Some progresses regarding climate forcing and feedback analysis at McGill

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Outline

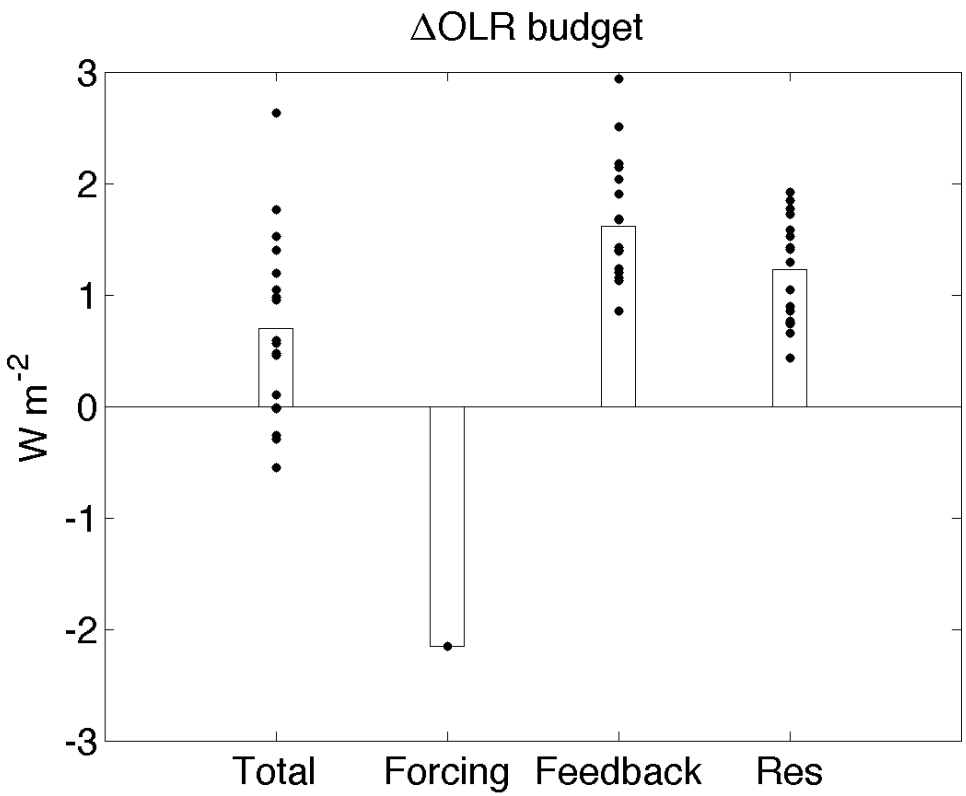
- A new forcing analysis method
- Radiative forcing of 4xCO2
- Stratospheric feedback
- Poleward heat transport in warmer climate

How well is the radiation budget understood?

- $\Delta R = \Delta R_{Forcing} + \Sigma(\Delta R_{Feedback}) + res$

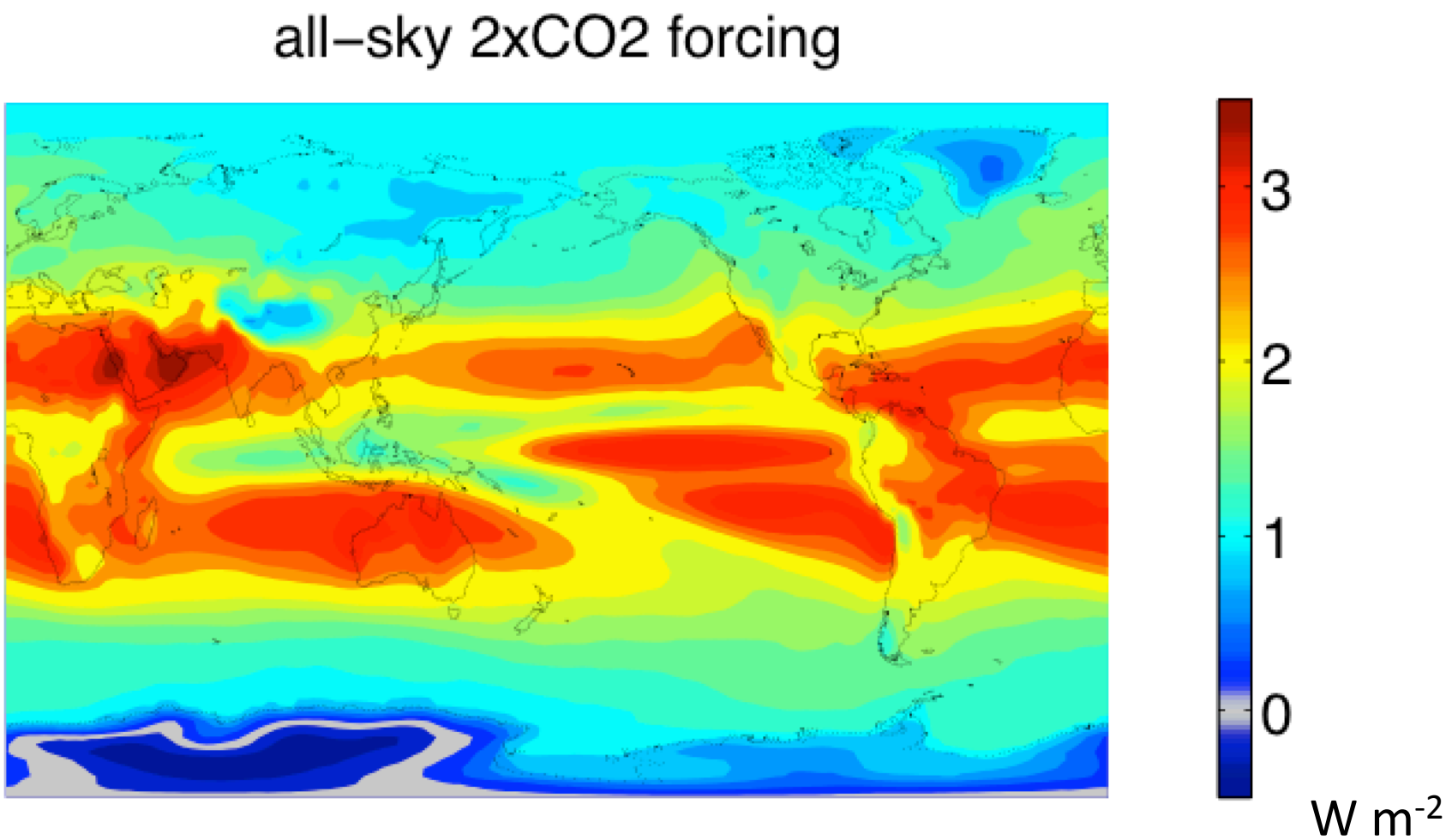
- Outstanding issues [Huang 2013 J. Clim.]:
  1) Considerable magnitude
     $Res/\Delta R \sim O(100\%)$
  2) Substantial inter-model spread;
  3) Significant corr(res, ΔT_S)
     (r = 0.55, 18 models)

- Suspects:
  1) Forcing uncertainty
[Zhang&Huang, accepted, J. Clim.]
  2) Stratospheric effect
[Huang et al. 2014 AGU talk]



Huang 2013 J. Clim.

Forcing uncertainty



Geographic variation reflects forcing dependence on climate state.

Estimate forcing

- A new proposal [Huang 2013; Zhang&Huang 2014]:

  1) Obtain clear-sky forcing G^C based on ΔR breakdown:

  $$G^C = \Delta R^C - \Sigma(\Delta R^C_X)$$

  Here we use kernels for non-cloud feedbacks ΔR^C_X (T and w.v.)

