Model for estimating the transient climate response to changes in atmospheric aerosols and radiatively-active well-mixed gases

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Introduction

Natural and anthropogenic atmospheric aerosols play an important role in the formation of the radiation balance of the atmosphere and the Earth's climate system (ECS) as a whole. Being a dispersed system, atmospheric aerosol scatters and absorbs solar and terrestrial radiation and, in addition, affects the cloud formation processes and radiation properties of clouds by changing the microstructural characteristics of cloud particles. Along with atmospheric aerosols, the redistribution of radiation fluxes in the ECS is significantly affected by various gas components of the Earth's atmosphere. In the context of the climate change aerosols and radiatively-active gases are of interest whose concentrations in the atmosphere vary globally due to natural causes (volcanic eruptions, dust and sandstorms, forest and steppe fires), as well as due to anthropogenic activities. The current historical moment is characterized by a steady increase in the amount of greenhouse gases in the atmosphere such as carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_20), as well as a significant change in the composition and content of aerosols that affect atmospheric radiation fluxes. It is believed that one of the main reasons for these changes is the anthropogenic impact on ECS, which ultimately plays the role of a determining factor in increasing the average planetary temperature. The question of how ECS reacts to changes in the atmospheric content of natural and anthropogenic aerosols and radiatively-active gases (AAG) including greenhouse gases, has been the subject of numerous studies. The impact of AAG on the ECS can be accurately assessed using complex coupled climate models, but simple climate models (e.g., energy-balance models [1]) are considered to be convenient and quite effective tools of obtaining quantitative estimates of the effect of AAG on the ECS. Since EBMs are linear (linearized around some equilibrium climate state), then the response of ECS to radiative forcing due to AAG can be evaluated as a convolution of impulse response function (IRF) $h(t)$ and forcing $F(t)$ [2]:

$$T(t) = h(t) * F(t) = \int_0^t h(\tau)F(t-\tau)d\tau$$

Here, we obtain the IRF for the two-box EBM and then calculate the ECS response to forcing, given for two idealized scenarios (abrupt 2×CO_2 and 1pctCO_2), four RCPs scenarios, and the Pinatubo eruption.

Methods

Model of the ECS. The ECS model is a 2box EBM consisting of two interacting subsystems: (1) the atmosphere and the upper mixed layer of the ocean (the "fast" subsystem), (2) the deep layers of the ocean (the "slow" subsystem). The state variable of the "fast" subsystem is the anomaly of the mean global surface temperature T, and the state variable of the "slow" subsystem is the anomaly of the globally averaged temperature of the deep layers of the ocean T_D. The model equations are [3, 4]:

$$C(dT/dt) = -\lambda T - \gamma(T - T_D) + F$$
$$C_D(dT_D/dt) = \gamma(T - T_D)$$

where C and C_D are effective heat capacities for "fast" and "slow" subsystems; λ is the feedback parameter; γ is a coupling parameter (the ocean heat uptake parameter); F is AAG radiative forcing. The following average values of model parameters were obtained using a specially developed calibration procedure applied for the CMIP5 model results [4]: $C = 7.34\ W\ yr/m^2$, C_D=105.5 $W\ yr/m^2$, λ=1.13 $W/(m^2K)$, λ=0.73 $W/(m^2K)$. From the model equations we can derive the following second-order differential equation for forced decay oscillations:

$$d^2T_D/dt^2 + 2\beta\,(dT_D/dt) + \omega_0^2 T_D = (\gamma/CC_D)F$$

where $\beta = [\gamma C + (\lambda + \gamma)C_D]$ is the decay parameter, $\omega_0 = \sqrt{\lambda\gamma/CC_D}$ is a natural frequency. The ECS response to external forcing is characterized by relaxation times of the "fast" and "slow" subsystems. It can be shown that

$$\tau_f = \frac{\beta - (\beta^2 - \omega_0^2)^{1/2}}{\omega_0^2} \approx 3.9\ yr, \qquad \tau_s = \frac{\beta + (\beta^2 - \omega_0^2)^{1/2}}{\omega_0^2} \approx 240\ yr$$

Impulse response function. IRF is defined as the inverse Laplace transform of the system's transfer function $H(p)$: $h(t) = \mathcal{L}^{-1}\{H(p)\}$. It can be shown that

$$H(p) = \frac{\gamma + pC_D}{CC_Dp^2 + [\gamma C + (\lambda + \gamma)C_D]p + \lambda\gamma}$$

