Robust non-local effects of ocean heat uptake on radiative feedback and subtropical cloud cover

or

Why it's easy to under-estimate equilibrium climate sensitivity from transients

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and

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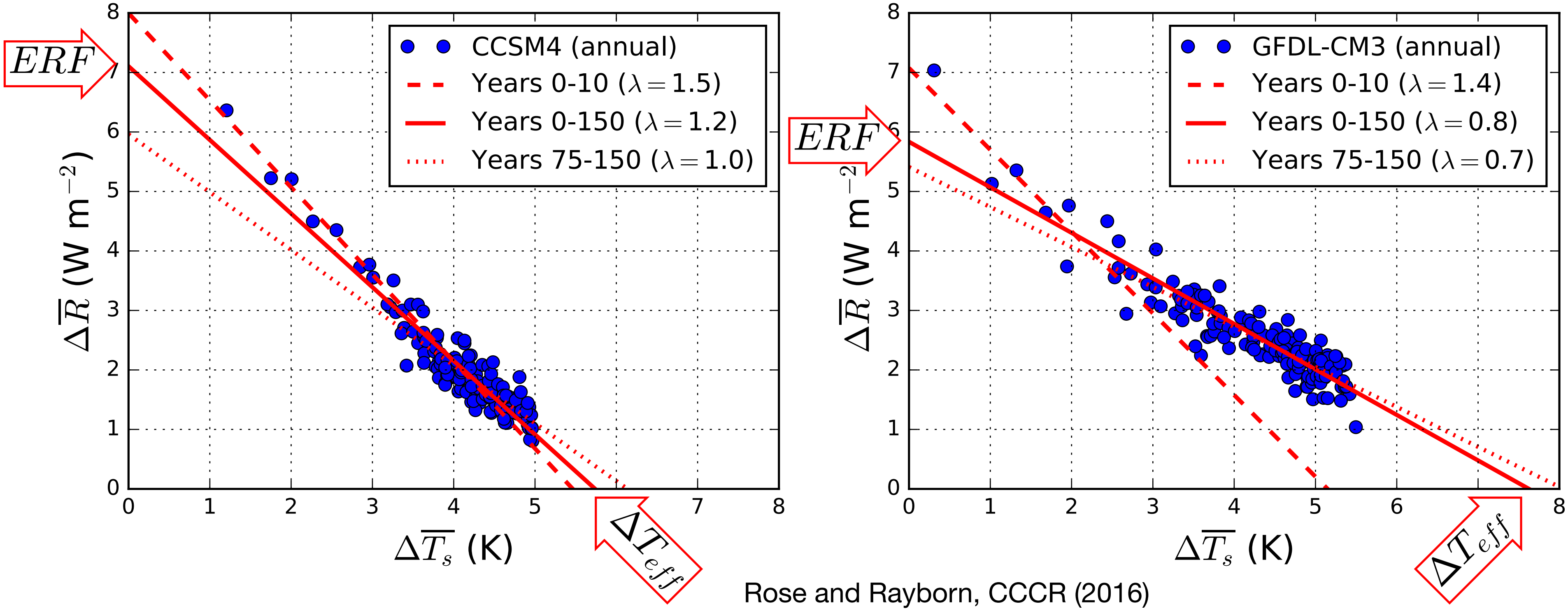
CMIP5 (and previous generations too!):

Climate sensitivity **increases** as models warm up



Rose and Rayborn, CCCR (2016)

TOA radiative imbalance vs. surface temperature (global mean anomalies) after abrupt 4xCO2

