Regional feedback patterns and regional climate predictability

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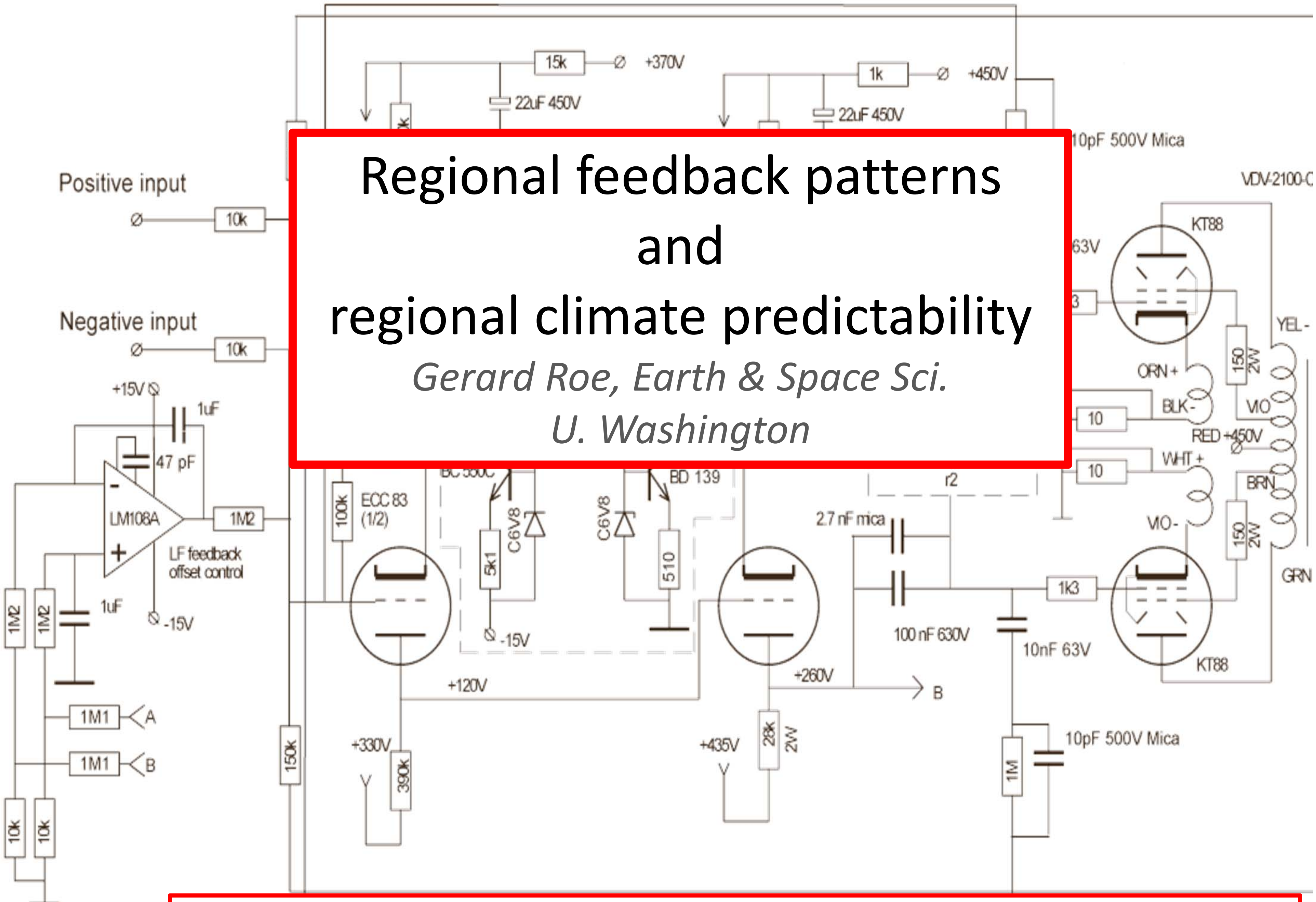
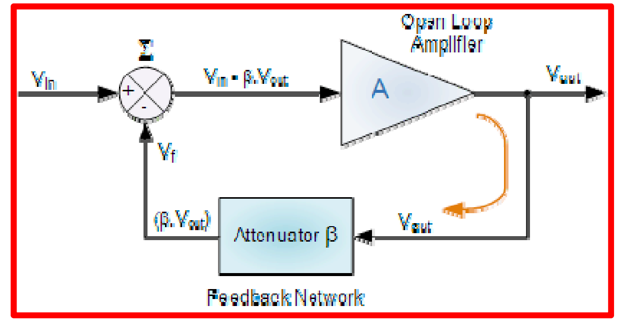


Thanks: Nicole Feldl, Kyle Armour, Aaron Donohoe, Dargan Frierson, Marcia Baker

Feedback analysis



- Originates in early amplifier design & control systems theory

- Formal method for evaluating how interacting components of a dynamical system combine to give the system response.

- For climate at the global scale, there is well-oiled machinery

$$\Delta T = \lambda_0 \frac{\Delta R_f}{1 - \sum f_i}$$

ΔT = response
ΔR_f = forcing
f_i = feedback factors

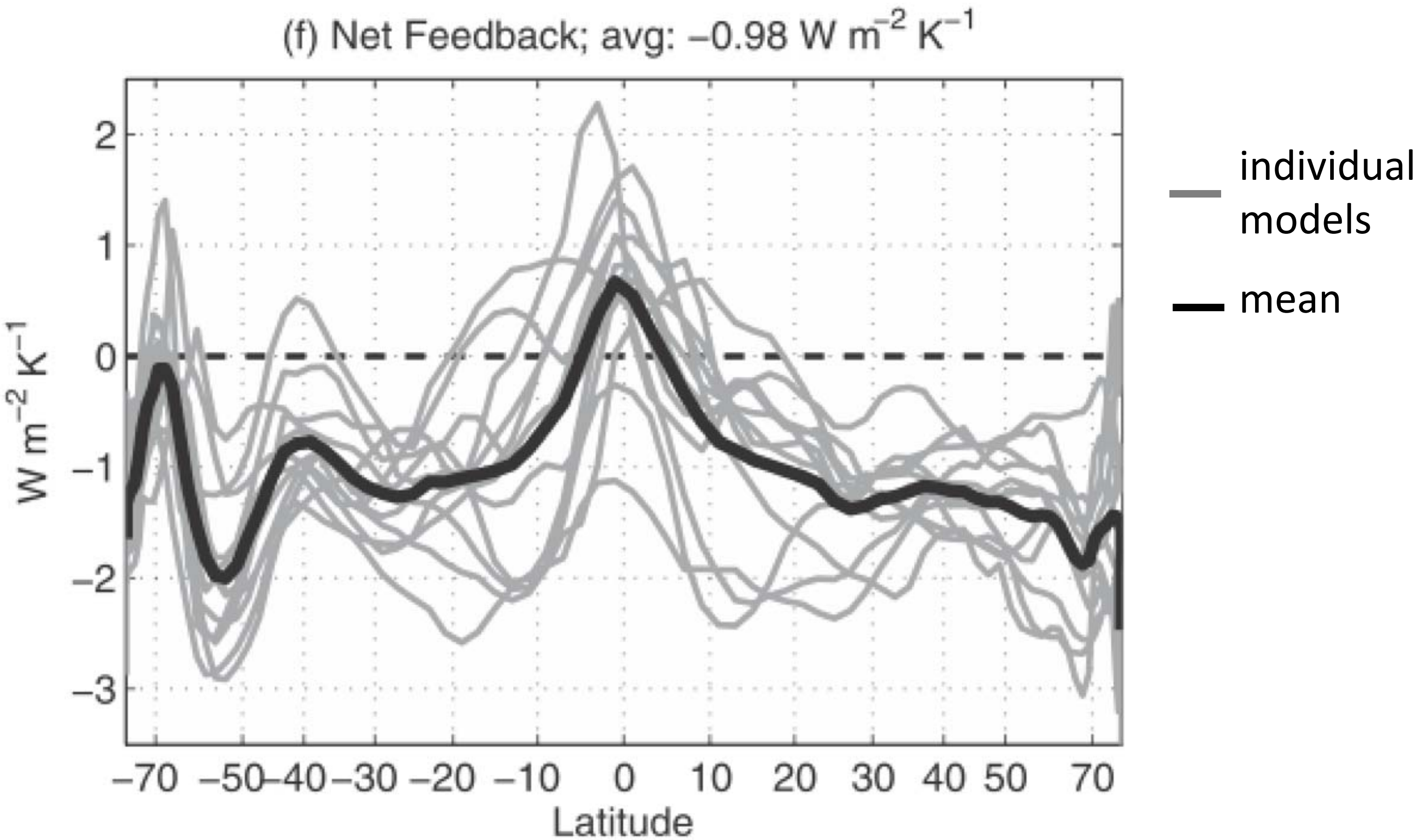
- How does uncertainty in physical process lead to uncertainty in climate response?

- What happens when it is applied to the regional scale?

The spread in zonal mean feedbacks in CMIP3 models

(Zelinka and Hartman, 2011)

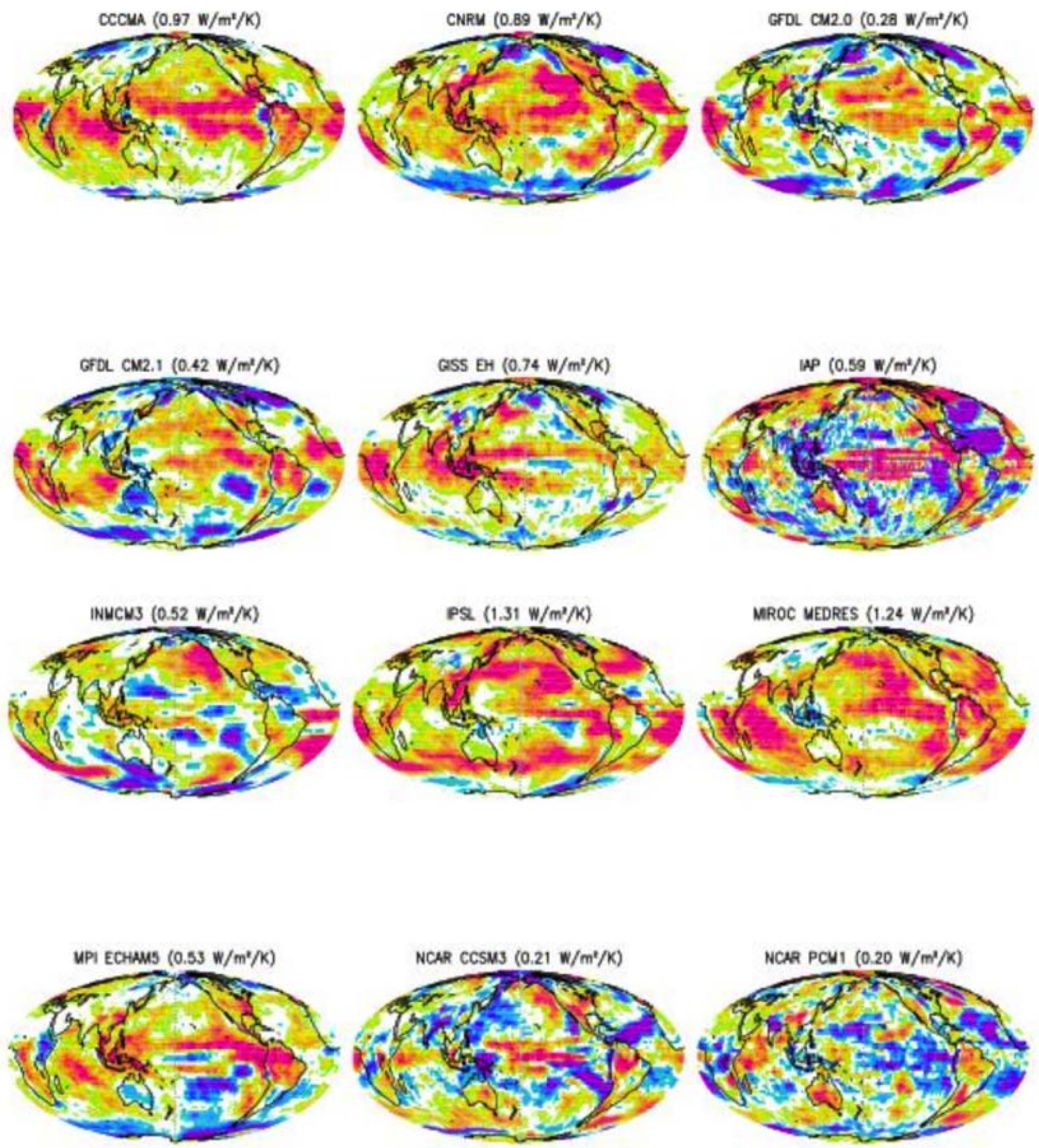
Spaghetti…



- If it were possible to discriminate among the strands, what would be consequences for the local and nonlocal climate response?

The variation in cloud feedbacks in CMIP3 models

Soden and Vecchi, 2011



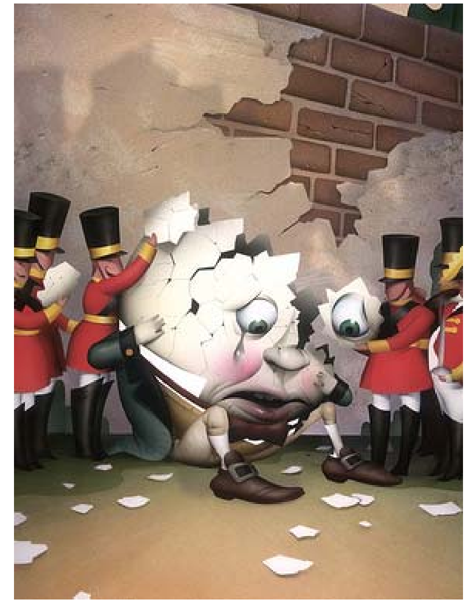
Net cloud feedback among CMIP3 models

Soden and Vecchi (2011)

Regional feedbacks

Some questions

- Are the regional feedbacks *linear enough* to have predictive power?
  (i.e., can you put the pieces back together again?)



