Feedback temperature dependence

Presentation of the personal work • LPHYS2162

Academic year 2022–2023

The understanding of the response of the climate system to changes in forcing is crucial, especially in the current context of increased human-made greenhouse gases. It is often assumed that the global warming caused by enhanced atmospheric CO_2 concentration is proportional to the radiative forcing associated with this CO_2 increase. However, for large enough forcings, the strength of the feedbacks involved can change, making the linear assumption invalid. This likely results in an underestimation of the risk of high warming following a CO_2 increase. For their personal work, the students will examine the relationship between radiative forcing and changes in temperature, using a zero-dimensional energy balance model that takes into account a temperature-dependent feedback. This model and its application are fully described in:

> Bloch-Johnson, J., Pierrehumbert, R. T., and Abbot, D. S. : Feedback temperature dependence determines the risk of high warming, Geophysical Research Letters, 42, 4973–4980, doi :10.1002/2015GL064240, 2015.

Model description

The model applied is a zero-dimensional energy balance model. It allows computing the increase in the global annual means of surface temperature ΔT caused by the radiative forcing F, taking into account the climate feedback parameter λ. F determines the increase of the net top-of-atmosphere energy flux N following an increased CO_2 concentration. The increase in temperature is computed relative to the preindustrial conditions which are supposed to be in equilibrium ($N(T_0, CO_{20}) = 0$), with $T_0 \approx 287$ K and $CO_{2\,0} \approx 270$ ppm.

If N varies linearly with T, the equilibrium warming can be inferred from:

$$\Delta T = -F\lambda^{-1} \tag{1}$$

The non-linearity between the temperature change and the forcings can be considered by adding a quadratic term which represents the temperature dependence of the feedback, ie. $\alpha\Delta T^2$. The quadratic estimate of ΔT following a given forcing F can then be obtained by solving the following equation:

$$-F = \lambda\Delta T + \alpha\Delta T^2 \tag{2}$$

See Bloch-Johnson et al. (2015) for more details.

Instructions

This work will be carried on in pairs, composed of students who do not belong to the same cursus if possible. There are no limits for the number of pages allowed, but an extensive discussion is expected. The report must be in English, and is due two weeks before the date of the exam. All questions can be addressed to Quentin Dalaiden: `quentin.dalaiden@uclouvain.be`

Part 1

It is first asked to the students to solve the above equations and to reproduce the figures 1a, 1d, 2a and 2b (regarding the figure 2, only the curves must be drawn) of Bloch-Johnson et al. (2015). The values of the forcing corresponding to a doubling CO_2 ($F_{2\times}$) is equal to 3.71 W m^{-2}. When the atmospheric CO_2 concentration is multiplied by n, $F_{n\times} = log_2(n) 3.71$ W m^{-2}. The values of λ and α change depending on the case considered, and are given in Bloch-Johnson et al. (2015).

The role of the thermal inertia and the transient behaviour of the model will then be investigated by considering the heat capacity C in the differential equation:

$$C\frac{d\Delta T}{dt} = F + \lambda\Delta T + \alpha\Delta T^2 \tag{3}$$

where C is equal to 8.36×10^8 J K^{-1}m^{-2}. The values of F, λ and α that have to be taken into account are the ones that were previously used in the equation 2 (the values that are shown in the figures 1a, 1d, 2a and 2b of Bloch-Johnson et al. (2015)), which allows having a meaningful comparison of the results obtained from equations 2 and 3. The resulting time series of ΔT over 200 years will be shown in a figure. For your information, a similar exercise is performed in Chapter 4 of Goosse (2015), with the results shown in figure 4.10.

After a description of the above results, they must be discussed with a particular focus on the physical mechanisms that can lead to an indefinite warming, as observed in the results for some choices of the parameters used, and on the realism of this simple model. This discussion will be based on other scientific studies dealing with a similar topic. Suggestions are the studies of Gregory et al. (2002), Roe and Baker (2007) Rohrschneider et al. (2019), and Jonko et al. (2013).

Part 2

While runaway states are physically possible for planetary atmospheres, in the long term the quadratic nonlinearity would lead to an unphysical infinite temperature. This means that, as temperature increases, higher order terms must eventually kick in to avoid a true runaway.

In figure S2 of the Supplementary material Bloch-Johnson et al. (2015) show how the inclusion of a fifth order term can model this reequilibration effect, with the appearance of a new, warmer equilibrium, "after" the initial quadratic temperature increase.

The equation of the model is now

$$C\frac{d\Delta \mathrm{T}}{d\mathrm{t}} = F + \lambda\Delta\mathrm{T} + \alpha\Delta\mathrm{T}^2 + \beta\Delta\mathrm{T}^5 \tag{4}$$

where the values of λ, α and β can be found in the caption of figure S2. In this figure, the authors show the emergence of multiple equilibria as F is increased, in terms of the zeros of the right-hand side of equation (4).

Task 1. Remake figure S2, but plotting instead the potential of equation (4) as a function of ΔT, as seen in class. Discuss how the new figure relates to figure S2, how you can identify the equilibria in the new figure, and how you can visually determine their stability.

Task 2. For a selection of relevant values of F (chosen to highlight different behaviours), integrate equation (4) starting from initial condition ΔT=0, and plot time series of ΔT to observe the relaxation to equilibrium. Explain the results in terms of what obtained in Task 1.

The presence of noise, modelling the chaotic fluctuations of the climate system, can substantially impact the dynamics of the model. Let's consider the stochastic differential equation

$$C\frac{d\Delta \mathrm{T}}{d\mathrm{t}} = F + \lambda\Delta\mathrm{T} + \alpha\Delta\mathrm{T}^2 + \beta\Delta\mathrm{T}^5 + D\xi \tag{5}$$

where $\xi(t)$ is a Gaussian white noise term such that $\mathbb{E}[\xi(t)\xi(s)] = \delta_{ts}$, as seen in class. Set the amplitude of the noise at D=5753 $\mathrm{Wm}^{-2}\mathrm{s}^{1/2}$. This value is chosen so that the standard deviation of the temperature fluctuations of the stationary solution when F=0 is about 0.15 K (which is a realistic value for annual global temperature fluctuations).

Task 3. Integrate numerically equation (5) for different values of F, and discuss the results. Suggestion: try F=0, 2, and 3.7 Wm^{-2}. Then try F=3.45 and 3.5 Wm^{-2}. For each case perform an ensemble of simulations and plot the results as we have seen in class. Feel free to play with the model changing F or other parameters, discussing the physical implications of the setups.

References

Bloch-Johnson, J., Pierrehumbert, R. T., and Abbot, D. S. (2015). Feedback temperature dependence determines the risk of high warming. *Geophysical Research Letters*, 42(12):4973–4980.

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Gregory, J. M., Stouffer, R. J., Raper, S. C. B., Stott, P. A., and Rayner, N. A. (2002). An observationally based estimate of the climate sensitivity. *Journal of Climate*, 15(22):3117 – 3121.

Jonko, A. K., Shell, K. M., Sanderson, B. M., and Danabasoglu, G. (2013). Climate feedbacks in ccsm3 under changing co2 forcing. part ii: Variation of climate feedbacks and sensitivity with forcing. *Journal of Climate*, 26(9):2784 – 2795.

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