Many studies have implicated changes in **shortwave cloud feedback**

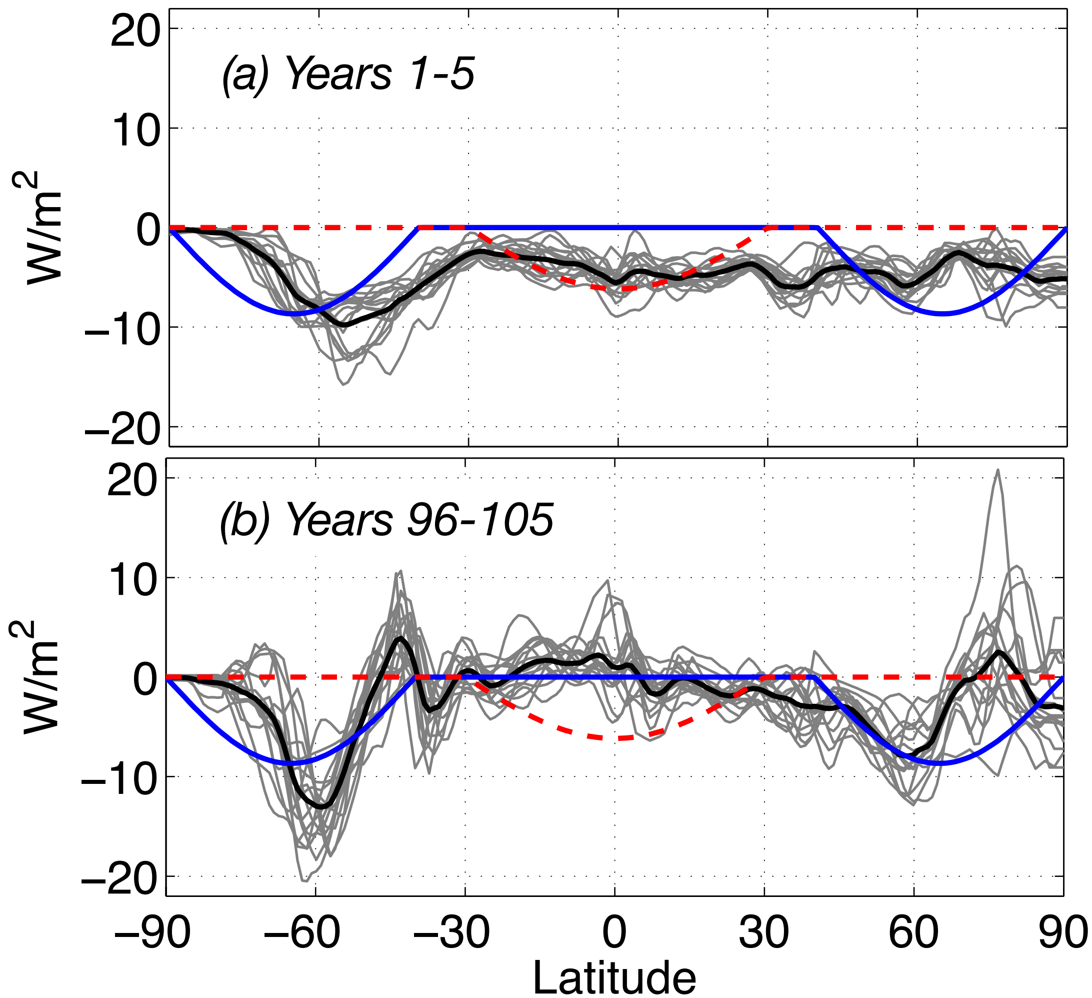
Why / how do the feedbacks change over time?

Is the coupled climate system irretrievably **non-linear**?

How knowable is the **equilibrium sensitivity** from transient observations?

CMIP5:

Distinct spatial structures in **ocean heat uptake** emerge over time.