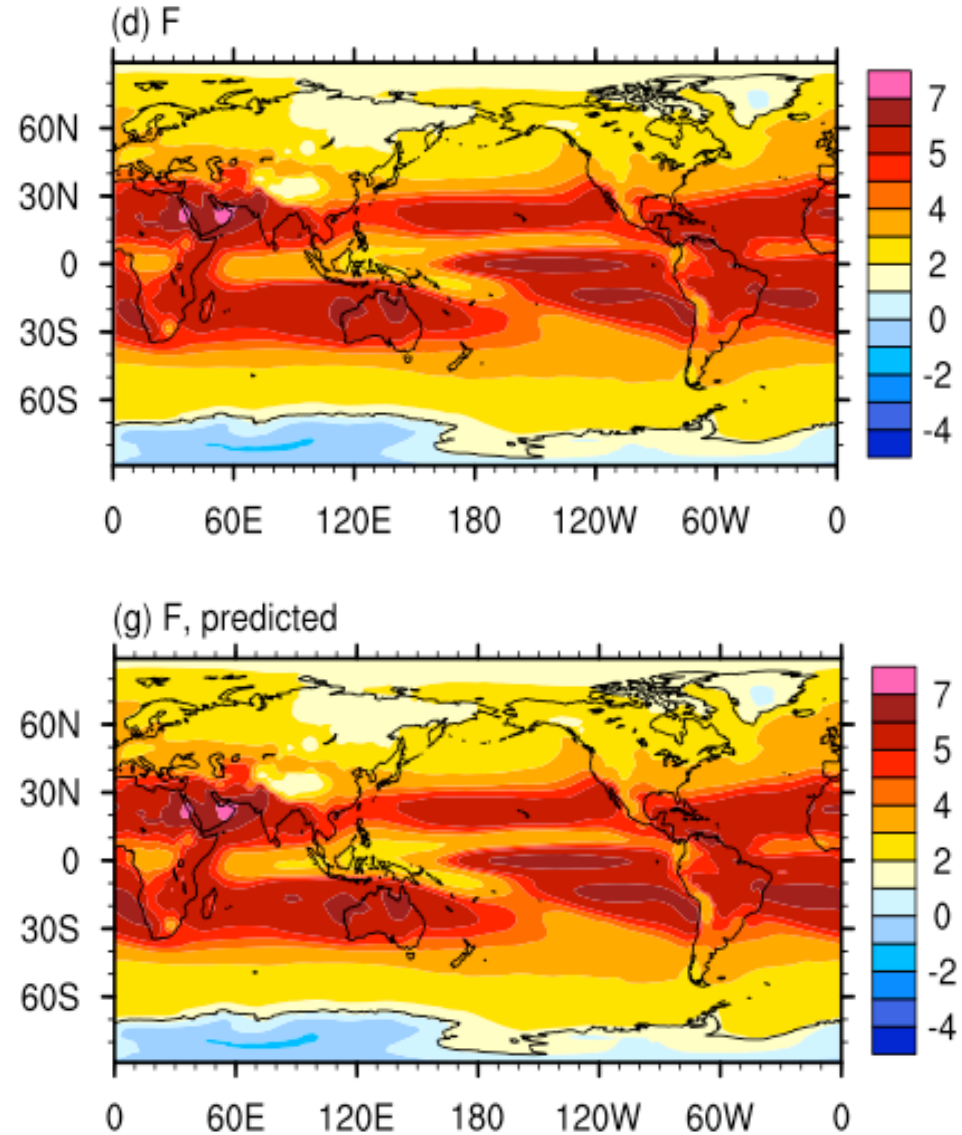
  $\Delta R_X = (\partial R/\partial X)dX$;

  2) Obtain all-sky forcing using cloud-forcing scaling $G^C/G=1.16$, or better:

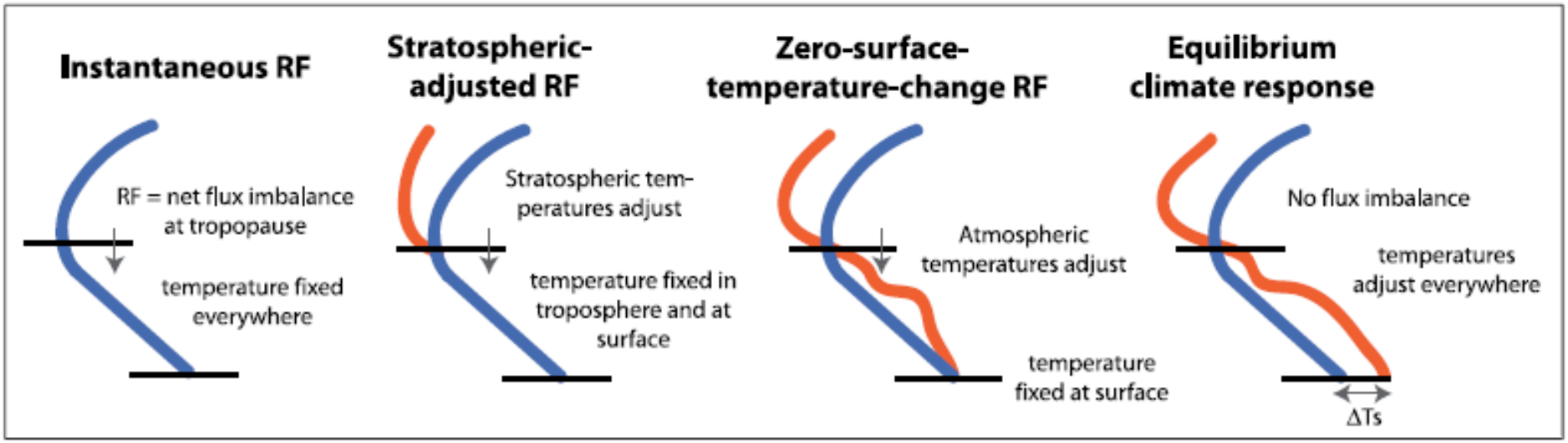
  $$(G^C-G)/G^c_{ref} = (0.16/1.16)*(CF/CF_{ref})$$

  CF: cloud forcing: R^C-R

$4xCO_2$ forcing, W m^{-2} [Zhang&Huang 2014]



Radiative forcing components



$$G = F_i + F_S + F_T$$

F_i : instantaneous forcing

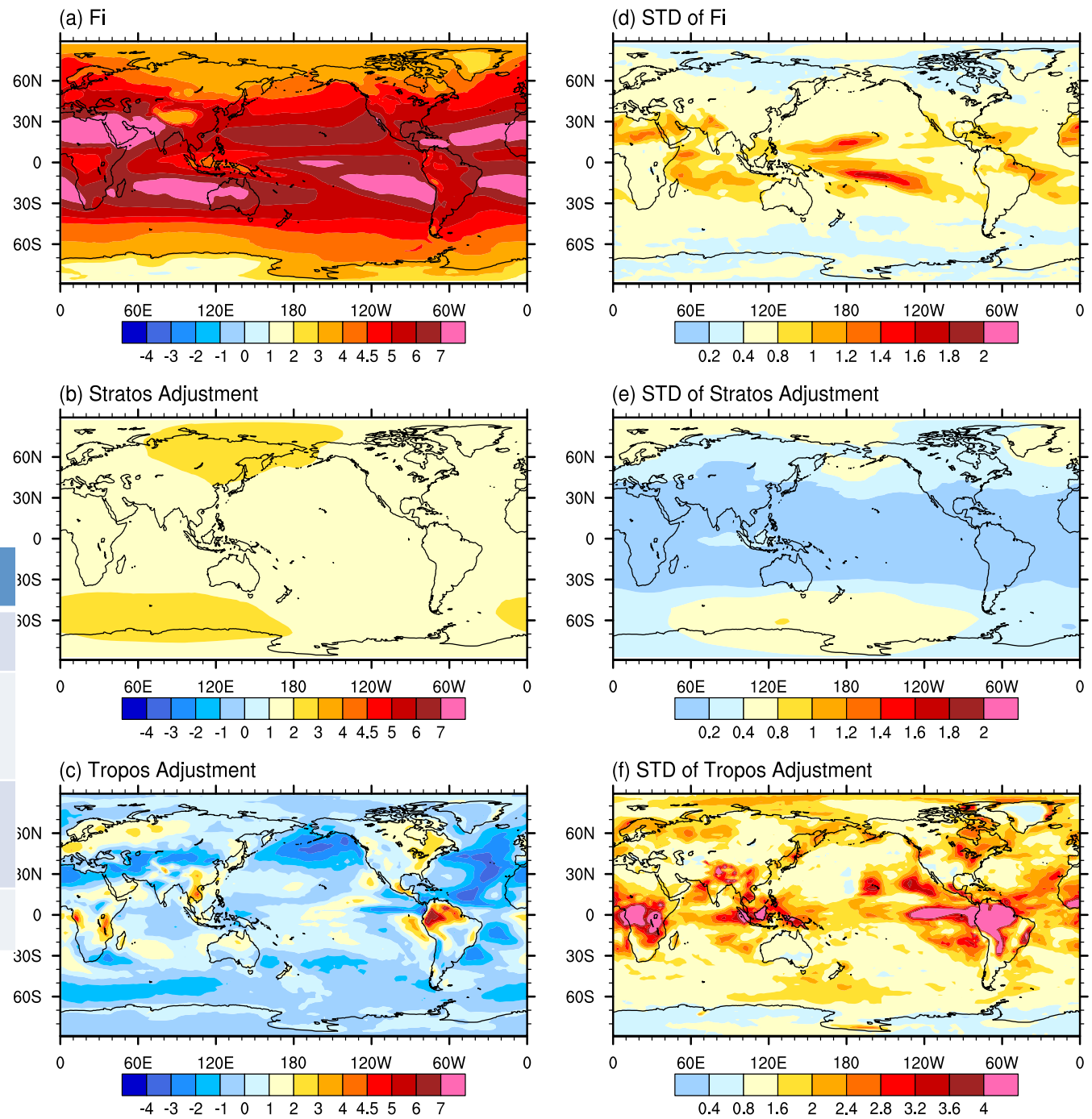
F_S : stratos adjustment

F_T : tropos adjustment

$4xCO_2$ Forcing components and their uncertainties

Global mean

Unit: W m^{-2}	mean	std
Inst forcing	5.3	0.5
Strat adjmnt	1.9	0.2
Trop adjmnt	-0.1	0.5
Total	7.2	0.7



Contribution to temperature projection uncertainty

$\Delta R = \Delta R_F + S^{-1}\Delta T_S$ => error budget of ΔT_S :

$$\delta(\Delta T_s) = \frac{\delta(\Delta R - \Delta R_F)}{(S^{-1})_m} - (\Delta T_s)_m \frac{\delta(S^{-1})}{S^{-1}}$$

