The Unknowns of the Radiative Forcing of Doubling CO_2

Yi Huang, Minghong Zhang, Maziar Bani Shahabadi

Department of Atmospheric and Oceanic Sciences

McGill University

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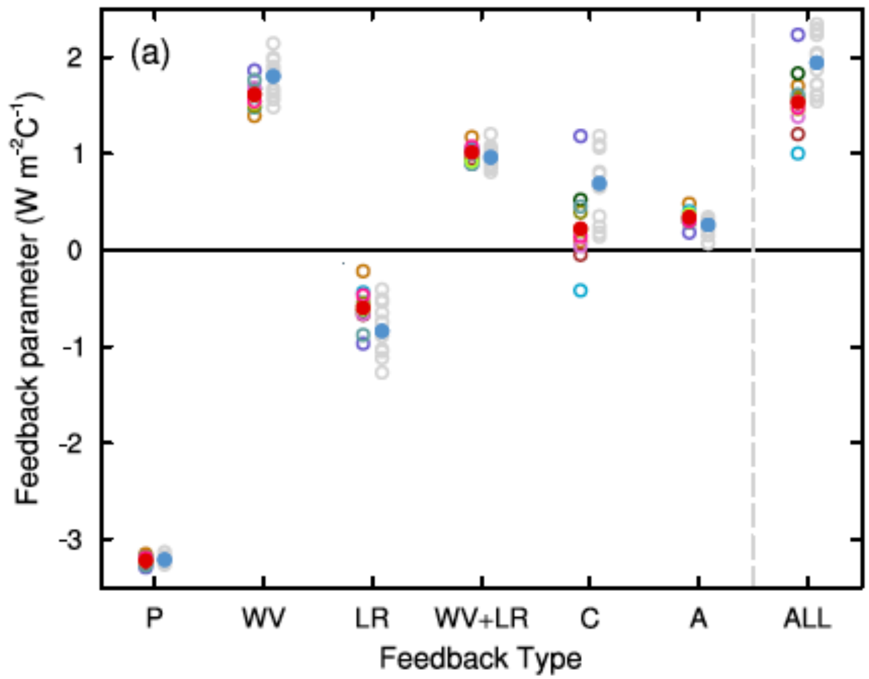
Radiative feedback analysis: breakdown of the ΔR budget

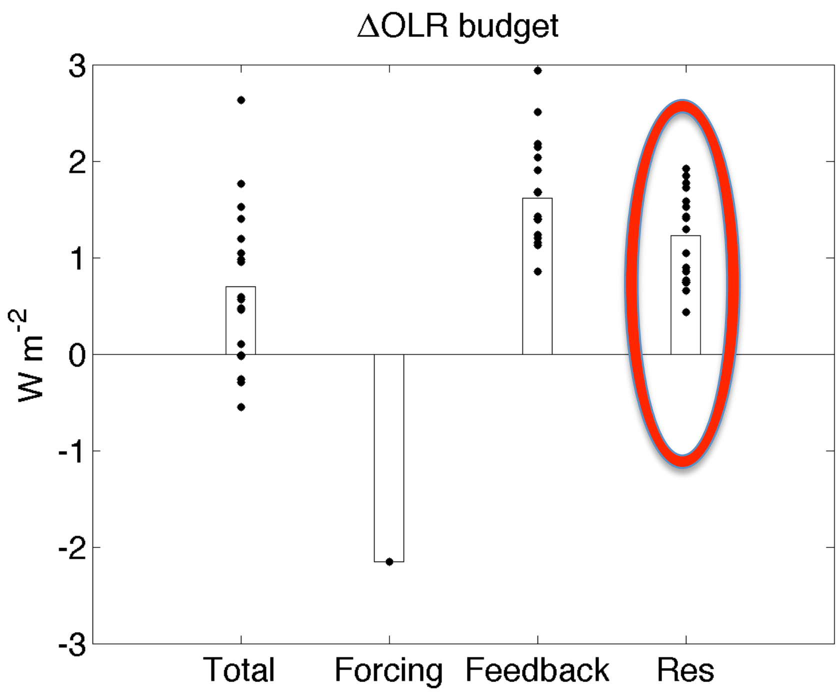


IPCC AR5 Fig 9.43

Analysis of radiative feedbacks essentially decomposes the change in radiation energy budget: $\Delta R_{total} = F + \Sigma(\Delta R_X)$ + Res

ΔR_{total}: change in net radiation;
F: radiative forcing
ΔR_X: partial contributions, i.e., feedbacks
$\Delta R_X = (dR/dX)\ \Delta X$: kernel method [Soden et al. 2008]

Radiative feedback analysis: unclosed radiation budget



Huang 2013 J. Clim.

$$\Delta R_{total} = F + \Sigma(\Delta R_X) + Res$$

The radiation budget is NOT closed – considerable residual not explained in the decomposition of ΔR!

- ΔR_X – e.g., stratospheric feedback? [Huang 2013; Huang et al. under review]
- F – instantaneous forcing + rapid adjustments [focus here!]

