Volcanoes and the Transient Climate Response

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Part I

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Overview

- ECS or TCS
  The literature trying to connect volcanic responses to climate sensitivity has focused too much on equilibrium sensitivity rather than directly constraining the TCR.

How to study connections between volcanoes and TCR

How to design the experiments?

In my opinion

- Control: 1%/yr increase in CO_2 concentration until doubled
- Control + volcanic forcing(aerosol forcing)

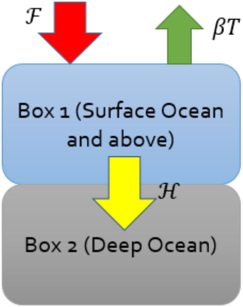
The author's method

The same as mine? NO!
How does he design? And Why?

Global Climate Model (GCM)

- A 10-member ensemble of 20-yr simulations forced by abrupt CO_2 doubling and halving.
- An ensemble forced by stratospheric aerosol forcing designed to represent the 1991 eruption of Mount Pinatubo with diffrent phase of ENSO.
- Get changes of global mean surface temperature(ΔT) and change of TOA net radiative forcing(ΔN).

Two-box energy balance model



$$c_F \frac{dT}{dt} = \mathcal{F}(t) - \beta T - \mathcal{H}$$

$$c_D \frac{dT_D}{dt} = \mathcal{H}$$

$$\mathcal{H} = \gamma(T - T_D) \approx \gamma T$$

$\Rightarrow$

$$c_F \frac{dT}{dt} = \mathcal{F}(t) - \beta T - \gamma T$$

GCM and fit results

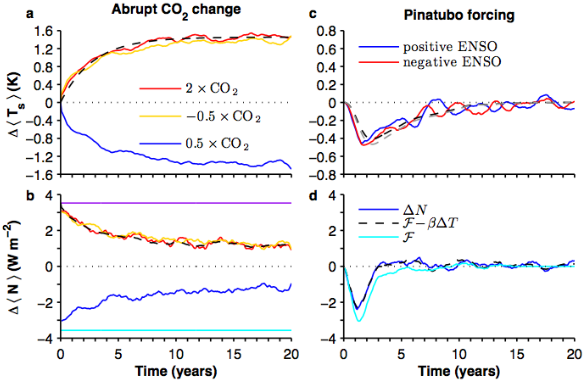


Fig 1.**(a)**Change in global-mean surface temperature for abrupt CO_2 simulations (reflection of 0.5 $\times$ CO_2 about zero, yellow line) with black dashed line showing the estimated parameters of the two-box model **(b)** Change in global-mean TOA net radiation [colors as in (a)], radiative forcing indicated by straight lines, and net radiation implied by the best estimate of β (black dashed line). **(c)** Change in global-mean surface temperature for Pinatubo simulations with dashed lines showing the integral fit TCS estimate plotted with the CO_2 time scale.**(d)** Change in global-mean TOA net radiation for positive ENSO phase simulations (blue), radiative forcing (light blue), and net radiation implied by the best estimate of b (black dashed line). Negative ENSO phase simulations are similar (not shown).

How to fit the GCM with two-box model

From last slide, we get

$$c_F \frac{dT}{dt} = \mathcal{F}(t) - (\beta + \gamma) T$$

First we solve the homogenous equation

$$c_F \frac{dT}{dt} = -(\beta + \gamma) T$$

and we can get

$$T = K e^{-\frac{\beta+\gamma}{c_F} t}, \text{where } K \text{ is constant.}$$

Now use method of variation of constant, that is to say, we see K as $K(t)$,

$$T = K(t) e^{-\frac{\beta+\gamma}{c_F} t}$$

How to fit the GCM with two-box model

$$T'(t) = K'(t)e^{-\frac{\beta+\gamma}{c_F}t} - \frac{\beta+\gamma}{c_F}K(t)e^{-\frac{\beta+\gamma}{c_F}t}$$

compare to

$$c_F\frac{dT}{dt} = \mathcal{F}(t) - (\beta+\gamma)T$$

we get

$$c_F K'(t)e^{-\frac{\beta+\gamma}{c_F}t} = \mathcal{F}(t)$$

so we can get

$$K(t) = \int \frac{1}{c_F}\mathcal{F}(t)e^{\frac{\beta+\gamma}{c_F}t}dt$$

As we can see from the blog, the author set $F(t) = const$, so

$$K(t) = \frac{\mathcal{F}}{\beta+\gamma}(e^{\frac{\beta+\gamma}{c_F}t} + M), \text{where } M \text{ is constant.}$$