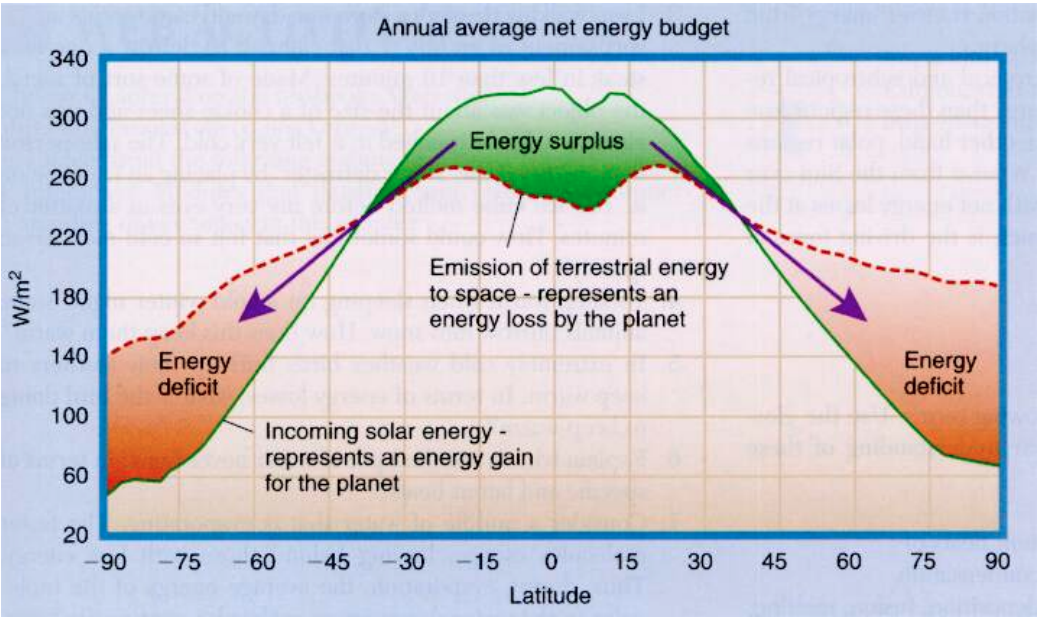
1.0 K 1.3 K

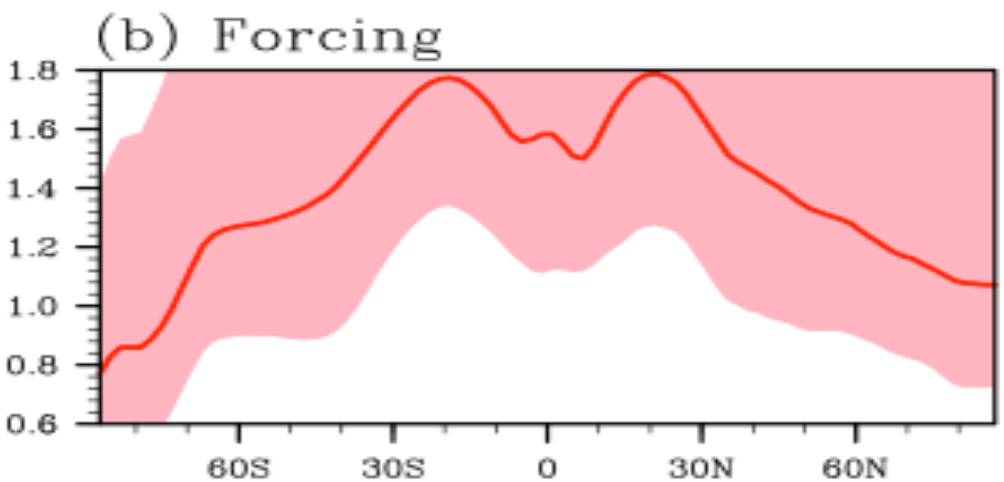
$\delta(\Delta R) \sim \delta(\Delta R_F)$

=> Forcing uncertainty $\delta(\Delta R_F)$ accounts for about 1/4 of the inter-model spread in surface warming projection.

(in agreement w/ Geoffrey et al. 2012; Webb et al. 2012)

Non-uniform forcing => more poleward energy transport



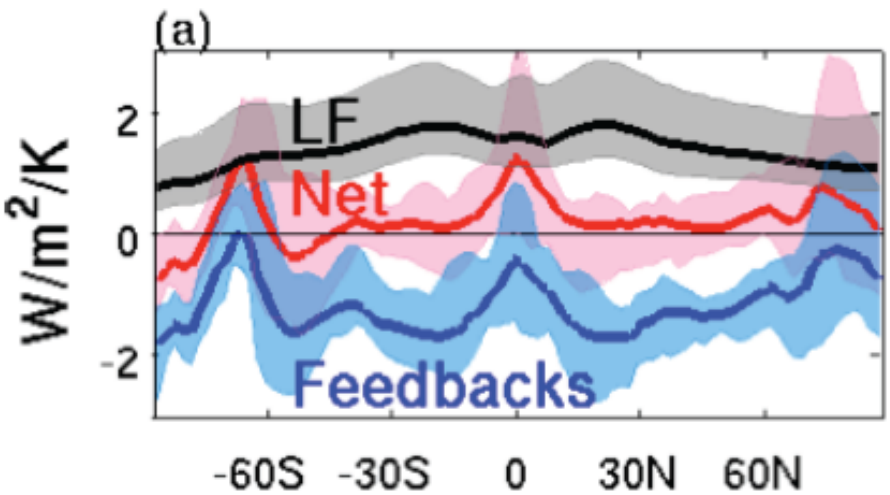


- Net radiation: surplus at equator, deficit at poles.
- PET required for balancing energy budget in each latitude band.
- Radiative forcing of GHG deepens latitudinal radiation imbalance and thus requires more PET. [Huang&Zhang, submitted]
- Note enhanced PET is a general feature shown by GCMs [e.g. Held&Soden 2006]

Zonal mean ΔR and implied ΔPET

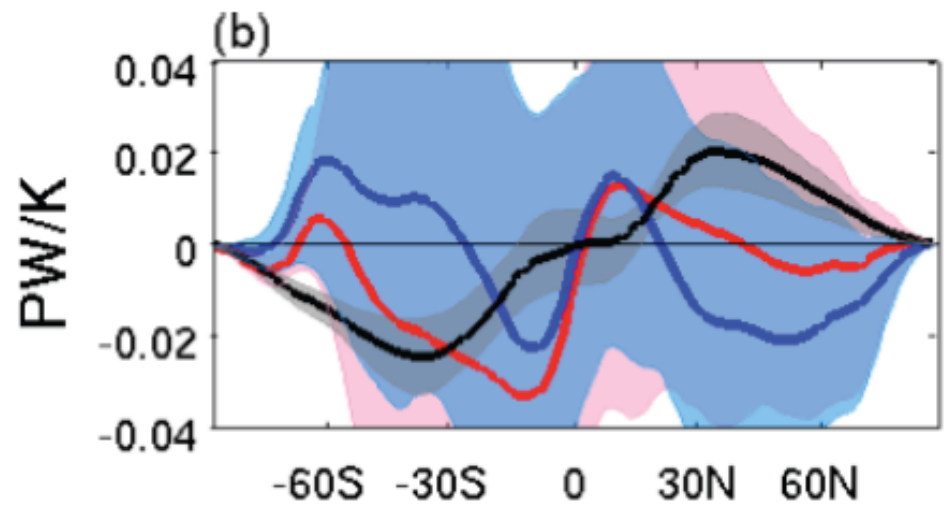
CMIP5 4xCO2 experiment

ΔR due to forcing and feedback



Implied transport

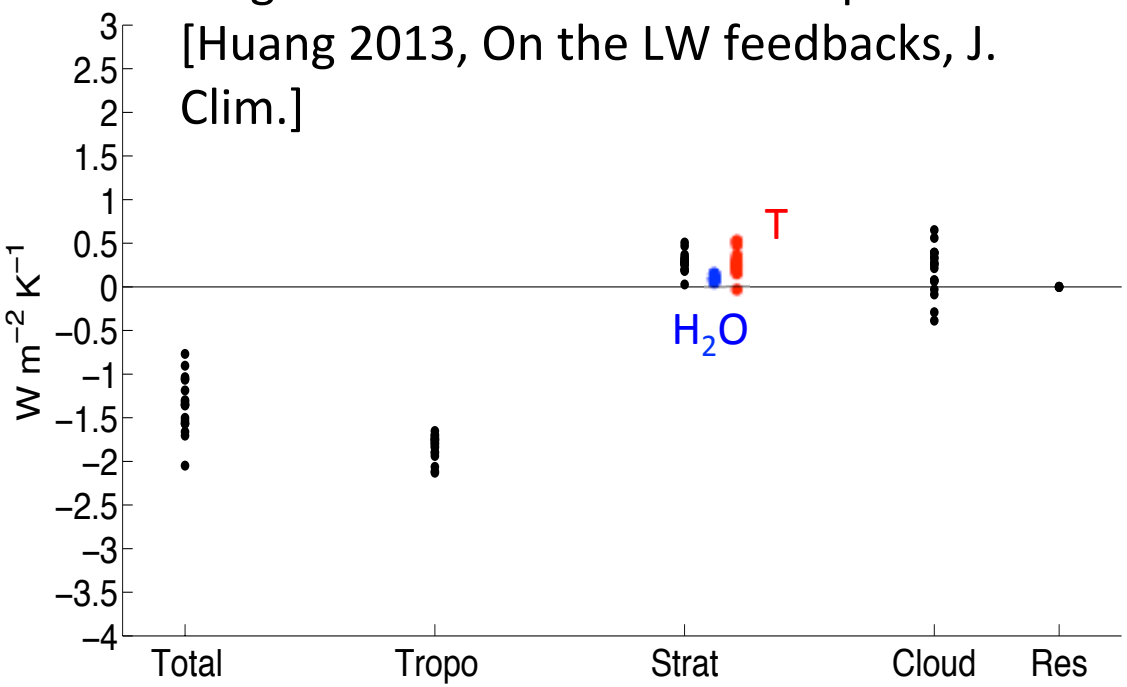
$$F(\phi) = \int_{-\frac{\pi}{2}}^{\phi}\int_{0}^{2\pi} R'_X(\lambda,\phi)\alpha^2 \cos\phi \, d\lambda \, d\phi$$



- It is forcing, rather than feedback as suggested by Zelinka&Hartmann [2012], that deepens latitudinal gradient of net radiation and demands more PET.

