Heterogenous CO_2 forcing from surface-stratosphere temperature contrast

Nadir Jeevanjee[1,2], Jacob T. Seeley[3], David Paynter[2], Stephan Fueglistaler[1]

1. Dept. of Geosciences, Princeton University 2. NOAA/GFDL 3. Dept. of Earth and Planetary Sciences, UC Berkeley

Introduction

CO_2 forcing varies significantly over the globe, with a strong meridional gradient as well as zonal variations, even in clear-skies (see also Huang 2016):

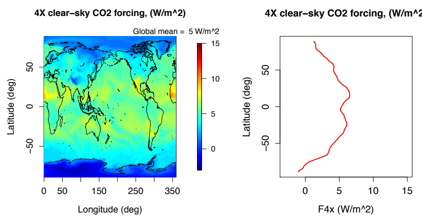


Fig. above: 4X CO_2 forcing, evaluated for a March 1981 snapshot of an AM3 historical run, as calculated line-by-line using RFM (Dudhia 2016).

Research Question: What physics governs these variations? Can we emulate them with a simple model?

Theory

Step 1. Parameterize CO_2 mass abortion coefficients κ (m^2/kg) as in Wilson (2012):

$$\kappa(k) = \kappa_0 \exp\left(-\frac{|k-k_0|}{l_k}\right)$$

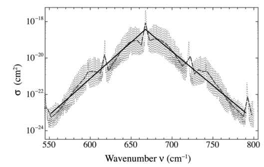


Fig. 1. Absorption cross-section, in cm^2, for a CO_2 molecule as a function of frequency around 15 μm wavelength (light gray dotted curve); note the logarithmic scale. Also shown are a "coarse grained" spectrum (medium gray dashed curve) obtained by averaging over intervals of width 5 cm^{-1}, and a drastically simplified version (black, solid line) that we use for the analytical order-of-magnitude estimates. Wilson 2012

Step 2. Calculate optical depth and find emission levels, i.e. levels of unit optical depth, denoted $p_1(k)$:

$$\tau_k(p) = \kappa(k)\int_0^p \frac{p'}{p_s} q \frac{dp'}{g} = \kappa(k)\frac{qp^2}{2gp_s}$$

$$\implies p_1(k) = \underbrace{\sqrt{\frac{2gp_s}{q\kappa_0}}}_{p_0(q)} \exp\left(\frac{|k-k_0|}{2l_k}\right)$$

Step 3. Construct a picture for CO_2 forcing

All orange emission levels exist for both 1x and 4x CO_2. So only change in emission with 4X CO_2 is loss of some surface emission (red) and addition of new stratospheric emission (blue).

⟹ CO_2 forcing only depends on surface-stratosphere temperature contrast!

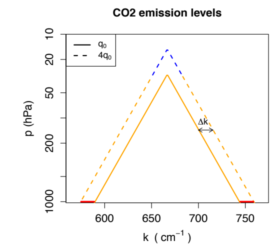


Fig. above: graph of $p_1(k)$ for q_0 corresponding to 280 ppmv

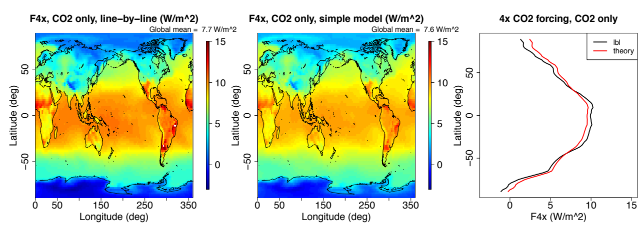
Step 4. Use the above accounting to estimate the CO_2 forcing:

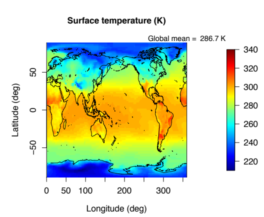
$$F_{4\times} = 2\underbrace{l_k \ln 4}_{\Delta k}\left[\underbrace{\pi B(k_0,T_s)}_{\text{surface}} - \underbrace{\pi B(k_0,T(p_0))}_{\text{stratosphere}}\right]$$

Wilson 2012

Only inputs are surface and stratosphere temperatures!

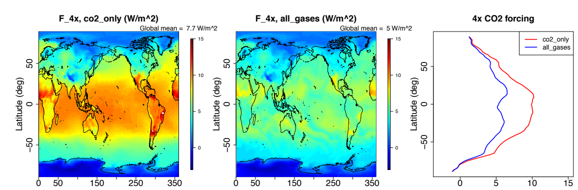
Validation for CO_2 only





- The simple formula reproduces clear-sky CO_2-only forcing remarkably well (figure above)
- The spatial heterogeneity in forcing is driven by surface temperature variations (figure left)

Future work – H_2O effects



- Figure above shows that effect of H_2O on CO_2 forcing is signifcant, particularly in tropics where large H_2O path lengths means that H_2O and CO_2 bands overlap
- Meridional gradient in CO_2 forcing strongly dampened by H_2O
- **Step 5**: Elaborate on simple model to account for this

Conclusions + References

- We develop a picture for CO_2 forcing based upon the simplified spectroscopy of Wilson (2012).
- The resulting formula is a function of surface-stratosphere temperature contrast only. It predicts spatial variations in CO_2 forcing remarkably well.
- These spatial variations are are driven by spatial variations in surface temperature. Water vapor strongly dampens the meridional forcing gradient.

References:
- Dudhia, *The Reference Forward Model (RFM)* , JQSRT 2016
- Wilson and Gea-Banacloche, *Simple model to estimate the contribution of atmospheric CO2 to the Earth's greenhouse effect,* Am. J. Phys. 2012
- Huang et al., *Inhomogeneous radiative forcing of homogeneous greenhouse gases,* JGR 2016