Radiative forcing

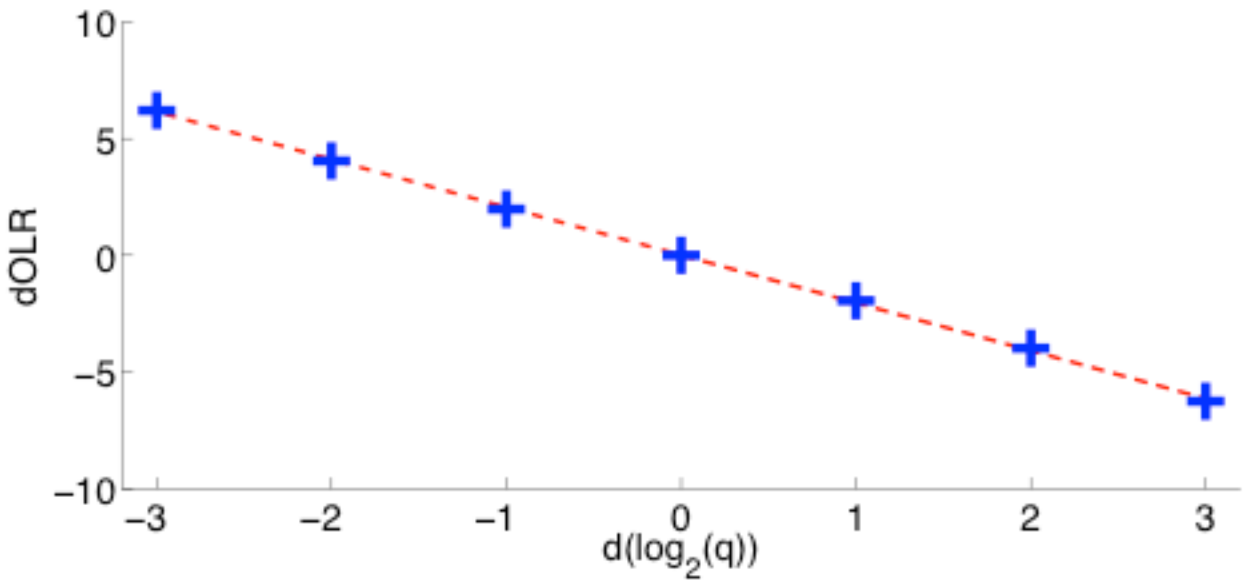
- Radiative forcing (RF)
  - Instantaneous RF
  - Stratospherically adjusted RF
  - Stratopsherically+tropospherically adjusted RF ("effective RF" in AR5)

- $F_{ins} \sim \log_2(CO_2)$ [IPCC 1990, …]
  - Q1: Why logarithmic?

    [Huang and Bani Shahabadi, *J. Atm. Sci.*, under review]
  - Q2: $F_{ins} = 4$ W m^{-2} , exactly?

    [*Zhang and Huang, J. Clim., 2014*]

Logarithmic relationship

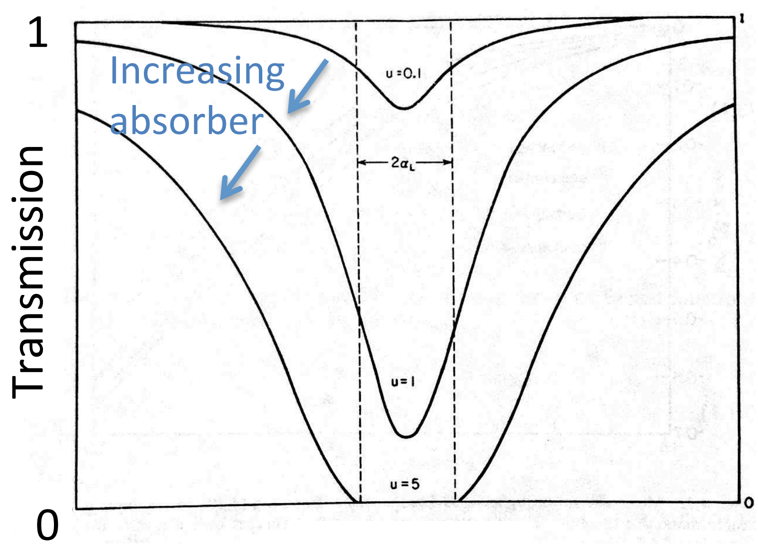


Radiative forcing [W m^{-2}] calculated using R.T. model by perturbing atmospheric CO_2 concentration (q).

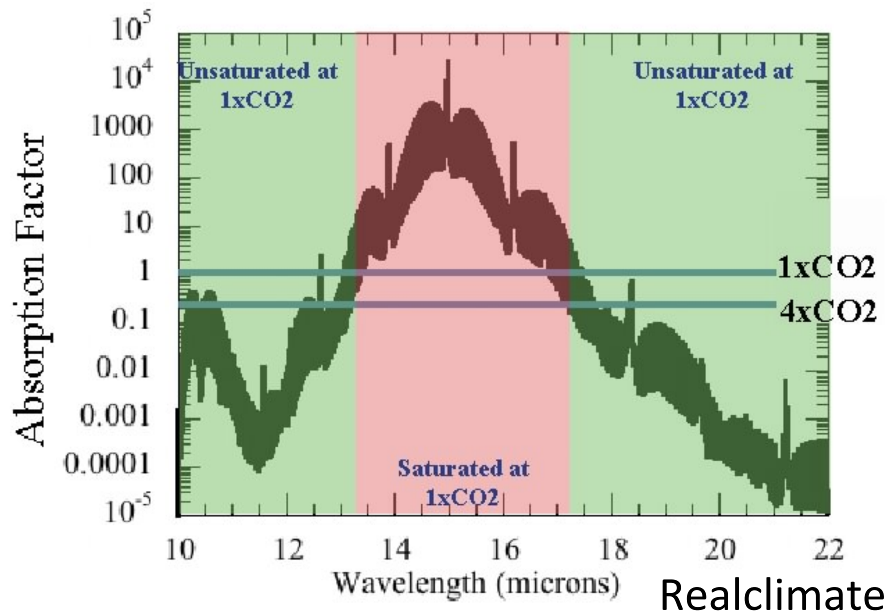
- Log relationship can be verified with any RT model
- Log estimation formula widely adopted
  - $F = F_0 \log(q/q_0)$
  [IPCC AR1,2,3,…; Wikipedia, …]