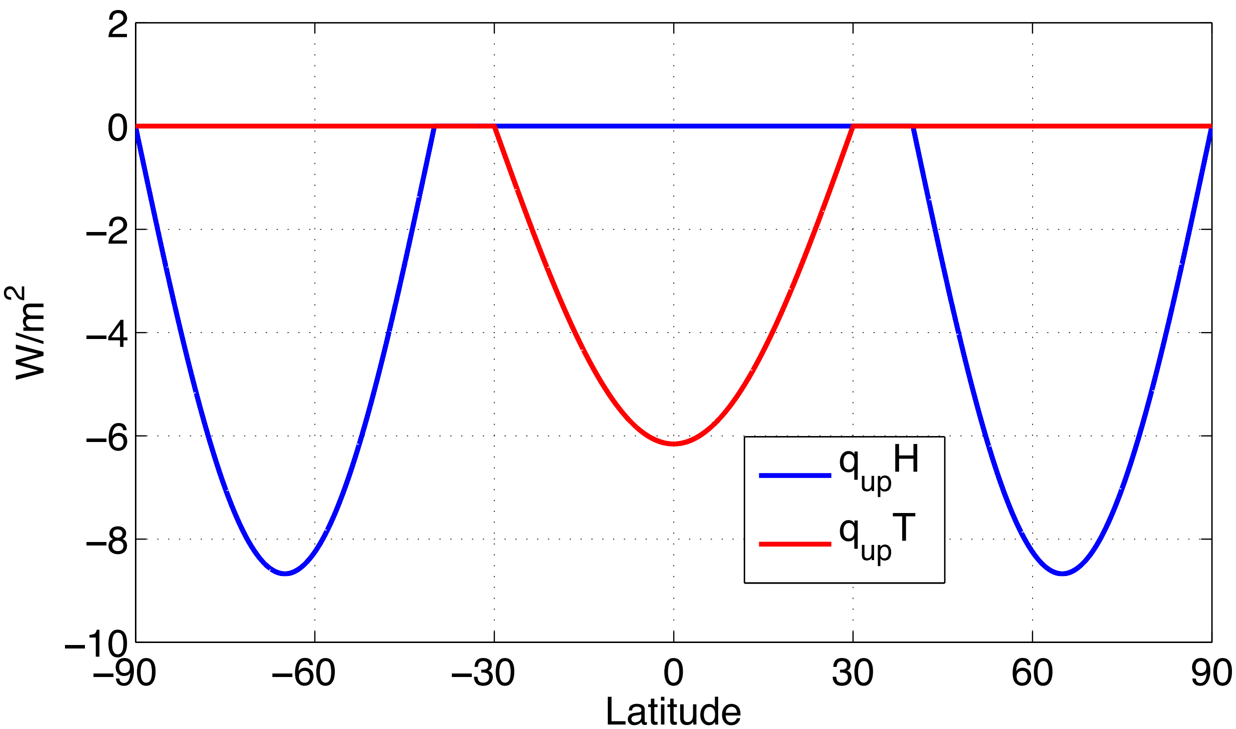


CMIP5 abrupt4xCO2 scenario, anomalous surface flux data compiled by Kyle Armour

Does the spatial structure of the ocean heat uptake matter?

- Ignore ocean dynamics (*slab ocean models*)
- Treat the heat uptake / release as a prescribed, steady forcing (*"q-flux"*)
- Study the quasi-equilibrium atmospheric response to sea surface heating
- For simplicity, use aquaplanet GCMs (but with full physics - radiation, clouds, etc)
- Repeat the calculation with various models to evaluate robustness