The Humpty Dumpty challenge

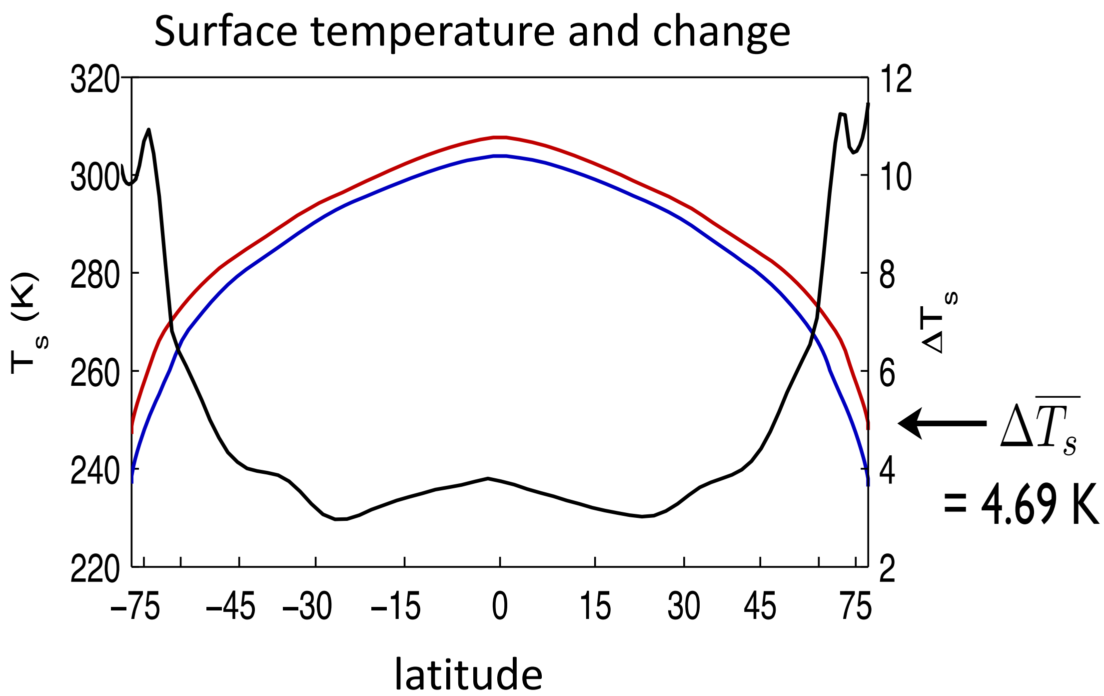
- How does uncertainty in the physics of one region affect uncertainty in the response of another region?
  (i.e., how do tropical clouds feedbacks affect polar amplification?)

Calculating regional feedbacks

A stripped down climate model (Nicole Feldl's PhD)

GFDL AM2 model

- Aquaplanet, perpetual equinox, 20-m mixed layer, simple sea ice,
- 2×CO_2 to equilibrium



Climate sensitivity of 4.69K

Calculating regional feedbacks

Deconstructing the local energy balance

A Taylor series of the local TOA energy balance:
(new equilibrium)

$$-\Delta R_f(x) = -\Delta(\nabla \cdot F(x)) + \sum_i c_i(x)\Delta T + \mathcal{O}(\Delta T^2)$$

Calculating regional feedbacks

Deconstructing the local energy balance

A Taylor series of the local TOA energy balance:
(new equilibrium)

$$-\Delta R_f(x) = -\Delta(\nabla \cdot F(x)) + \sum_i c_i(x)\Delta T + \mathcal{O}(\Delta T^2)$$

Forcing
Strat.adj.
or fixed SST

Transport
changes

Linear
Feedbacks

Left-over
Residual
(nonlinear term,
cross terms)

How to get the coefficients, the c_i's?

Calculating regional feedbacks

Deconstructing the local energy balance

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$$-\Delta R_f(x) = -\Delta(\nabla \cdot F(x)) + \sum_i c_i(x)\Delta T + \mathcal{O}(\Delta T^2)$$

The Kernel method for feedbacks (Soden and Held, 2006)

- Build the partial derivatives:

$$c_i = \frac{\partial R}{\partial \alpha}\frac{\Delta \alpha}{\Delta T}$$

α is temperature, water vapor, clouds, surface albedo

Calculating regional feedbacks

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The Kernel, K_i: built from one year of six-hourly calls to the stand-alone radiation code, nudging each variable by a small amount *keeping everything else constant,* and then doing *a lot* of averaging. (Nicole built custom kernels for this set-up)

Calculating regional feedbacks

Deconstructing the local energy balance

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The Kernel method for feedbacks (Soden and Held, 2006)

- Clouds are too messy, so

$$c_{cld}\Delta T = \Delta \mathrm{CRF} + \sum_i (K^o_{\alpha_i} - K_{\alpha_i})d\alpha$$

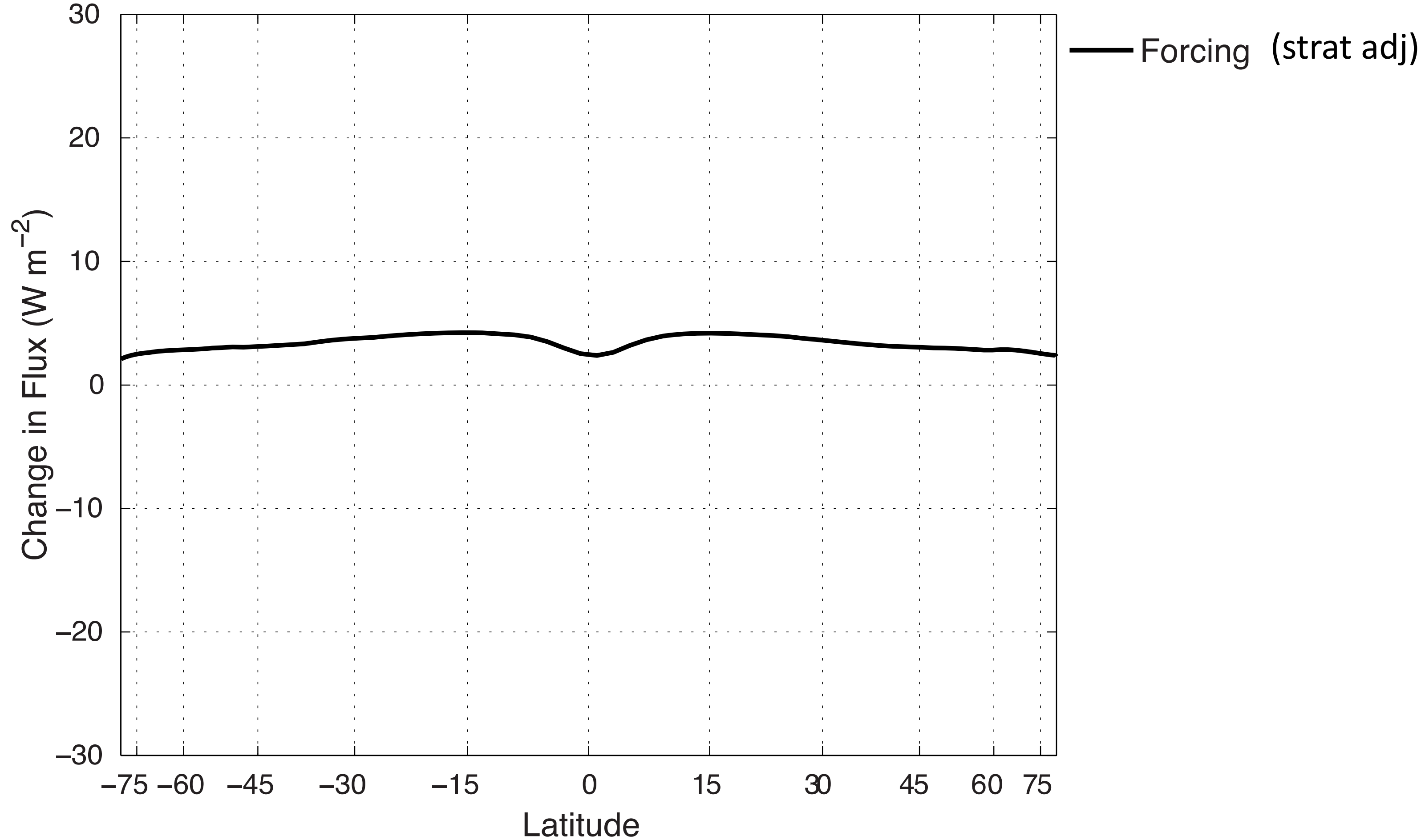
ΔCRF = cloud radiative forcing

Corrections to account for overlap

- There are other ways of calculating feedbacks, but Kernels comes closest to the tangent linear calculation underlying the feedback concept.

Calculating regional feedbacks

First, he pieces of the local energy budget in W m^{-2}



Calculating regional feedbacks

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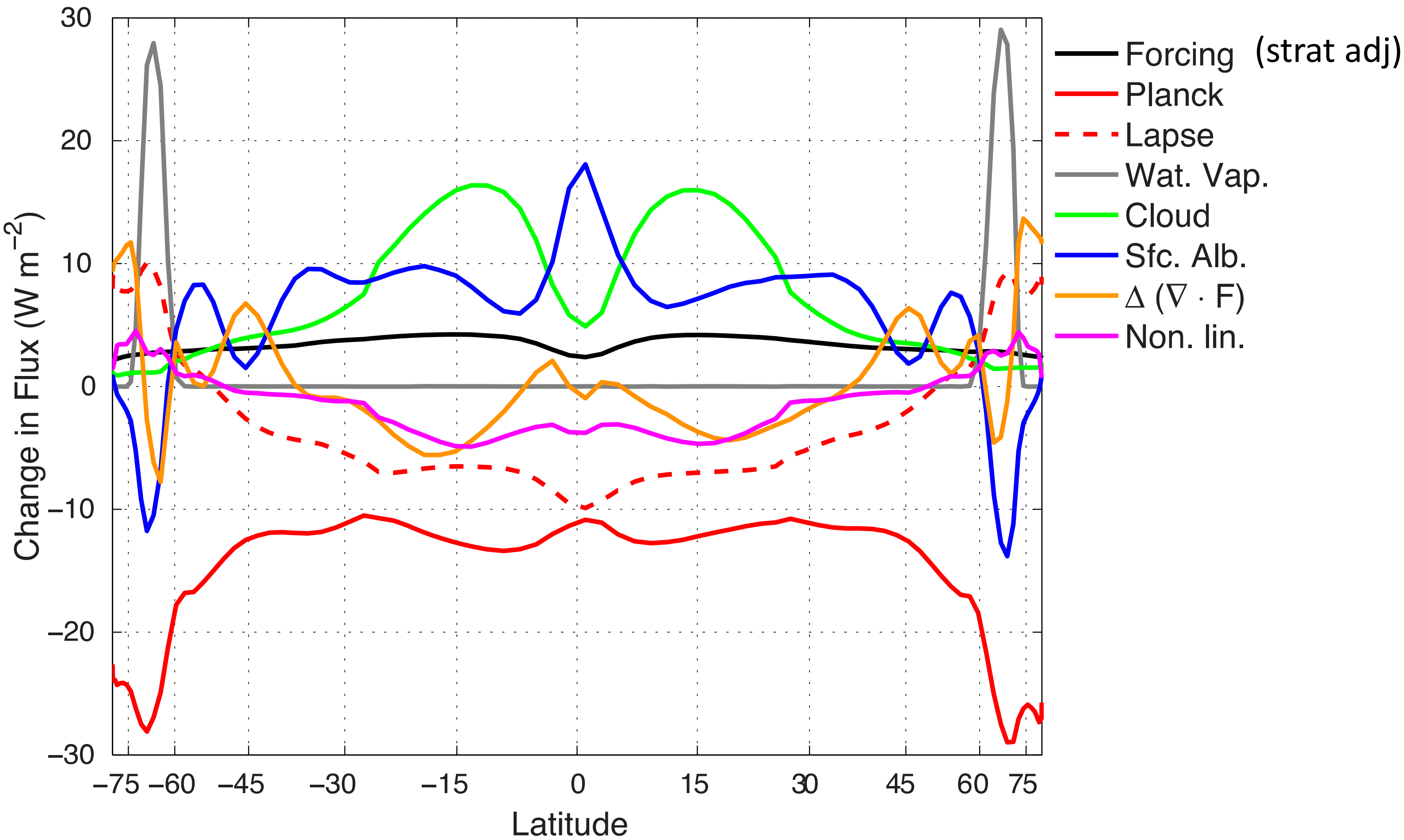

- The forcing is a small term in the budget compared to the responses.
- Climate prediction is hard!

Calculating regional feedbacks

An aside: the definition matters…

Taylor series:

$$-\Delta R_f(x) = -\Delta(\nabla \cdot F(x)) + \sum_i c_i(x)\Delta T + \mathcal{O}(\Delta T^2)$$

Usually assumed to be global-mean *T*, but could also be local *T(x)*

Can have either globally or locally defined feedbacks:

$$c_i = \frac{\partial R}{\partial \alpha}\frac{\Delta \alpha}{\Delta T}$$

Can use ΔT(x) or <ΔT>

Calculating regional feedbacks

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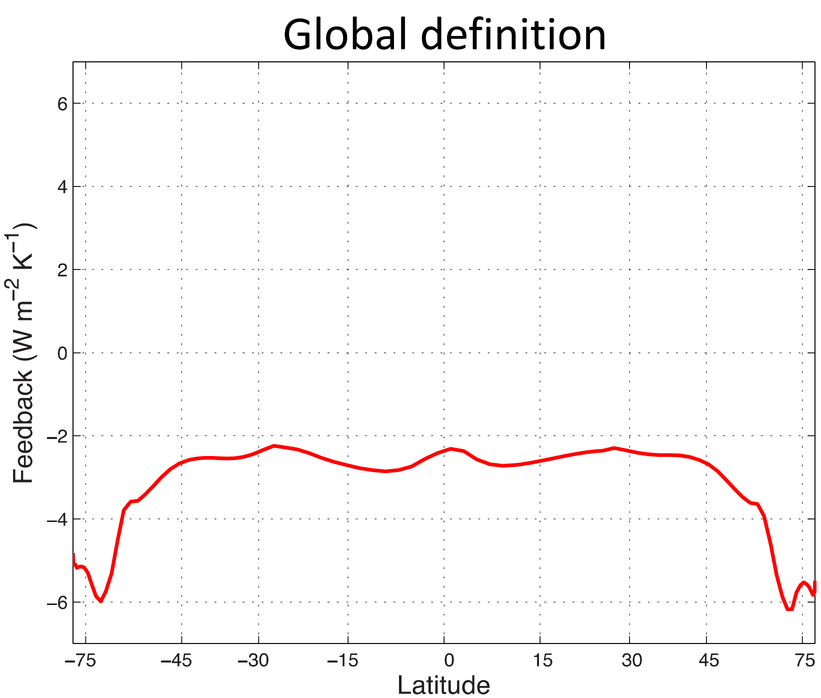
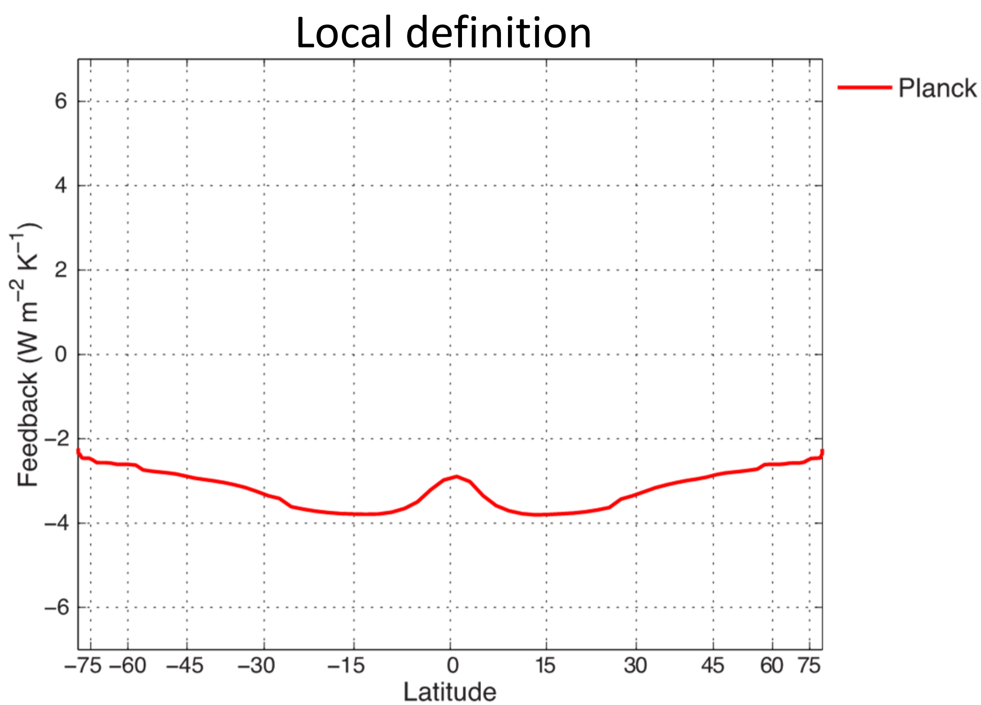
Usually assumed to be global-mean *T*, but could also be local *T(x)*