Thus

$$h(t) = \mathcal{L}^{-1}\{H(p)\} = \frac{1}{2\pi i}\int_{\sigma-i\infty}^{\sigma+i\infty} H(p)e^{pt}dp = \sum_{j=1}^{2} \mathrm{Res}H(p)e^{pt}\Big|_{p=p_j}$$

where p_j are poles of $H(p)$ and Res is the notation for residuals. Finally we have

$$h(t) = \frac{\tau_f\tau_s}{C(\tau_s - \tau_f)}\left[\left(\frac{\gamma}{C_D} - \frac{1}{\tau_s}\right)e^{-t/\tau_s} - \left(\frac{\gamma}{C_D} - \frac{1}{\tau_f}\right)e^{-t/\tau_f}\right]$$

In Fig. 1 the plots of IRF, its "fast" mode and the IRF for the 1-box EBM are shown. Equation for 1-box EBM is:

$$C(dT/dt) = -\lambda T + F$$

Since $\tau_s \gg \tau_f$, we have the following approximation of IRF for 2-box EBM:

$$h(t) \approx \frac{1}{C}e^{-t/\tau_f} + \frac{\tau_f}{C}\left(\frac{\gamma}{C_D} - \frac{1}{\tau_s}\right)e^{-t/\tau_s}$$

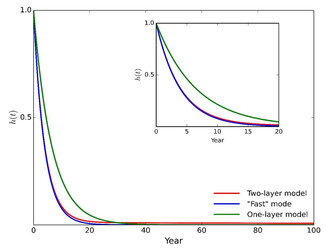


Figure 1. Normalized IRF for 2-box EBM, its "fast" mode, and IRF for 1-box EBM.

Results

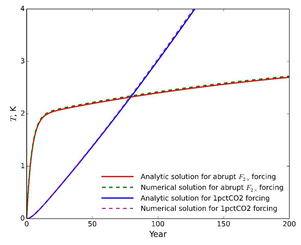


Figure 2. Model response on two idealized forcing: abrupt 2×CO_2 and 1pctCO_2.

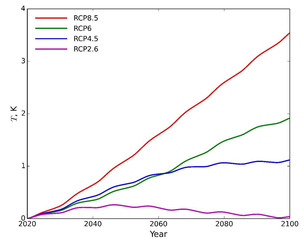


Figure 3. Model response on RCP forcing.

Table 1. Calculated T in 2100

Scenario	RCP 8.5	RCP 6.0	RCP 4.5	RCP 2.6
T ℃	3.92	2.17	1.42	0.36

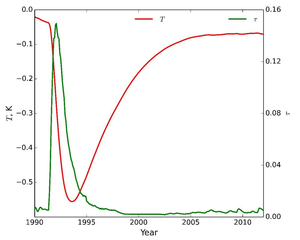


Figure 4. Model response on the Pinatubo volcano aerosol forcing (background stratospheric aerosols was not excluded.

Some results of calculations are shown in Figs. 2-4. The method is sufficiently accurate (Fig. 2) and allows us to estimate the TCR on radiative forcing generated by stratospheric aerosols and radiatively-active atmospheric gases (e.g. greenhouse gases).

Concluding remarks

Results obtained numerically agree fairly well with the results of previous studies. Since the method considered is quite accurate and computationally inexpensive it can serve as a tool for express analysis of the response of the ECS to arbitrary forcing from natural and anthropogenic aerosols, and radiatively-active gases.

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References

1. North G.R., Kim K.-Y. Energy balance climate model. Weinheim: Wiley-VCH, 2017. 369 p.
2. Rypdal K. Global warming projections derived from observation-based minimal model. Earth System Dynamics, 2016, 7, 51-70.
3. Gregory J.M. Vertical heat transport in the ocean and their effect on time-dependent climate change. Climate Dynamics, 2000, 16, 501-515.
4. Geoffroy O., Saint-Martin D., Olivié D.J.L. et al. Transient climate response in a two-layer energy-balance model. Part I: Analytical solution and parameter calibration using CMIP5 AOGCM experiments. J. Climate, 2013, 26, 1841-1857.

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