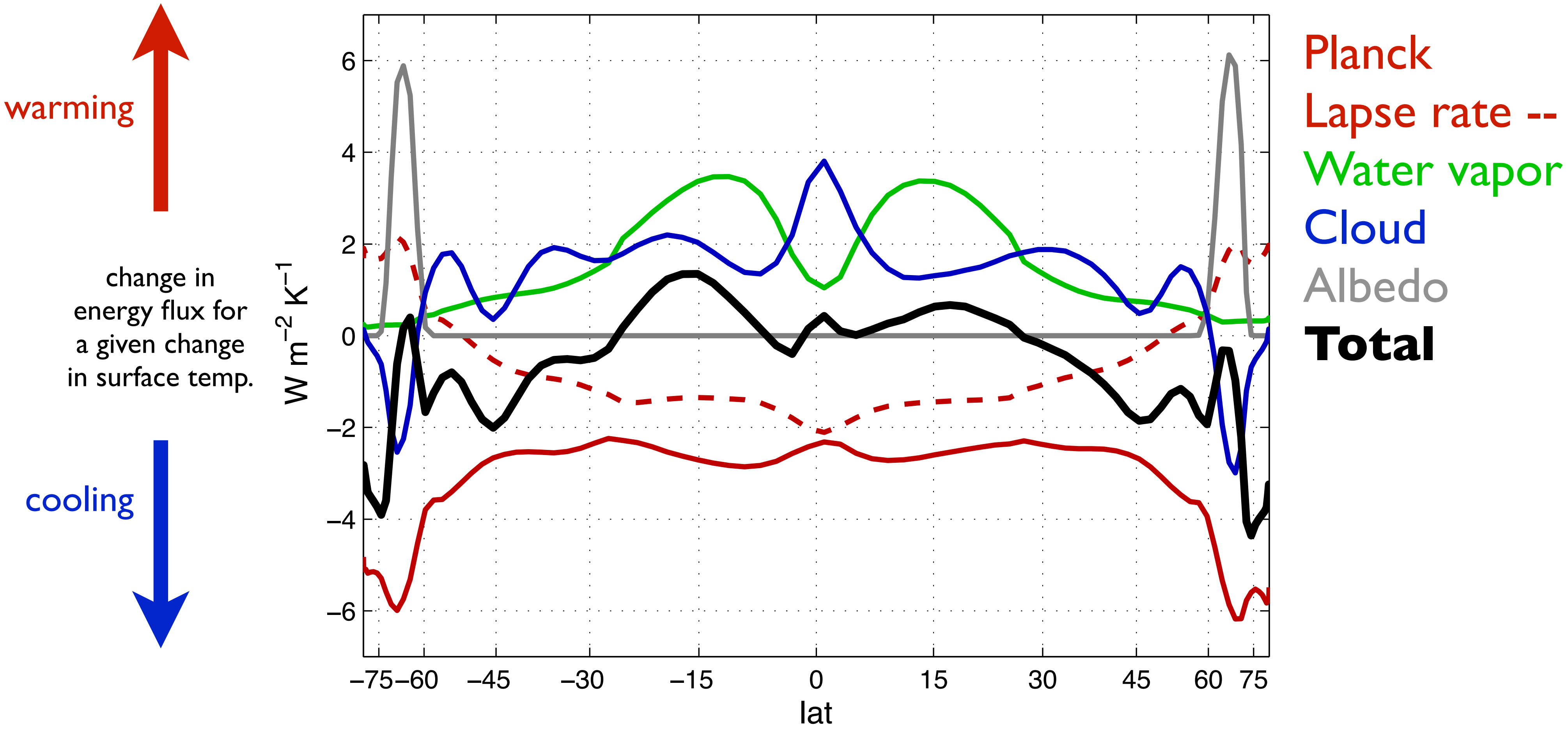

change in
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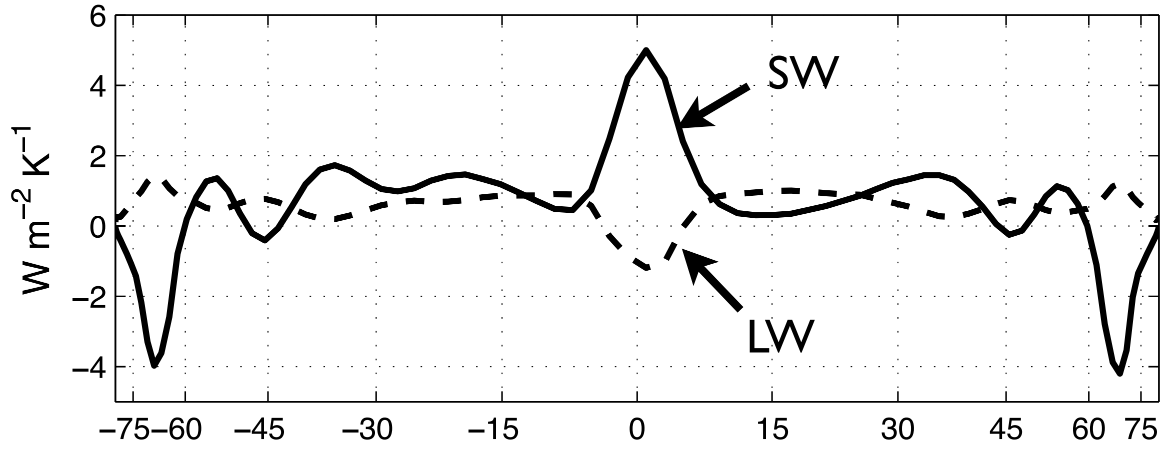
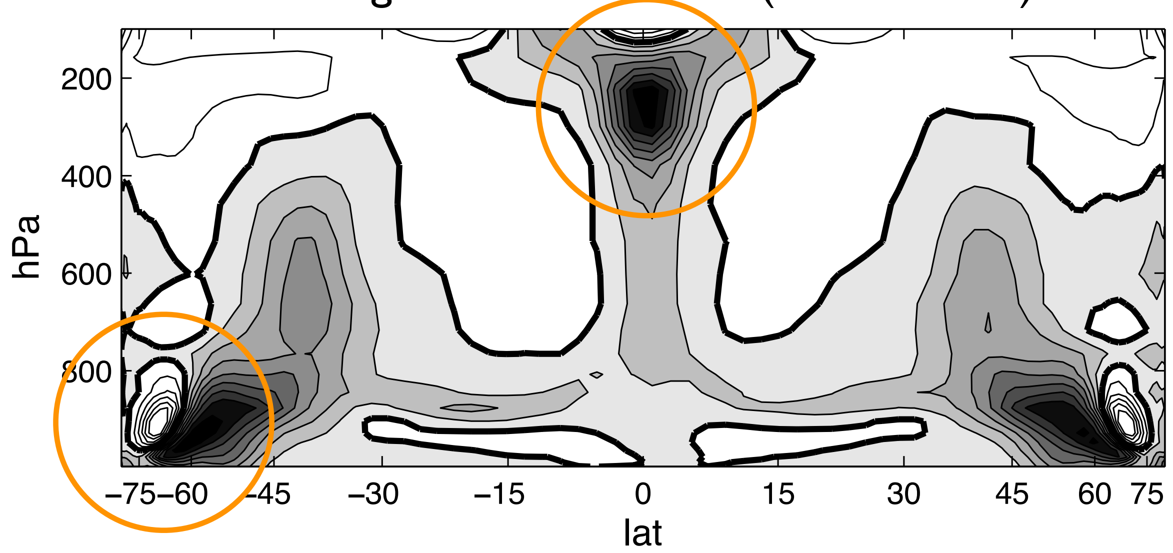
Cloud feedback

The net cloud feedback goes as the SW:



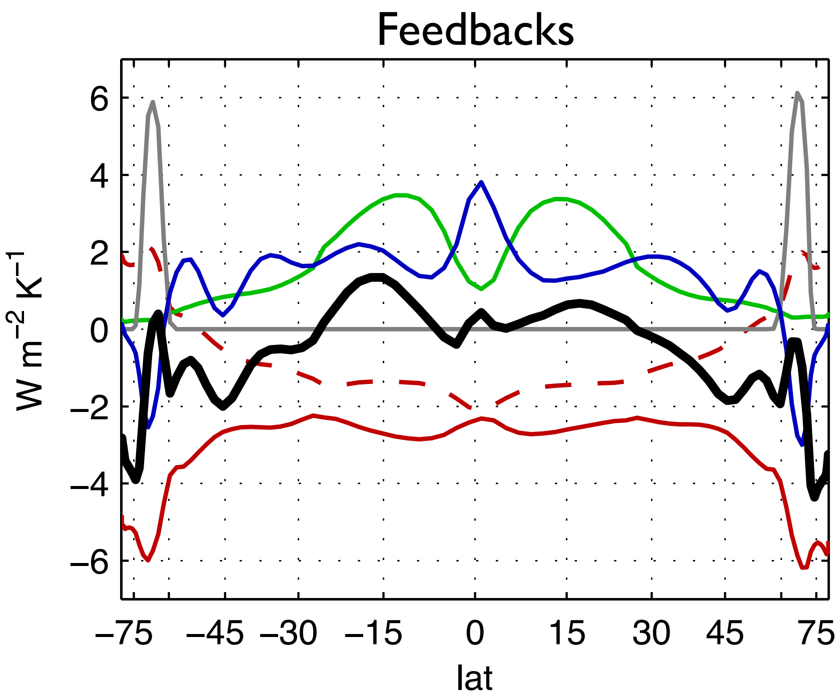
Change in cloud fraction (2% contours)



Reduction of tropical upper troposphere clouds, increase in low bright clouds at high latitudes

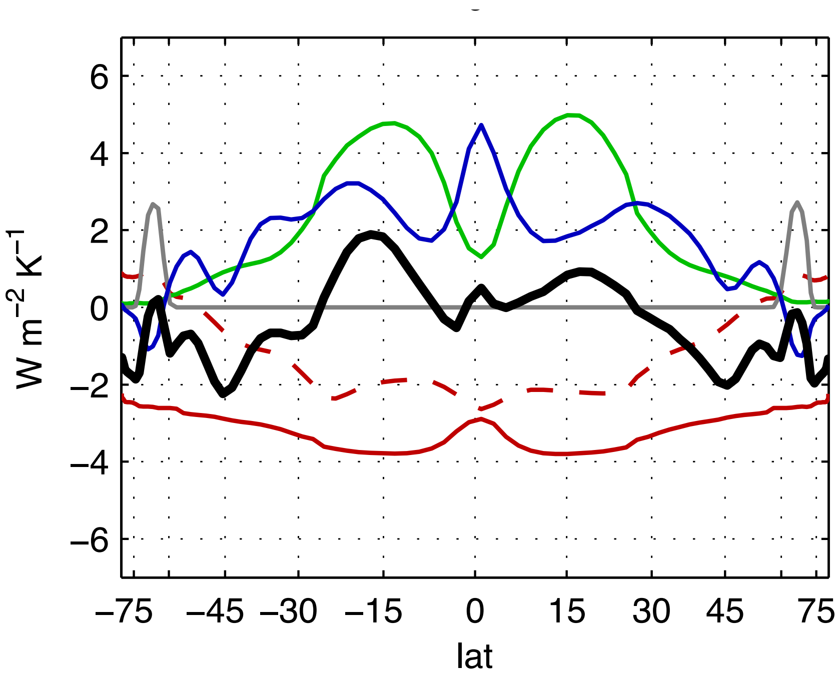
An aside: normalizing energy flux changes

Conventional, global mean



$$\lambda_x = \frac{\partial R}{\partial x} \cdot \frac{dx}{d\overline{T}_s}$$

Local



$$\lambda_x = \frac{\partial R}{\partial x} \cdot \frac{dx}{dT_s}$$

(Get to divide by a bigger number at high latitudes)