How to fit the GCM with two-box model

Substitute $K(t)$ in $T(t)$, we get

$$T(t) = \frac{\mathcal{F}}{\beta+\gamma}(1 + Me^{-\frac{\beta+\gamma}{c_F}t})$$

Apply the boundary condition, when $t = 0$, $T = 0$, so we get $M = -1$, and in this case, when $t \to \infty$, $T = \frac{\mathcal{F}}{\beta+\gamma}$(balance state).
At last, we get

$$T(t) = \mathcal{F}\alpha(1 - e^{-\frac{t}{\tau}})$$

where $\alpha = \frac{1}{\widetilde{\beta}}, \tau = \frac{c_F}{\widetilde{\beta}}$ and $\widetilde{\beta} = \beta + \gamma$.
In fact, we have a fast component and a slow component, so we use

$$T(t) = \mathcal{F}_{2\times}\sum_{i=1}^{2}\alpha_i(1 - e^{-\frac{t}{\tau_i}})$$

to fit.

How to estimate the parameters

We know $\widetilde{\beta}$ and τ are very important parameters, we can get the TCR from $\widetilde{\beta}$, that is $TCR = \frac{\mathcal{F}}{\widetilde{\beta}}, \widetilde{\beta} = \beta + \gamma$.

1. Two parameter fit
   We simulate $\widetilde{\beta}$ and τ_F by minimizing the squared error over 20yr simulations.
2. Integral fit
   Impulsive radiative forcing such as that due to a volcanic eruption at time t=0, the time integrated temperature response is approximated by the ratio of the integrated radiative forcing and $\widetilde{\beta}$,

$$\int_0^{\tau_I} T dt \approx \frac{\int_0^{\tau_I} \mathcal{F} dt}{\widetilde{\beta}}$$

   so we can get

$$\widetilde{\beta} \approx \frac{\int_0^{\tau_I} \mathcal{F} dt}{\int_0^{\tau_I} T dt} = \frac{\widetilde{\mathcal{F}}}{\int_0^{\tau_I} T dt}$$

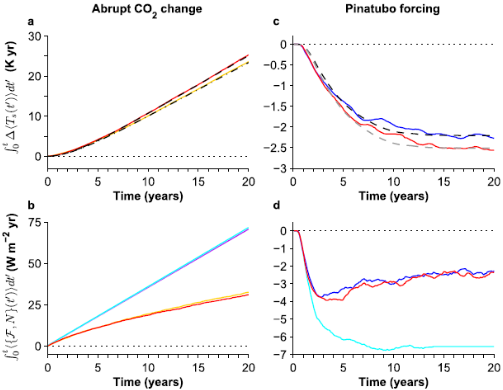


Fig 2. **(a)** Time-integrated change in global-mean surface temperature for abrupt CO_2 simulations ($2 \times CO_2$, red line, and the reflection of $0.5 \times CO_2$ about zero, yellow line) with black dashed line showing the two-box fit model for $2 \times CO_2$ and black dashed-dotted line showing the two-box model fit for $0.5 \times CO_2$. **(b)** Time-integrated global-mean TOA radiative forcing (coinciding light blue and purple lines) and net radiation for CO_2 simulations (with $0.5 \times CO_2$ reflected about zero). **(c)** Time-integrated change in global-mean surface temperature for Pinatubo simulations (positive ENSO, blue, and negative ENSO, red) with dashed lines showing the integral fit TCS estimate plotted with the CO_2 time scale (positive ENSO, black, and negative ENSO, gray). **(d)** Time-integrated global-mean TOA net radiation and radiative forcing (light blue) for Pinatubo simulations.

