Dynamics of the Global Energy Budget: the Time Dependence of the Climate Feedback Parameter and Climate Sensitivity.

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Abstract

The most simple representation of the dynamics of the global energy budget is the 0-dimensional energy balance model (EBM) introduced by Budyko (1965). Budyko's EBM assumes a linear relationship between the Earth's radiative response and the global surface temperature such that the dynamics of the global energy budget reads CdTs/dt = N = F - λ Ts, where Ts is the global surface temperature, N is the Earth Energy Imbalance, C is the ocean heat capacity and λ is the constant climate feedback parameter. Such simple conceptual model depicts reasonably well the centennial time scale response of the steady state preindustrial global energy budget under an anomalous forcing such as the increase of atmospheric greenhouse gases concentrations. For this reason it has served as the basis for the definition of the effective climate sensitivity to atmospheric CO2 concentrations. However recent studies identified limitations to Budyko's EBM. Indeed climate model simulations show that the radiative response of the Earth not only depends on the global surface temperature but also on its geographical pattern: the so-called "pattern effect". It arises from changes in the mix of radiative forcings, lag-dependent responses to forcings, or unforced variability and it leads to an apparent time variation in λ. This time variation must be accounted for in Budyko's EBM to represent the longer term response of the global energy budget under increased CO2 concentrations. Here, a simple theory is developed to account for the time dependency of λ in the global energy budget. The resulting differential equation accurately reproduces the long term response (i.e. >200 years) of climate under abrupt changes in CO2 concentrations as simulated in the longrunmip experiment. Analysis of the asymptotic form of the differential equation yields a new expression of the climate sensitivity which not only depends on the climate feedback parameter but also on its temporal change. We evaluate this new climate sensitivity for all runs of the longrunmip experiment and show how it relates with the classical effective climate sensitivity from Gregory et al. (2004). We find that the spread in climate sensitivity among climate models of the longrunmip experiment is essentially due to different temporal changes in λ (and thus different pattern effect) among models.

Dynamics of the Global Energy Budget with a time dependant Climate Feedback Parameter

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The 0-dimensional linearised energy balance model (EBM) introduced by Budyko (1968) allows us to study the response of the climate system to a radiative forcing such that an increase of atmospheric CO2. This EBM reads: CdTs/dt = N = F - λ Ts, where C is the ocean heat capacity, Ts is the global surface temperature, N is the Earth Energy Imbalance and λ is the constant climate feedback parameter.

However, recent studies show that a constant climate feedback parameter cannot represent accurately the long term dynamics of the climate response, notably due to the dependence of λ on the pattern of warming (Armour et al. 2013).

Here, we introduce the time dependence of λ in a simple energy balance model and develop the consequences on climate sensitivity.

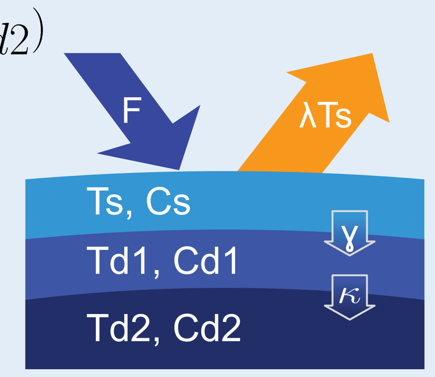
Theoretical framework

1. Energy Balance Model

$$C_s\frac{dT_s}{dt} = F - \lambda T_s - \gamma\,(T_s - T_{d1}) \quad (1)$$

$$C_{d1}\frac{dT_{d1}}{dt} = \gamma\,(T_s - T_{d1}) - \kappa\,(T_{d1} - T_{d2}) \quad (2)$$

$$C_{d2}\frac{dT_{d2}}{dt} = \kappa\,(T_{d1} - T_{d2}) \quad (3)$$



Three layers energy balance model, adapted from Geoffroy et al. (2013)

2. Hypotheses

- The climate system is a forced dynamical system. We assume the existence of steady states variables: T_{s0}, F_0 and λ_0.
- When δF is applied, the system deviates from its steady state and tends to reach a new equilibrium.
- The perturbation theory allows us to study this new dynamical system system. **We hypothesise that our study is in the scope of the pertubation theory.**

3. Applying perturbation theory

We apply perturbation theory to the surface equation to derive the perturbed anomaly system.