Cause of logarithmic relationship
Answer 1: it is due to spectroscopy

Saturation of an absorption line



Saturation of an absorption band



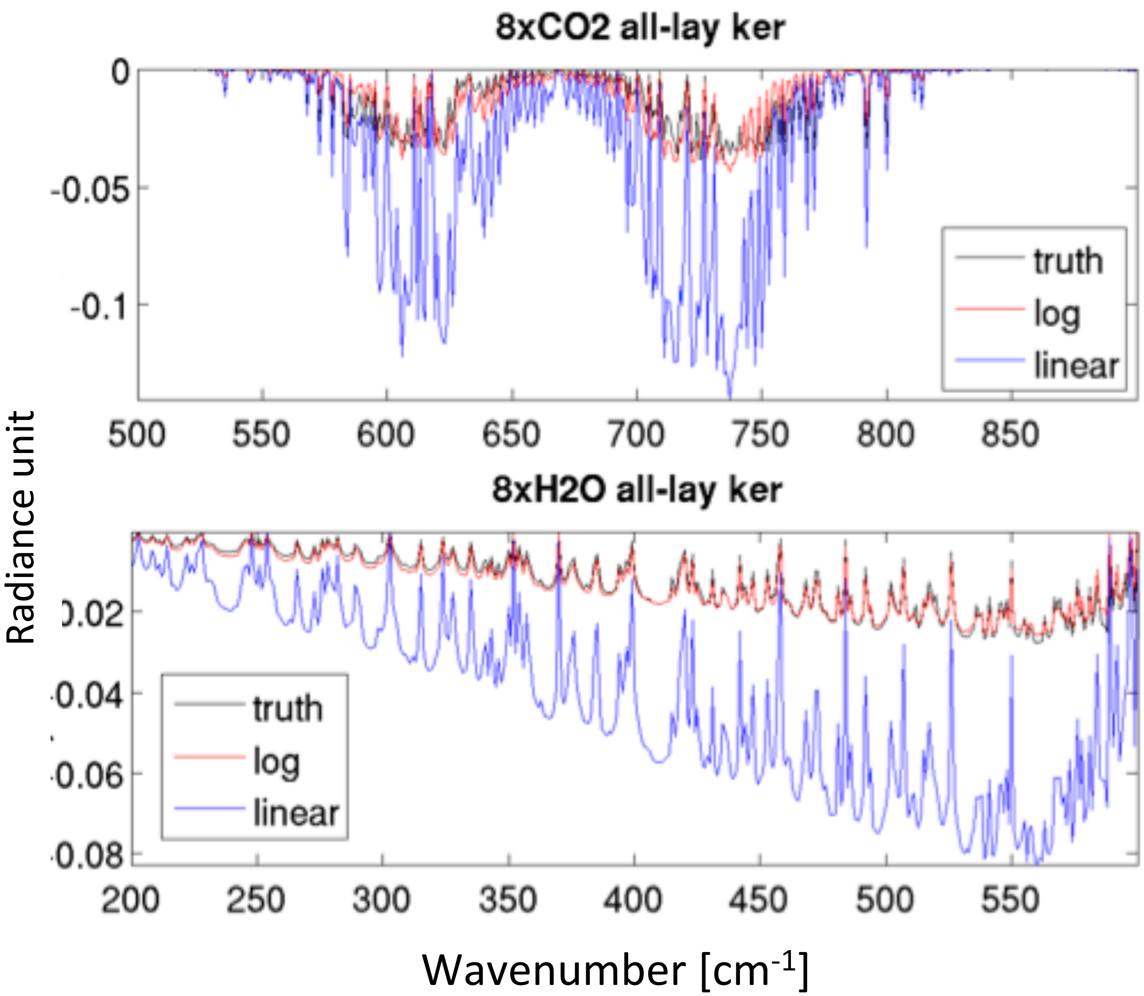
Realclimate.org

Radiative forcing ∝ increased absorption ∝ saturation from line center to wing: "curve of growth" theorem [Goody&Yung 1989]; from band center to wing [Pierrehumbert 2010]

→

The log relationship applies to spectrally integrated (broadband) radiation flux.

Counterevidence: Logarithmic relationship holds even for monochromatic radiance!