Estimate TCR from volcanoes using integral fit

$$TCR = \frac{\mathcal{F}_{2\times}}{\widetilde{\beta}} = \frac{\mathcal{F}_{2\times}}{\widetilde{\mathcal{F}}} \int_0^{\tau_I} T dt$$

Example: From the figure 1(c), we can $\mathcal{F}_{2\times} = 3.5Wm^{-2}$, from the figure 2(c) and 2(d), we can get the ensemble mean integrated response up to year 20 is $2.35K \cdot yrs$, and the integrated volcanic radiative impulse is $-6.5Wm^{-2} \cdot yrs$, so we can get

$$TCR = \frac{\mathcal{F}_{2\times}}{\widetilde{\mathcal{F}}} \int_0^{\tau_I} T dt = \frac{3.5Wm^{-2}}{6.5Wm^{-2} \cdot yrs} \times 2.35K \cdot yrs = 1.2654K \approx 1.3K$$

Estimate TCR from volcanoes using two parameters fit

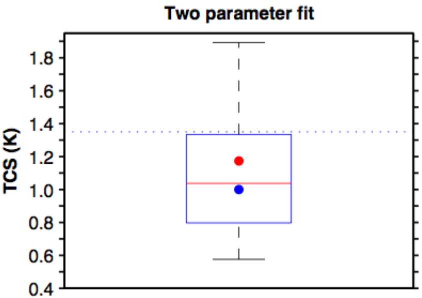


Fig 3. Box-and-whiskers plot of the estimated TCS for 20 individual realizations of Pinatubo in CM2.1 (combining realizations initialized in the positive and negative phase of ENSO) with red line indicating the median estimate, horizontal blue lines indicating the first and third quartile estimate, black whiskers indicating the most extreme estimate, and filled circles showing the estimate from the ensemble mean (positive ENSO in blue and negative ENSO in red). The blue dotted line is the ensemble-mean TCS from the $0.5 \times CO_2$ simulations. The TCS is estimated using the twoparameter ($\widetilde{\beta}$, c_F) fitting technique. The ensemble-mean estimates use anomalies defined with respect to the corresponding control simulations, while the individual realizations do not.

Estimation Results

Table 1. Summary of estimates of two-box model parameters for the ensemble mean of CM2.1 simulations with different radiative perturbations. For the $1\%yr^{-1}CO_2$ increase scenario, we use the published temperature change (1.5K), TOA net radiation ($1.0Wm^{-2}$), and radiative forcing($3.5Wm^{-2}$) at the time of CO_2 doubling from Winton et al.(2010) and assume the surface energy storage is negligible to estimate $\widetilde{\beta}$ [i.e.,$\widetilde{\beta} = \mathcal{F}_{2\times CO_2}/T(t_{2\times CO_2})$].

Radiative perturbation	Estimation technique	TCS(K)	$\widetilde{\beta}(Wm^{-2}K^{-1})$	β	γ	$\tau(yr)$
$2 \times CO_2$	Two parameter	1.45	2.4	1.6	0.85	2.8
$0.5 \times CO_2$	Two parameter	1.35	2.7	1.65	1.05	2.7
$1\%yr^{-1}CO_2$ increase	See caption	1.5(TCR)	2.33	1.67	0.67	-
Pinatubo (positive ENSO)	Two parameter	1.0	3.5	1.9	1.6	2.1
Pinatubo (negative ENSO)	Two parameter	1.2	3.0	1.7	1.3	2.3
Pinatubo (positive ENSO)	Integral	1.2	3.0	1.9	1.1	-
Pinatubo (negative ENSO)	Integral	1.4	2.6	1.7	0.9	-

Results Analysis

For volconic forcing on TCR, which is sensitive because:

- Estimation procedure
  Integral fit method, TCS=1.3K $>$ Two parameters fit, TCS=1.1K
- Internal variability

The Next

- If we use a different model, CM3(Only atmosphere part differs from CM2.1), what will happen to the estimation of TCR constrained by volcanoes?
- If we take intermediate time scale into consideration, what will happen to the results?