Stratospheric radiative effect: important, poorly quantified

Diagnosis of the CMIP3 A1B experiment [Huang 2013, On the LW feedbacks, J. Clim.]



Radiative effects of stratospheric T and H_2O are assessed by the kernel method :

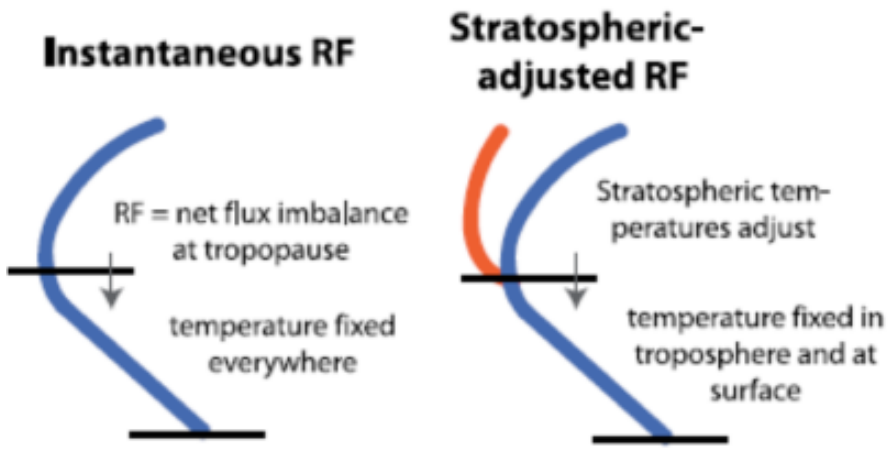
$\Delta R_X = (dR/dX)\ \Delta X$

(R: TOA radiation)

	Mean/Std
Tropo	-1.84 ± 0.14
Strato	0.30 ± 0.12
Cloud	0.19 ± 0.27

- Much inter-model spread in stratospheric radiative effect, dominated by temperature contribution

Conventional wisdom: Stratospheric radiative effect is a forcing effect



Diagnostic equation for climate change

$$N = F + \lambda \Delta T_S$$

N: Net radiation

F: Radiative forcing

λ: Climate sensitivity (feedback) parameter

ΔT_S: Surface temperature change

- Forcing
  e.g. T change due to CO_2
- Feedback
  e.g. Water vapor [Forster&Shine 1997; Stuber et al 2001; Huang 2013; Dessler et al 2013 …]

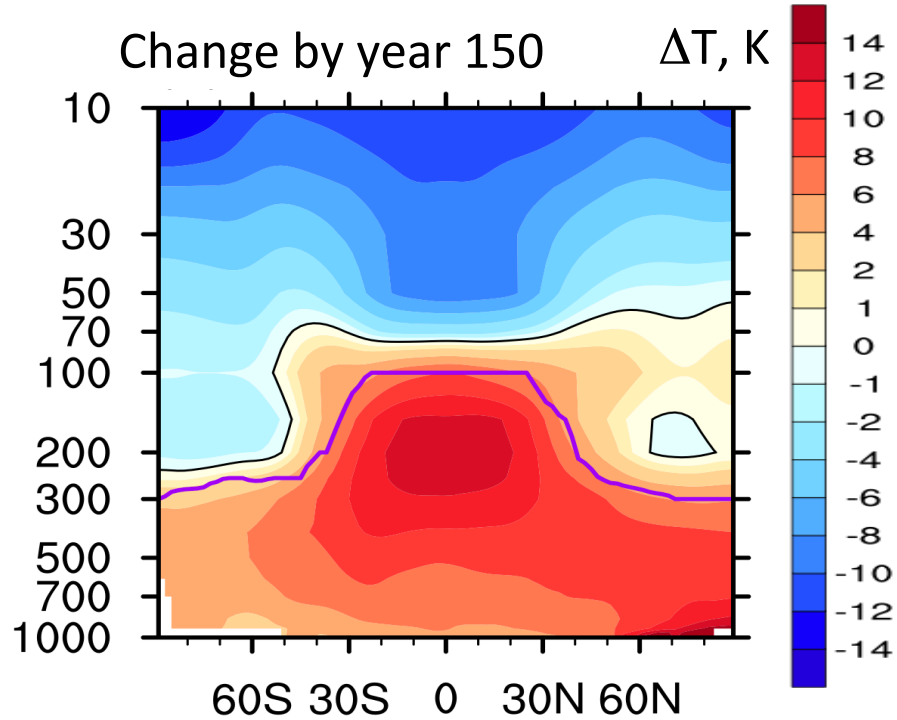
A new diagnosis

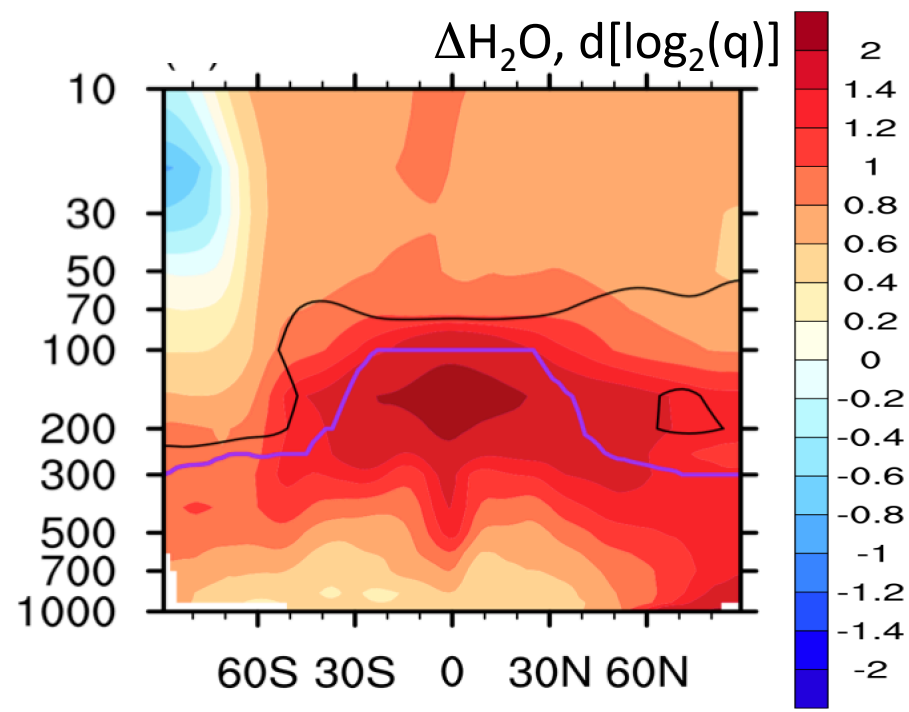
- CMIP5 experiments
  - AOGCM Abrupt4xCO2: 150-yr run, instant quadrupling (cntl: piControl)
  - AGCM sstClim4xCO2: 30-yr run, instant quadrupling while fixing SST (cntl: sstClim)

- Adjustment
  sstClim4xCO2: $(\Delta T)_{adj} = (\Delta T)_{fixed\text{-}SST}$

- Feedback
  abrupt4xCO2: $(\Delta T)_{total} - (\Delta T)_{adj}$

- Diagnosis method [Zhang&Huang 2014, Rad Forcing of $4xCO_2$, J. Clim.]
  Model-dependent geographical forcing distribution