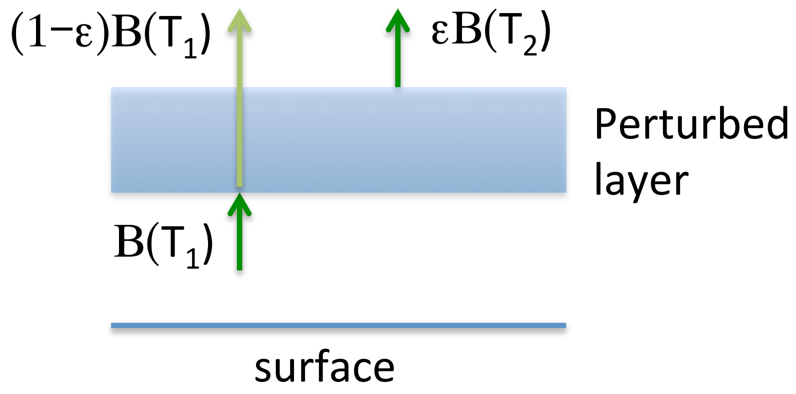
Truth:
$\Delta R(8x) = R(8x) – R(1x)$
Calculated using LBL RT model

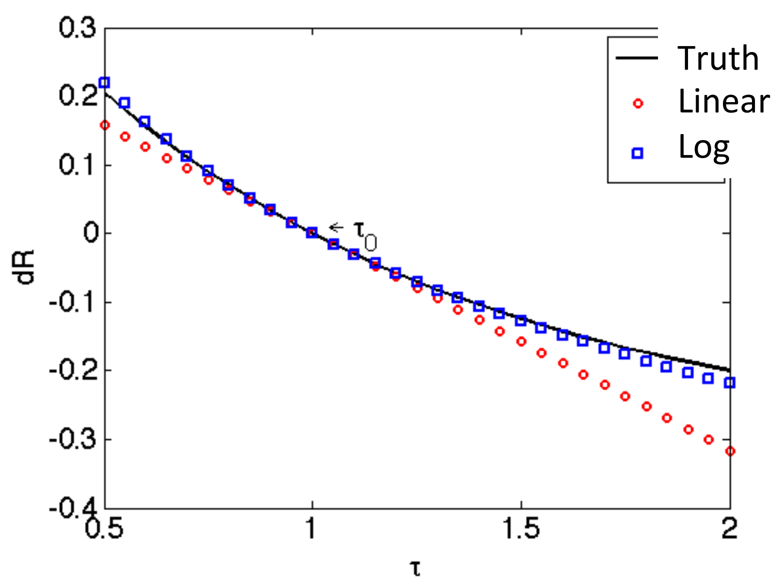
Log scaling:
$\Delta R(8x) = \Delta R(1.1x) * \log(8)/\log(1.1)$

Linear scaling:
$\Delta R(8x) = \Delta R(1.1x) * (8-1)/0.1$

- Log-scaling well reproduces radiance change
- Log dependence holds for CO_2 as well as H_2O forcing

Cause of logarithmic relationship
Answer 2: it is due to radiative transfer





- Can a 1-layer model explain it?

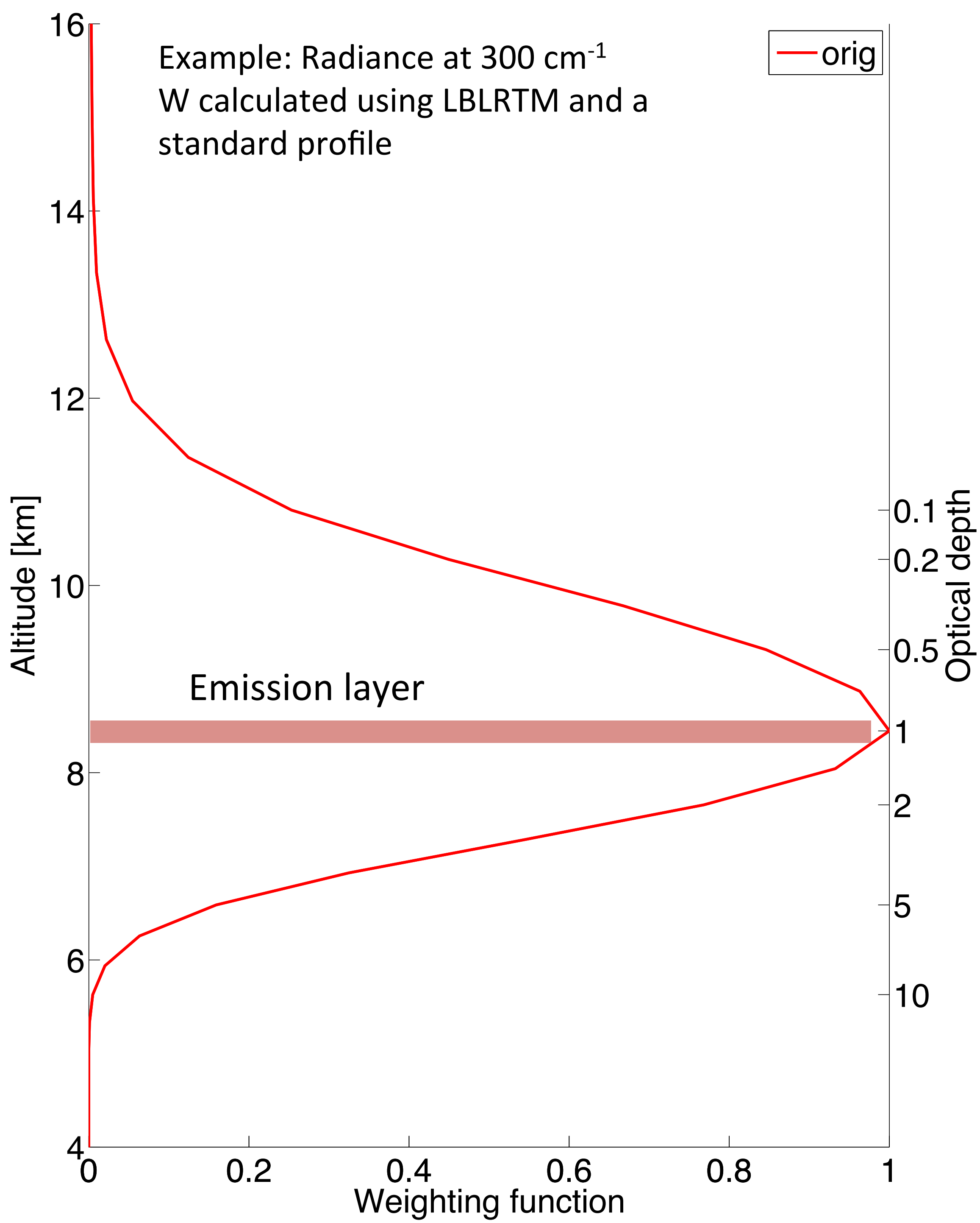
OLR = $B_1*(1-\varepsilon) + B_2*\varepsilon$
Here emissivity: $\varepsilon=1-\exp(-\tau)$;
optical depth: $\tau \propto q$ (absorber amount)