Taylor series:

$$-\Delta R_f(x) = -\Delta(\nabla \cdot F(x)) + \sum_i c_i(x)\Delta T + \mathcal{O}(\Delta T^2)$$

Example: Planck "Feedback" (i.e., you think of this as $4\sigma T^3$)





Calculating regional feedbacks

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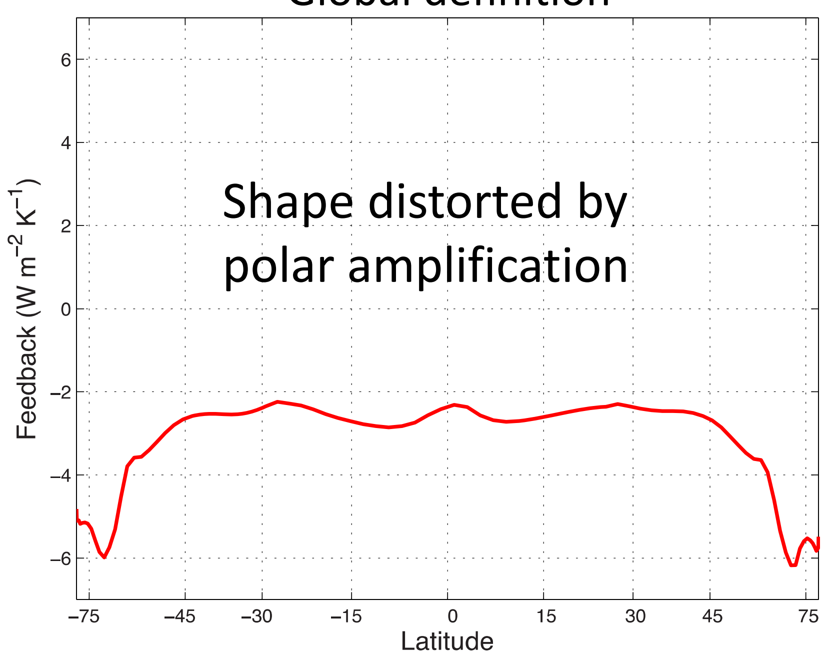
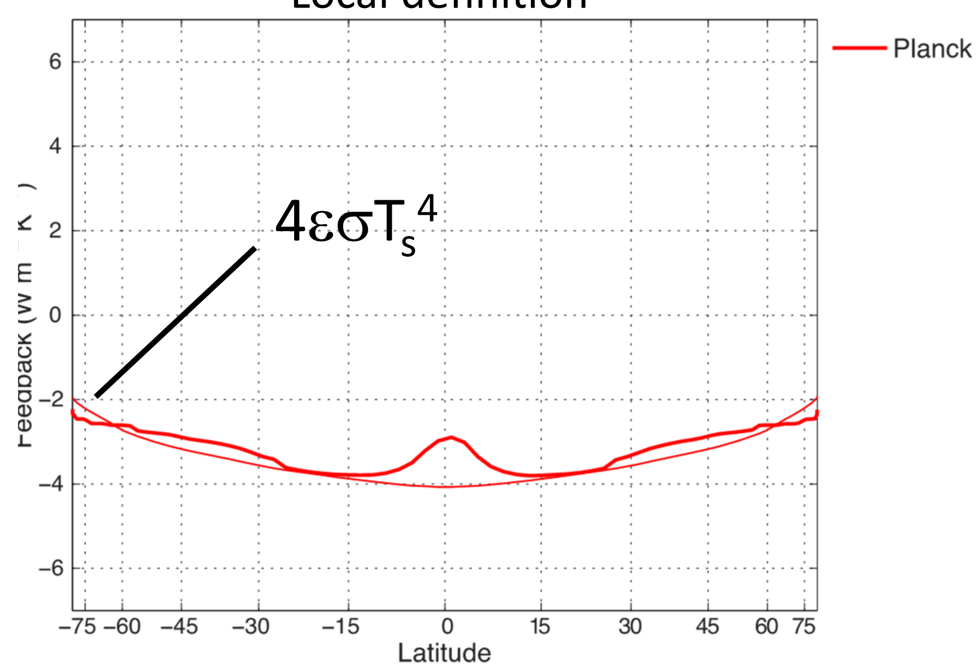
Global definition

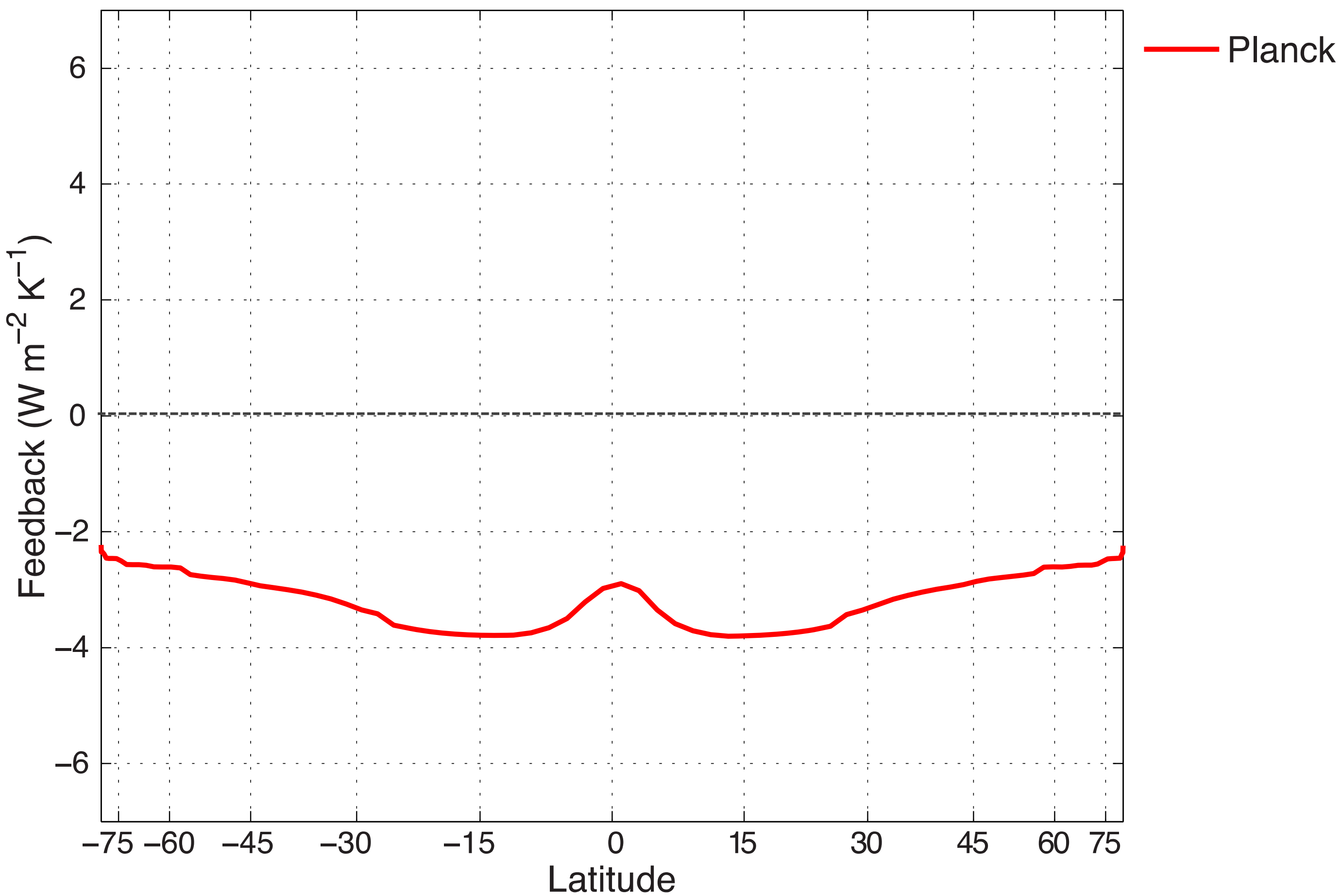


Local definition



Patterns of regional feedbacks

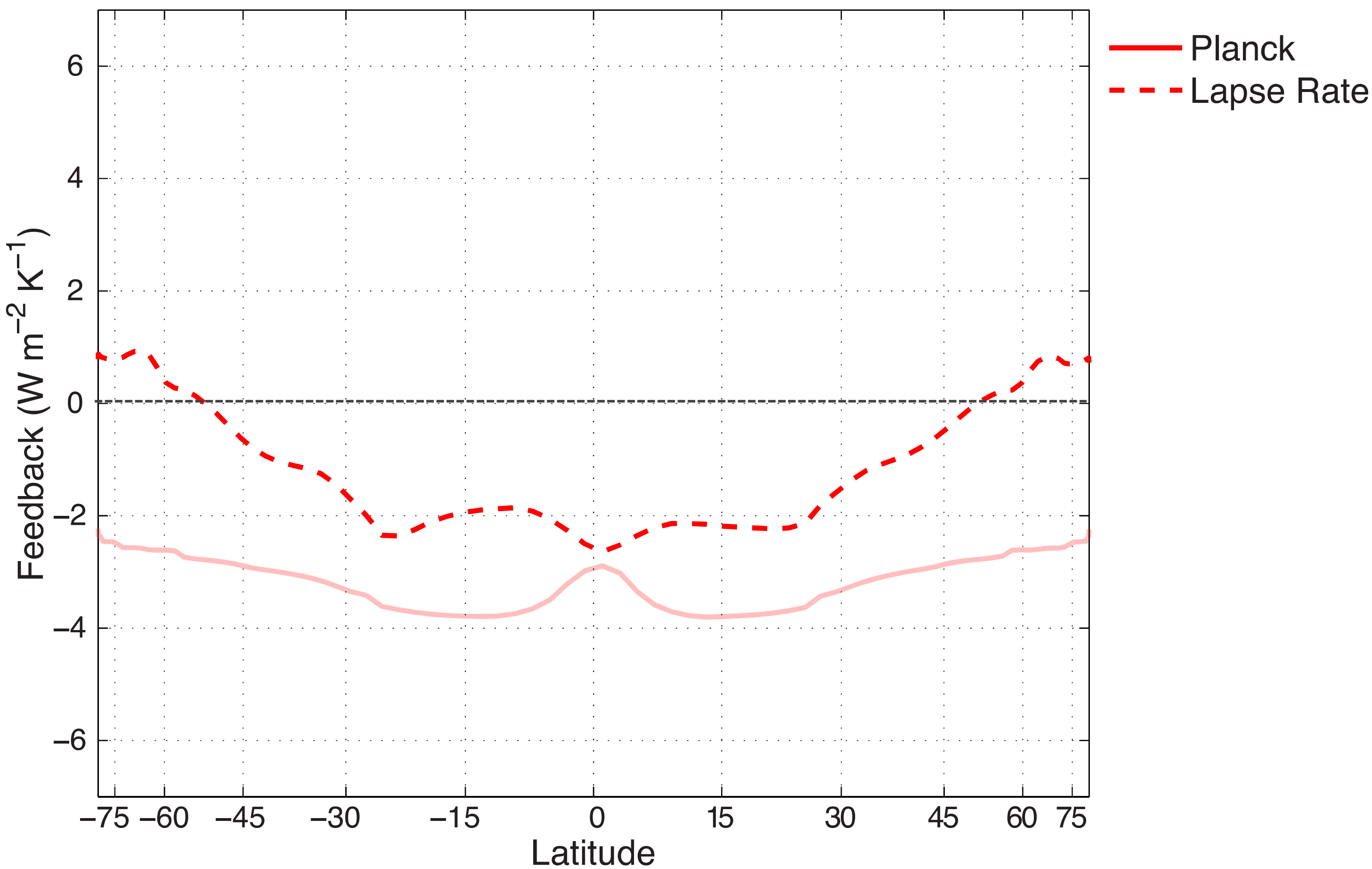
(locally defined)



- Deep clouds mask temperature response in deep tropics…

Patterns of regional feedbacks

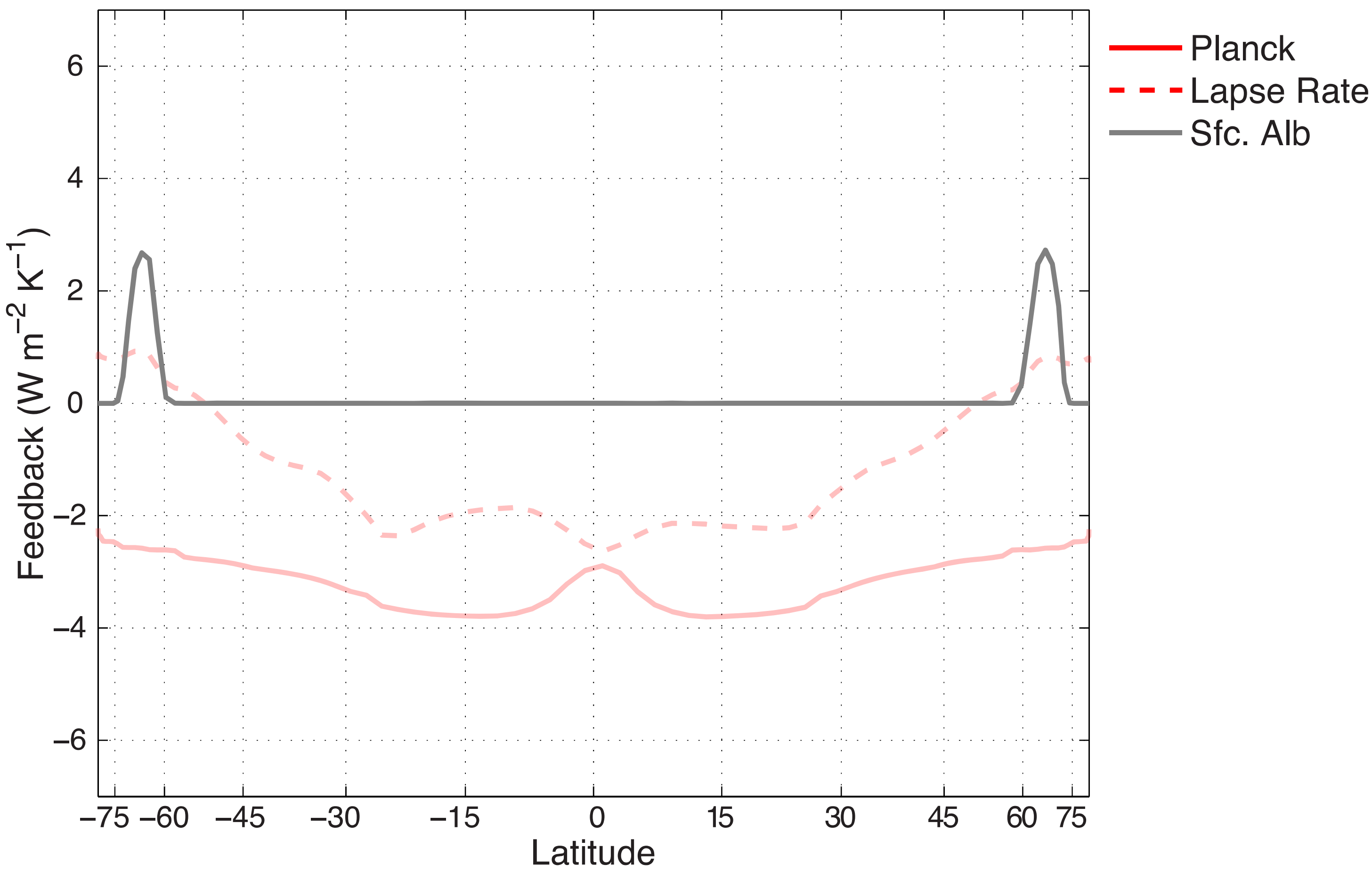
(locally defined)