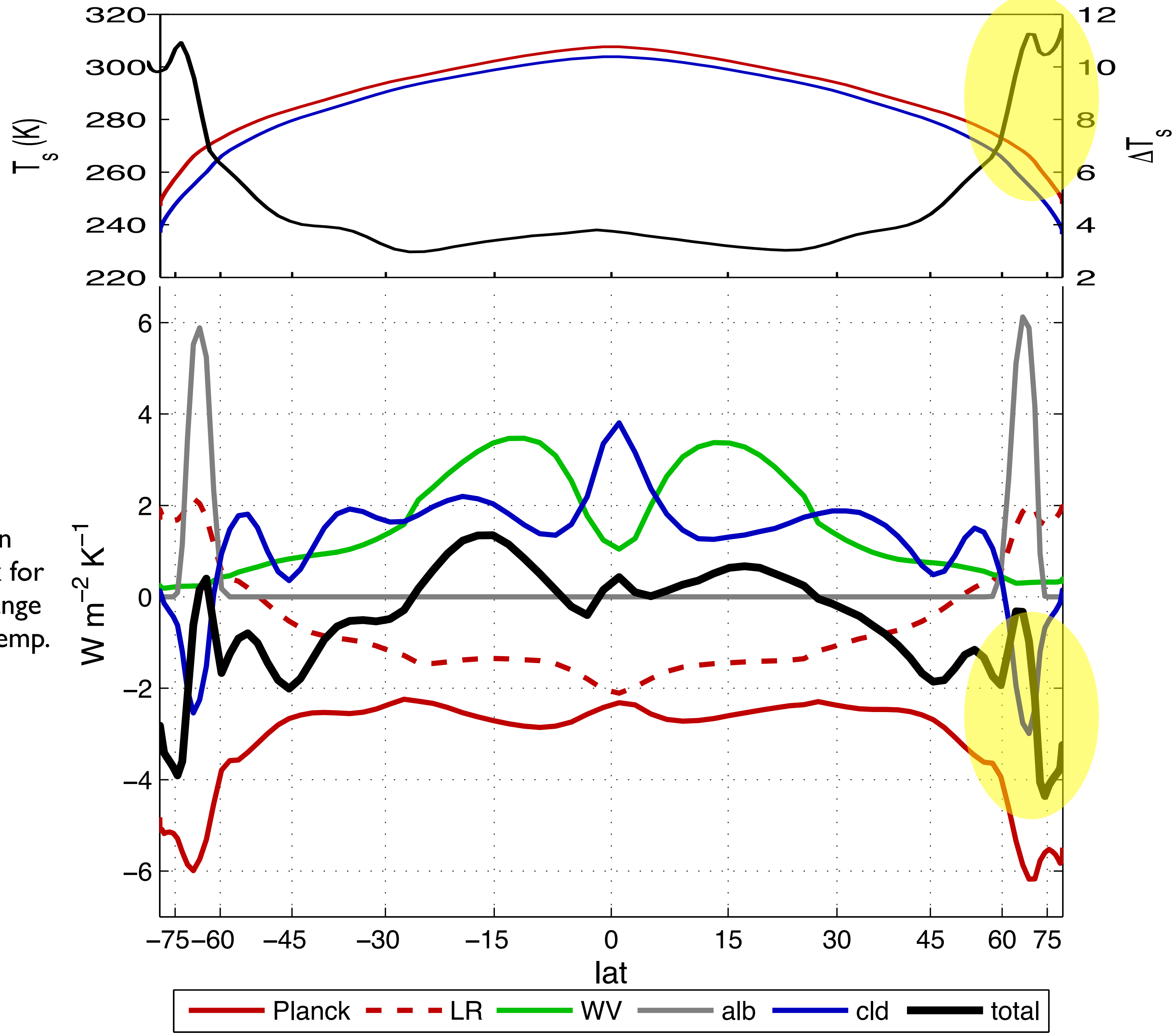
Disconnect between patterns of feedback and warming

Greatest warming

warming

change in energy flux for a given change in surface temp.

cooling

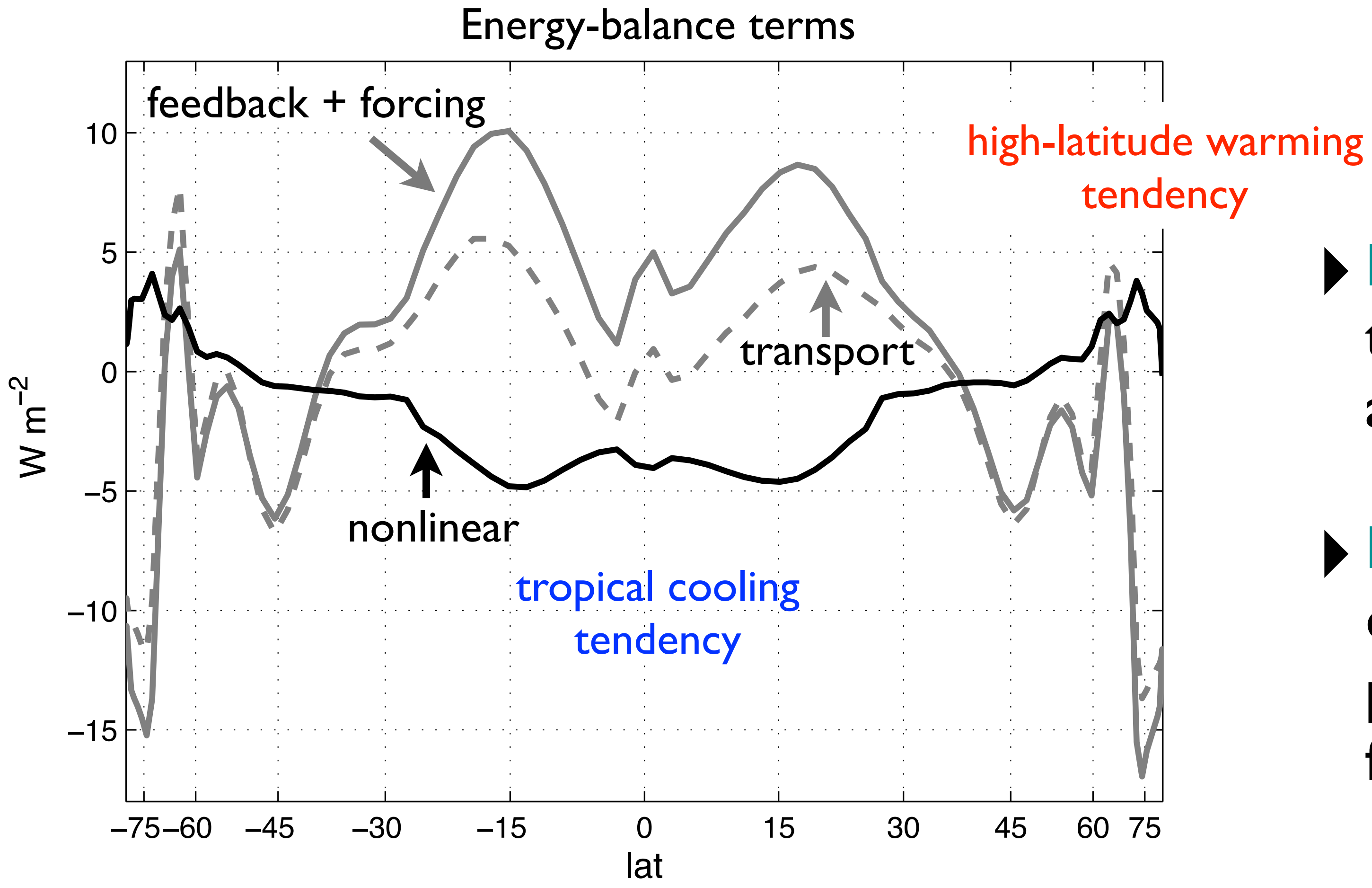


Most negative feedback (stabilizing)

Positive subtropical feedback and polar amplification implies critical roles for transport and/or nonlinearities (1) to maintain stability and (2) to export heat to high latitudes

A closer look into transport and nonlinear terms

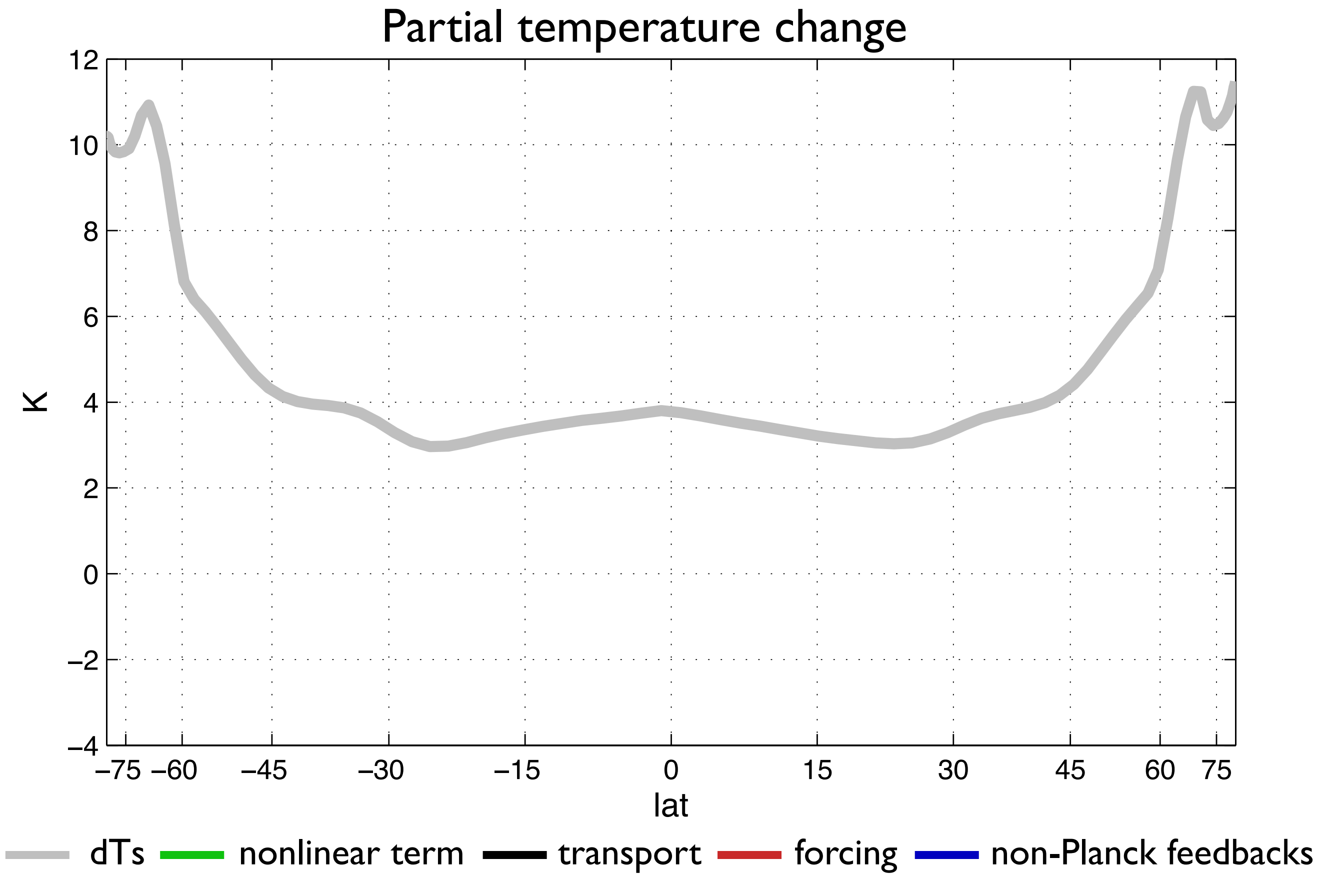
Recall this equation ... $\Delta\left(\nabla \cdot \vec{F}\right) = \Delta R_f + \sum_i \lambda_i \Delta T_s + O(\Delta T_s^2)$



- In a linear world, changes in transport would balance feedback and forcing.
- In a nonlinear world, incomplete divergence of heat away from positive feedbacks and into negative feedbacks.

Nonlinearity compensates the total linear feedback meridionally

Relative importance of energy-balance terms to pattern of warming



Energy balance, rearranged:

(n.b. local not global-mean)

$$\Delta T_s = \frac{1}{\lambda_P}\left[\Delta R - \left(\sum_i \lambda_{NP_i}\right)\Delta T_s - \Delta \widetilde{R}_f - \mathcal{R}\right]$$

Pattern of warming controlled by heat transport away from strong positive feedbacks (ice line, subtropics), towards more negative feedbacks (midlatitudes, poles).