- For a perturbation $q' = \alpha * q$

$\Delta R = K_{log}[\log(\alpha) + O(\log(\alpha)^3)]$
$\Delta R = K_{linear}[(\alpha-1) + O((\alpha-1)^2)]$
Here K is sensitivity kernel, calculated using small perturbation.

Log-scaling yields more accurate estimation than linear-scaling when perturbation (α) is big.

However, accuracy is limited $O(\log(\alpha)^3)]$
Fractional error > 100% if α is large (e.g. 8x).

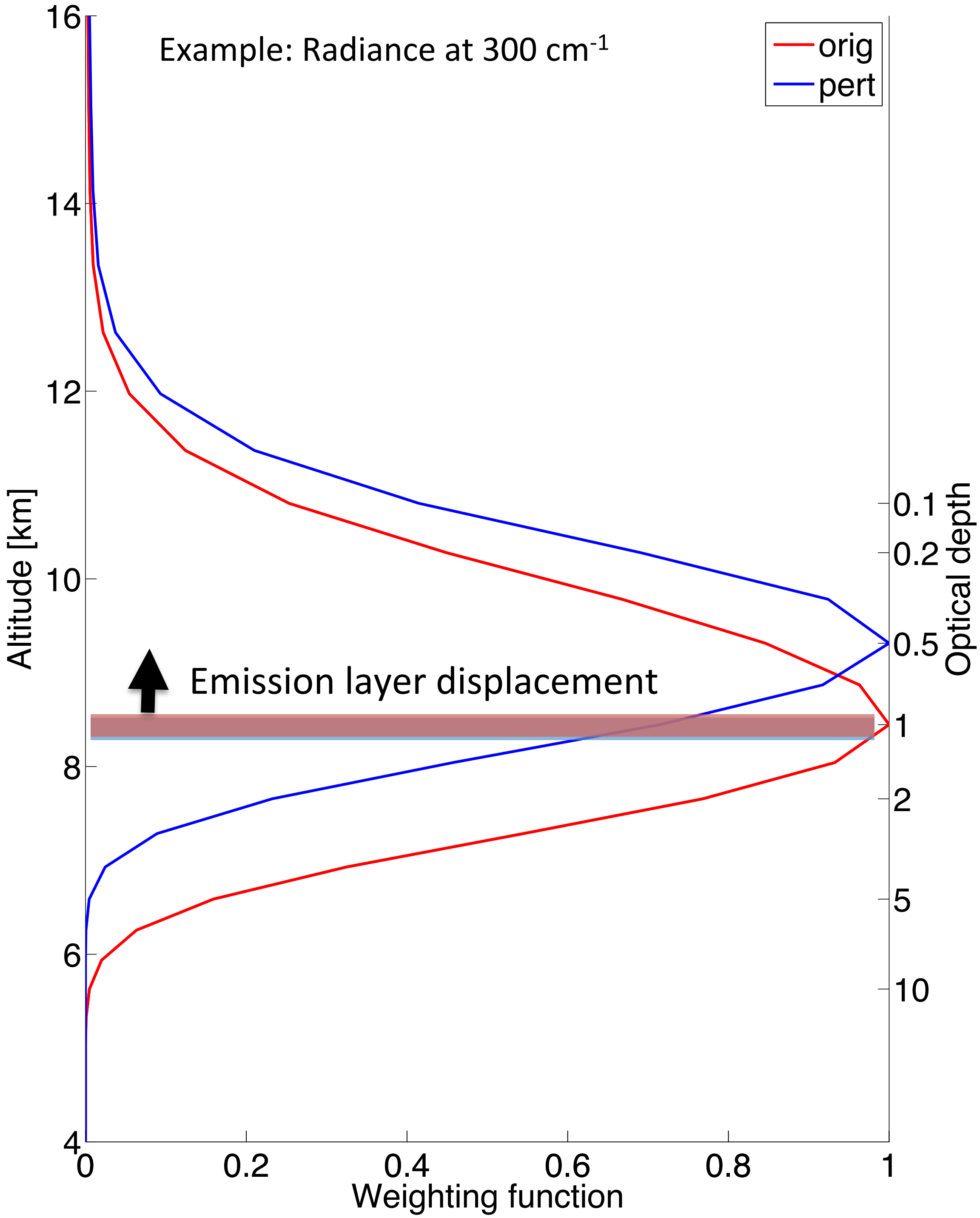


Emission layer displacement model

Solution to non-scattering R.T. Eq. can be generalized as:
$R = \Sigma\{W_i * B_i\}$

W_i: weighting function for layer i, a function of optical depth τ measured from TOA to layer i.

B_i: Planck function of layer tempreature (T_i)



Emission layer displacement model

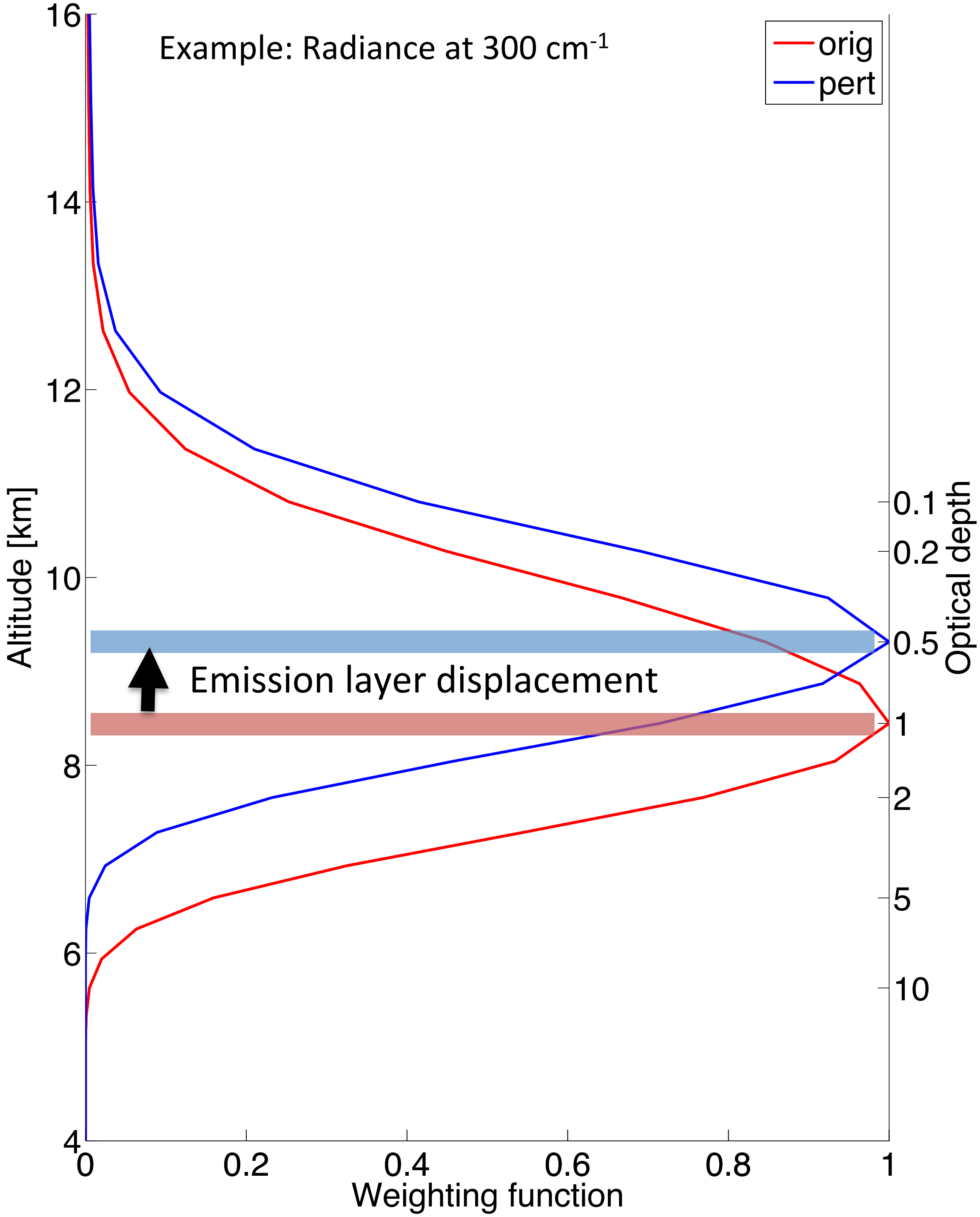
Solution to non-scattering R.T. Eq. can be generalized as:
$R = \Sigma\{W_i * B_i\}$

Perturbation of absorber amount (α x q) equivalently displaces all the contributing layers to higher altitudes.

As $W = W(\tau)$ and $\tau \propto q$, each emission layer is displaced from τ to $\tau' = \tau/\alpha$.