- Lapse rate is negative (strongest in tropics)
  (+ve at high latitudes where there are T inversions)

Patterns of regional feedbacks

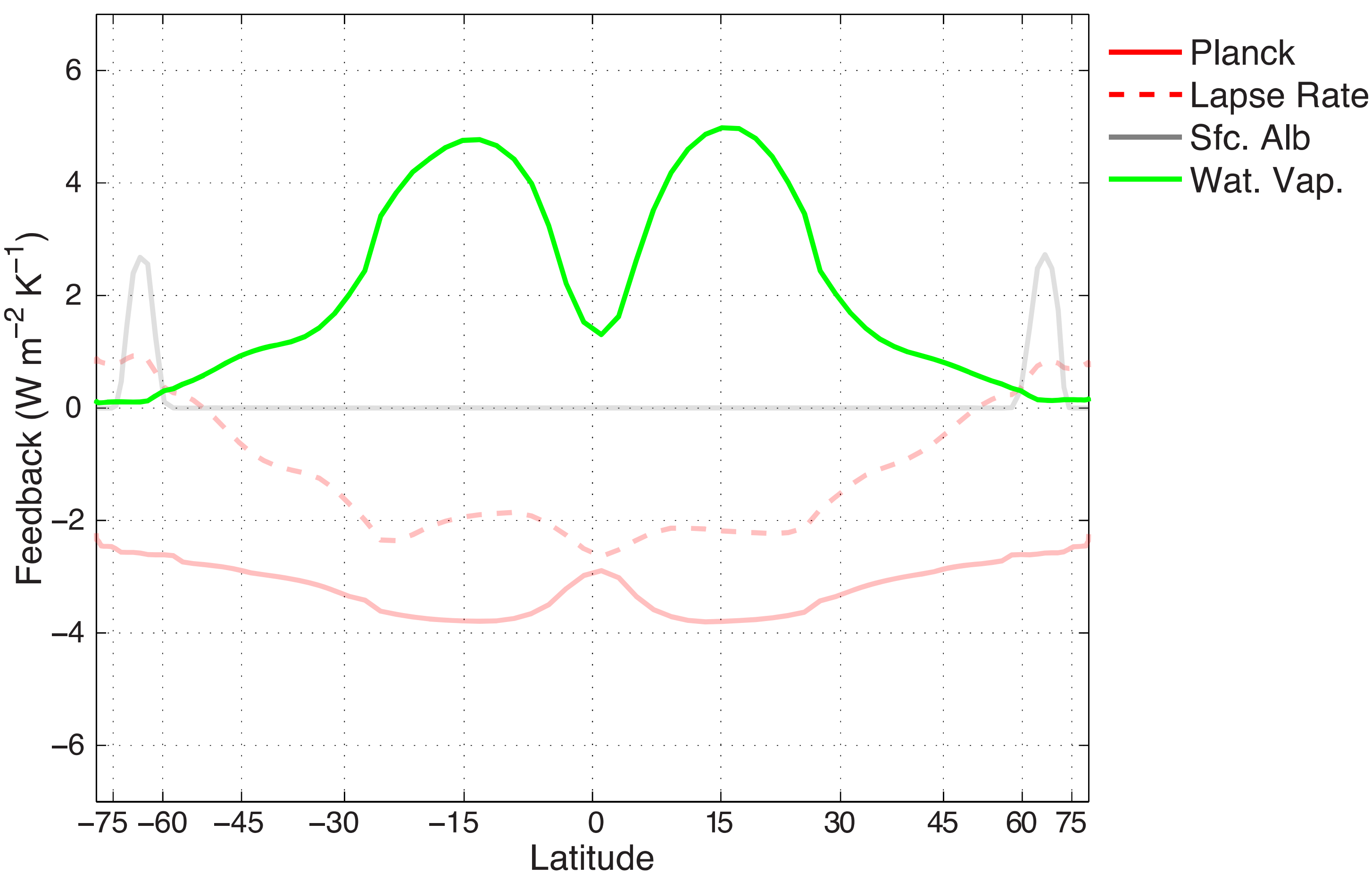
(locally defined)



- Ice albedo feedback only operates *at the ice line*.

Patterns of regional feedbacks

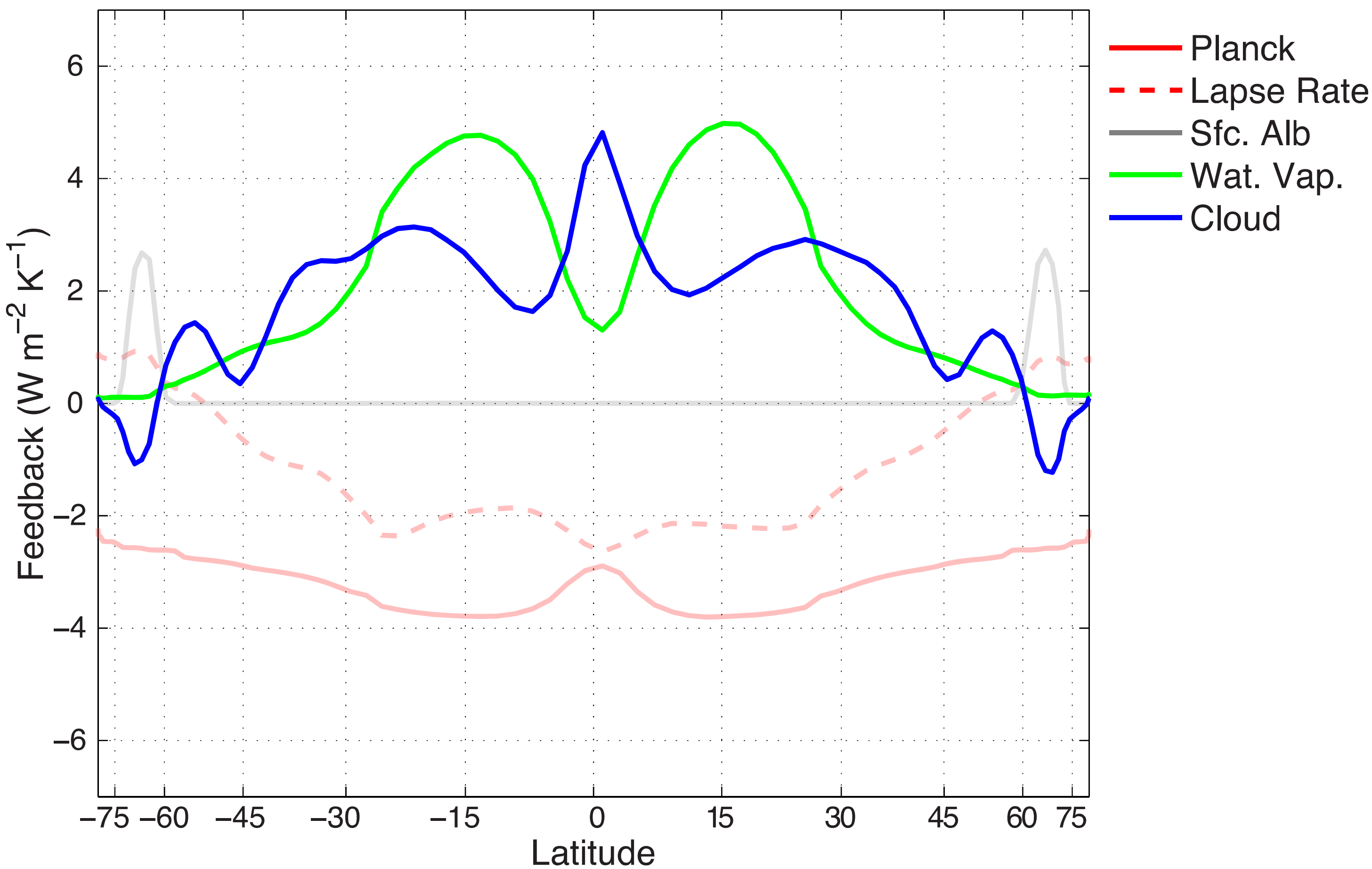
(locally defined)



- Water vapor feedback is strongest in subtropics (clear skies).

Patterns of regional feedbacks

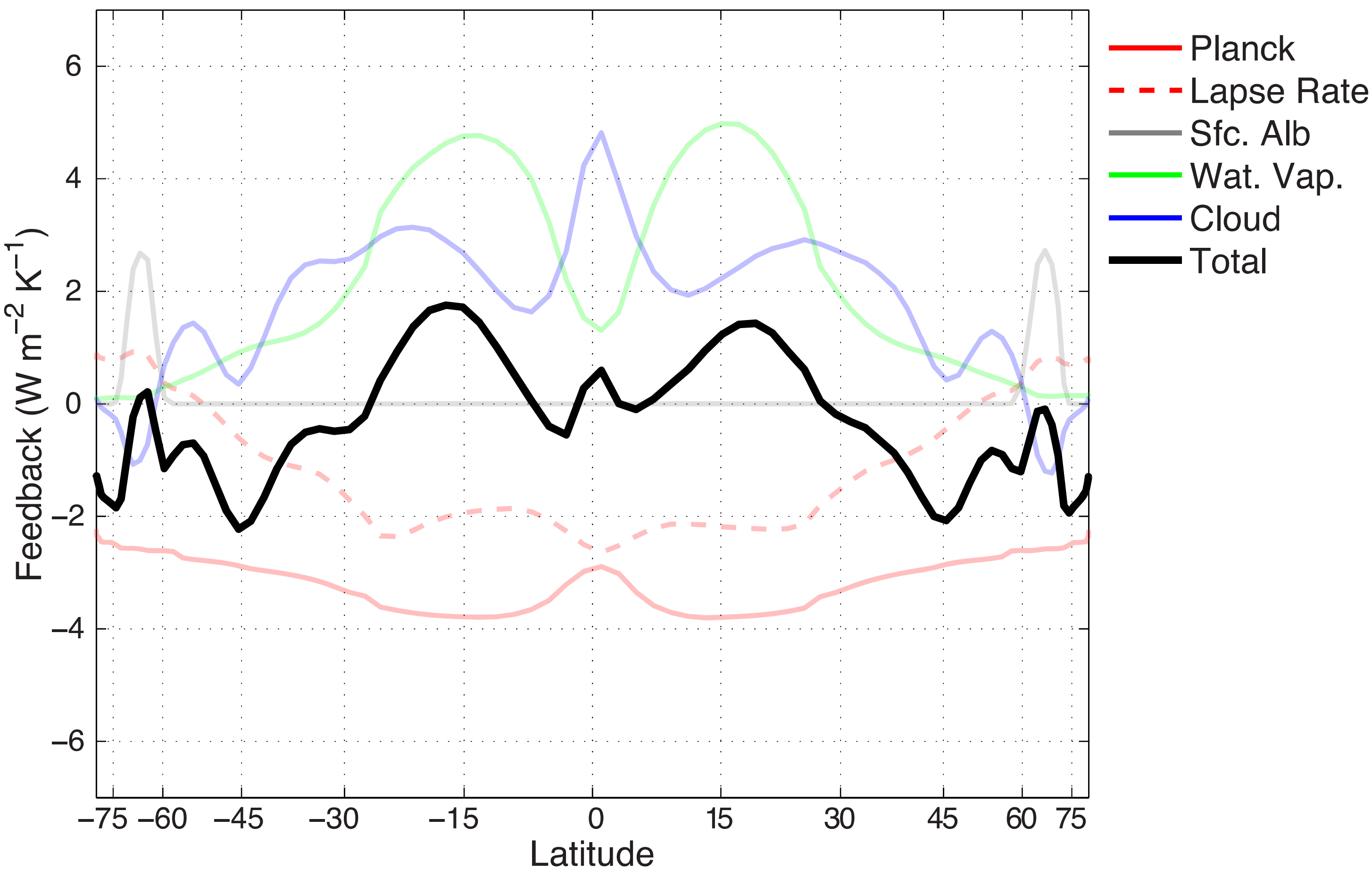
(locally defined)



- Cloud feedback generally +ve (due to decrease in cloud fraction).
- Can see covariance among feedback patters (tropics and ice line)

Patterns of regional feedbacks

(locally defined)



- Locally unstable ($\Sigma_i c_i > 0$) in the tropics and ice line.
- Strongest +ve feedbacks in tropics, where response is weakest (weird)

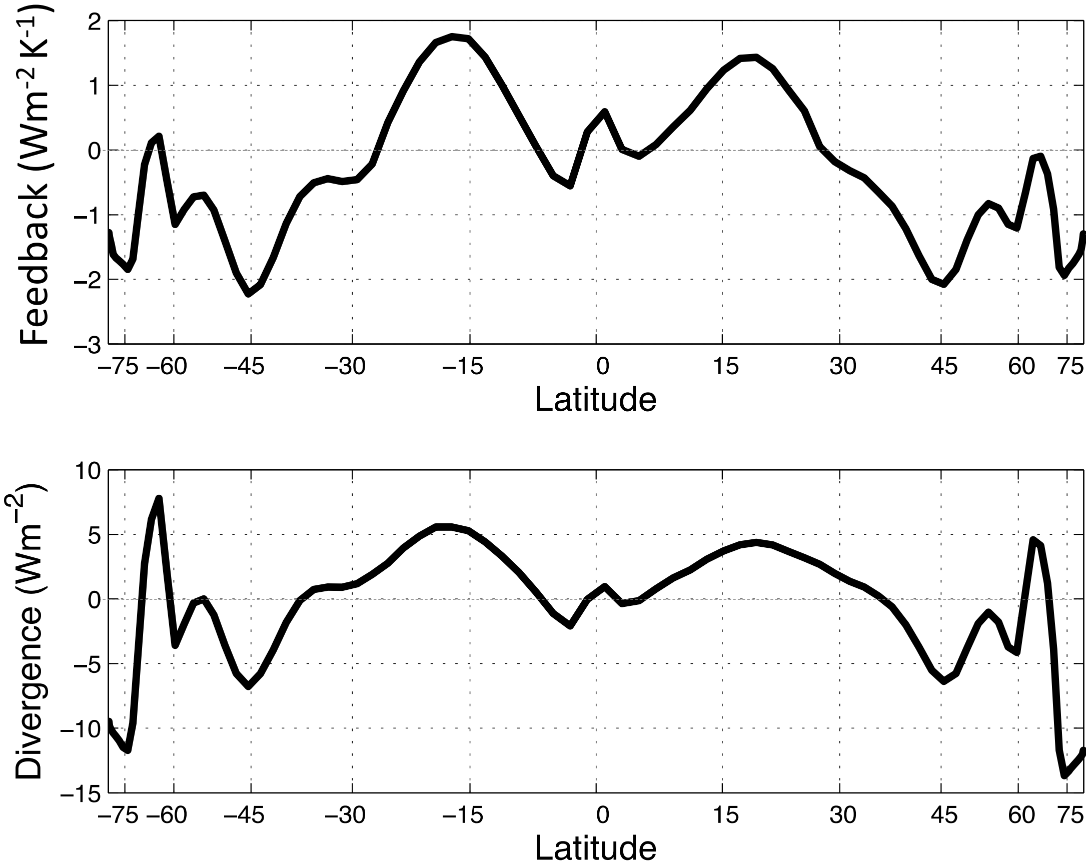
Key result: Feedback patterns drive transport changes