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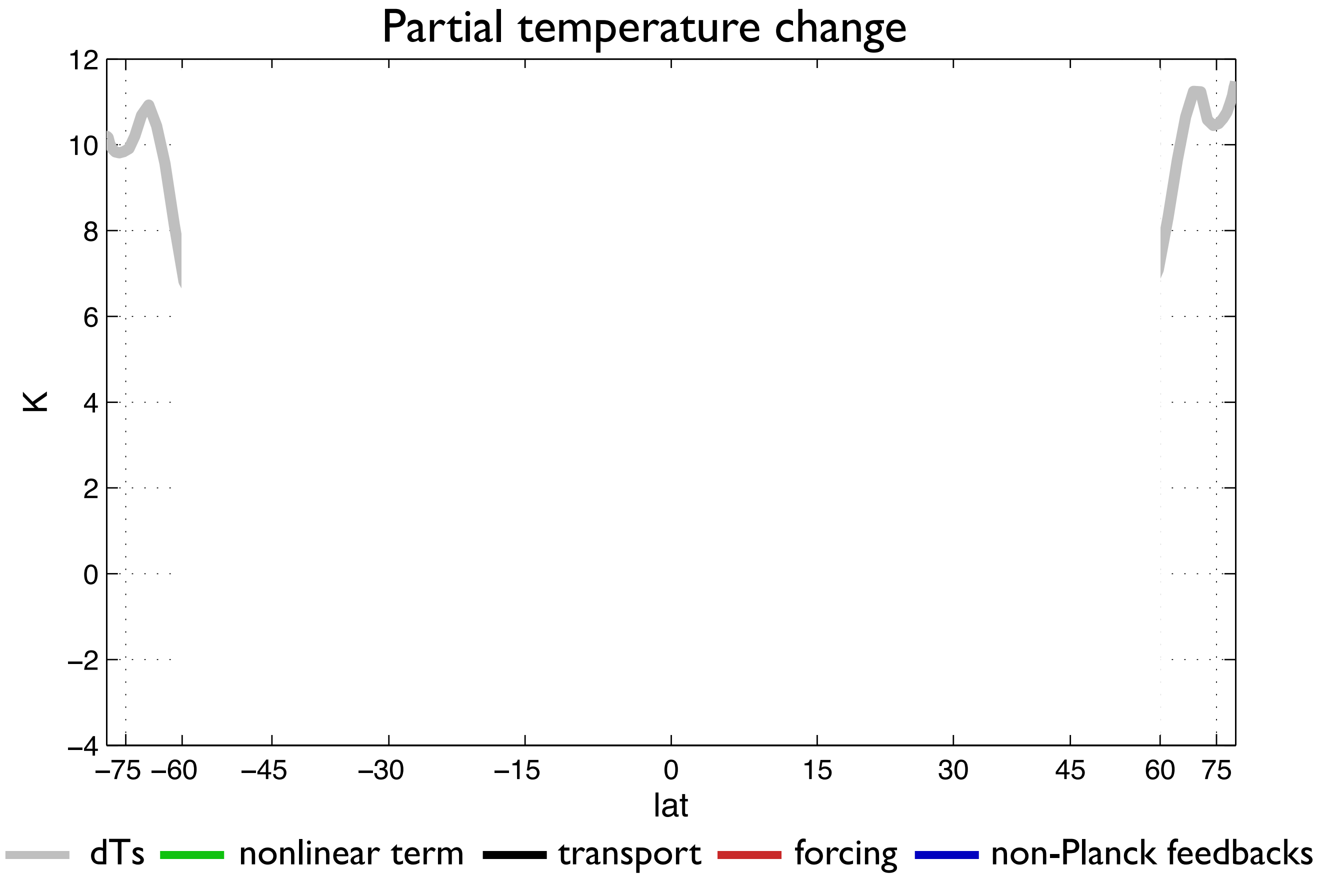

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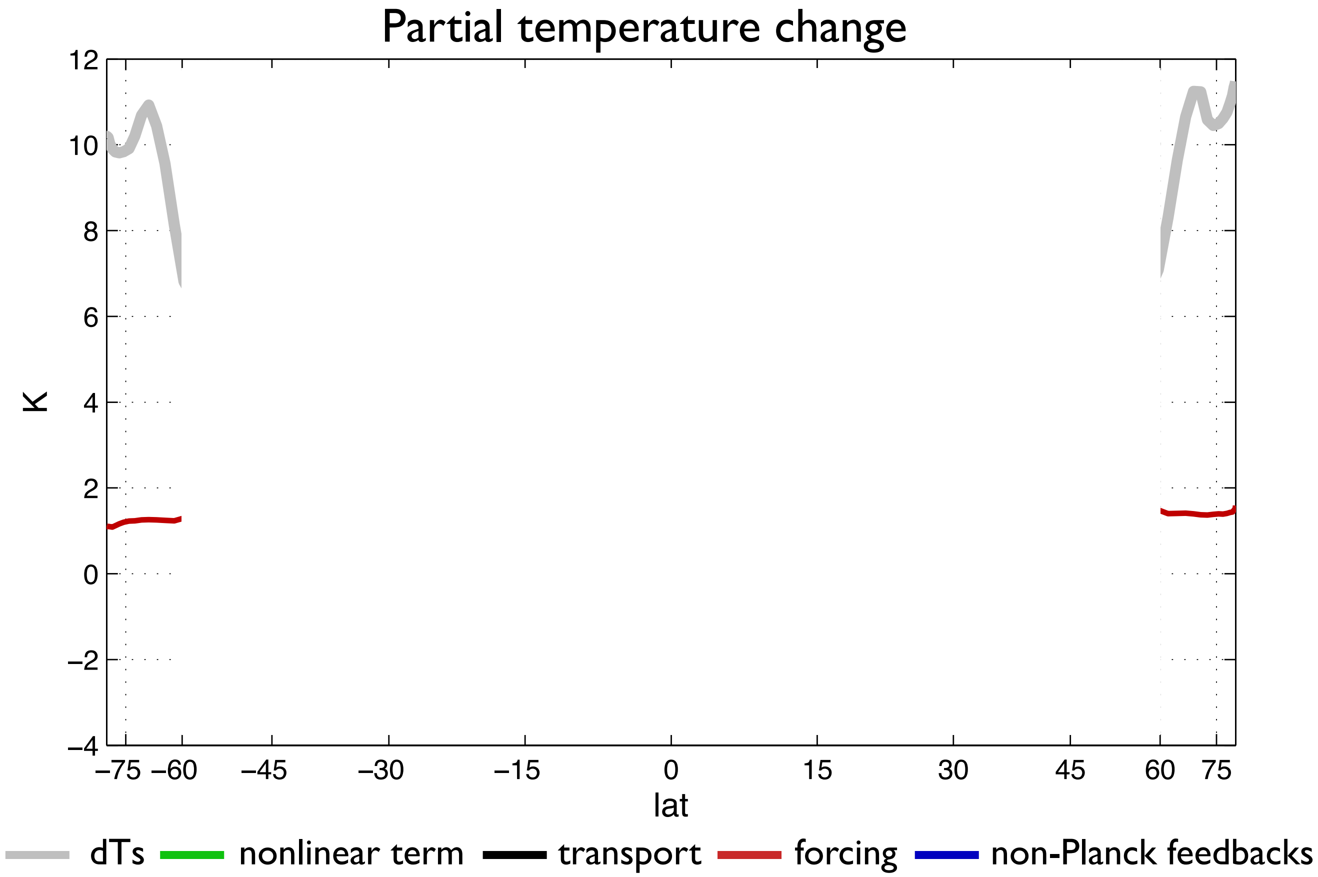

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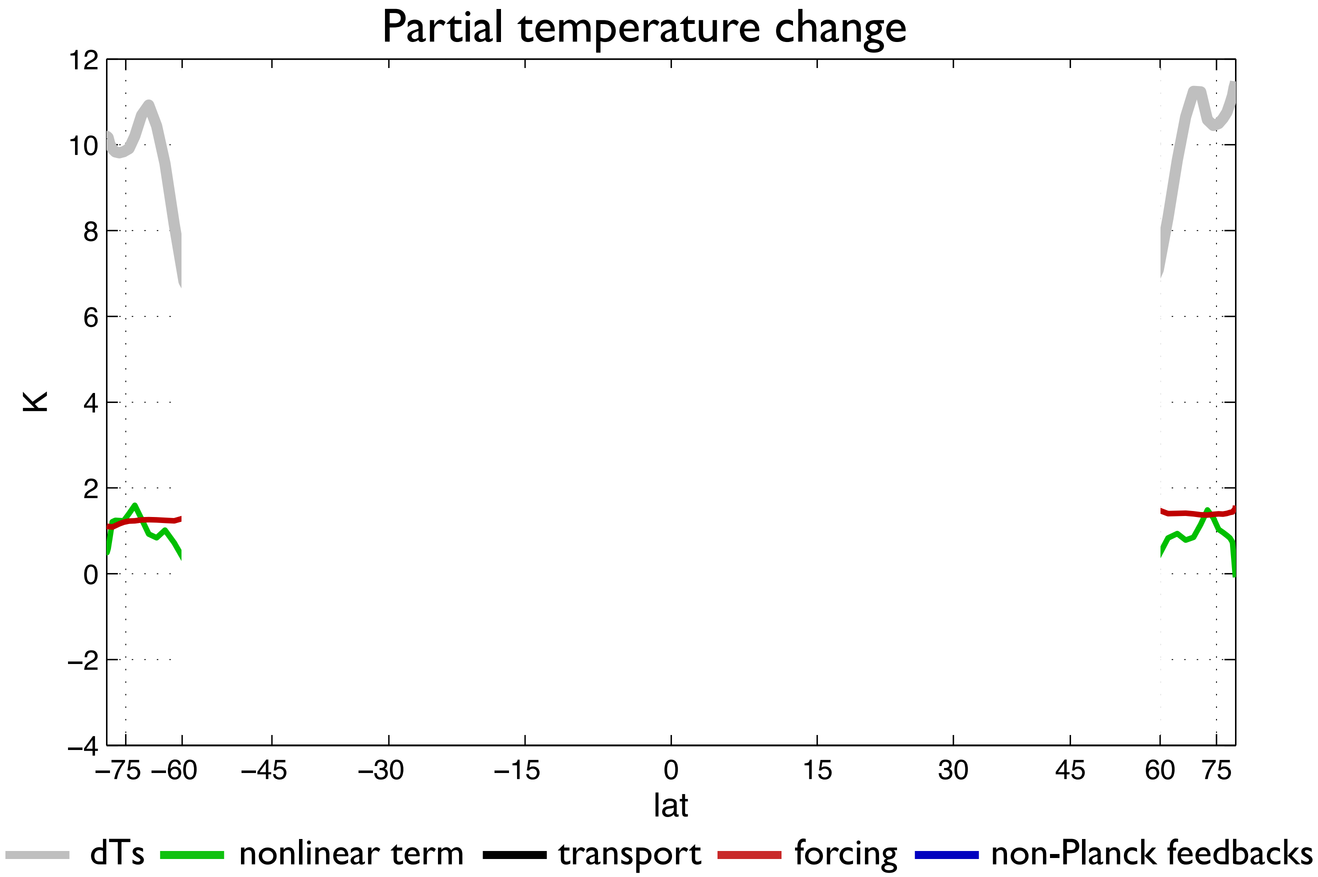