Given $T=T_0-z*\Gamma$, it can be shown
$B \propto \log(\tau)$, and thus
$B(\tau')-B(\tau) \propto \log(\alpha)$

[Huang and Bani Shahabadi, *J. Atm. Sci.*, under review]



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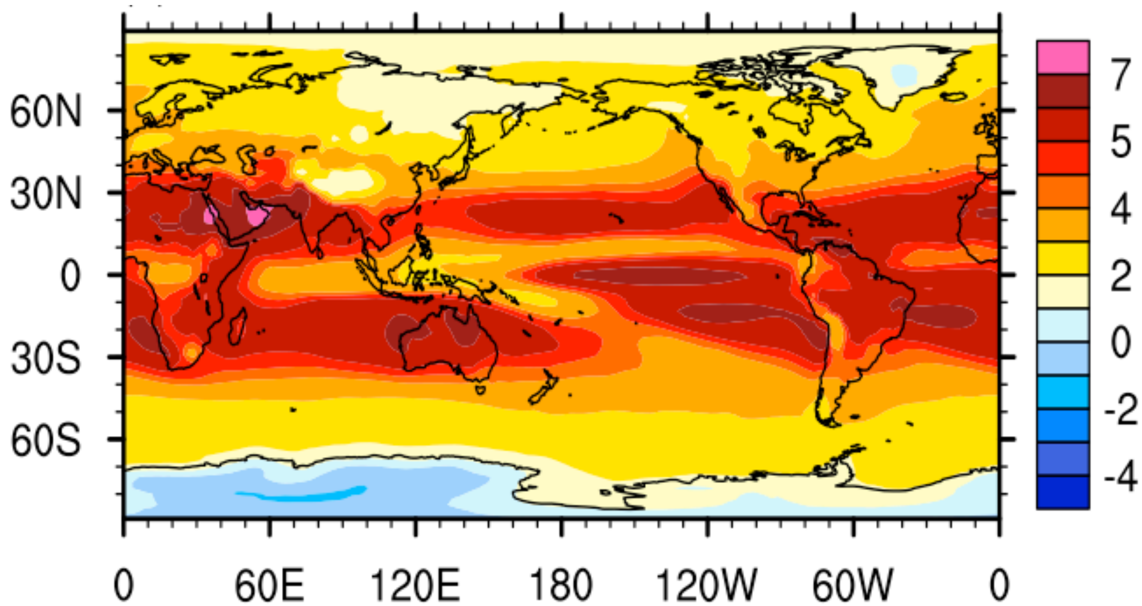
[Huang and Bani Shahabadi, *J. Atm. Sci.*, under review]

Q2: How many W m^{-2} exactly? $F = F_0 \log(q/q_0)$?



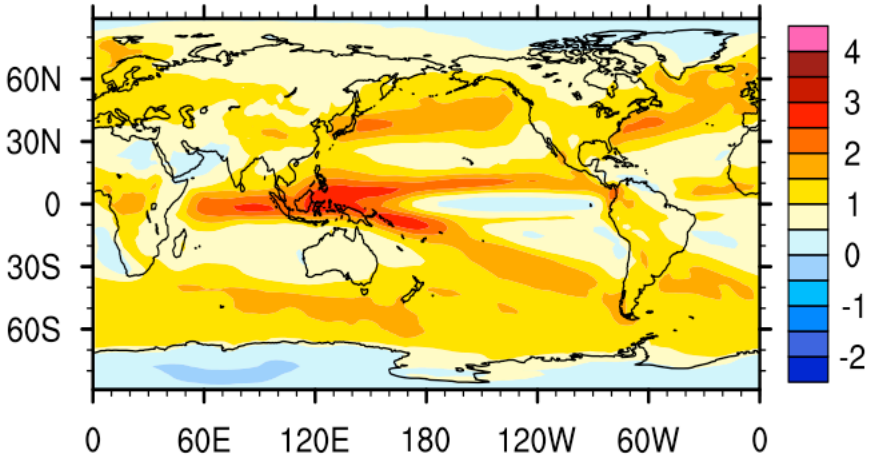
$F(4xCO_2)$ computed using a RT model and global atmos. Profiles.

CO_2 is uniformly increased from 190 to 760 ppm globally.

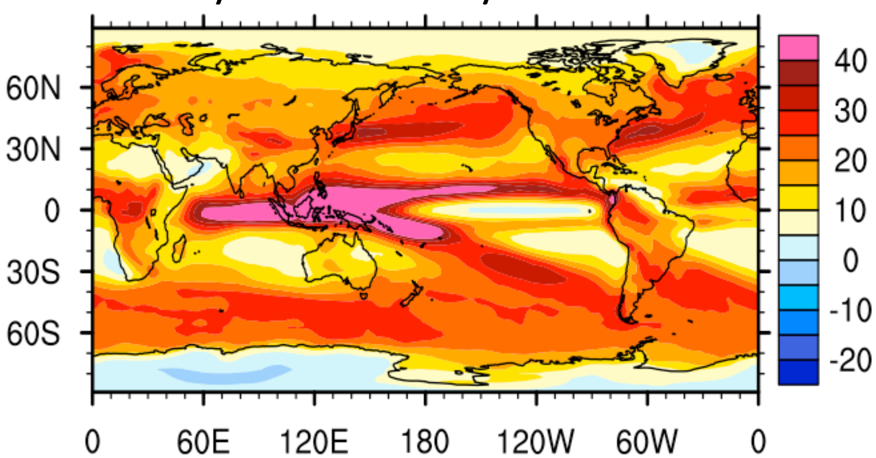
- F varies geographically because F is atmosphere dependent!
  =>
- F may differ among climate models (e.g., CMIP) even if the CO_2 perturbation is prescribed identically in these models.