Net linear feedback

$$c_{tot}(x) = \sum_i c_i(x)$$

Transport changes from model

$$\Delta(\nabla \cdot F)$$

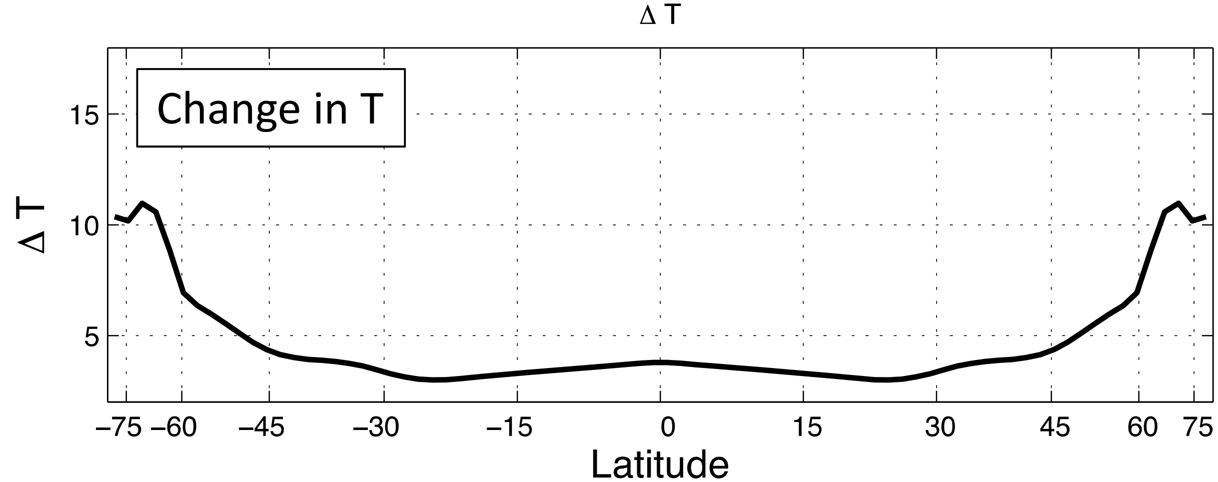


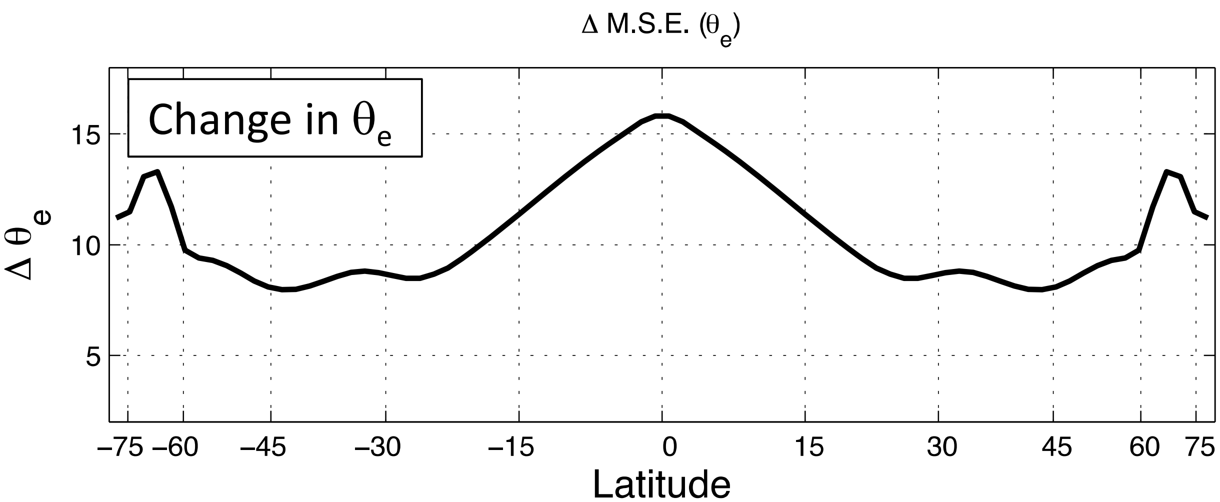
Three implications:

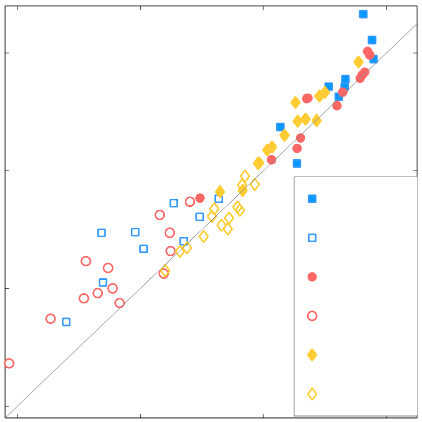
- Kernel method works (phew!)
- System exports energy away from regions of +ve feedbacks and towards regions of negative feedbacks
- Transport/circulation changes are slave to the feedbacks(!)

Ting and Dargan's Big Idea:

- Hwang and Frierson (2010) showed that, after subtracting the s.w. & cld impacts, inter-model differences in transport changes were consistent with diffusion of moist static energy.







Hwang and Frierson (GRL, 2010)

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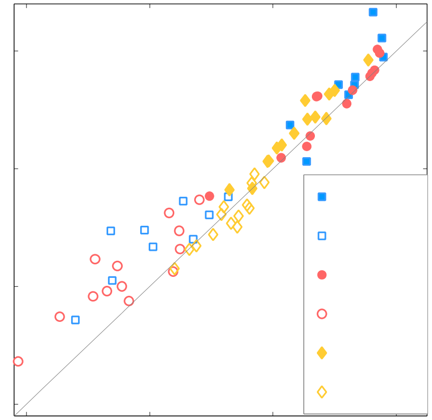

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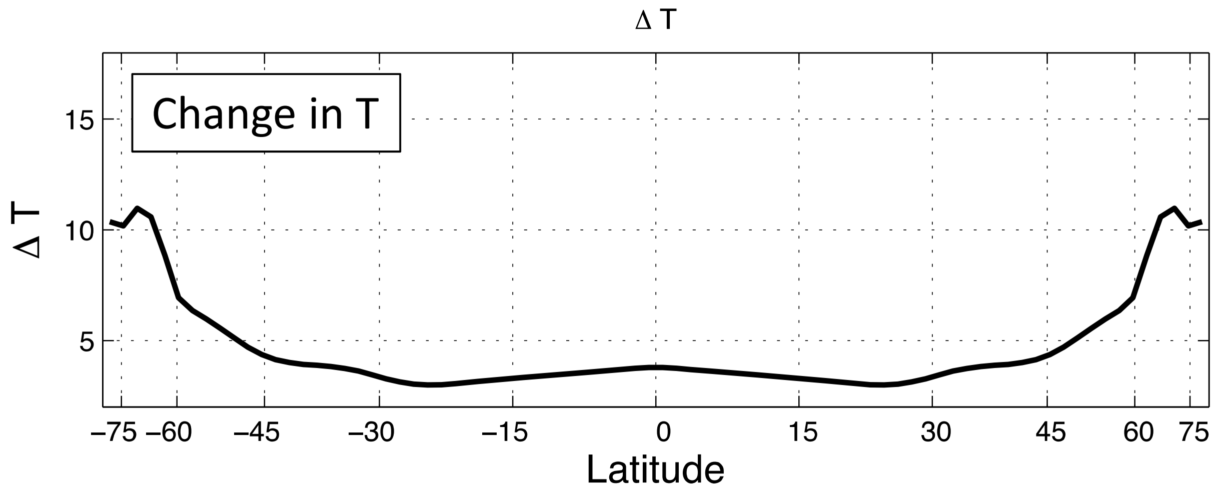
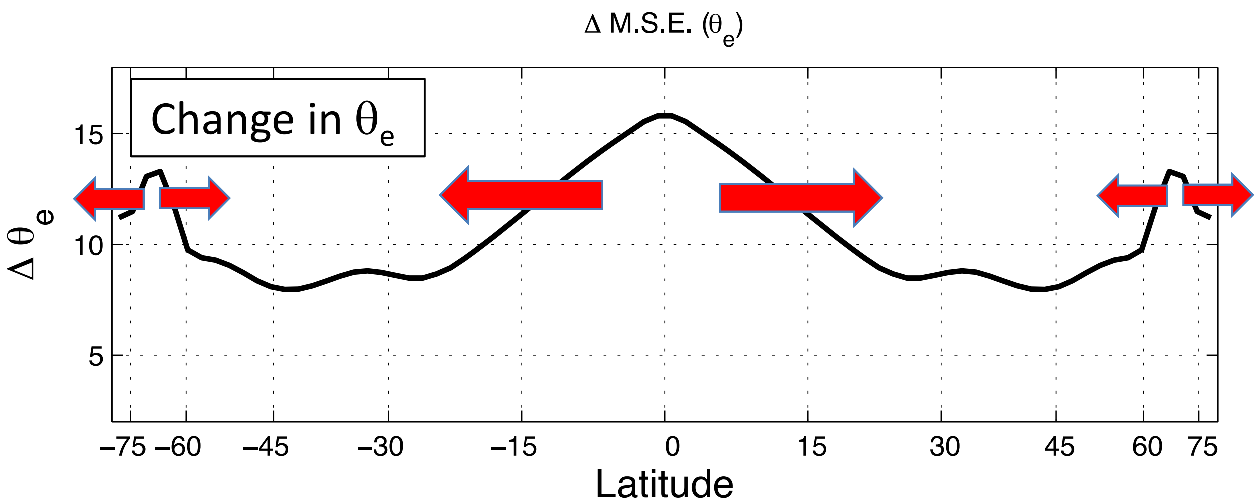




How well does a moist EBM do?

Diffuse moist static energy:

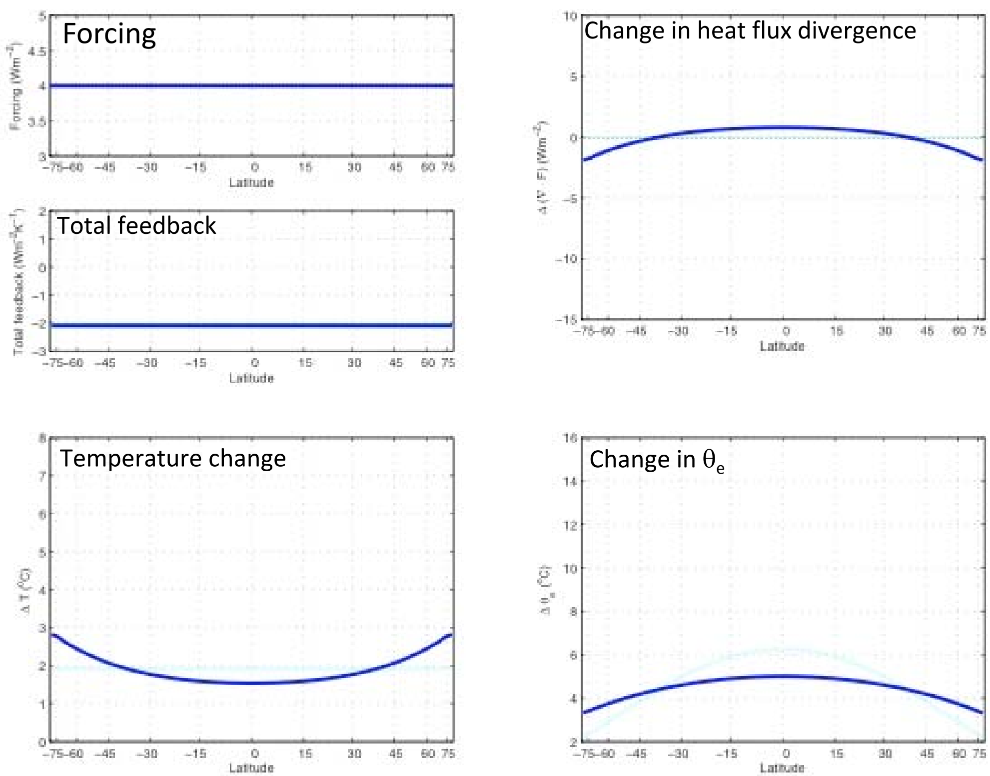
$$R_f = \Sigma_i c_i(x)\Delta T - \frac{d}{dx}D'(1-x^2)\frac{d}{dx}\Delta \text{m.s.e.}$$

forcing

feedbacks

transport

Uniform feedbacks



Result:

Divergence of m.s.e from tropics convergence at high latitudes

Some polar amplification from this alone,

How well does a moist EBM do?

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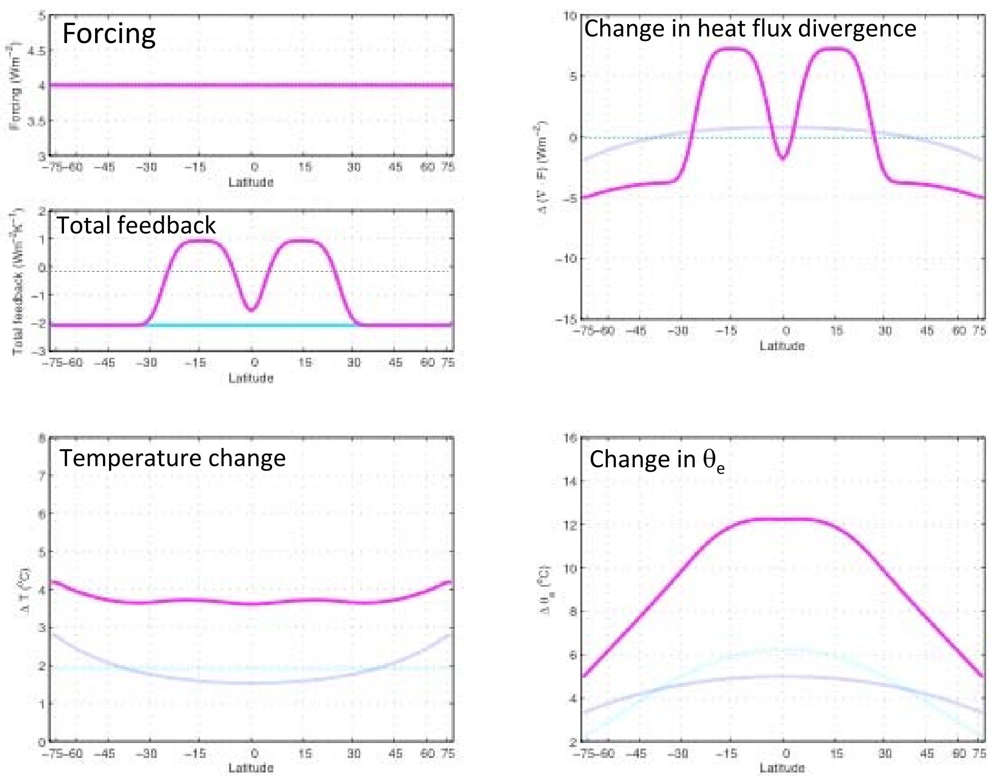
$$R_f = \Sigma_i c_i(x)\Delta T - \frac{d}{dx}D'(1-x^2)\frac{d}{dx}\Delta \text{m.s.e.}$$

forcing

feedbacks

transport

Add strong, locally unstable tropical feedbacks



Result:

Larger divergence of m.s.e from +ve feedback regions

Polar amplification remains, despite stronger feedbacks in tropics!