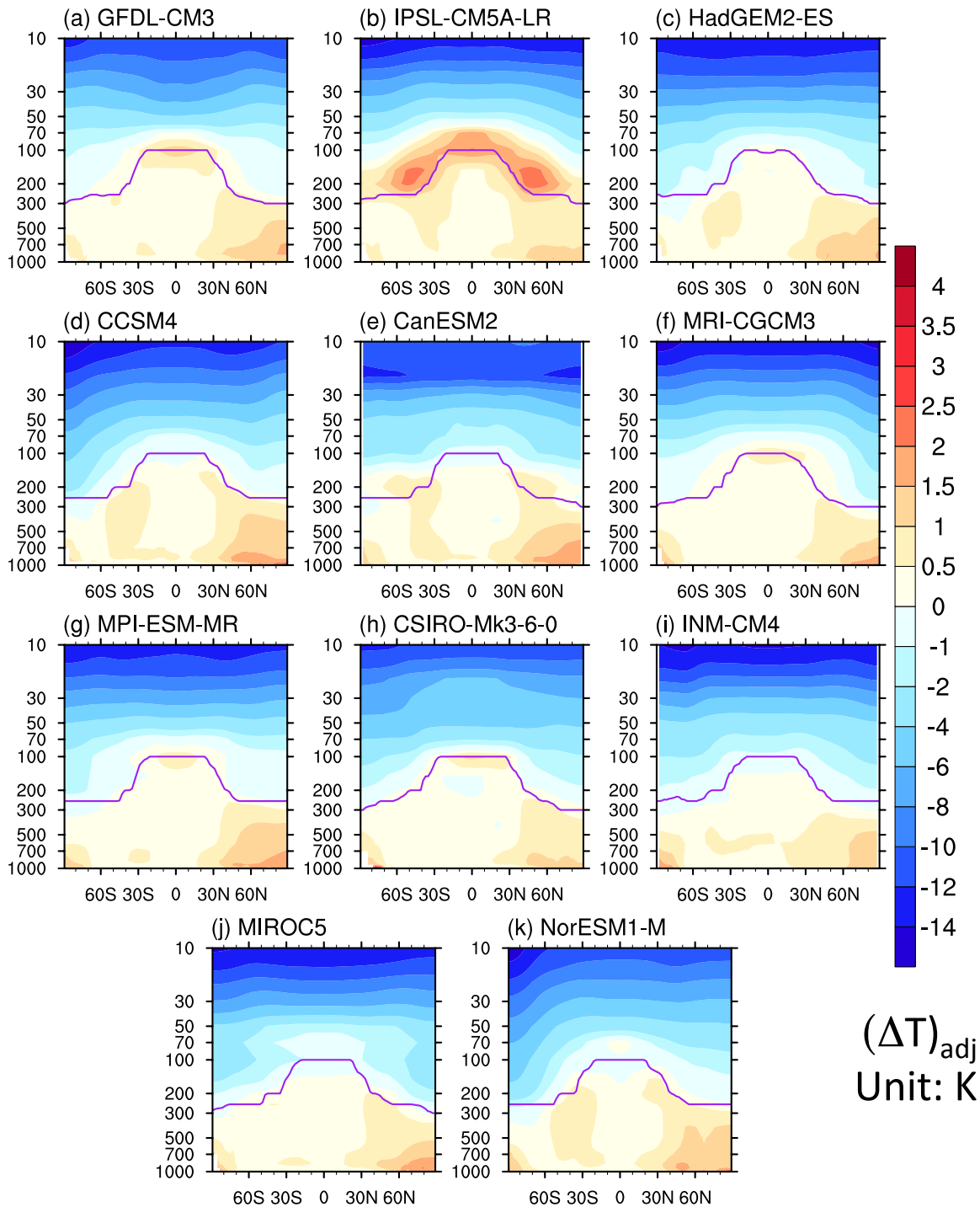
Forcing adjustment

- Stratospheric adjustment:
  $(\Delta T)_{adj}$ = sstClim4xCO2 – sstClim
  $\Delta R_{adj} = (dR/dT)\,(\Delta T)_{adj}$

- $\langle F_{inst} \rangle = 5.4\ W\ m^{-2}$
  $\langle \Delta R_{adj} \rangle = 1.9\ W\ m^{-2}$

- Radiative effect:
  Inter-model spread (max-min) = 30% of mean
  (forcing uncertainty)

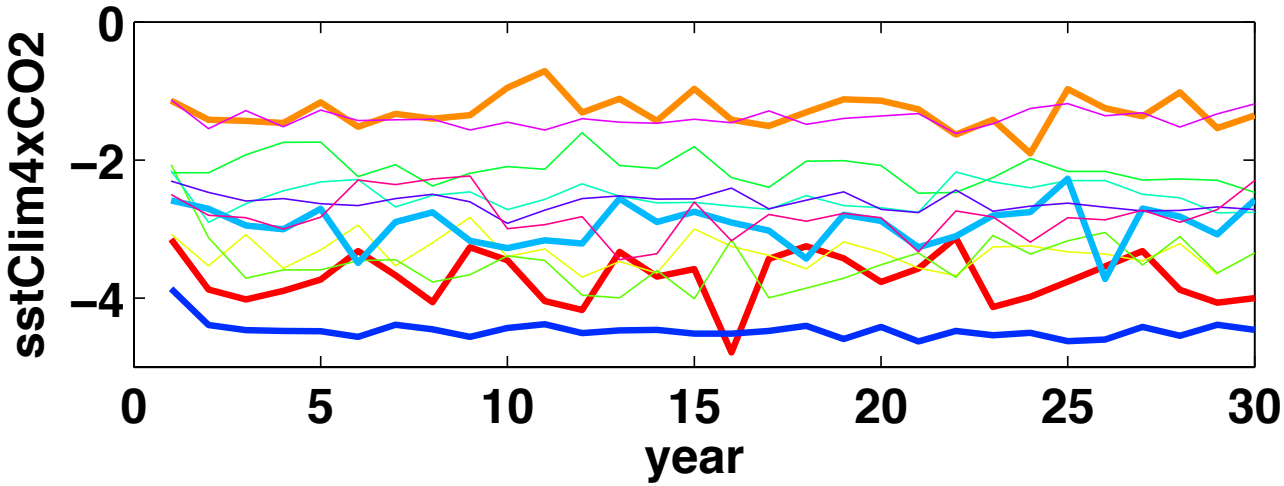
⇒ Caution: uncertainty in the forcing! [Huang 2013; Zhang&Huang 2014]



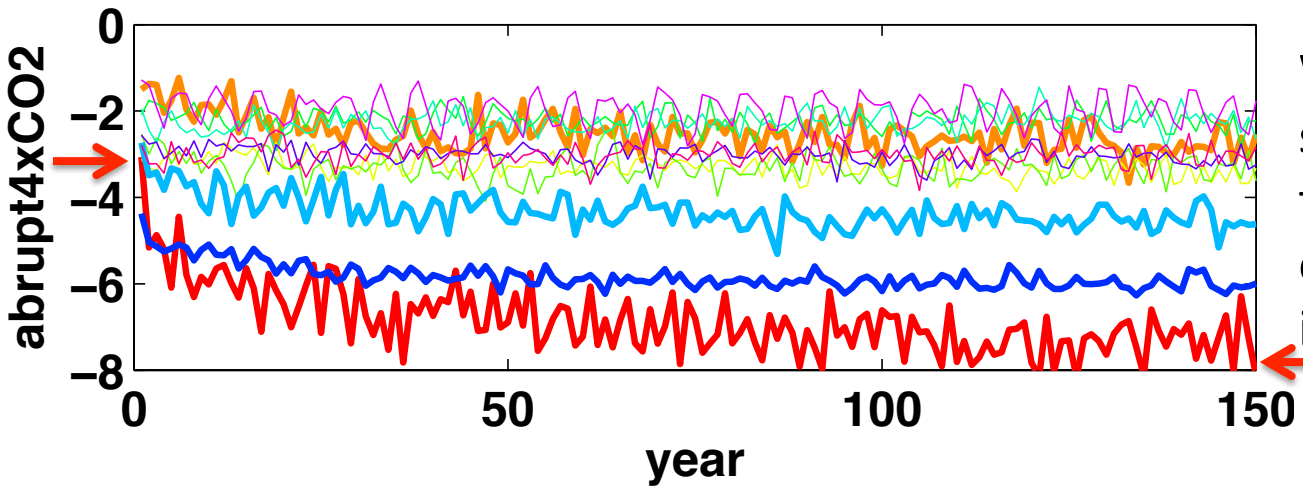
$(\Delta T)_{adj}$
Unit: K

Continued temperature change in the stratosphere

Global mean Ta (50 hPa) change, unit: K



When SST fixed, adjustment rapidly attained.



When SST varies, stratospheric temperature continues to vary in many models.