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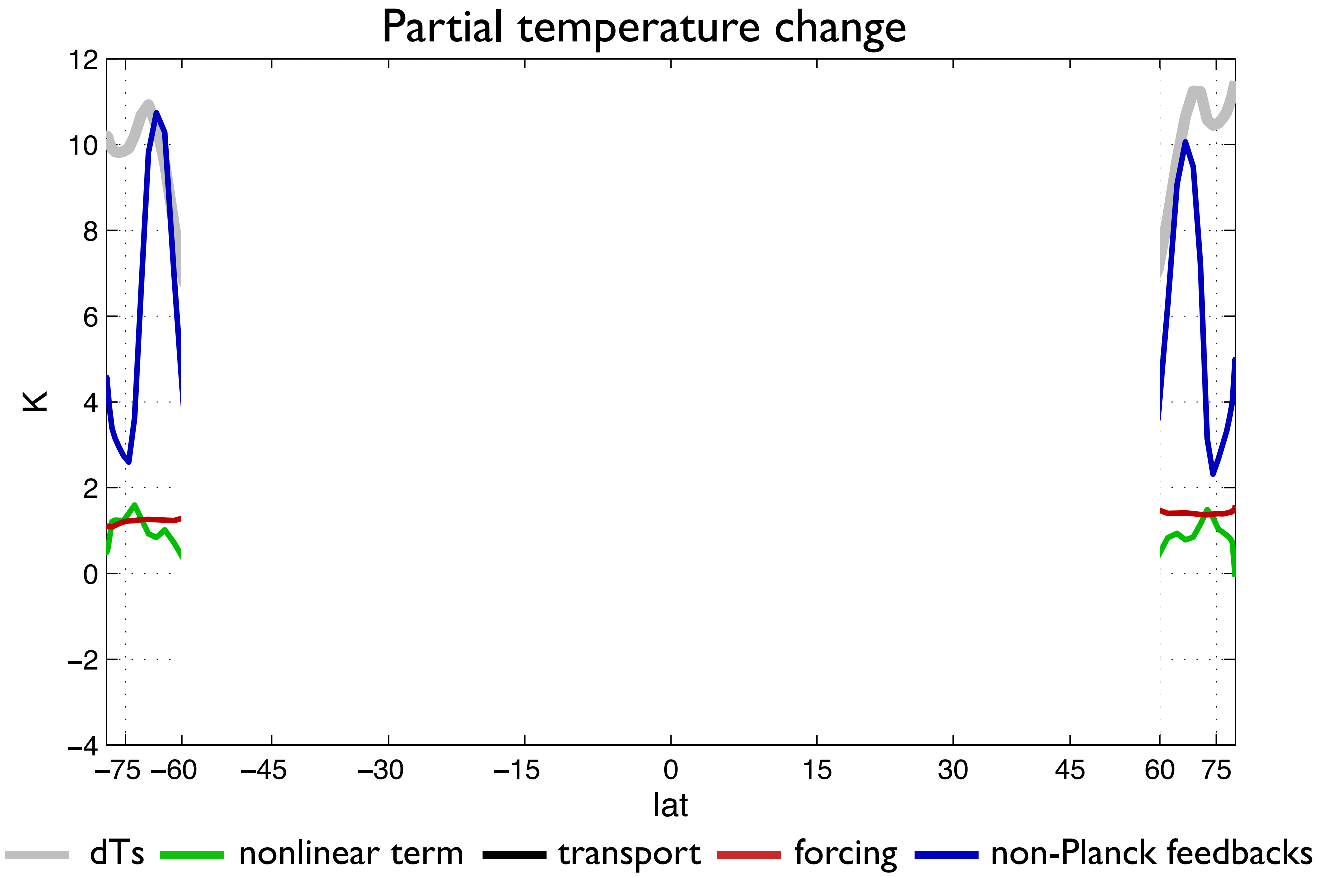

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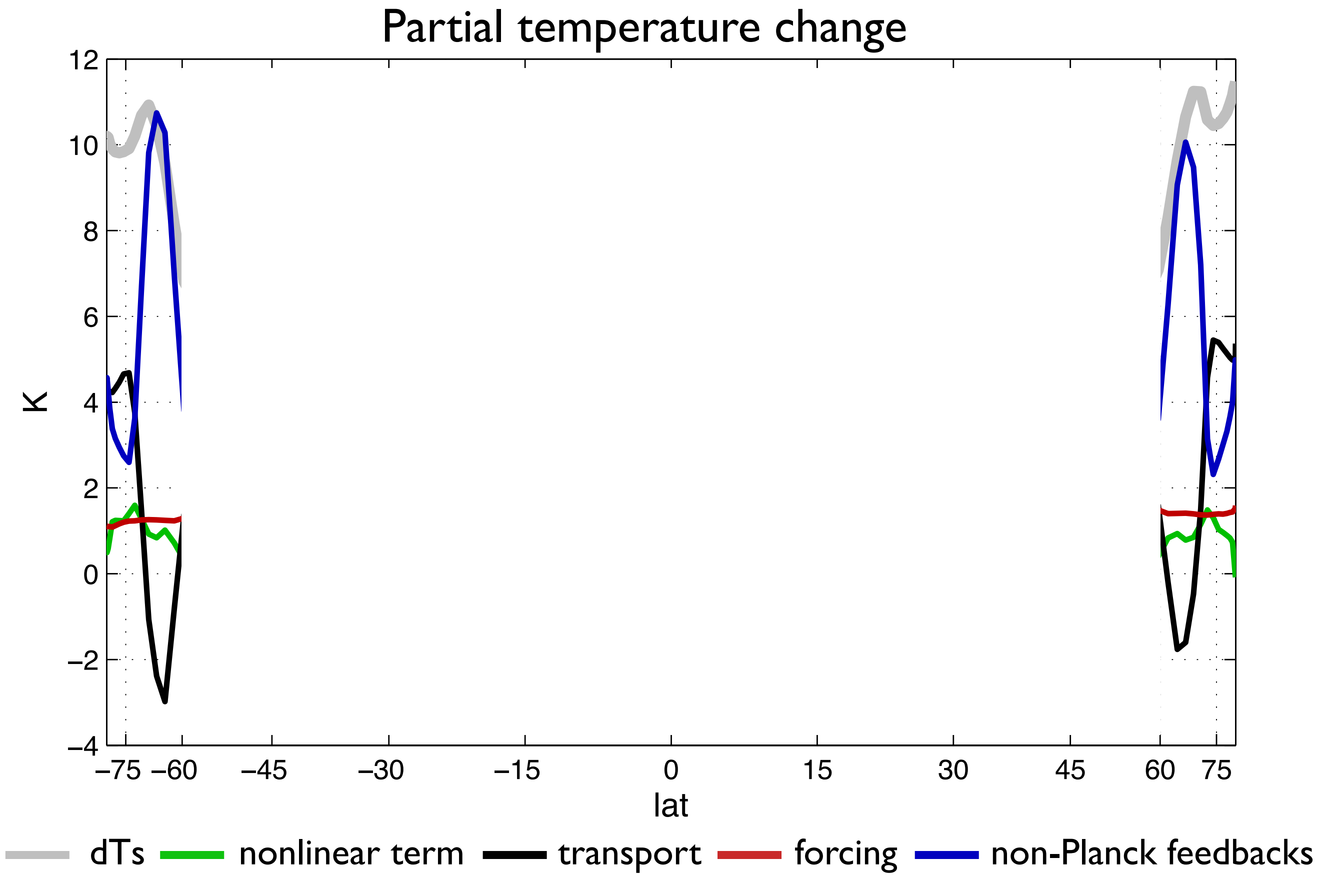

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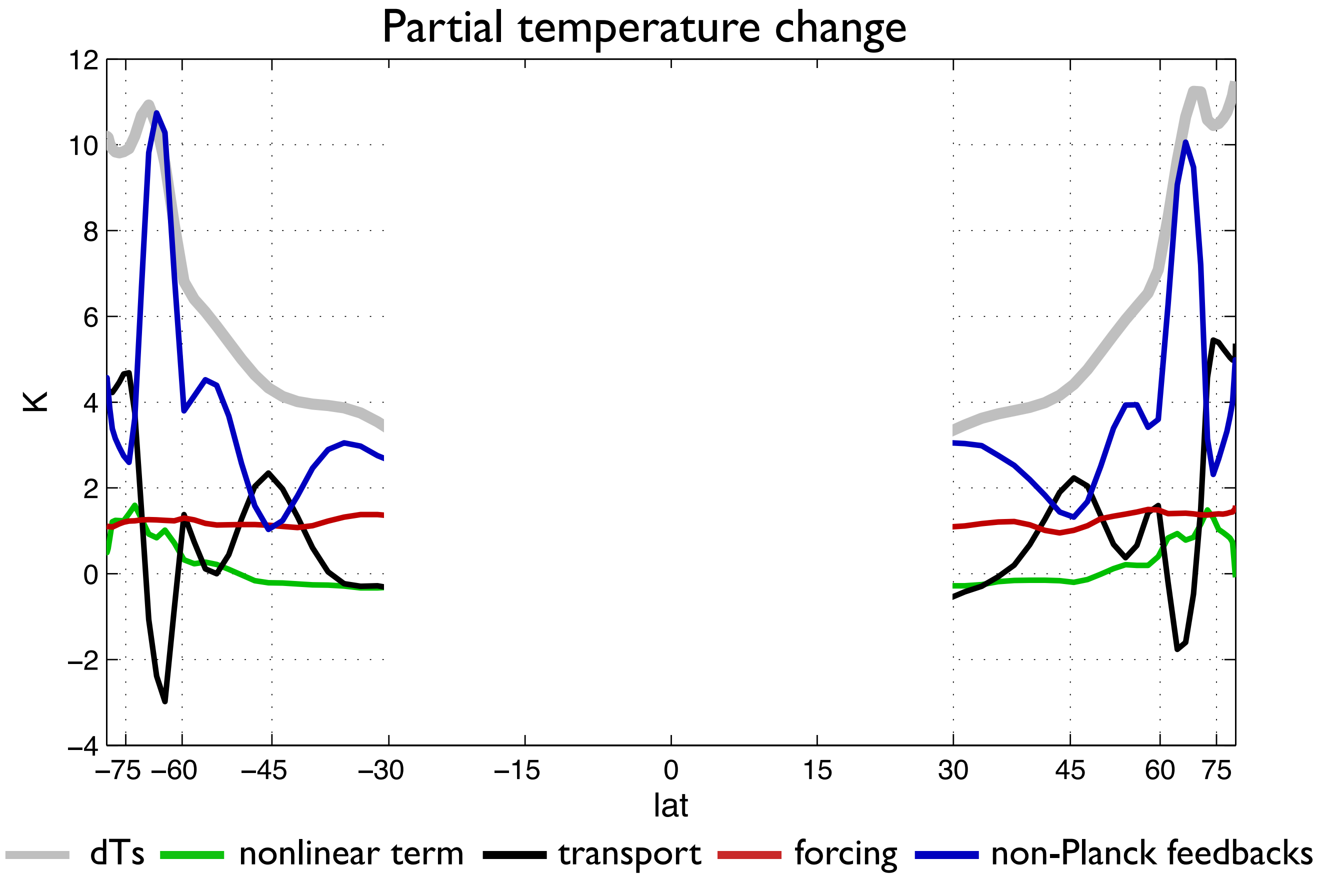

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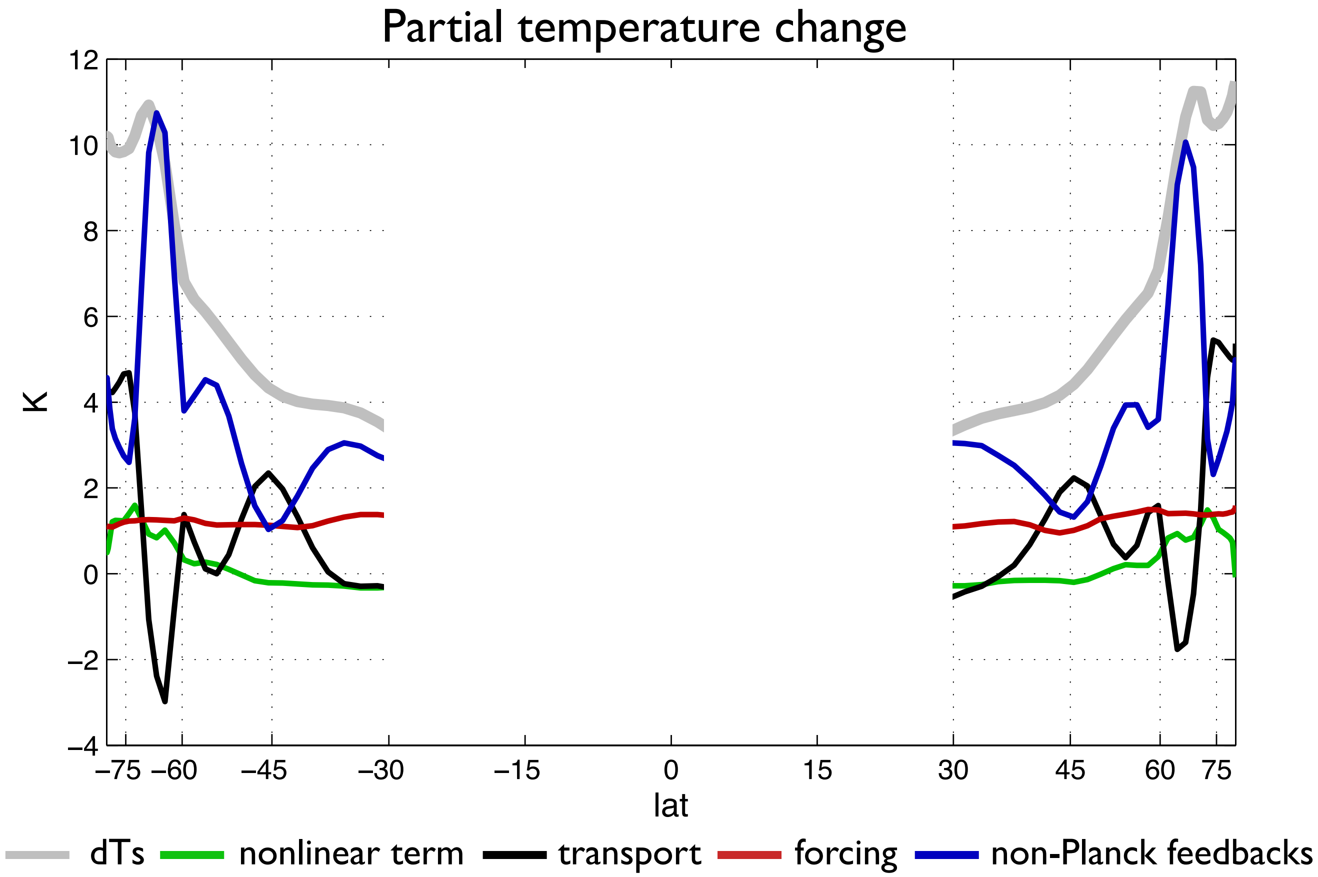