With a constant λ_0

$$C_s\frac{d}{dt}(\delta T_s) = \delta F - \lambda_0\,\delta T_s - \gamma\,(\delta T_s - \delta T_{d1})$$

With forced variation of λ

$$C_s\frac{d}{dt}(\delta T_s) = \delta F - \lambda_0\,\delta T_s - \delta\lambda(t) T_{s0} - \gamma\,(\delta T_s - \delta T_{d1})$$

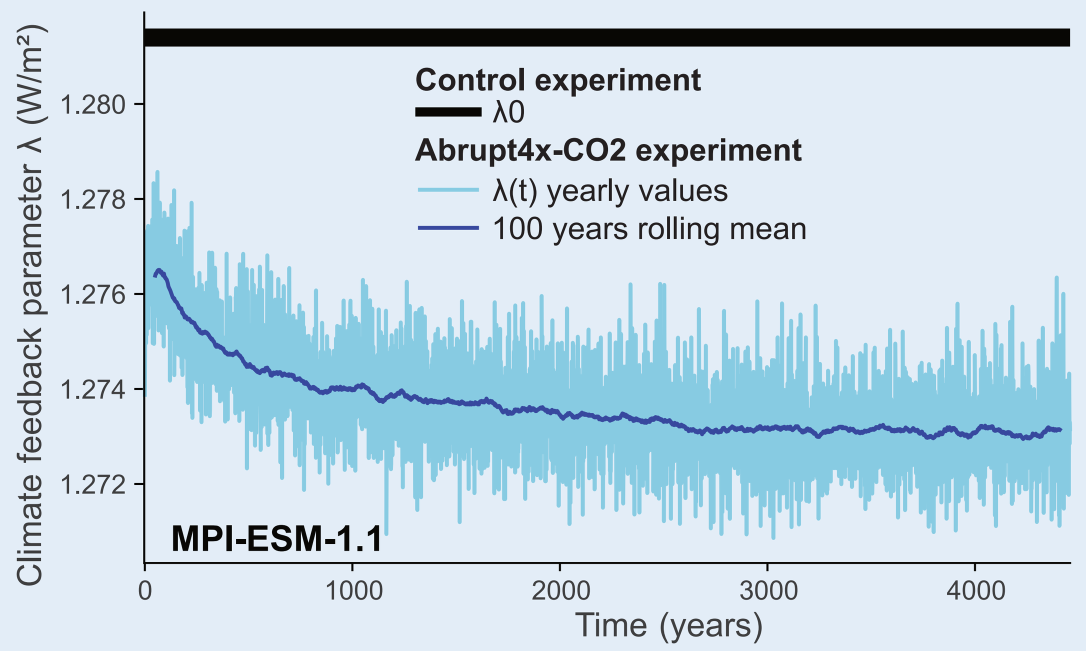
Assuming a variable λ leads to the emergence of a new term in the anomaly energy budget

Climate Feedback Parameter time series

With N = F - λ Ts, we can write

$$\lambda(t) = \frac{F_0 + \delta F - N(t)}{T_{s0} + \delta T_s(t)}$$

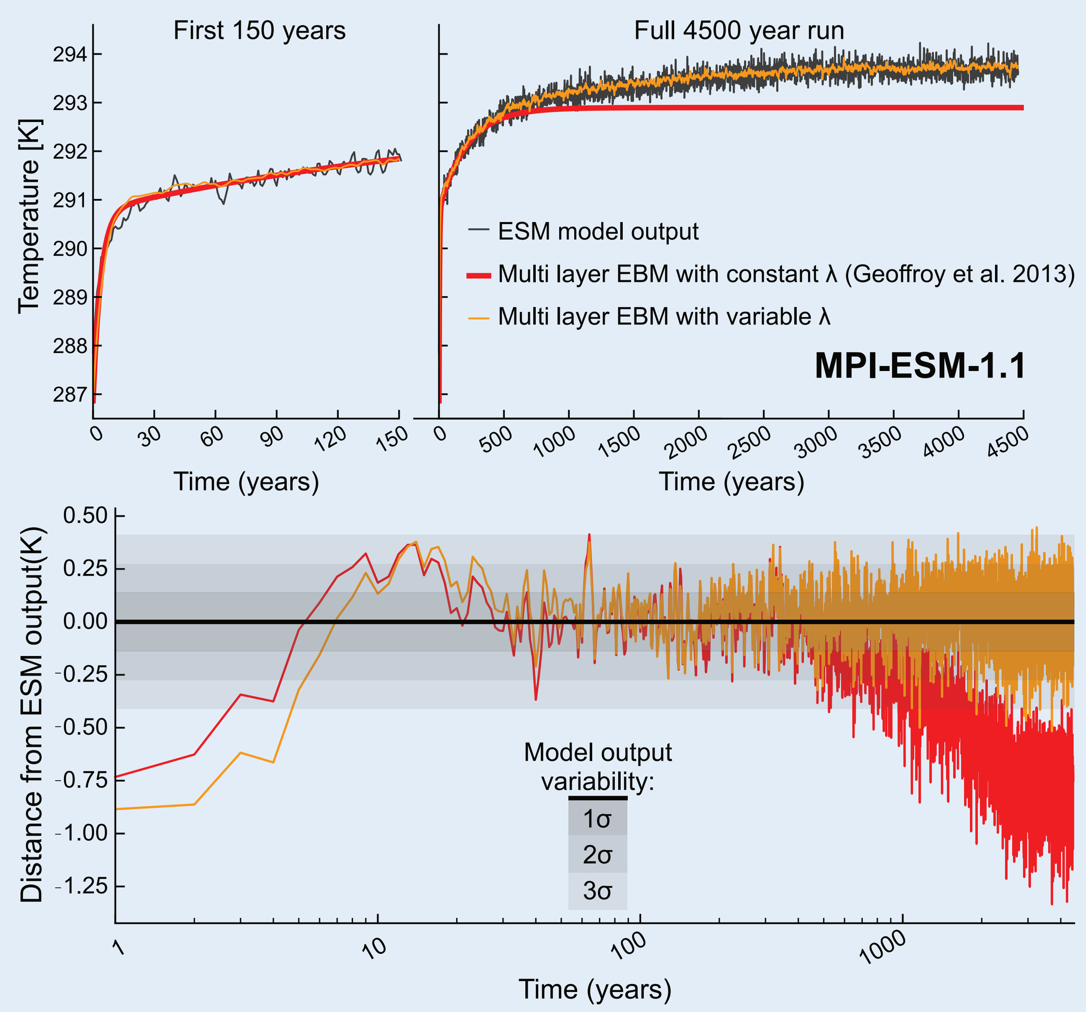
Which gives a times series of the climate feedback parameter.