Estimate F

Difference between all-sky and clear-sky forcing



Cloud radiative forcing: difference between all-sky and clear-sky OLR



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

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

$$F^C = \Delta R^C - \Sigma(\Delta R^C{}_X)$$

Here we use kernels for non-cloud feedbacks $\Delta R^C{}_X$ (T and w.v.)

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

2) Obtain all-sky forcing using cloud-forcing scaling :

$$(F^C\text{-}F)/F^c{}_{ref} = (0.16/1.16)*(CF/CF_{ref})$$

CF: cloud forcing: R^C-R

Impact of forcing uncertainty:
Contribution to temperature projection uncertainty

$\Delta R = F + \lambda * \Delta T_S$ => error budget of ΔT_S :

$$\delta(\Delta T_S) = \frac{\delta(\Delta R - F)}{<\lambda>_m} - <\Delta T_S>_m \frac{\delta\lambda}{\lambda}$$

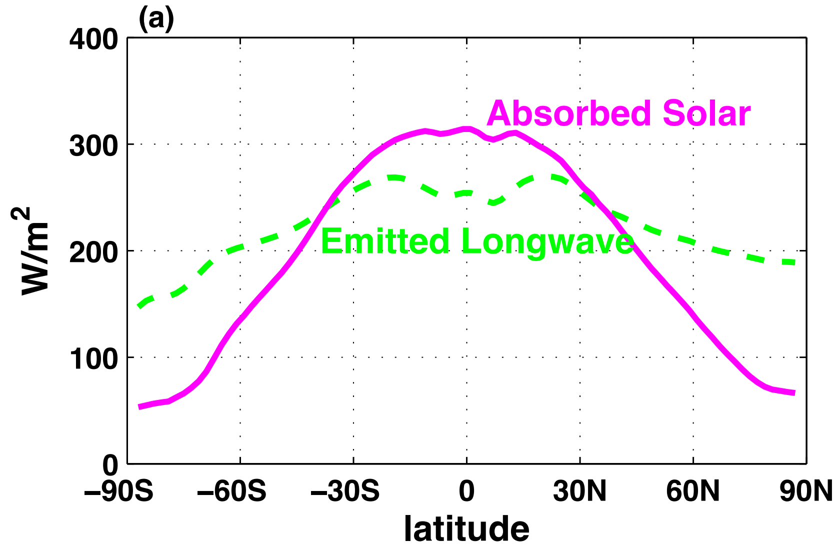
1.0 K 1.3 K

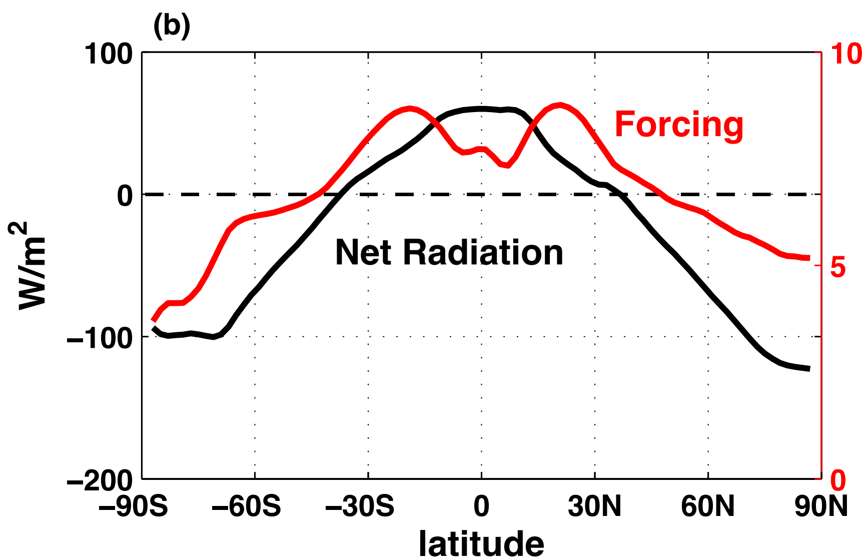
$\delta(\Delta R) \sim \delta(F) \sim 0.5K$

=> Forcing uncertainty accounts for about 1/4 of the inter-model spread in surface warming projection.
(Zhang&Huang 2014, in agreement with Geoffrey et al. 2012 and Webb et al. 2012)

Nonuniform forcing => more poleward energy transport

[Huang&Zhang, GRL, 2014]





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

Summary

- Logarithmic relationship between radiative forcing (F) and gas absorber concentration
  - Holds for monochromatic radiance (not only broadband flux)
  - Results from radiative transfer (not only spectroscopy)

- F is atmosphere-dependent
  - Model- and region-dependent F can be estimated using a cloud forcing scaling method
  - Forcing uncertainty contributes to projection discrepancy
  - Forcing peaks in Tropics => demands an increase in poleward energy transport

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