Forcing is much smaller than radiative adjustments by local processes; previously noted asymmetry has no effect

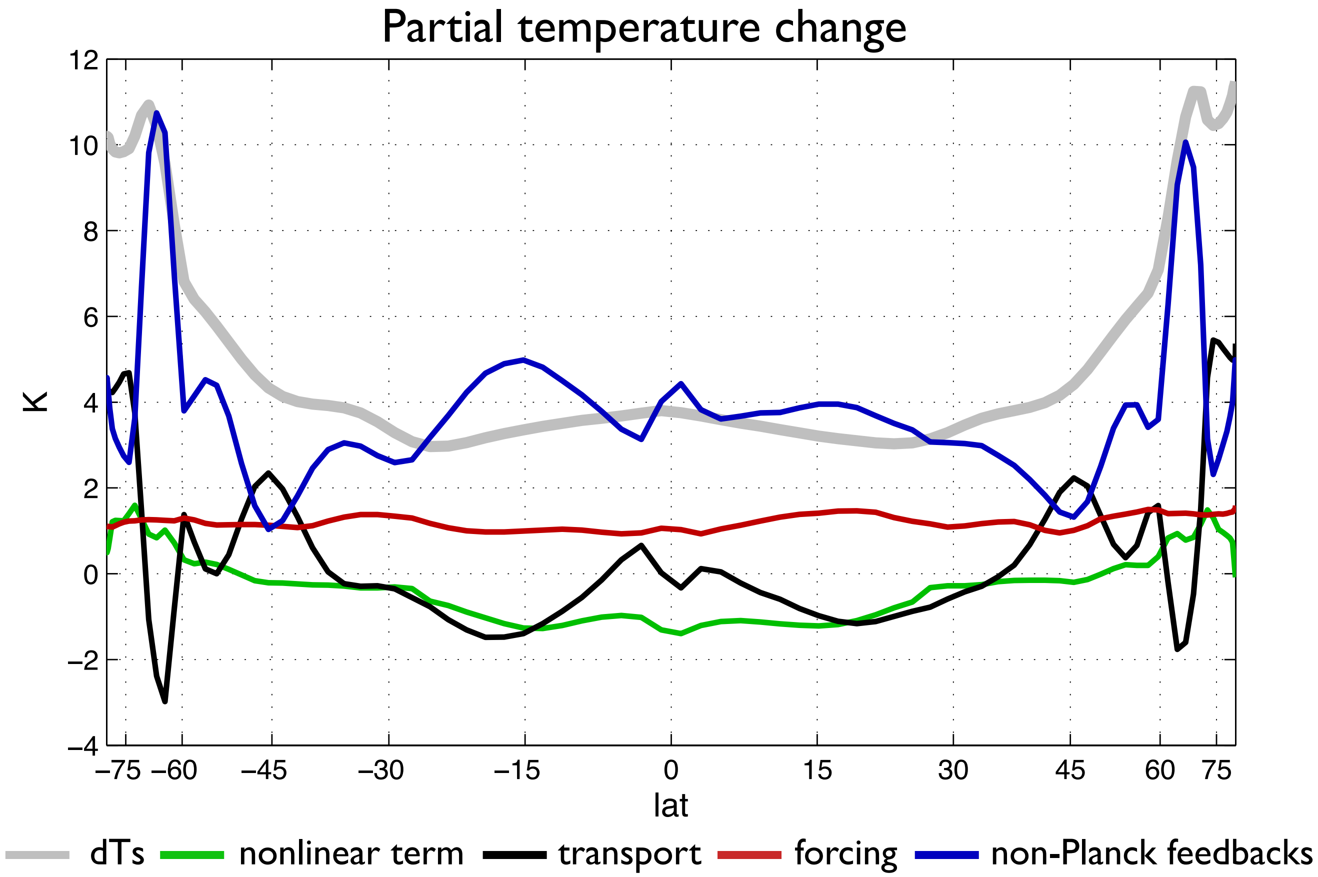
Energy balance, rearranged:

(n.b. local not global-mean)

$$\Delta T_s = \frac{1}{\lambda_P}\left[\Delta R - \left(\sum_i \lambda_{NP_i}\right)\Delta T_s - \Delta\widetilde{R}_f - \mathcal{R}\right]$$

Pattern of warming controlled by heat transport away from strong positive feedbacks (ice line, subtropics), towards more negative feedbacks (midlatitudes, poles).

Relative importance of energy-balance terms to pattern of warming



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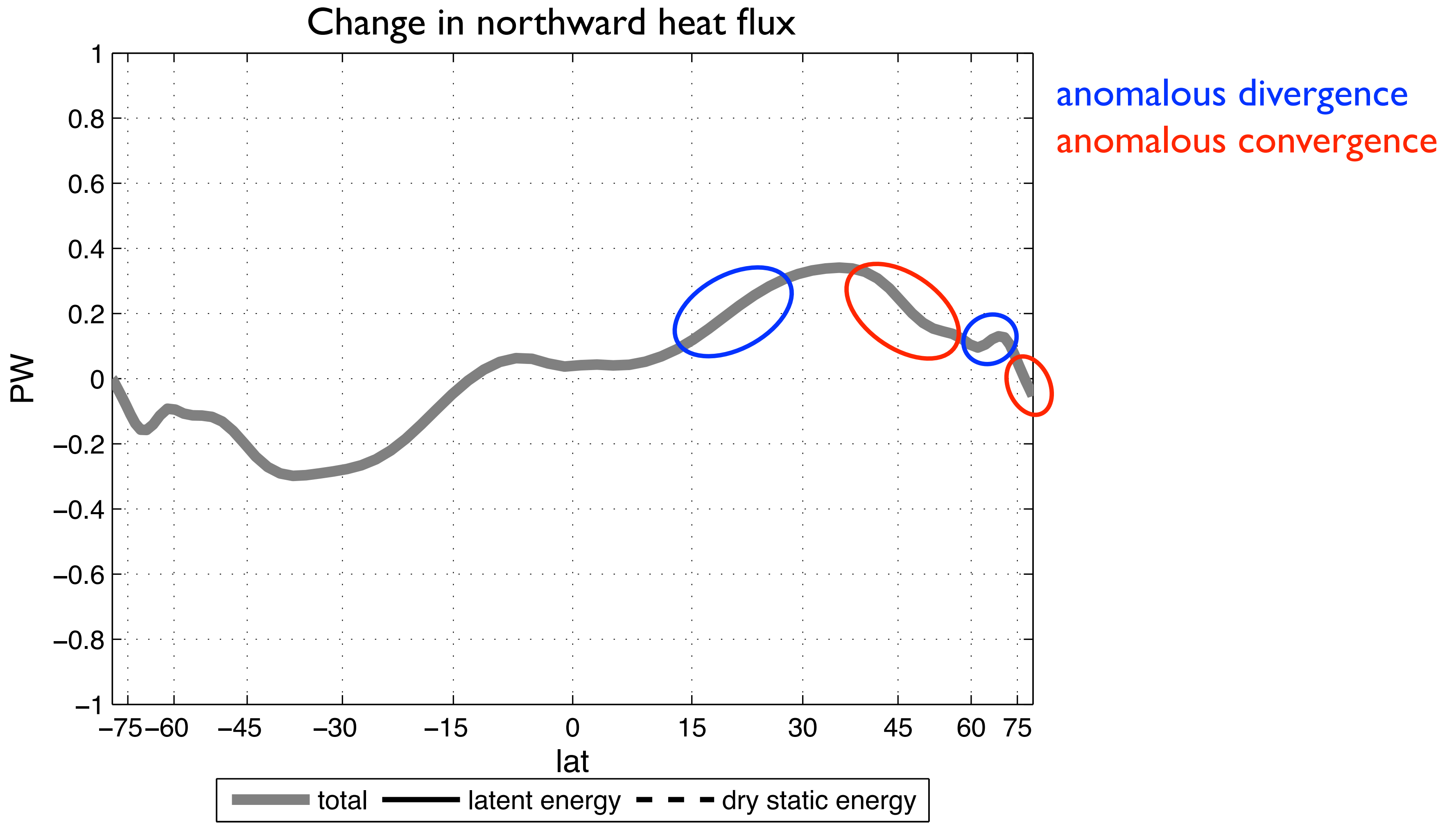
Breakdown of the transport term



*Contribution of transport to warming is explained by the **larger** increase in latent energy flux polewards of 30°, incompletely compensated*

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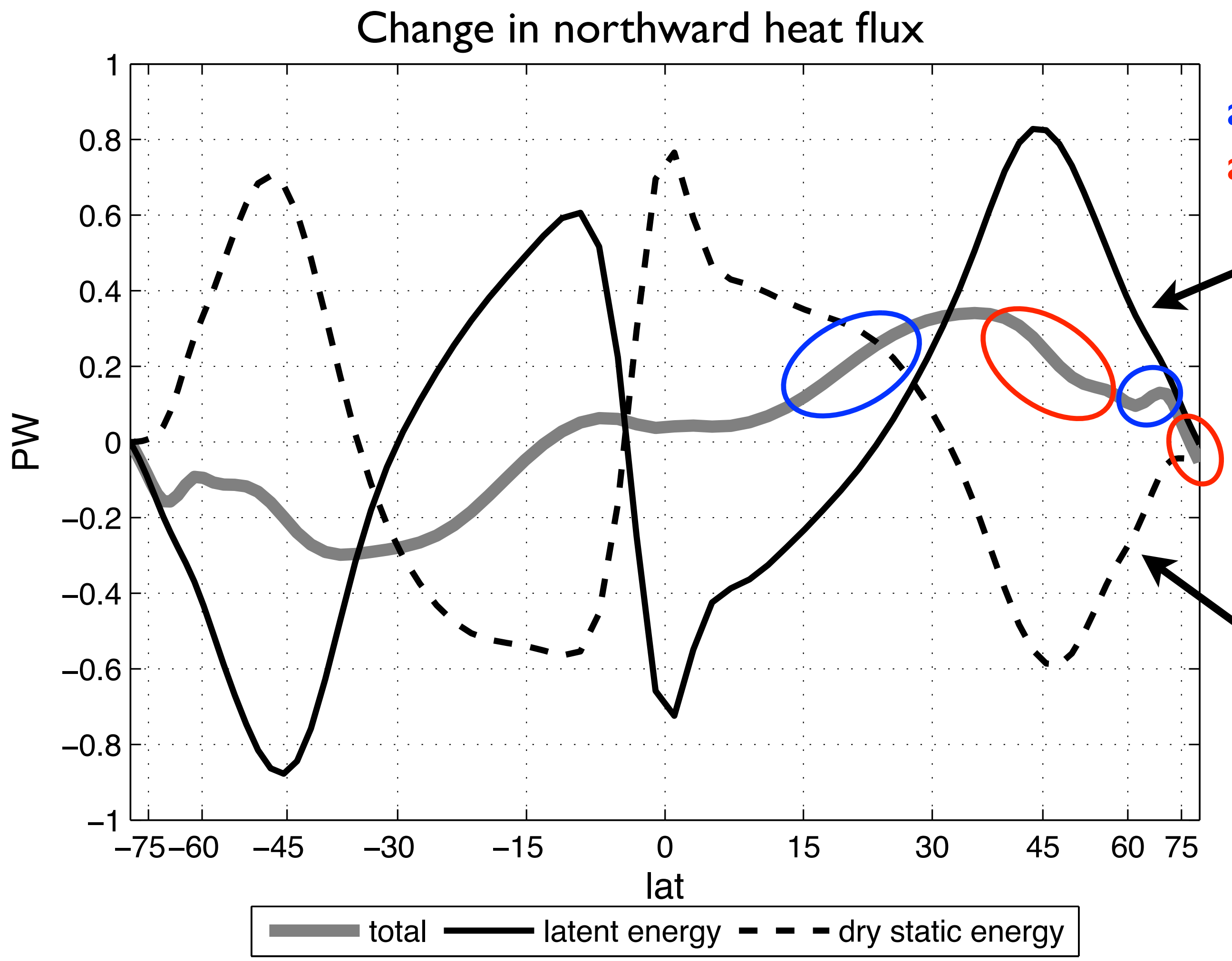