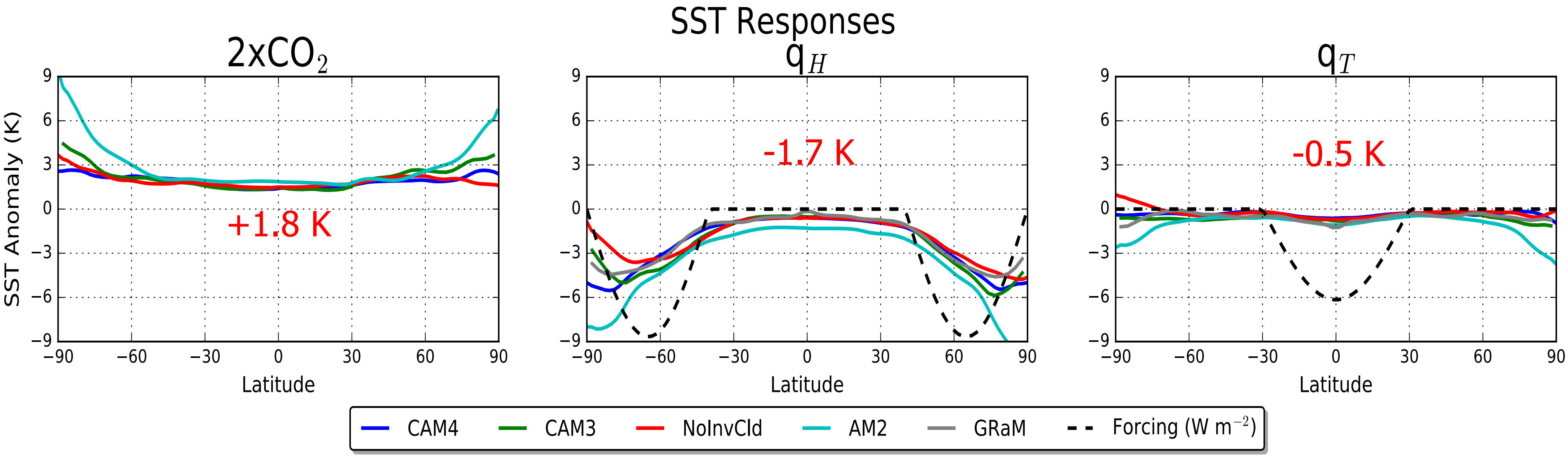
Idealized ocean heat uptake experiments



Heat uptake prescribed as a "q-flux" in slab-ocean aquaplanet GCMs

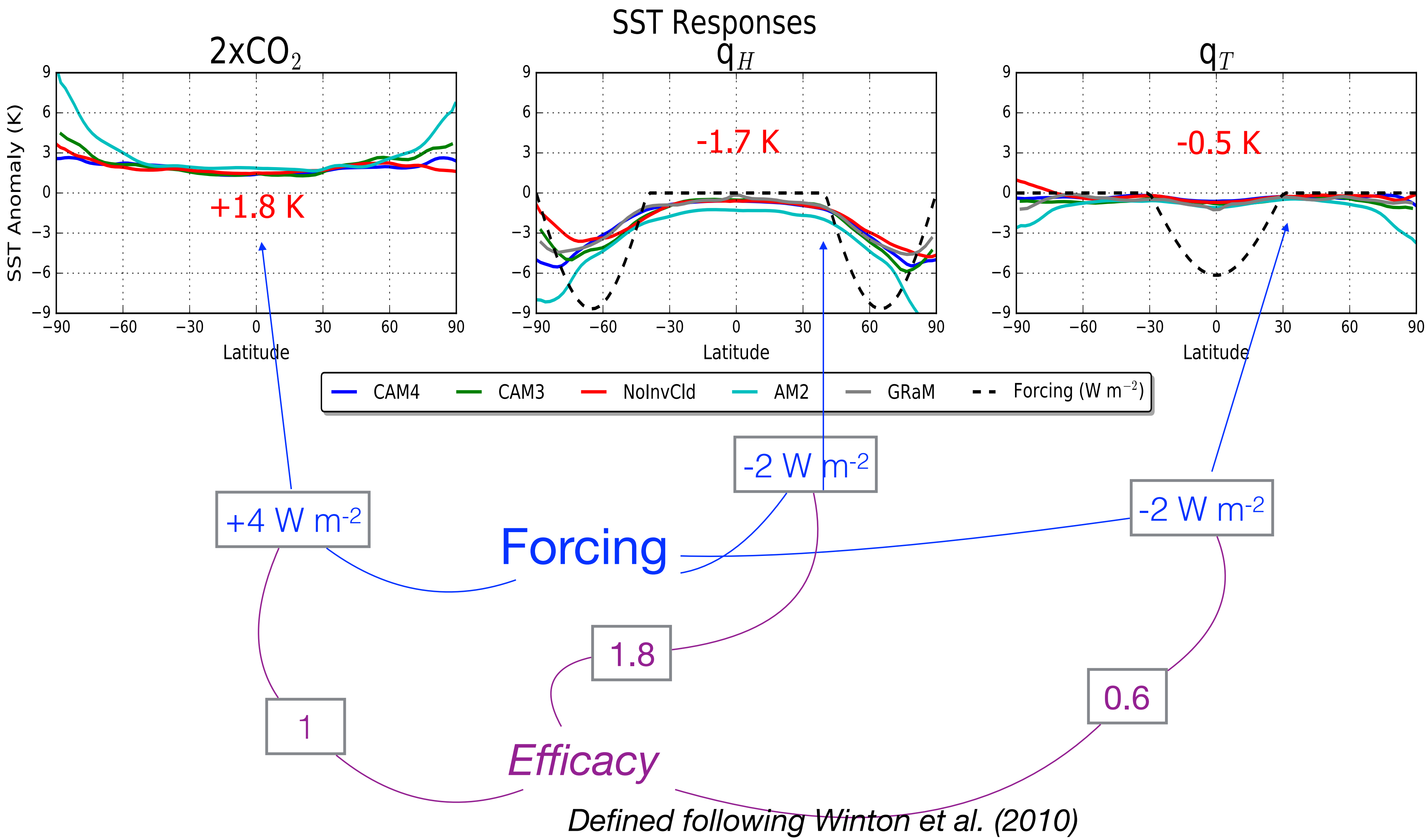
$H(x) = 2$ W m^{-2} in both cases!