Part II

by LI Xingrui

- CM2.1 & CM3: atmospheric components differ in numerous ways.
- The different treatment of sub-grid moist convection result in CM3 being a more sensitive model to CO2 increase.
- The metric of ESM2M, ESM2G and CM2.1 are similar.
- The analogous simulation with CM2.1 would be very close to the green and blue curves in the left panel.
- Evidently the temperature responses to Pinatubo are not providing any clear indication that CM3 is the more sensitive model.

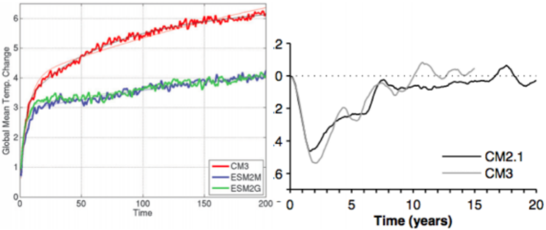


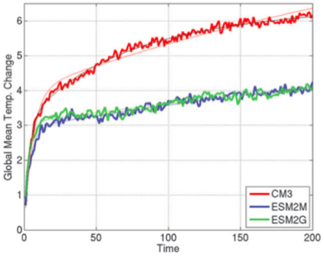
Fig 4. **Left:** The response to instantaneous quadrupling of CO_2 in three GFDL models. **Right:**The ensemble mean response of global mean surface air temperature to Pinatubo in two GFDL climate models.

Why do we use a three time-scale fit?

- CM3 & CM2.1: similar during the first 10 years; begin to build up between 10 and 50 years. CM3 increase very fast between 10 and 100 years.
- Earlier, we use two-exponential fit:

  $$T(t) = \mathcal{F}_{2\times}[\alpha_1(1-e^{-\frac{t}{\tau_1}})+\alpha_2(1-e^{-\frac{t}{\tau_2}})]$$

  But the two-exponential fit has larger error for CM3.
- We should add a intermediate time scale to achieve a similar accuracy for CM3.

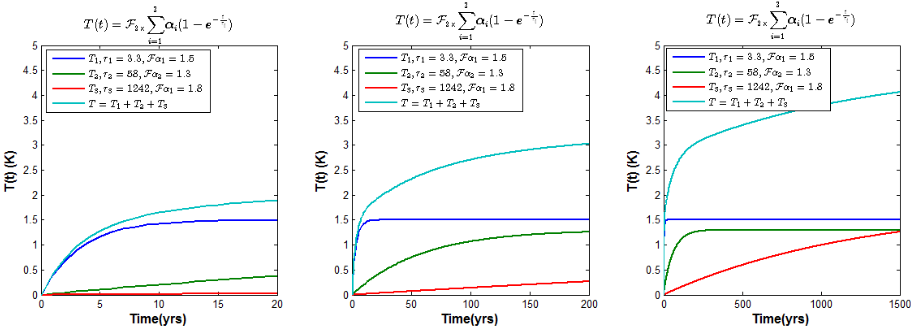


The meaning of the three time-scale fit

Winton et al. 2013a provide a three time-scale fit to CM3s response to instantaneous quadrupling of CO_2.

$$T(t) = \mathcal{F}_{2\times} \sum_{i=1}^{3} \alpha_i (1 - e^{-\frac{t}{\tau_i}}) \equiv \mathcal{F}_{2\times} h(t)$$

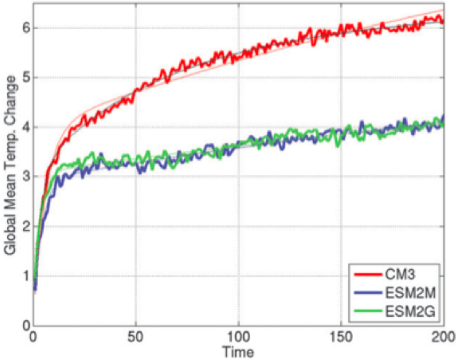
where
$\mathcal{F}_{2\times}[\alpha_1, \alpha_2, \alpha_3] = [1.5, 1.3, 1.8]K, [\tau_1, \tau_2, \tau_3] = [3.3, 58, 1242], \mathcal{F}_{2\times} = 3.5Wm^{-2}$.