anomalous divergence

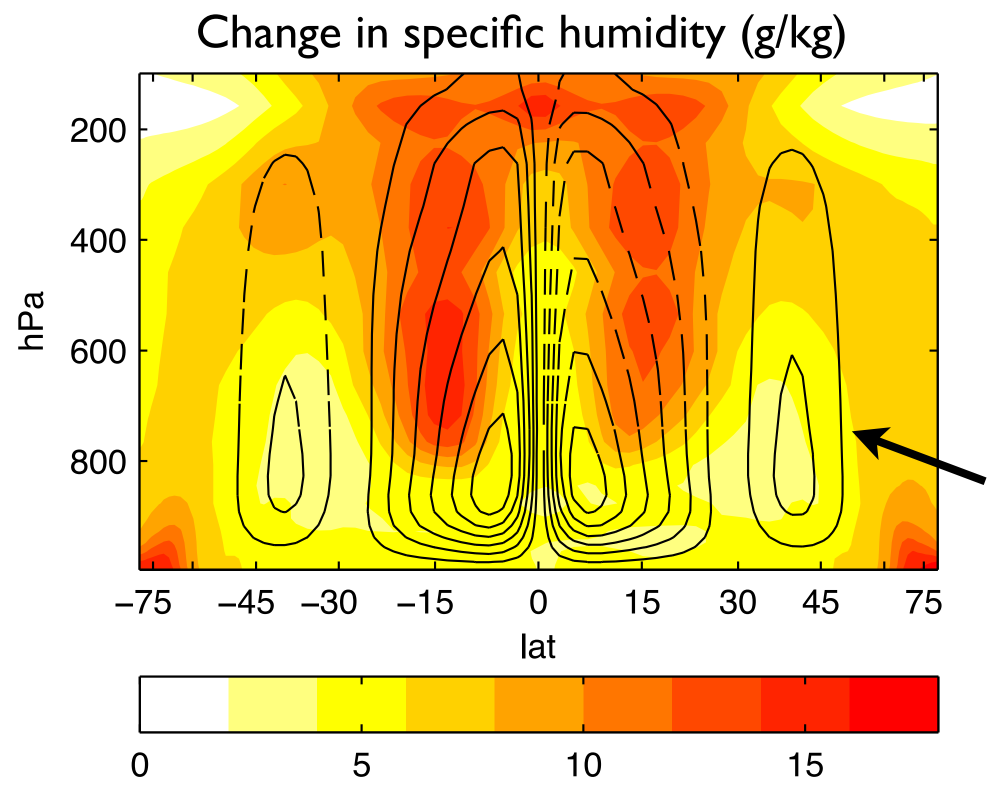
anomalous convergence

more moisture

weaker temperature gradients

Contribution of transport to warming is explained by the ***larger*** *increase in latent energy flux polewards of 30°, incompletely compensated*

Which interactions between feedbacks are responsible?



weakening and expansion of Hadley Cell

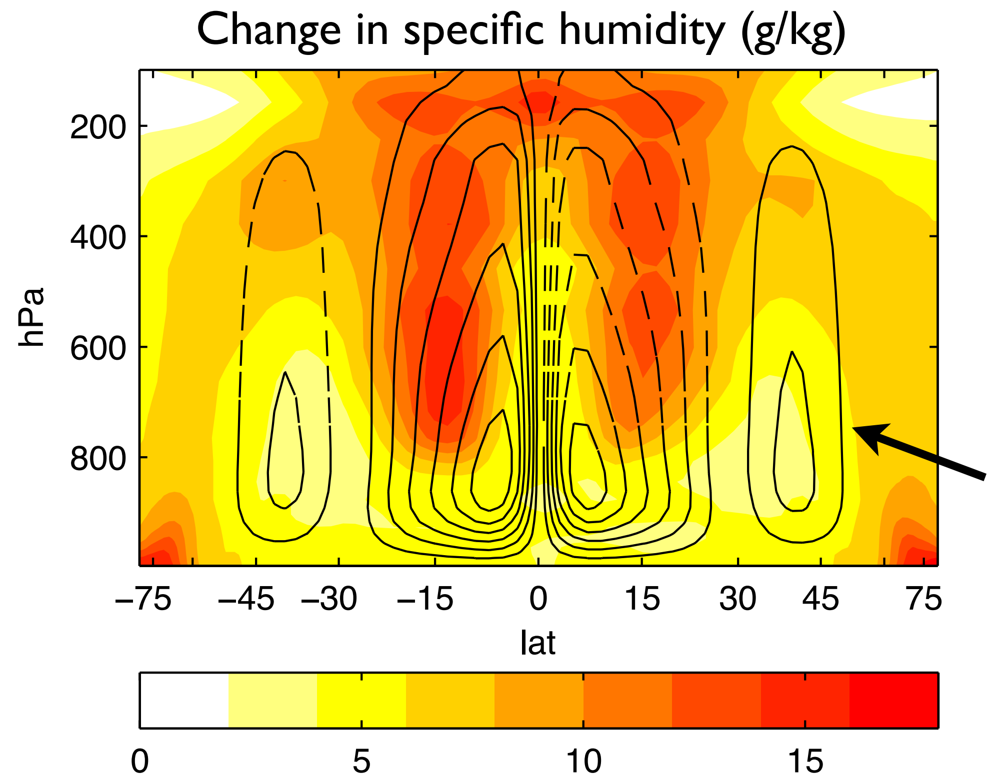
1×CO_2 streamlines

overall moistening

Linear model overestimates TOA fluxes in regions of strong upper-level moistening, which would manifest as a nonlinearity

Which interactions between feedbacks are responsible?

- Feedback framework assumes each vertical level and each variable is independent



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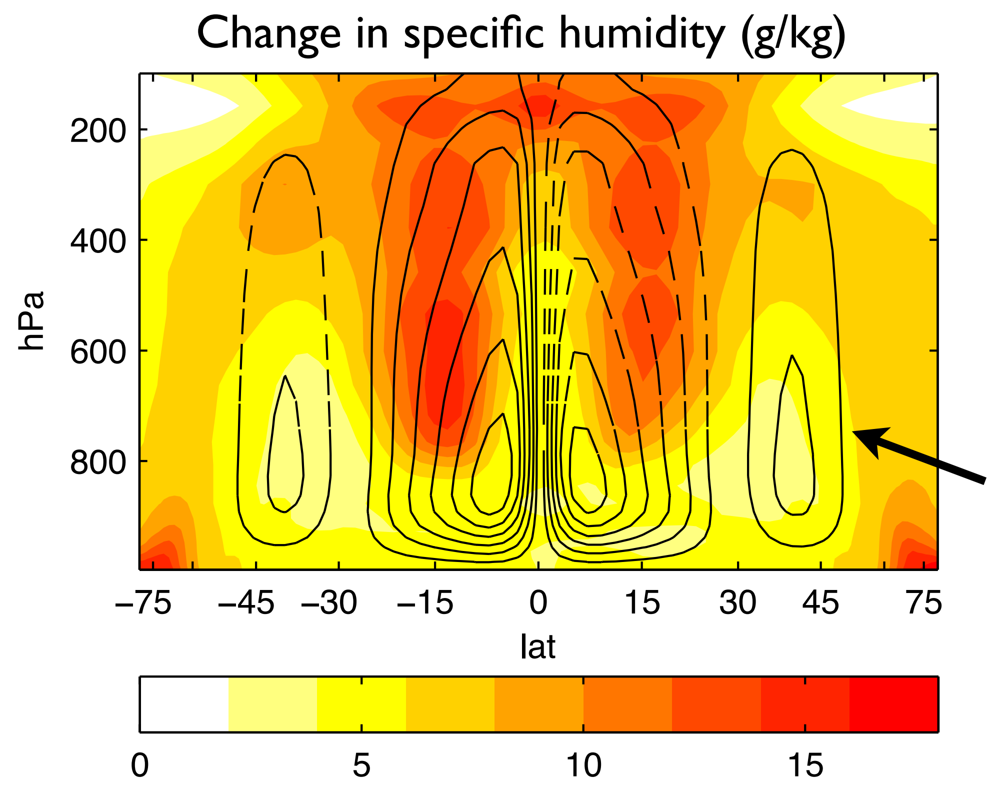
Linear model overestimates TOA fluxes in regions of strong upper-level moistening, which would manifest as a nonlinearity

Which interactions between feedbacks are responsible?

- Feedback framework assumes each vertical level and each variable is independent
- However vertical masking of clear-sky variables, and interactions between variables, could complicate this picture



weakening and expansion of Hadley Cell

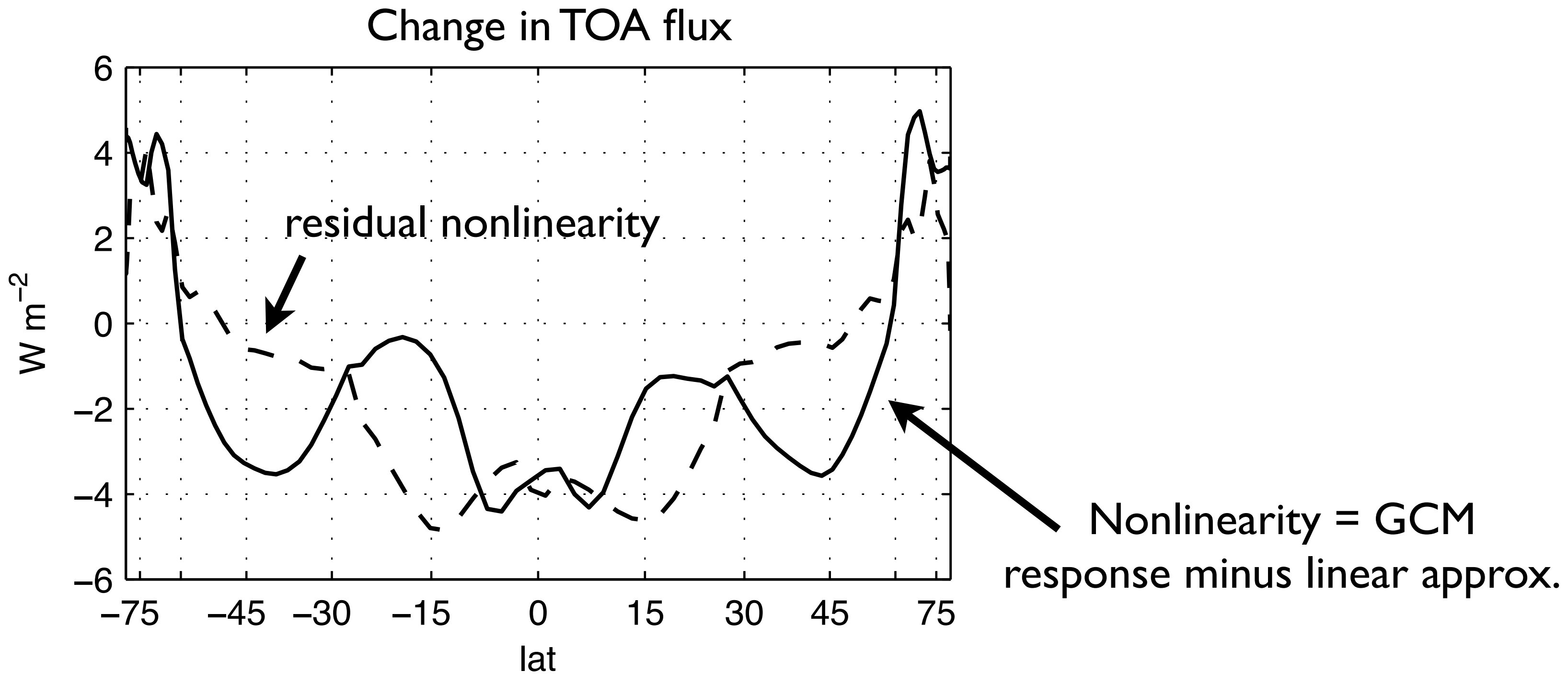
$1\times CO_2$ streamlines

overall moistening

Linear model overestimates TOA fluxes in regions of strong upper-level moistening, which would manifest as a nonlinearity