Which pattern produces more cooling in a climate model?



Multiple GCMs agree: subpolar heat uptake is far more effective

Rose et al. (2014) GRL
Rayborn et al. (in prep.)



Shortwave feedbacks from low clouds are the largest contributions to the differences in efficacy

Rose et al. (2014) GRL
Rayborn et al. (in prep.)

The dominant sub-polar mode of **ocean heat uptake** has a **large efficacy.**
What are the implications for transient climate sensitivity?

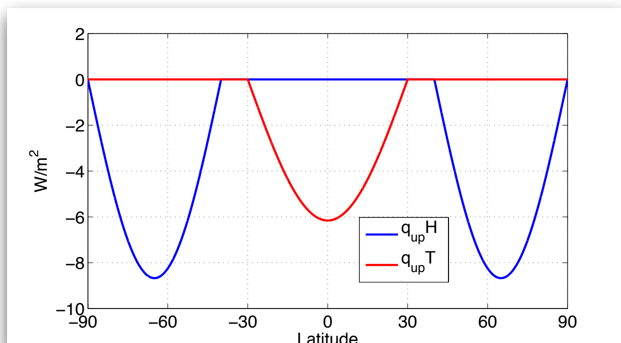
An illustrative linear model

*Suppose that the climate system behaves as a **linear system**,*
*so the transient response is **additive*:***

$$\Delta \overline{T}(t) = \Delta \overline{T_{CO2}} + \Delta \overline{T_{OHU}}(t)$$

** an excellent approximation for the aquaplanet GCMs*

<u>and</u> suppose that OHU is a linear combination of
two simple decaying modes (plus noise):



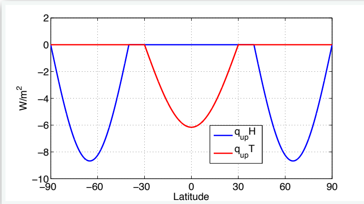
$$N(\mathbf{r}, t) = a_T(t) q_T(\mathbf{r}) + a_H(t) q_H(\mathbf{r})$$

$$a_T(t) = a_{T0} \exp\left(-t/\tau_T\right) + r_T(t) \qquad \tau_T = 20 \text{ years}$$

$$a_H(t) = a_{H0} \exp\left(-t/\tau_H\right) + r_H(t) \qquad \tau_H = 300 \text{ years}$$