Feedback

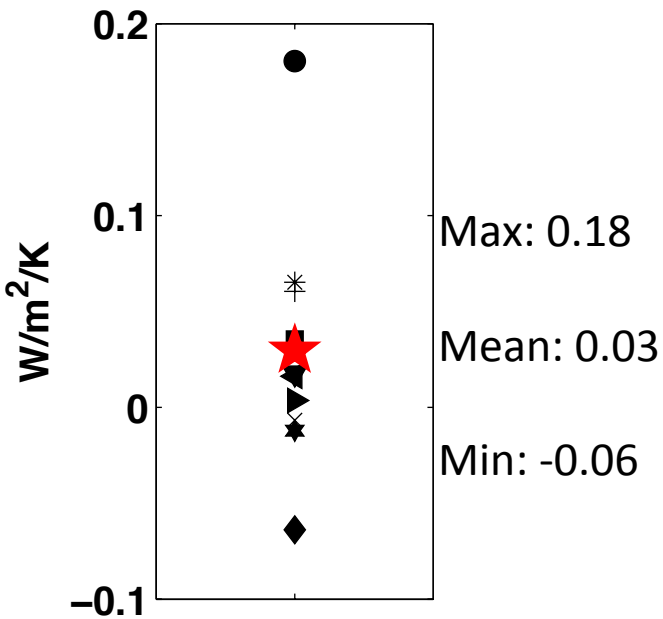
$$N = F + \lambda \, \Delta T_S$$

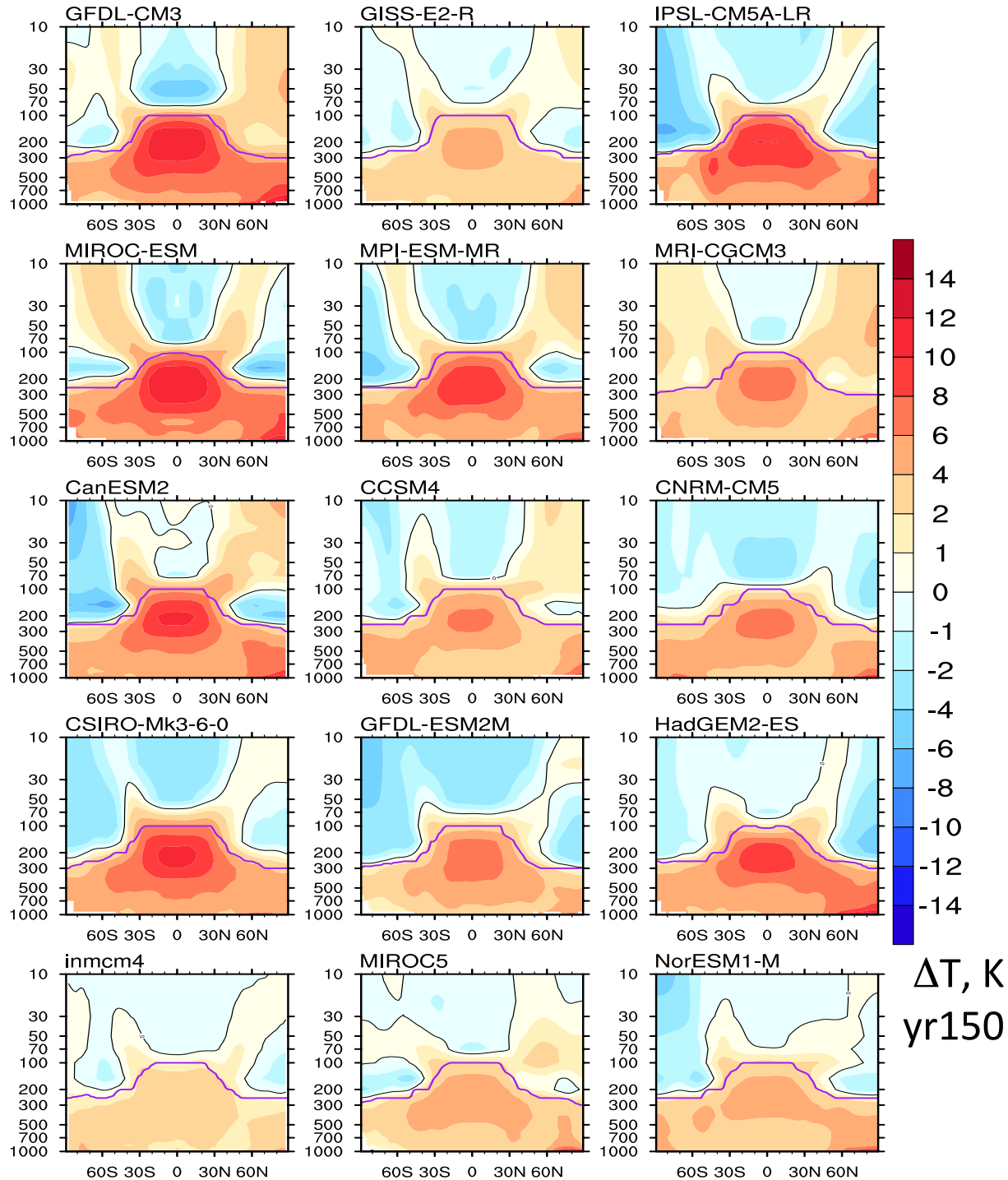
- Stratospheric T feedback

  $\Delta R_X = (dR/dX)\, \Delta X$

  $\lambda_X = \langle \Delta R_X \rangle / \langle \Delta T_S \rangle$

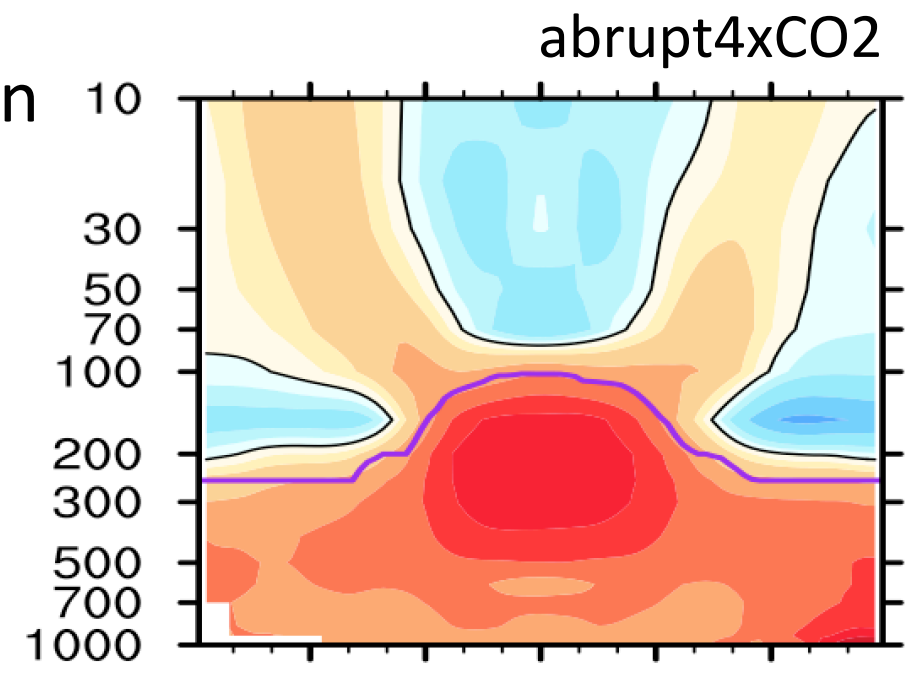
  $\langle \ldots \rangle$ global mean

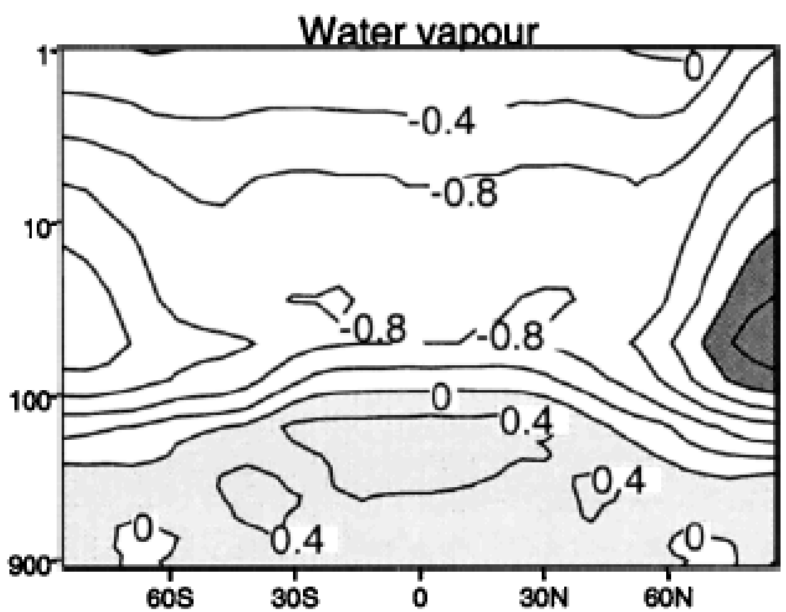




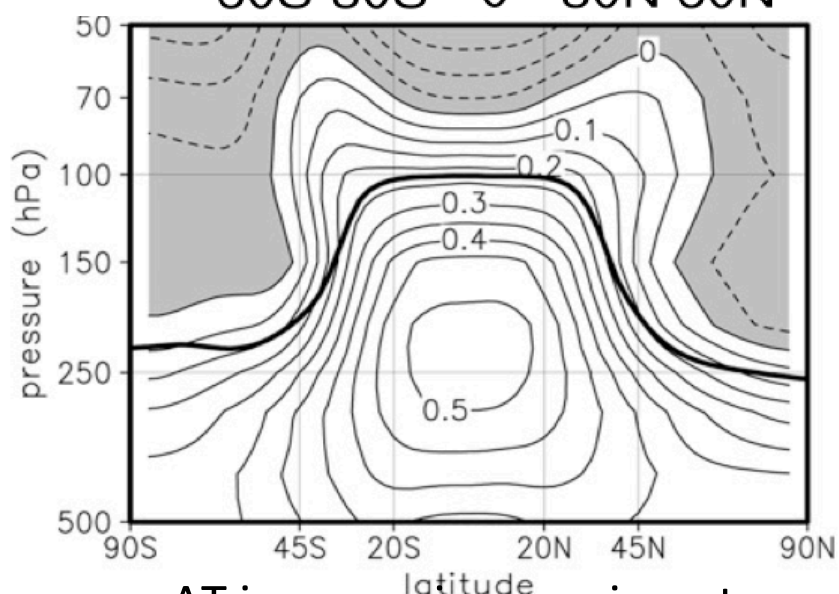
Stratospheric T change pattern

- Warming extending from the subtropical lower stratosphere region upward and poleward to middle and upper stratosphere; cooling elsewhere.