Important findings in the figure

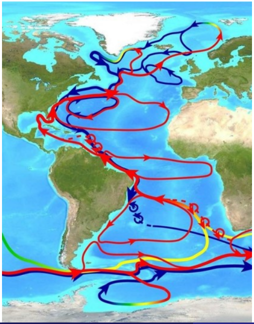
The difference in the shapes of the response function in CM2.1 and CM3 is important.

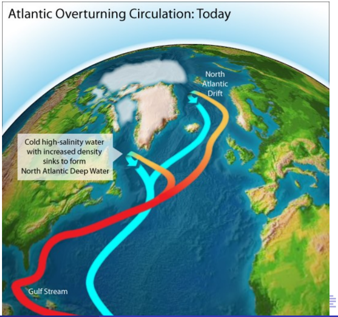
- How does the plateau-ish character form?
- Why is the GMTC so different between CM2.1 and CM3?



How does the plateau-ish character form?

1. The plateau-ish character is likely related to the behavior of the models Atlantic Meridional Overturning Circulation (AMOC).
2. AMOC:
   - primary four branch: warm surface water from south to north; downwelling; deep water flow from north to south; upwelling
   - can bring the heat from equator to high latitude in the northern hemisphere.
   - Weaker AMOC results in colder global mean temperature.





How does the plateau-ish character form?

3. AMOC declines in response to increasing CO_2, and then recovers slowly as the system equilibrates.

The plateau is due to a cancellation between the effects of the AMOC weakening and gradual warming and reduction of heat uptake efficiency when AMOC is fixed.

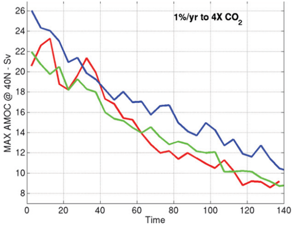
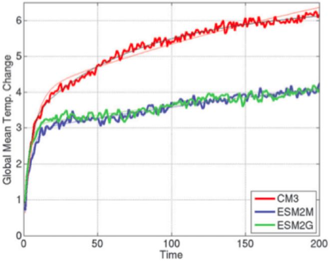


Fig 5. Maximum Atlantic overturning stream function at 40N in the 1% yr^{-1} CO_2 increase experiments. All values are based on 5-yr means.

Why is the GMTC so different between CM2.1 and CM3?

- CM3/ESM2M: same ocean model, similar reductions in AMOC, different atmospheric model.
- One hypothesis: Different atmosphere respond differently to similar change in AMOC, due to different cloud feedbacks.
- The importance of cloud feedbacks for the response to AMOC was analyzed in Zhang et al,2010.

- Modeling uncertainty in cloud feedback could result in uncertainty in the time evolution of global mean temperature.



Questions and Comments

1. Held thinks that volcanic forcing underestimate the TCR(I think it should have a difference), does he think that the estimation to TCR from volcano should be the same as the TCR when CO_2 increasing at $1\% yr^{-1}$ and doubled at last?
2. I don't understand the estimation method very well, why does he choose such a method?

$$T(t) = \frac{\mathcal{F}}{\widetilde{\beta}}(\text{–!!Balance state!!–}) \Rightarrow \int_0^{\tau_I} T dt \approx \frac{\int_0^{\tau_I} \mathcal{F} dt}{\widetilde{\beta}}$$

Is it OK for all values in $[0, \tau_I]$??

Questions and Comments

3. What does the sub-grid moist convection mean? What is the connection between sub-grid moist convection and cloud feedback?
4. Weaker AMOC results in colder global mean because warming in the south is weaker than the cooling in the north. Why?
5. The second blog pays attention to the difference in the response functions in CM2.1 and CM3. Actually, I dont understand the connection between this and TCR of volcanic.

The End

Thanks