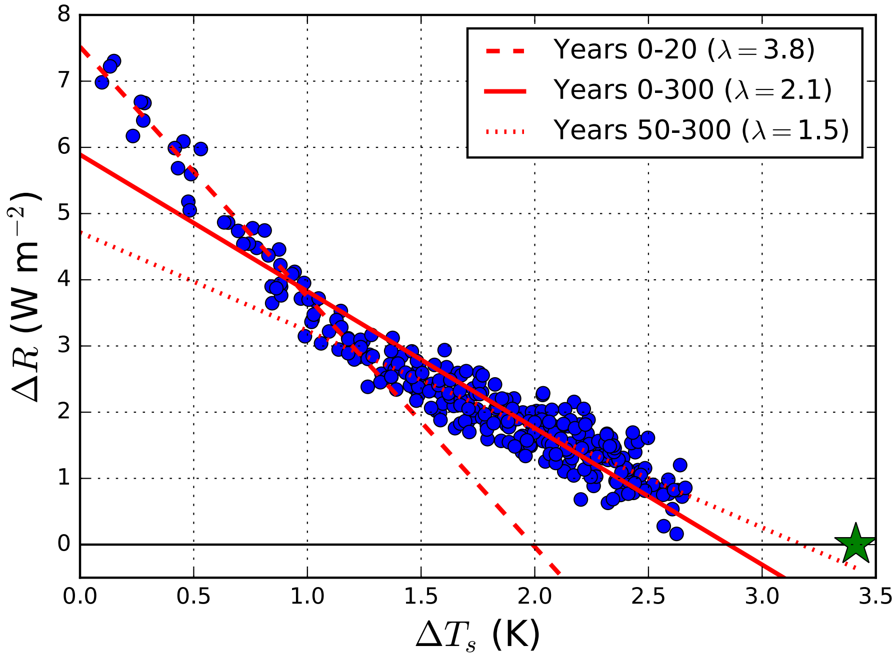
Use the single-forcing equilibrium responses of the aquaplanet GCM to
"reconstruct" offline the transient response of the linear model to abrupt 4xCO_2

Rose and Rayborn (2016) CCCR

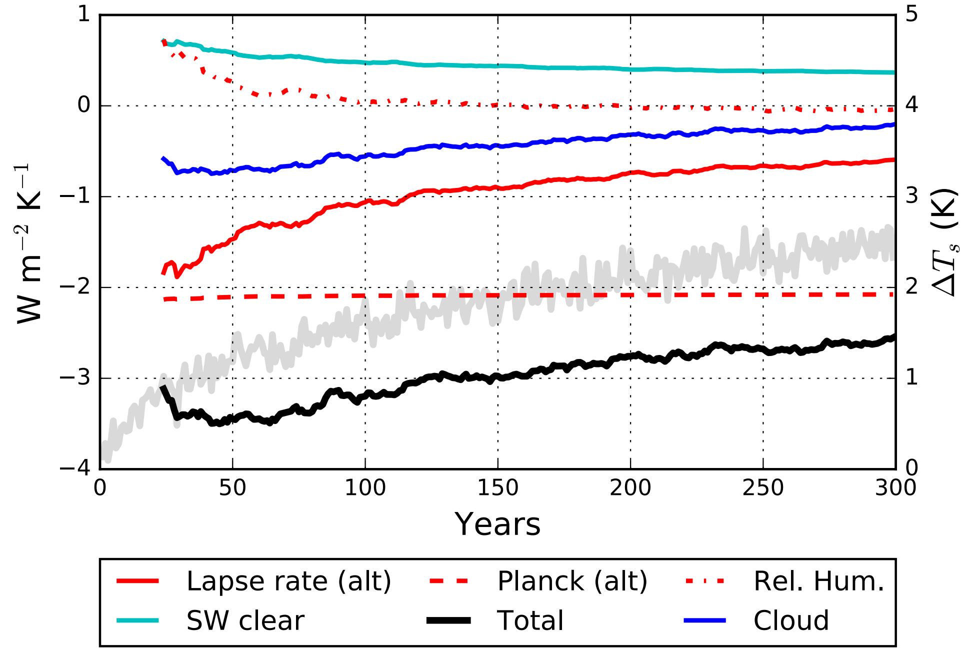


An illustrative linear model:

Time-dependent climate sensitivity from **decaying ocean heat uptake**



Feedback analysis using aquaplanet radiative kernels from Feldl and Roe (2013)