ΔT due to H_2O [Forster&Shine 1997]



ΔT in scenario experiments [Son et al 2009]

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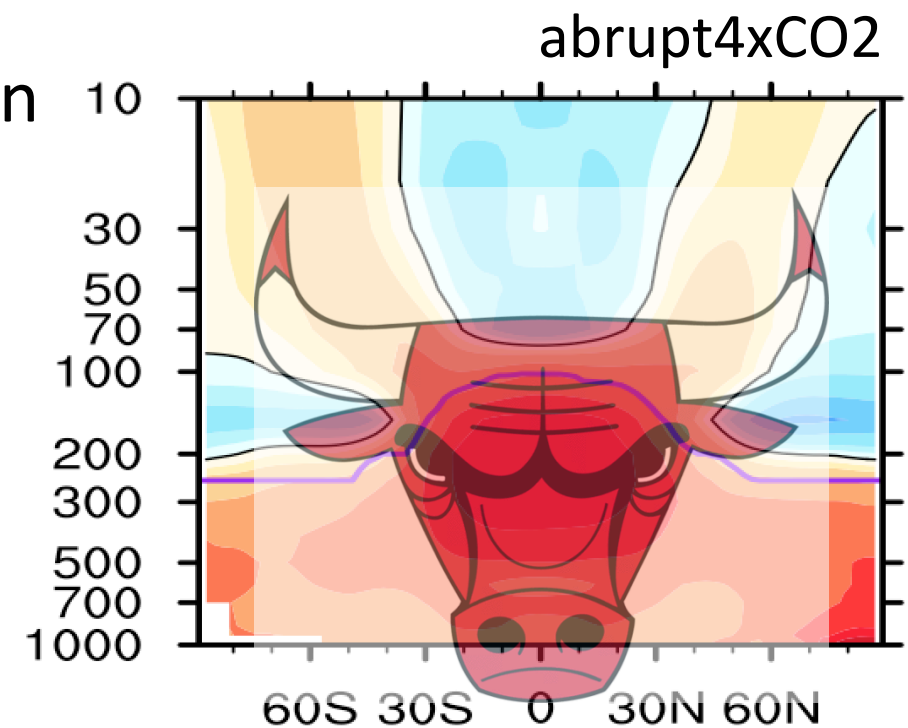

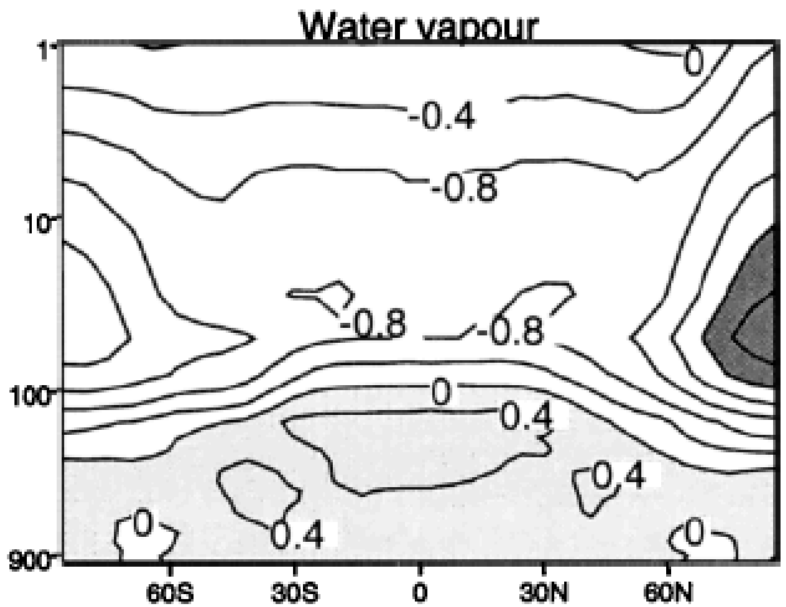

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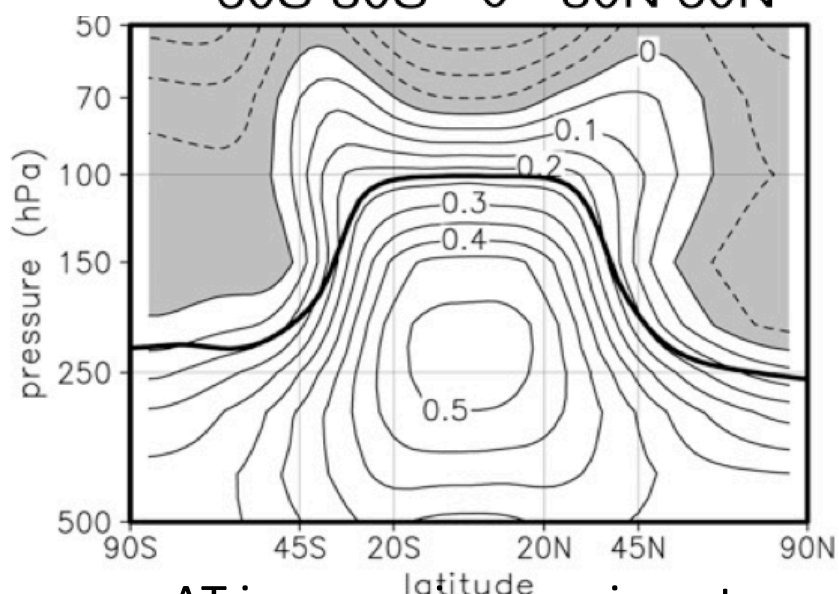
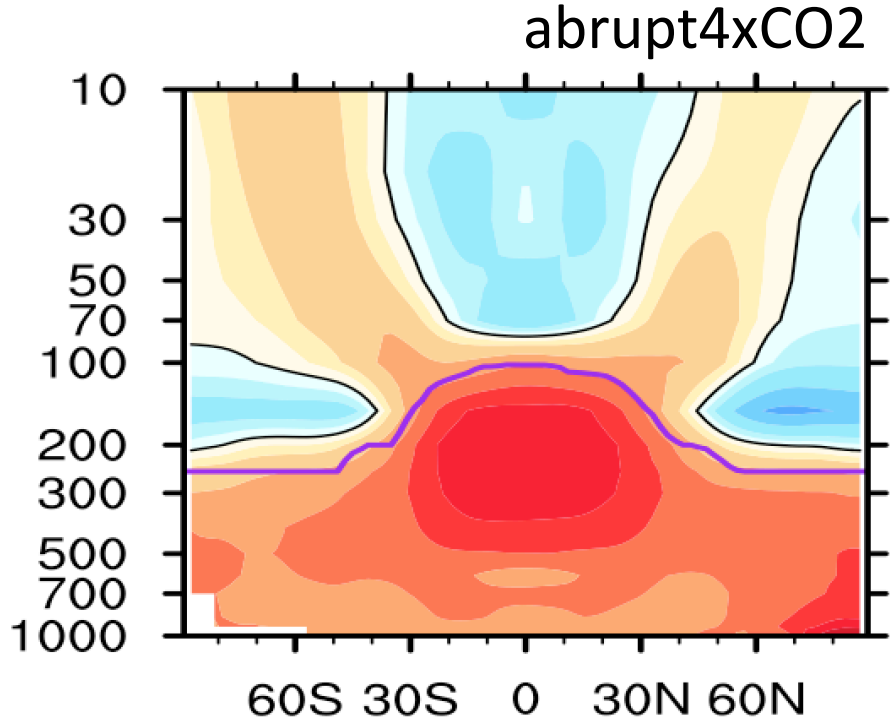