Anomalous transport is up the T gradient, but down the θ_e gradient

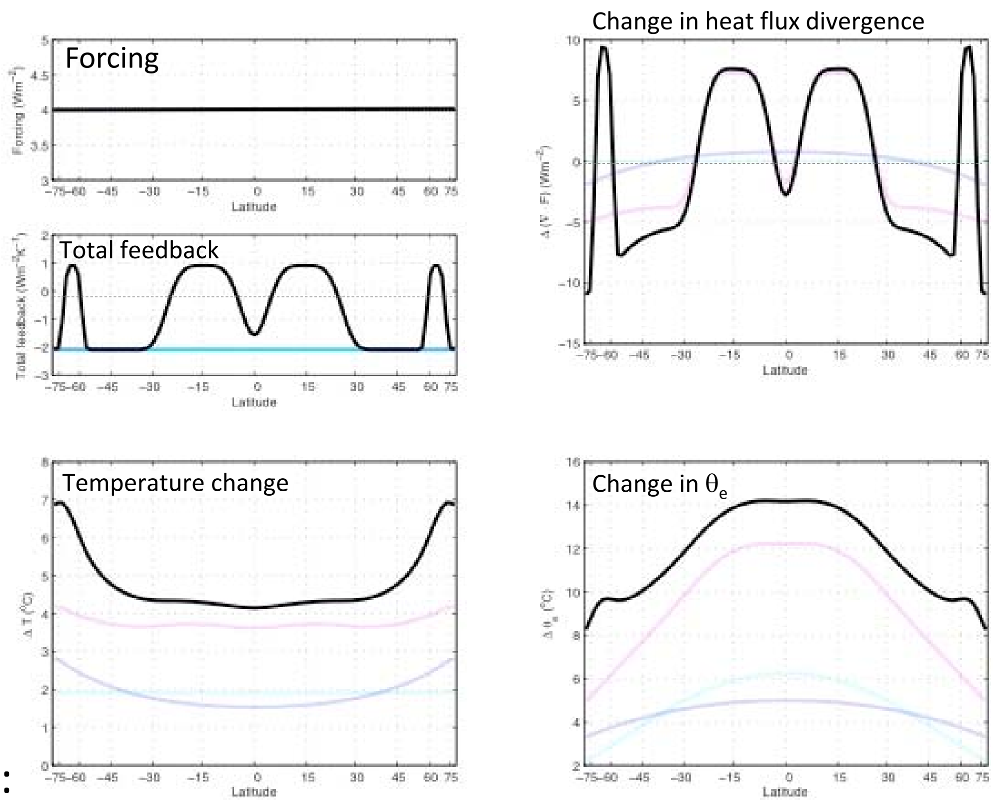
How well does a moist EBM do?

Diffuse moist static energy:

Add strong locally unstable feedbacks at the ice lines too

$$R_f = \Sigma_i c_i(x)\Delta T - \frac{d}{dx}D'(1-x^2)\frac{d}{dx}\Delta \mathrm{m.s.e.}$$

forcing | feedbacks | transport



Result:

-Large divergence of m.s.e. from +ve feedback regions (incl. away from the ice line)

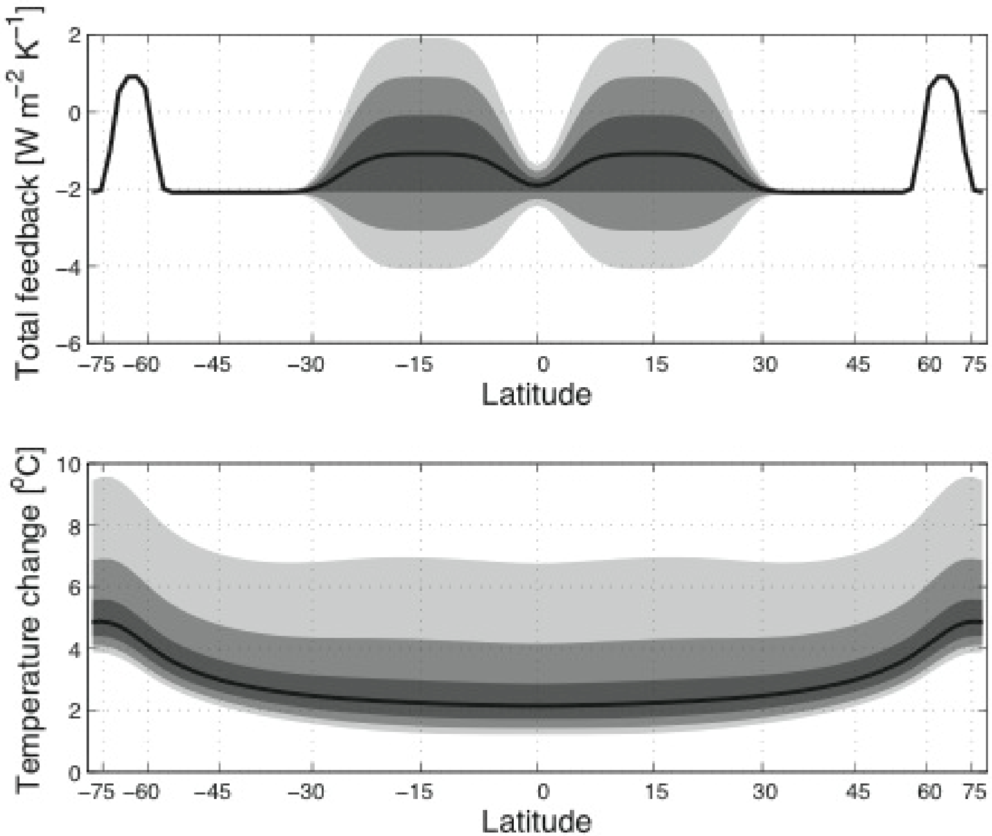
-Polar amplifications strongly enhanced; convergence of energy polewards of ice line

-Climate sensitivity is increasing rapidly as global mean feedback approaches zero

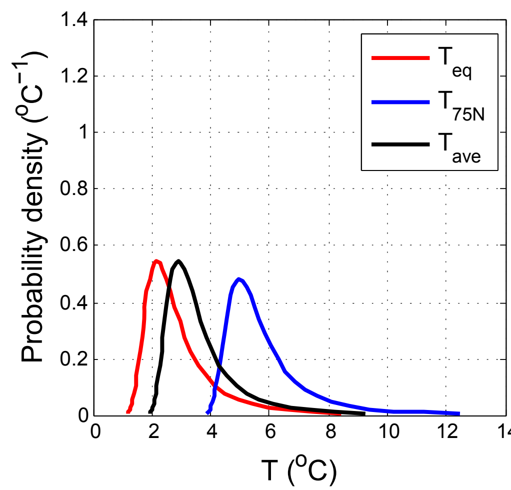
These all look a lot like the diagnosed behavior of Nicole's aquaplanet…

How does uncertainty in local feedbacks translate to uncertainty in the local and nonlocal climate response?

Vary strength of tropical feedbacks, consider pattern of climate response:
Top panel: hypothetical 1σ, 2σ, 3σ ranges in tropical feedback (made up, obviously)
Bottom panel: the climate response as a function of latitude.



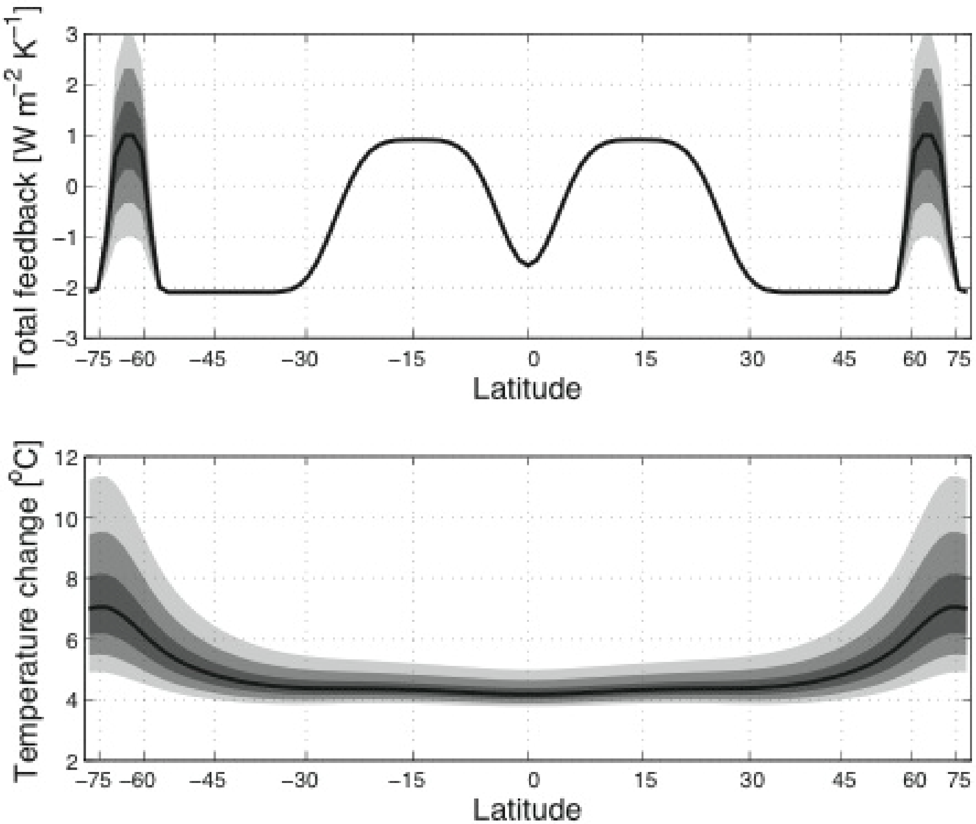
PDFs as a func^{n} of latitude



Results:
Overall skewed envelope of temperature response (just like the global case)
Uncertainty in response is spread to all latitudes

How does uncertainty in local feedbacks translate to uncertainty in the local and nonlocal climate response?

Vary strength of polar feedbacks, consider pattern of climate response:
Top panel: hypothetical 1σ, 2σ, 3σ ranges in sfc albedo feedback (made up, obviously)
Bottom panel: the climate response as a function of latitude.



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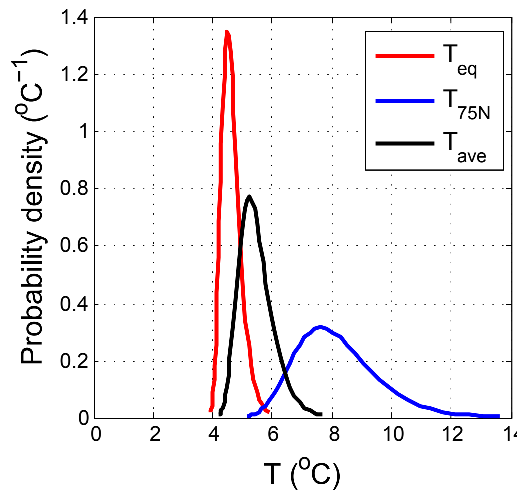
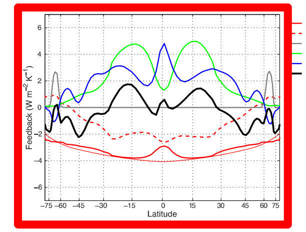


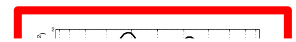
Results:
Overall skewed envelope of temperature response (just like the global case)
Uncertainty is largely confined to the high latitudes

Summary

- Kernel-based feedbacks combine to provide physically-meaningful patterns.

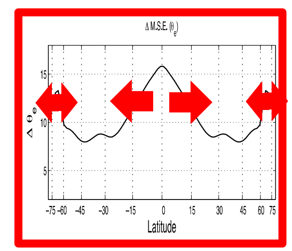
- The feedback patterns are dictated by the climatological circulation, but the climate response is dictated by the pattern of feedbacks



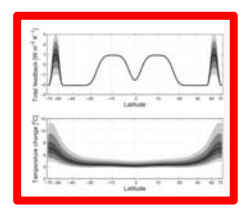


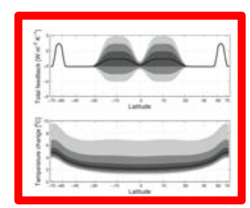
- Energy is driven away from regions of strong positive feedbacks towards regions of more negative feedbacks *(& two scales to polar amplification).*

- Simple down gradient transport of m.s.e. anomalies explains much of the model behavior



- Uncertainty in tropical process have a global impact/ uncertainty in polar processes confined largely to poles