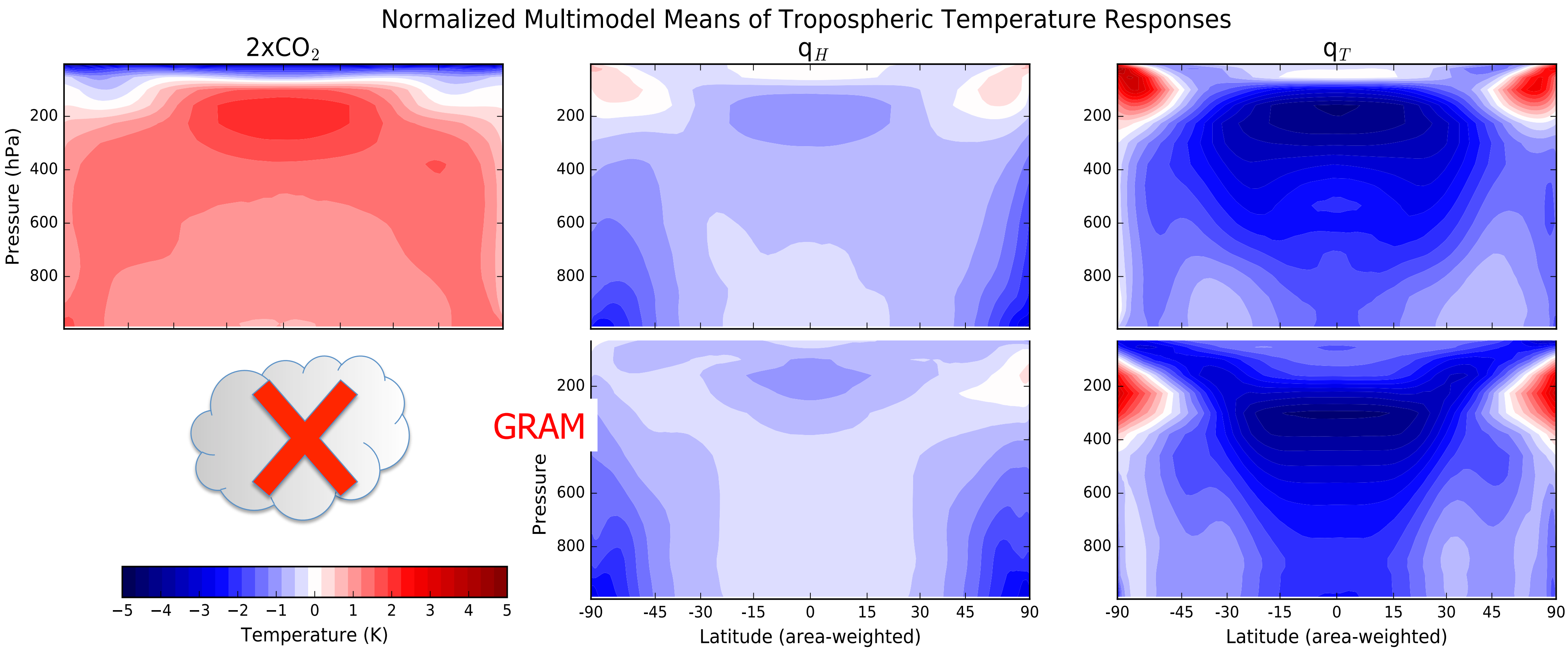


- Transient sensitivity increases over time, similarly to the coupled GCMs
- Regression lines all underestimate the (known) equilibrium sensitivity
- Drift to higher sensitivity on the long decay timescale of sub-polar heat uptake
- Kernel analysis: increased sensitivity is due to lapse rate and cloud feedbacks

Increasing sensitivity is a consequence of the slow decay of high-efficacy sub-polar mode of heat uptake

Rose and Rayborn (2016) CCCR

What determines the efficacy of ocean heat uptake?