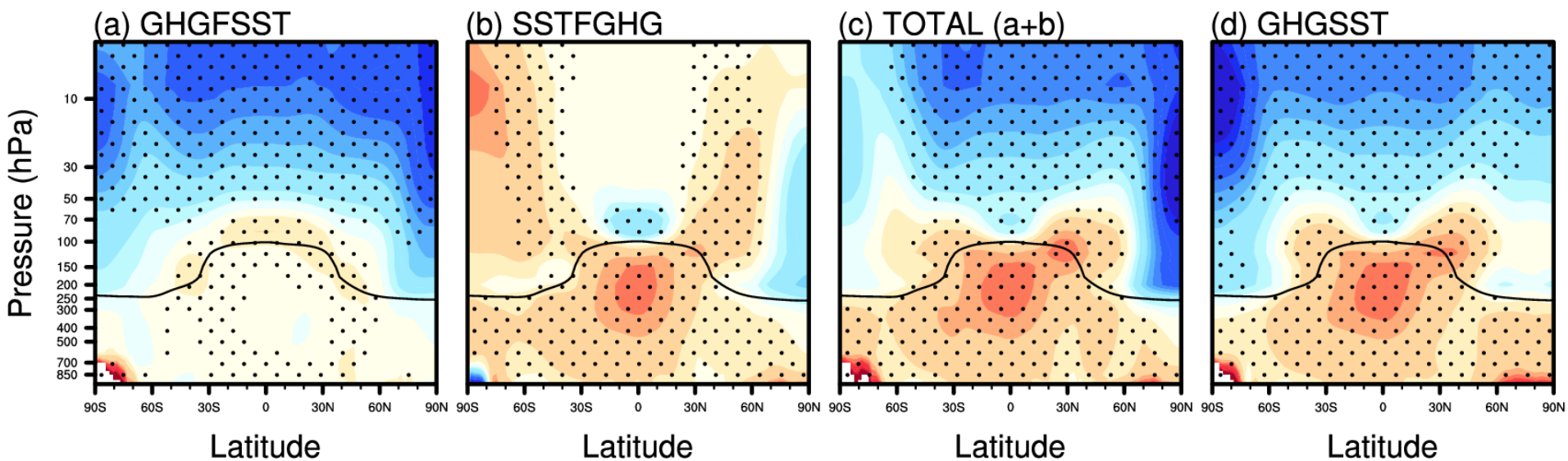
ΔT in scenario experiments [Son et al 2009]

A further diagnosis of ΔT_{strat}

- NCAR CAM5, integrated from 1960 to 2007
  a) varying GHG, fixed SST
  b) varying SST (historical), fixed GHG
  c) results of a + b
  d) varying SST and GHG

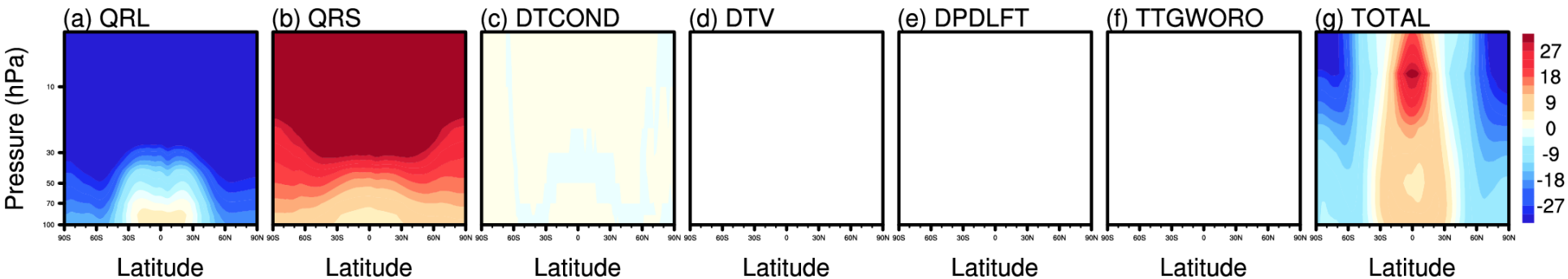
- Similar temperature feedback response pattern reproduced.





Attributing ΔT_{strat}

Dissecting the temperature tendency simulated in the CAM5 experiment



QRL: Longwave heating rate

QRS: Solar/Shortwave heating rate

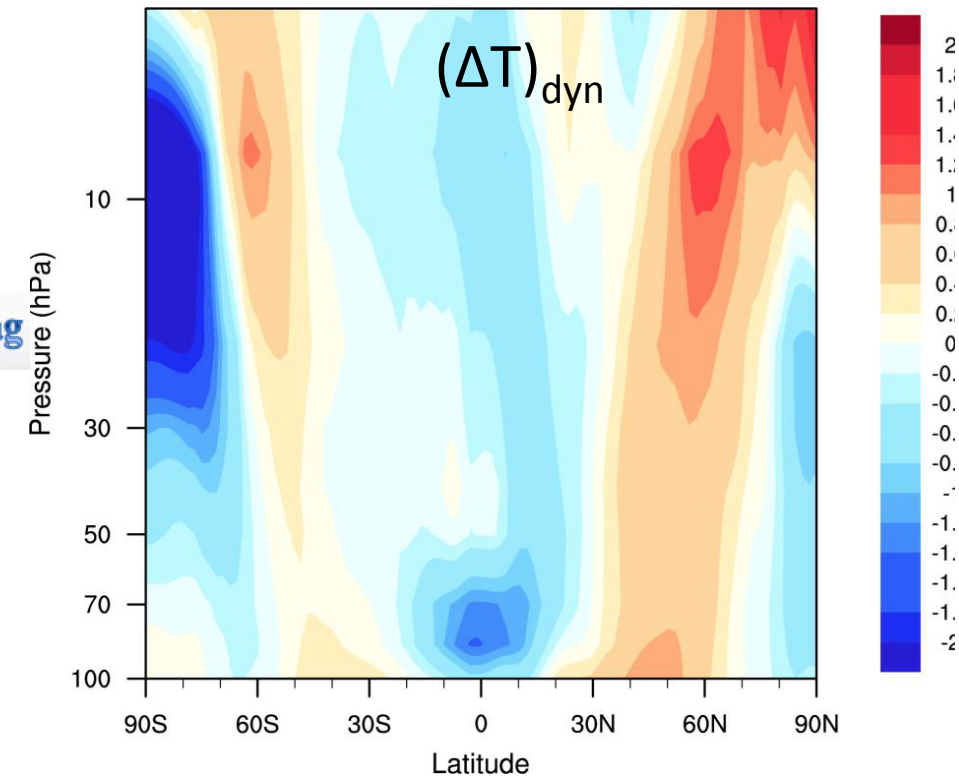
DTCOND: T tendency - Moist processes

DTV: T tendency - Vertical diffusion

DPDLFT: T tendency – Deep convective detrainment

TTGWORO: T tendency – orographic gravity wave drag

Change in the temperature tendency due to dynamics (as opposed to physics) well corresponds to the temperature change pattern.



Stratospheric temperature feedback strength

- CAM5 experiment (1960-2007)

  Instantaneous TOA forcing by GHGs:

  $1.2\ W\ m^{-2}$

  Forcing adjustment due to ΔT_{strat}:

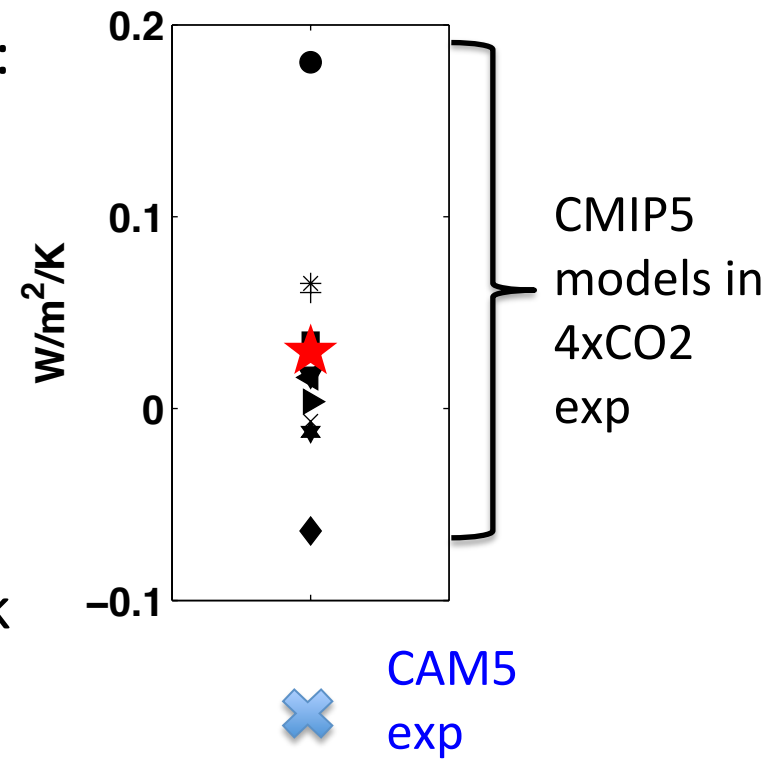
  $0.32\ W\ m^{-2}$

  Global mean ΔT_S:

  0.47 K

  Stratospheric temperature feedback (ΔT_{st} due to SST):

  $-0.17 W\ m^{-2}\ K^{-1}$



Summary

- A radiative forcing diagnosis method is developed for GCM feedback analysis.
- Forcing uncertainty contributes to GCM projection uncertainty.
- Non-uniform distribution of greenhouse gas forcing increases the latitudinal net radiation gradient and demands more poleward energy transport in a warmer climate.
- There is a non-negligible stratospheric feedback in some GCMs.

1) Huang, Y., (2013), On the longwave climate feedback. J. of Climate, 26, 7603–7610. doi:10.1175/JCLI-D-13- 00025.1.

2) Huang, Y., and M. Zhang, The implication of radiative forcing and feedback for poleward energy transport, Geophys. Res. Lett., submitted.

3) Huang, Y., M. Zhang, Y. Xia, Y. Hu and S. Son (2013), Is there a stratospheric feedback, AGU Fall meeting, San Francisco. (paper in prep)

4) Zhang, M. and Y. Huang, (2014), Radiative forcing of quadrupling CO2, J. of Climate, accepted.