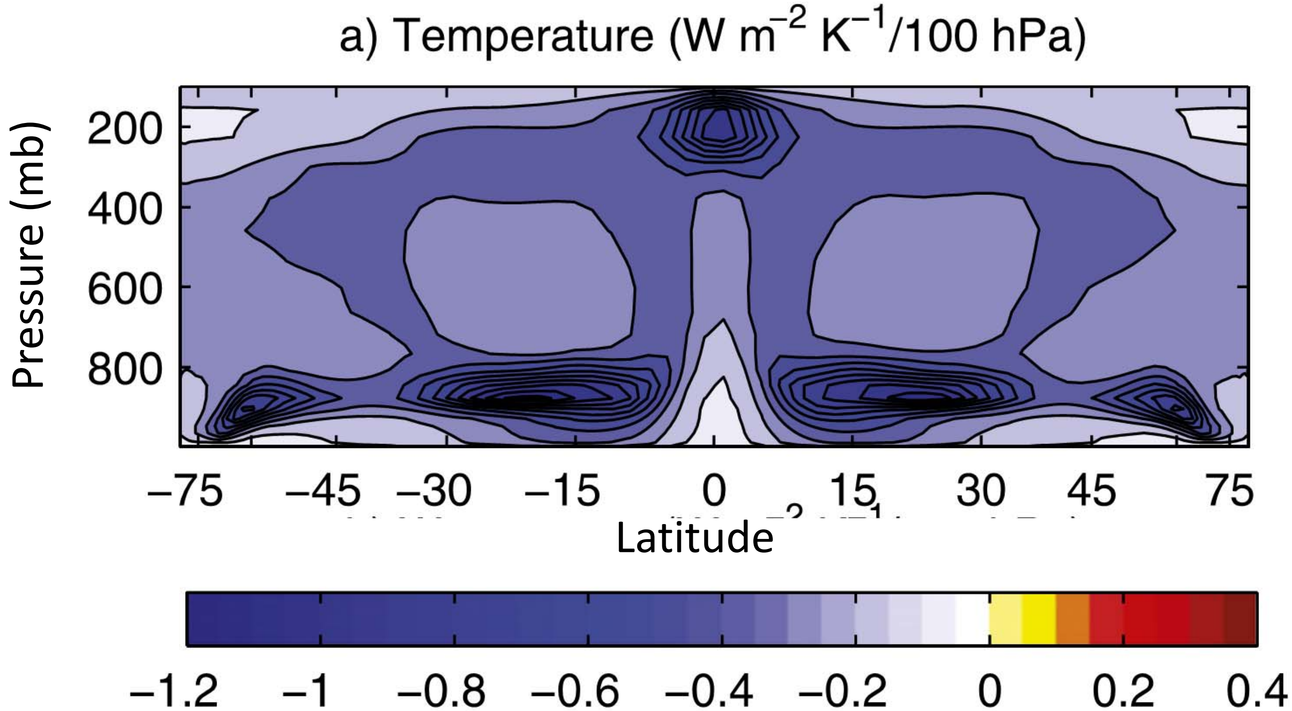




Calculating regional feedbacks

Some examples of Kernels

The temperature kernel, $\partial R / \partial T$



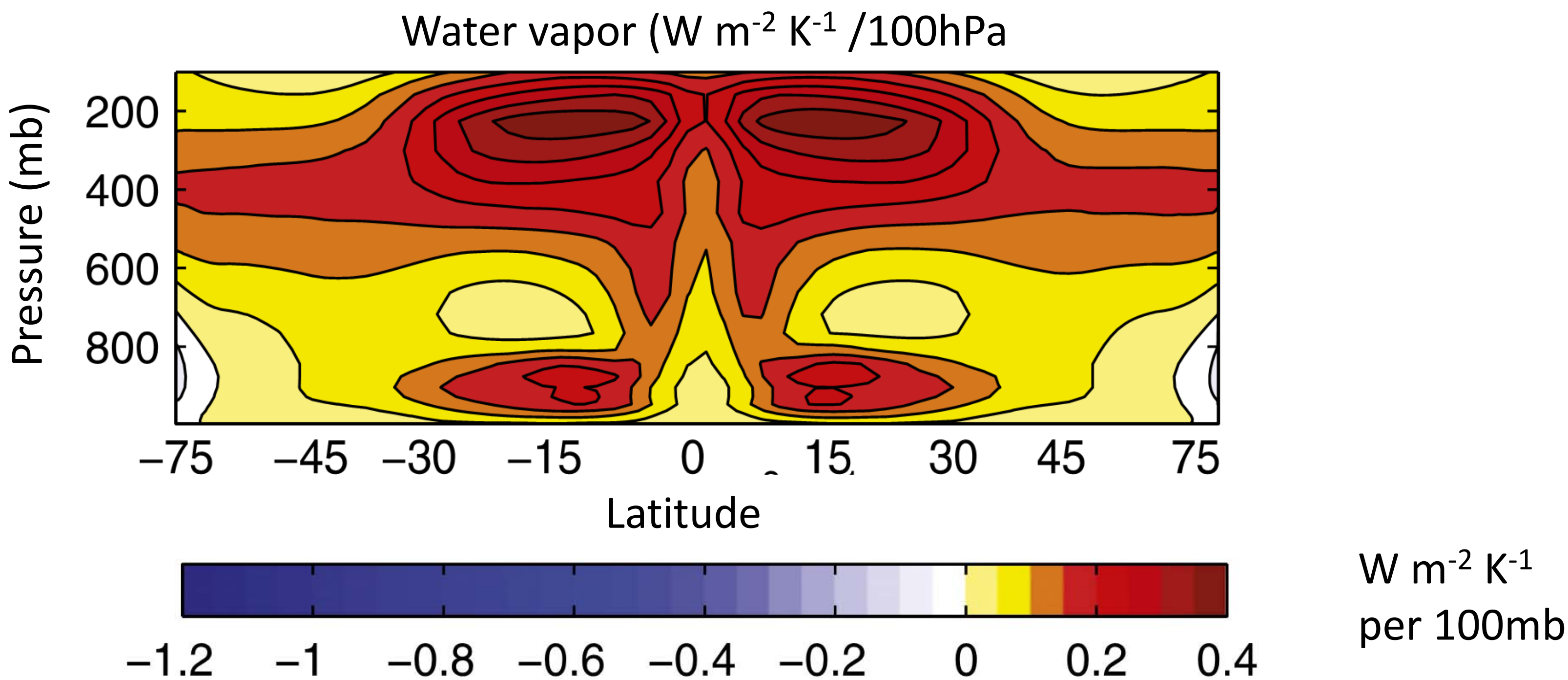
W m^{-2} K^{-1}
per 100mb

- Negative everywhere
- Biggest impact is from temp changes above cloud tops
- Temperature changes are *masked* beneath clouds

Calculating regional feedbacks

Some examples of Kernels

The water vapor kernel, $\partial R / \partial q$ (albeit in weird units)



- Positive everywhere (except at low levels and very high latitudes)
- TOA acutely sensitive to upper tropospheric humidity changes, (especially above cloud tops)

Relating feedbacks to the climate response

Partial temperature decomposition

Back to Taylor series

$$-\Delta R_f(x) = -\Delta(\nabla \cdot F(x)) + \sum_i c_i(x)\Delta T + \mathcal{O}(\Delta T^2)$$

Rearrange:

c_{Pl} (x) = Planck "feedback"

$$\Delta T_s(x) = \frac{1}{c_{Pl}(x)}\left[\Delta(\nabla \cdot F(x)) - \Delta R_f(x) - \mathcal{O}(\Delta T^2) - \left(\sum_{i \neq P} c_i\right)\Delta T_s(x)\right]$$

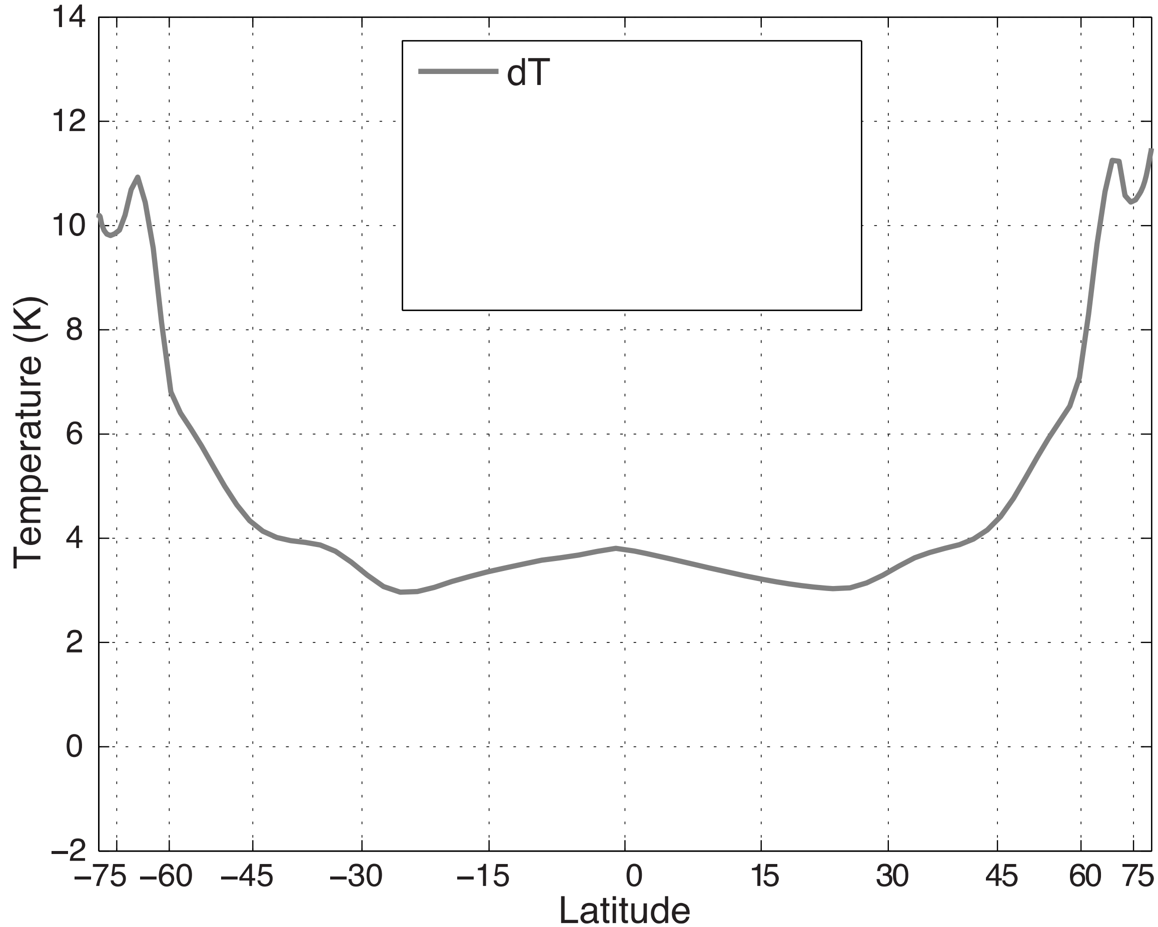
- Decompose the local temperature change into its constituent causes:

- Relates to original (i.e., proper) feedback factors:

$$\Delta T_s(x) = \lambda_0 \frac{\Delta R_f - \Delta(\nabla \cdot F)}{1 - \sum_i f_i(x)} \quad \text{where} \quad f_i(x) = -\frac{c_i(x)}{c_{Pl}(x)}$$

Relating feedbacks to the climate response

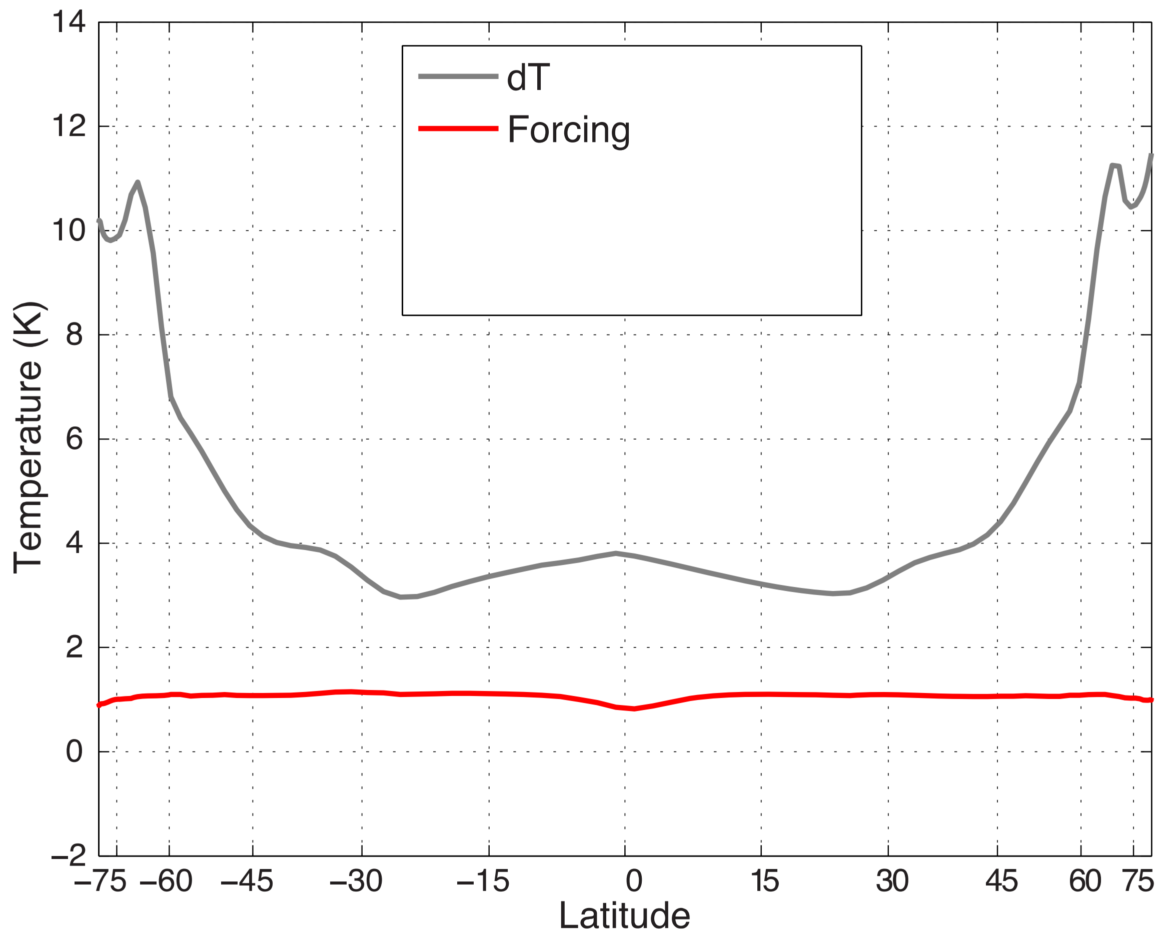
Partial temperature decomposition



- How do the pieces add up to this response?