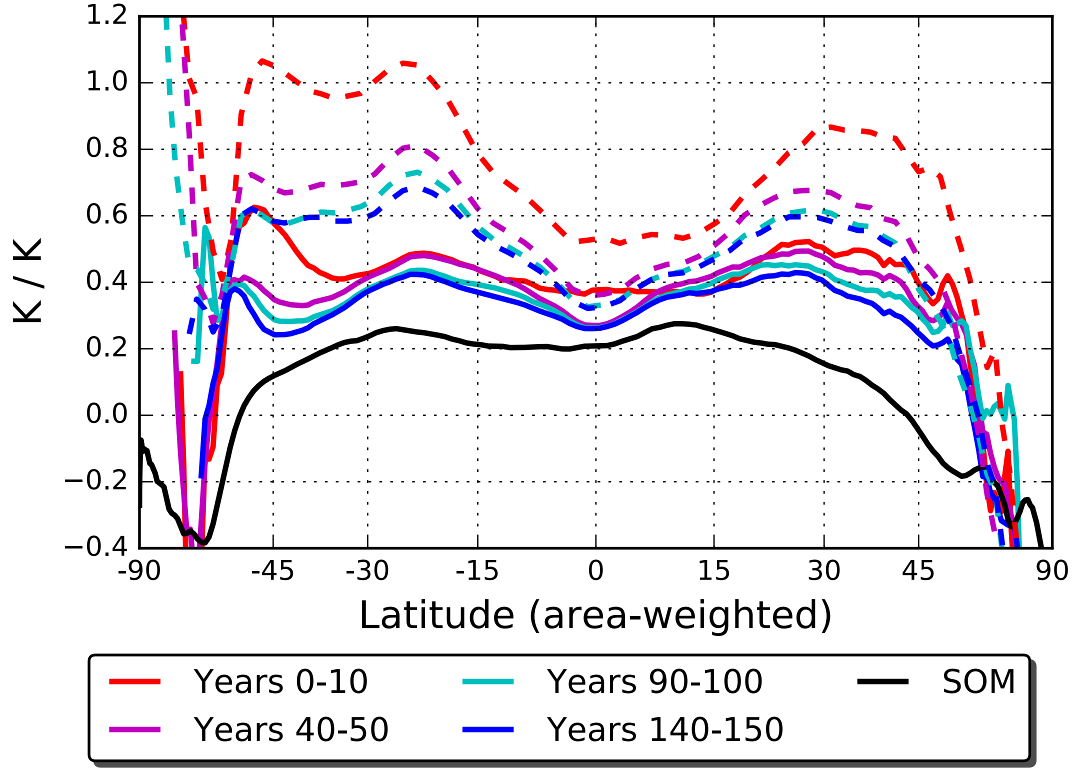
OHU —> lower tropospheric stratification —> low cloud changes

A metric for stability constraints on low-cloud feedbacks:

$\Delta EIS / \Delta T_s$ - EIS = "Estimated Inversion Strength" (Wood and Bretherton 2006)

How does the change in lower tropospheric stability per degree global warming vary over time in the coupled GCMs?

Two different CMIP5 models
- *GFDL-CM3* - - - - - - - -
- *CCSM4* ————



Inversion gets stronger with warming, but the rate of increase slows down with time. The surface starts to catch up with the warming mid-troposphere!

A probable cause for the trend toward more positive low-cloud feedbacks — and a subject for future work

Rose and Rayborn (2016) CCCR

Conclusions

- Does the **spatial structure** of ocean heat uptake affects its ability to delay global warming?
- **Yes:** sub-polar heat uptake is nearly 2x more effective than CO2 and 3-4x more effective than tropical heat uptake
- Low cloud feedbacks are an integral (but robust!) player in these efficacy differences
- Causal link appears to be through **lower-tropospheric stability**
    - ✤ Spatially localized ocean heat uptake is shaping global changes in stability, and thereby shaping global cloud cover and albedo
- Sub-polar heat uptake results in a temporary suppression of a positive low cloud feedback
- AR5 likely underestimates equilibrium sensitivity of the models

How much of the spread in low-cloud feedbacks in CMIP5 is actually driven in systematic ways by patterns of surface heat fluxes?

Idealized modeling of an idealized problem has led to new insight about a causal link between oceans and clouds that are probably operating in the full models, and perhaps even in nature

Rose, Armour, Battisti, Feldl and Koll (2014) GRL
Rose and Rayborn (2016) CCCR
+ Rayborn, Rose et al. (in prep.)