An independent test

- Actual changes *at all levels* in humidity, temperature, surface albedo; run *simultaneously* through offline radiation code
- Compare to linear sum of individual variables at each level (as feedback framework presumes)



Interactions amongst and within clear-sky feedbacks captures magnitude and qualitative shape of residual nonlinearity

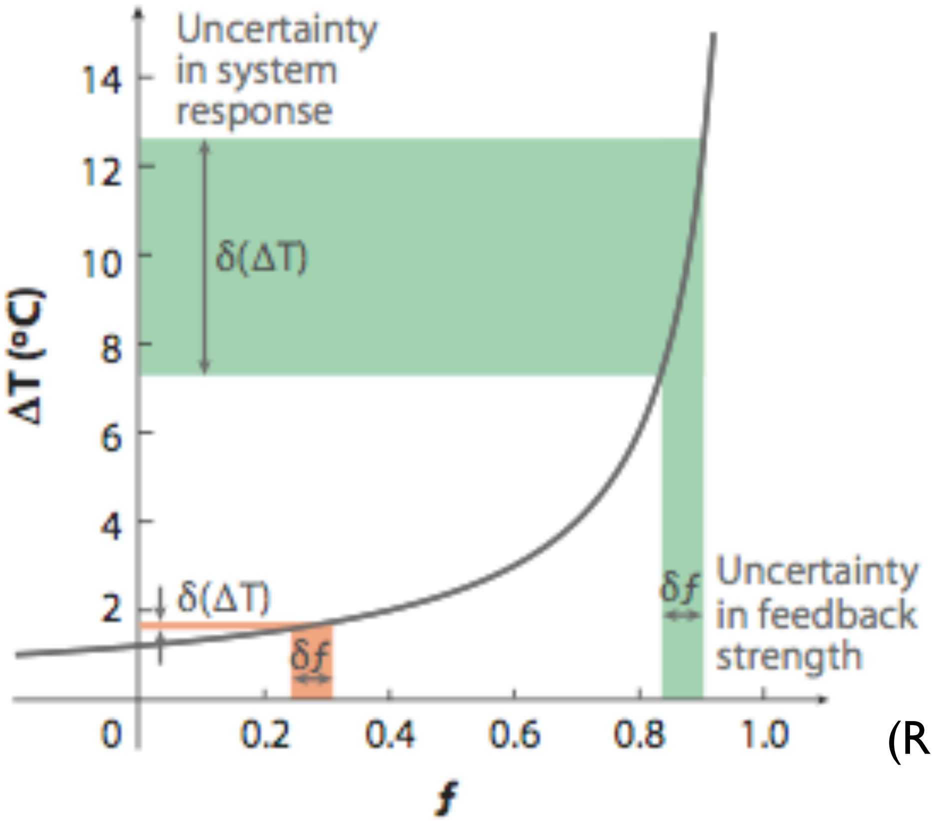
Summary

- High climate sensitivity (4.69 K) is consistent with subtropical regions of positive water vapor and cloud feedbacks. However warming in subtropics is small!
- Nonlocal: Two regions force anomalous divergence of heat flux: subtropics and ice line.
- Nonlinear: Interactions between and within *clear-sky* feedbacks reinforce pattern of tropical cooling and high-latitude warming tendencies; also reduces global climate sensitivity from very high to merely high.
- Resulting pattern of warming bears the signature of all of the above, but importantly, is not limited to the latitude where a particular physical process is active.

pdfs at http://nicolefeldl.com

New research underway

Climate response



(Roe 2009)

Feedback strength ($-\lambda/\lambda_P$)

- Very small changes in feedbacks can result in quite different climate responses

Insights into understanding high-sensitivity aquaplanet
(and perhaps high-sensitivity paleoclimates)?

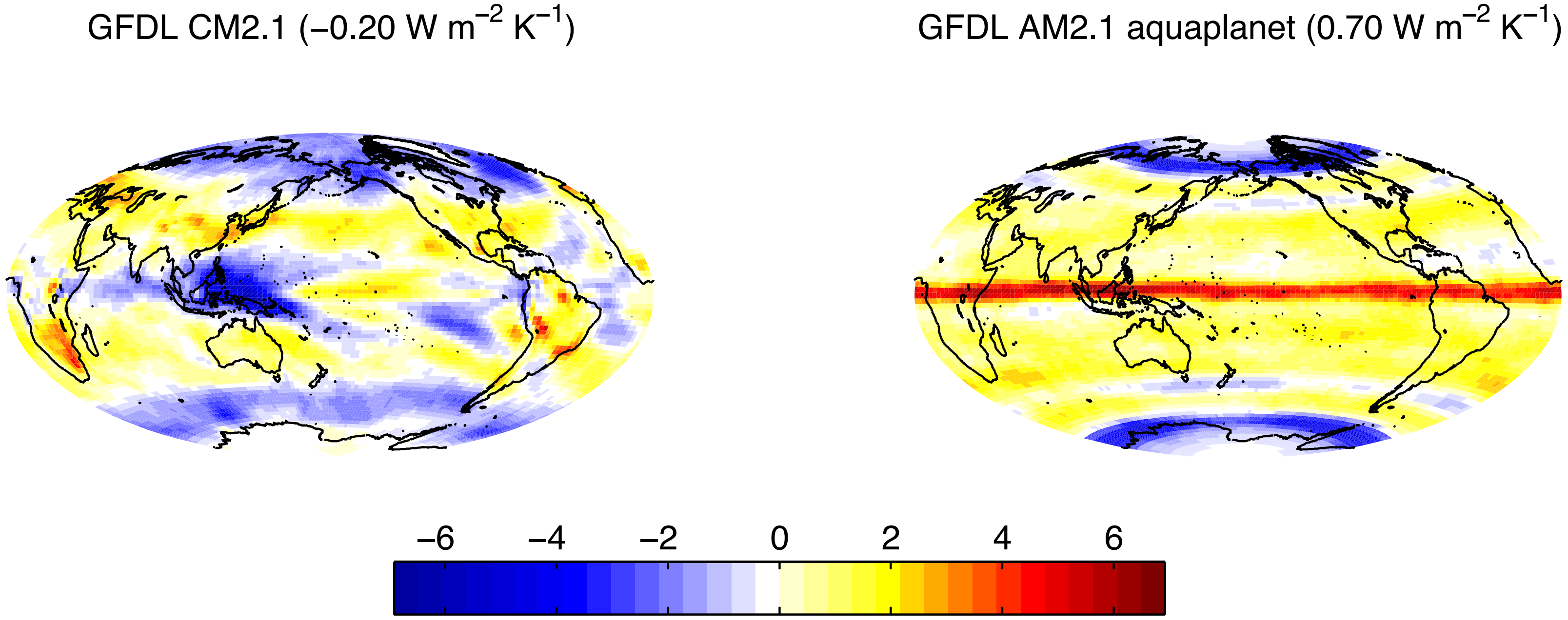
Positive shortwave cloud feedback explains high sensitivity

GFDL CM2.1 (–0.20 W m^{-2} K^{-1})

GFDL AM2.1 aquaplanet (0.70 W m^{-2} K^{-1})

Currently building a Walker Circulation into the aquaplanet, to test the sensitivity of global sensitivity to tropical circulation

Positive shortwave cloud feedback explains high sensitivity



Though extratropics are similar

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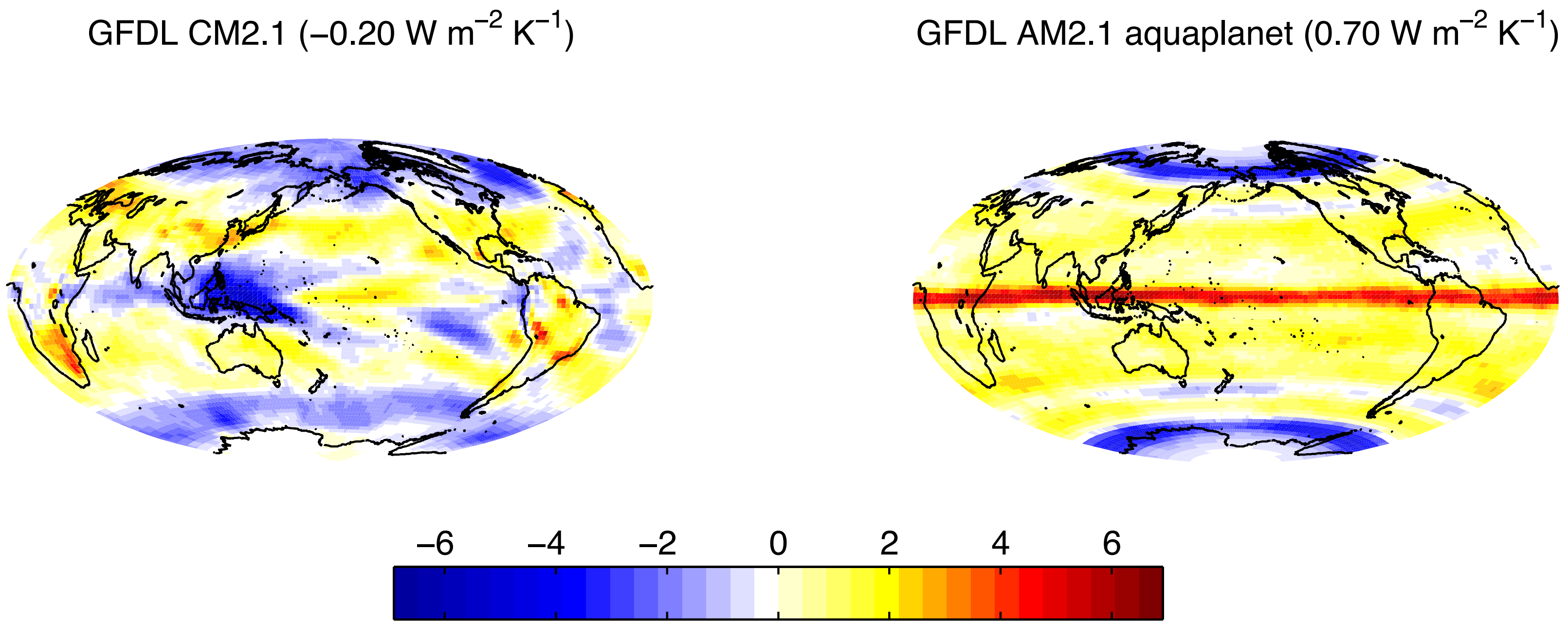

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- Cloud changes tied to circulation changes

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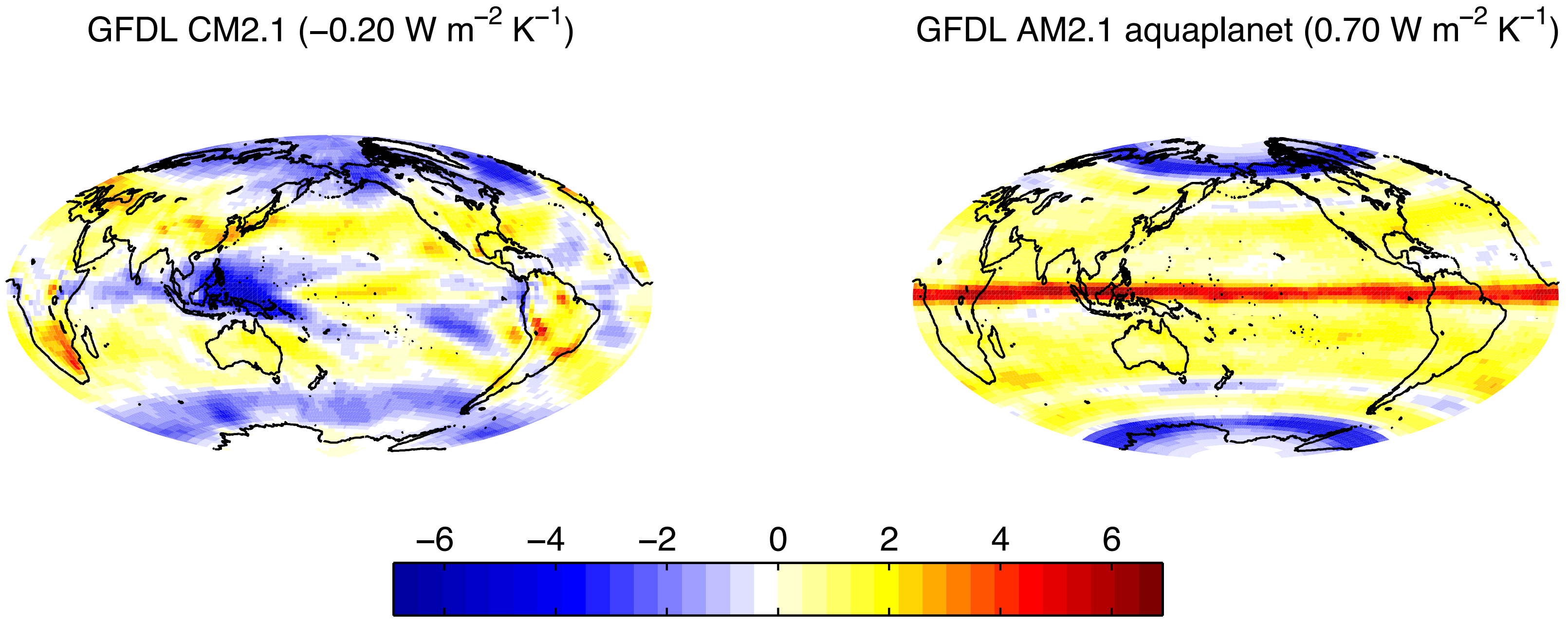