Relating feedbacks to the climate response

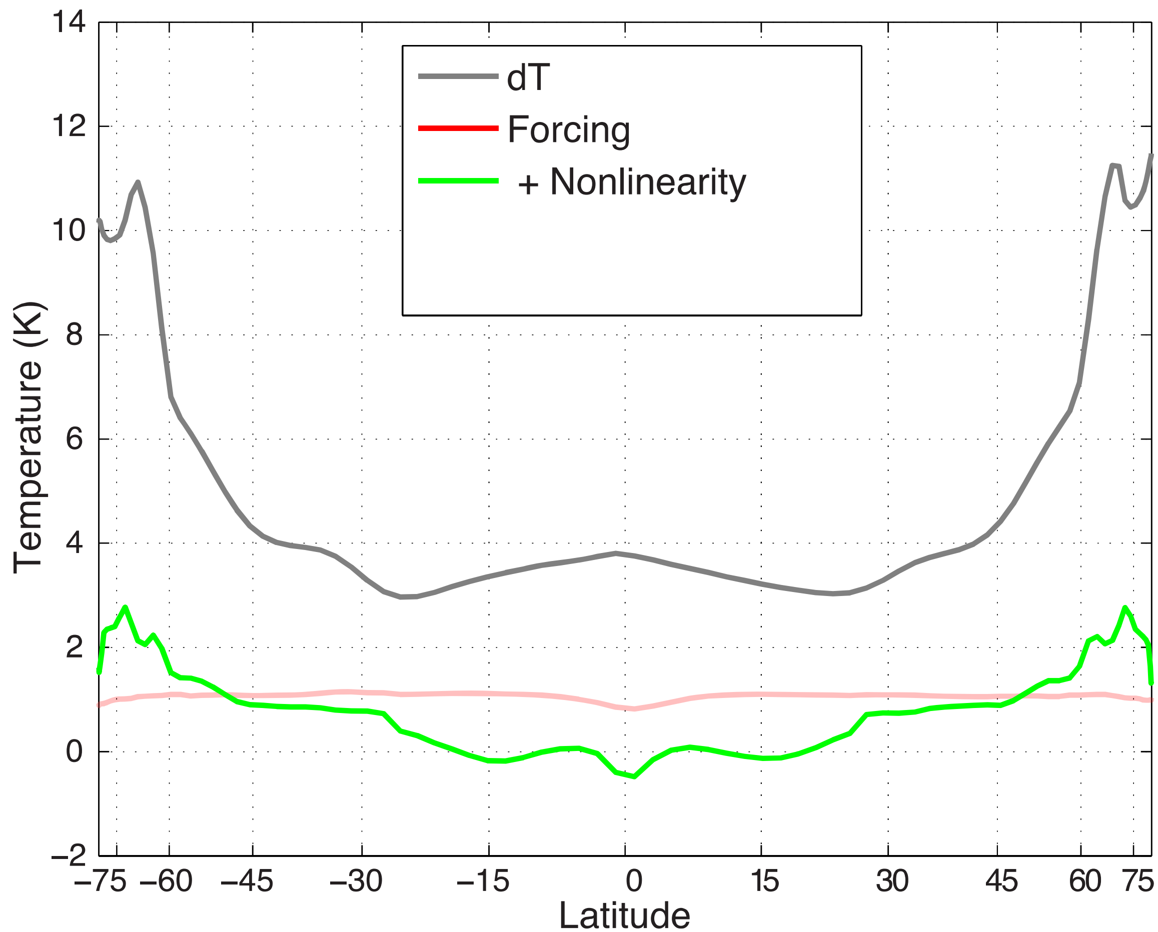
Partial temperature decomposition



- Forcing provides nearly uniform ~1.0^{o}C

Relating feedbacks to the climate response

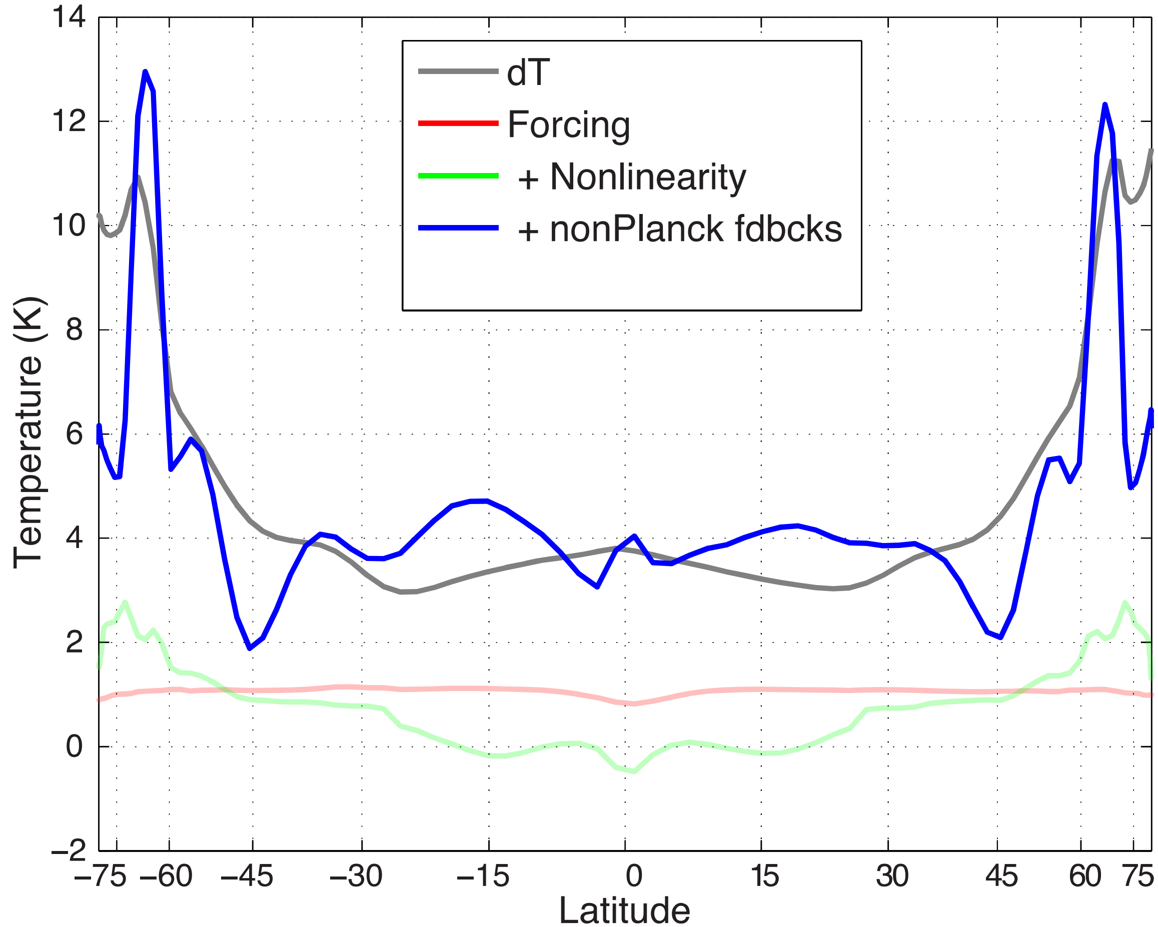
Partial temperature decomposition



- Nonlinearity also fairly small ~+/-1.0^{o}C (& due to clear-sky masking)

Relating feedbacks to the climate response

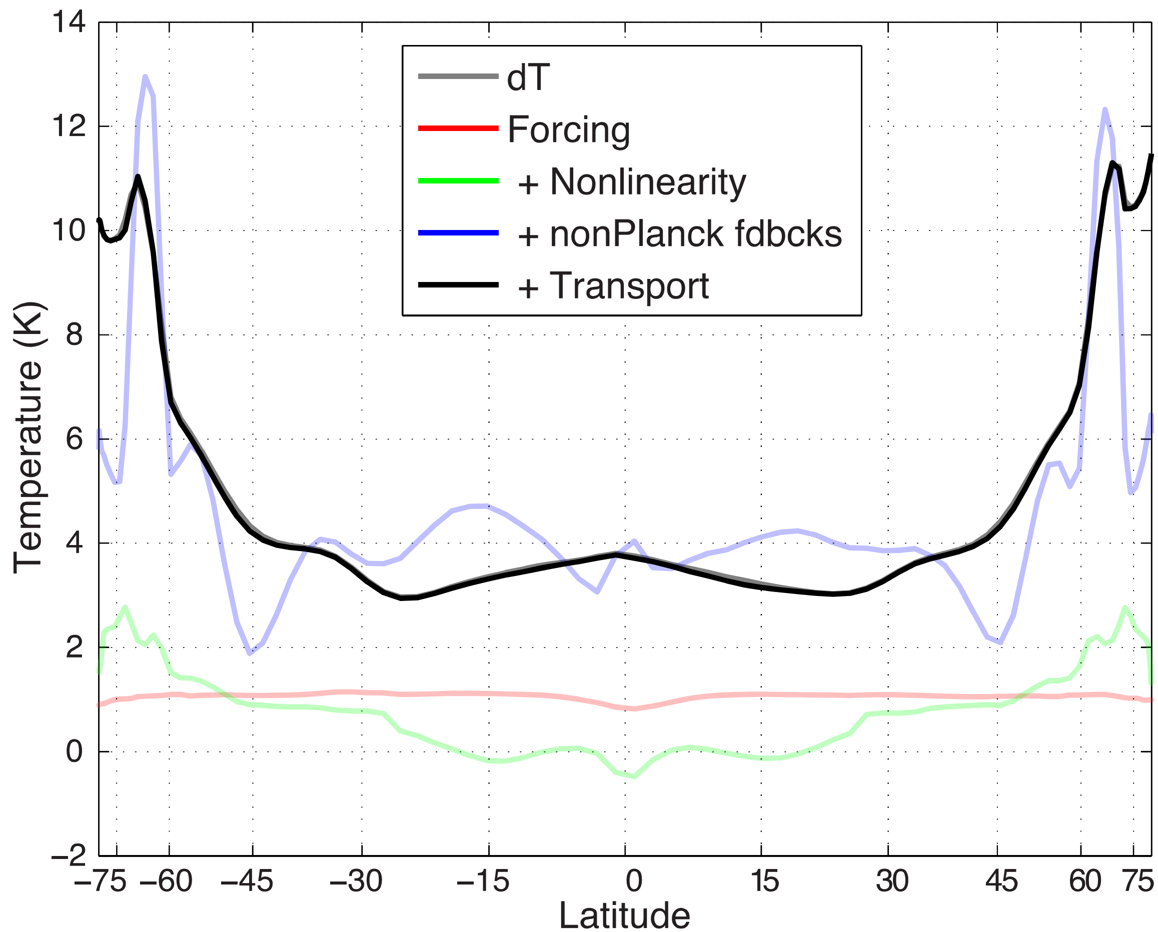
Partial temperature decomposition



- NonPlanck feedbacks do a lot – amplification in tropics & at ice line
- Too much warming in the tropics, not enough at high latitudes

Relating feedbacks to the climate response

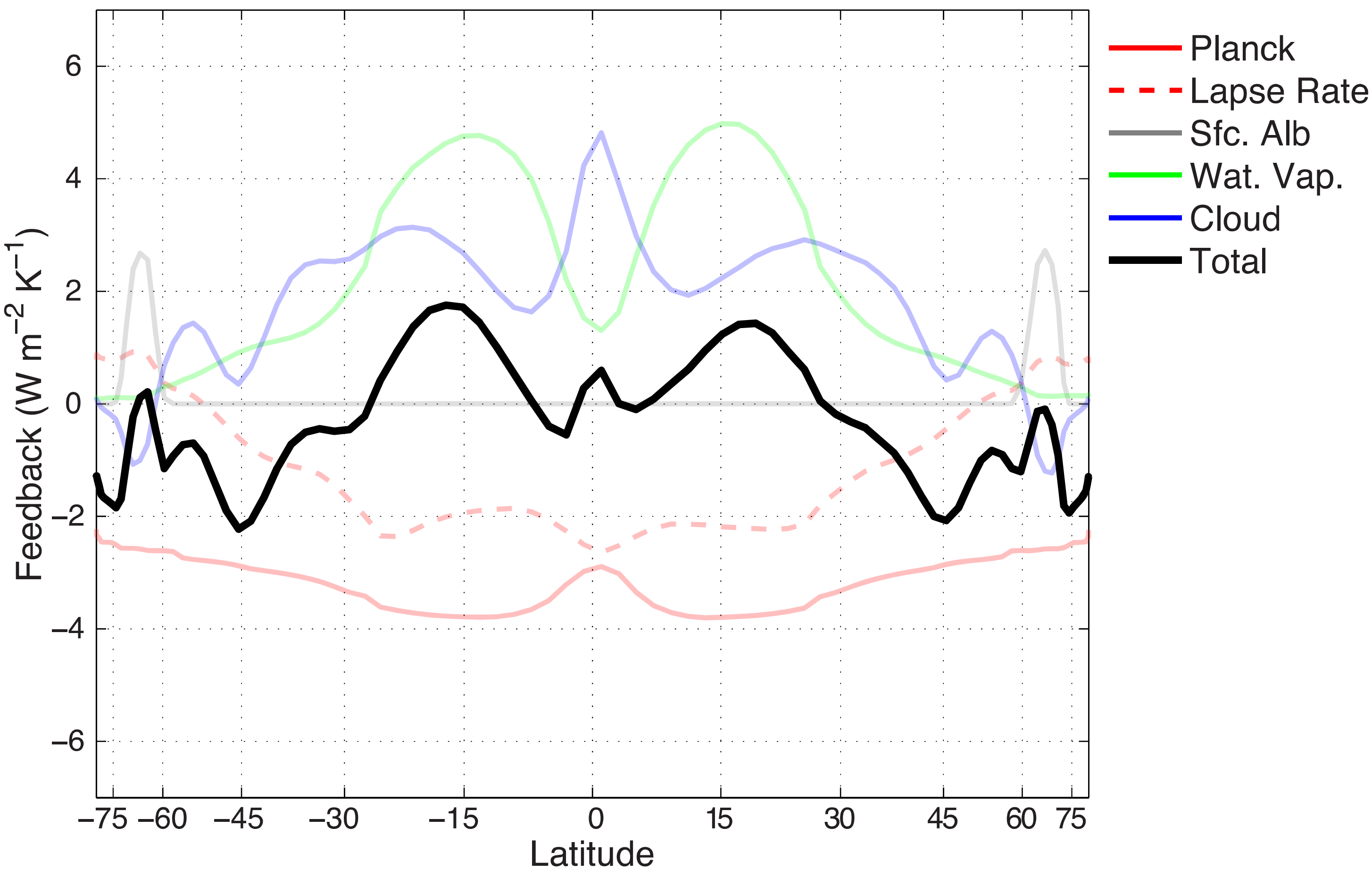
Partial temperature decomposition



- Transport (i.e., nonlocal impact of feedbacks) can >50% of response
- Two scales to polar amplification 1. >45°: export from tropics
  2. >75°: export from ice line

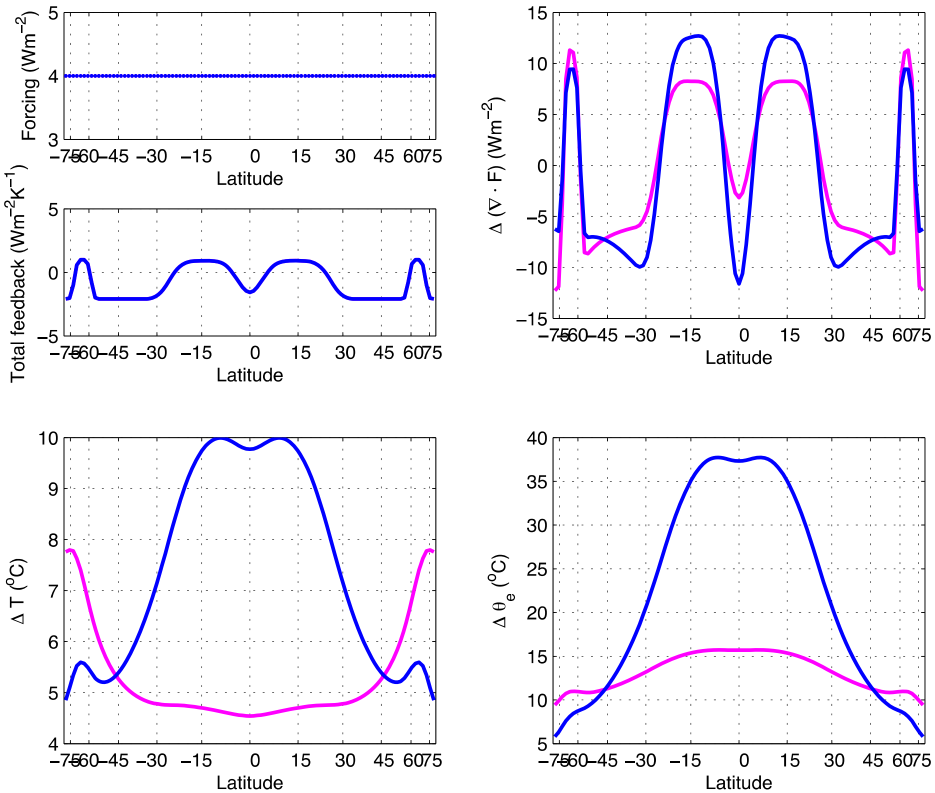
Patterns of regional feedbacks

(locally defined)



- Overall, the spatial patterns of feedbacks are slave to the circulation/climate regimes (ITCZ, subtropics, mid-latitudes, ice line)

Moist vs. dry static energy diffusion



Pink = m.s.e. diffusion
Blue = cpT only diffusion