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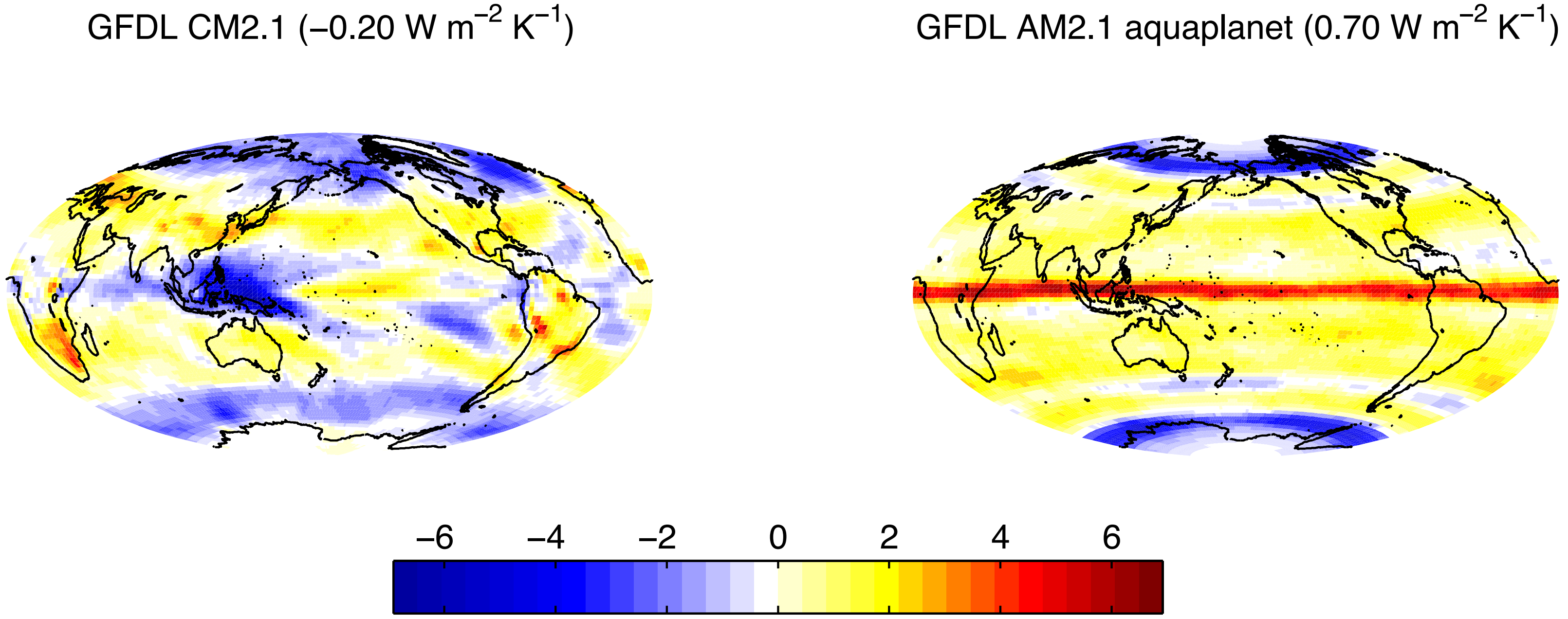


Though extratropics are similar

- Cloud changes tied to circulation changes
- Does the absence of a tropical Walker Circulation explain high sensitivity?
- Implications for interpreting high-sensitivity paleoclimates without invoking biosphere and ice-sheet interactions

Currently building a Walker Circulation into the aquaplanet, to test the sensitivity of global sensitivity to tropical circulation

Candidate sources of nonlinearity

$$\Delta R = \Delta \widetilde{R}_f^0 + \Delta CRF + \left(\sum_n \lambda_n^0 \right) \Delta \overline{T}_s$$

- ✓ Vertical masking of, and interactions between, clear-sky feedbacks. Accounts for majority of nonlinearity.
- ✓ Double counting of the rapid tropospheric adjustment to CO_2. Minor because residual is nearly identical for stratosphere-adjusted radiative forcing, which doesn't double count.
- ➡ 2nd-order terms associated with the effect of clouds on non-cloud fields (1st-order are accounted for in cloud feedback calculation).

Why a clear-sky residual?

Separate non-cloud from cloud feedbacks:

$$\Delta R = \Delta \widetilde{R}_f + \left(\sum_n \lambda_n \right) \Delta \overline{T}_s + \lambda_c \Delta \overline{T}_s$$

Substitute in equation for cloud feedback:

$$\Delta R = \Delta \widetilde{R}_f^0 + \Delta CRF + \left(\sum_n \lambda_n^0 \right) \Delta \overline{T}_s$$

Rearrange terms:

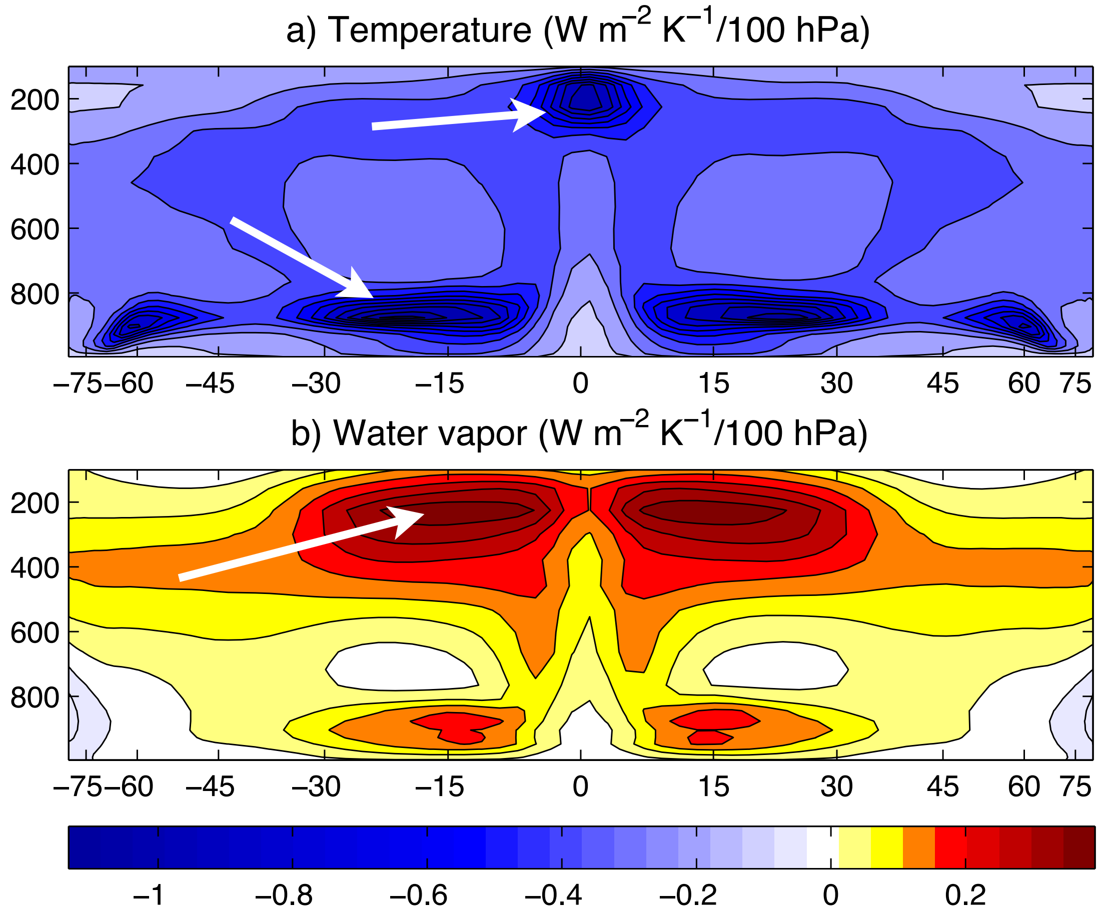
$$\mathcal{R} = (\Delta R - \Delta CRF) - \left[\Delta \widetilde{R}_f^0 + \left(\sum_n \lambda_n^0 \right) \Delta \overline{T}_s \right]$$

actual, model-produced clear-sky fluxes

feedback approximated clear-sky fluxes

Aquaplanet kernels

(offline run, 1 year 8×daily output, 1K perturbation)



Changes in cloud-top temperature

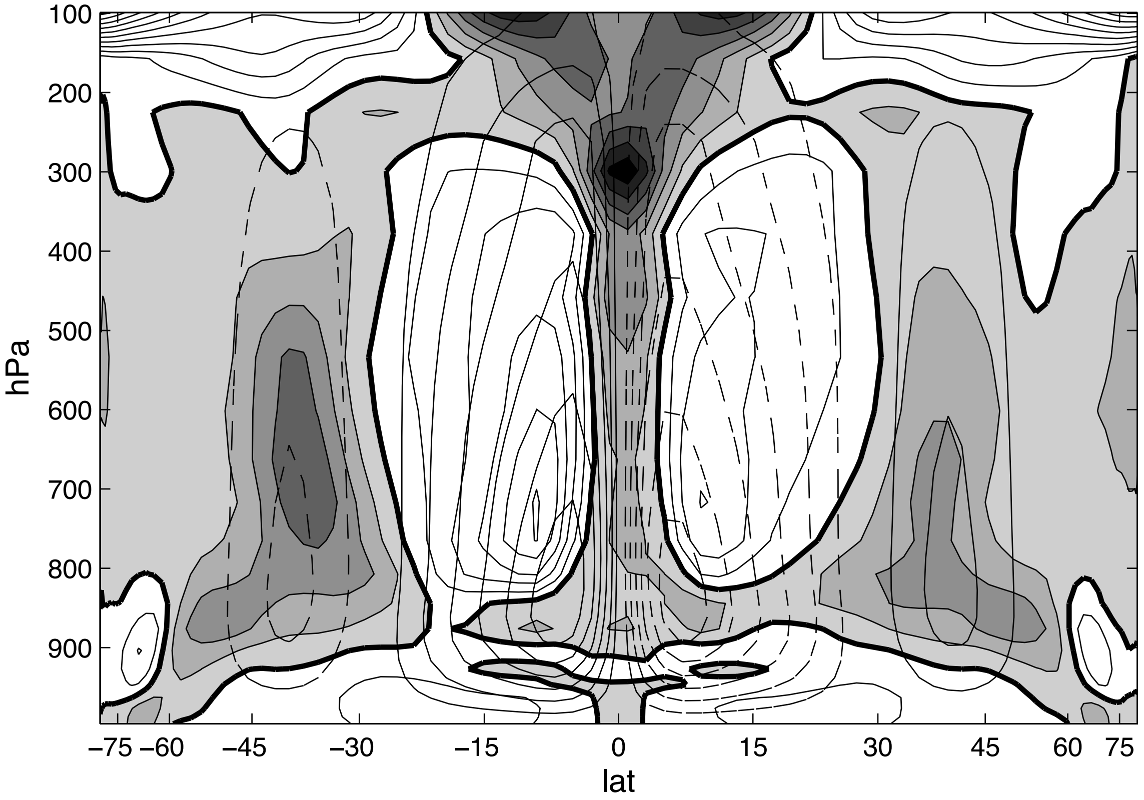
Changes in humidity most effective in dry upper troposphere

$$\lambda_x = \frac{\partial R}{\partial x} \times \frac{\Delta x}{\Delta T_s}$$

feedback kernel response

TOA radiative flux response to tropospheric warming and moistening

Change in relative humidity



Contour interval is 2%; dark colors are a decrease.
Contour lines show streamlines for control climate.