We verify $\delta\lambda \ll \lambda_0$
which validates the perturbation theory hypothesis.

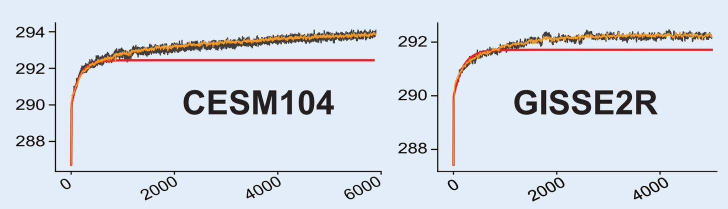
With such a climate feedback parameter, we expect to reproduce the dynamics of the global surface temperature in the model with the numerical integration of the system.

Numerical integration



We reproduce the dynamics of the global average surface temperature in the MPI-ESM1.1 abrupt4x-CO2 run from the longrunMIP experiment (Rugenstein et al. 2019) **at all time scales.**

How about other models?



Consequences on climate sensitivity

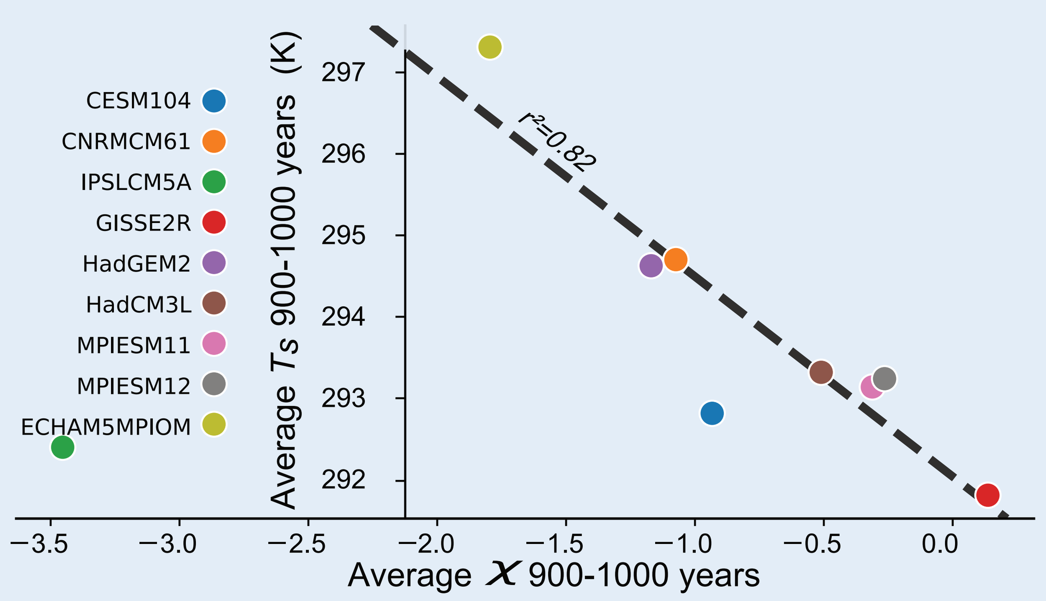
Getting λ from N = F-λTs and developping the new EBM to equilibrium leads to a new expression of the climate sensitivity:

$$S = S_0\,(1 - \chi)$$

$$\chi = \frac{F_0\,\delta\lambda}{\lambda_0\,\delta F} \qquad S_0 = \frac{\delta F}{\lambda_0}$$

Where χ is the **climate susceptibility** to forcing

- Explicit dependance on the initial climate state
- Explicit dependence on λ variations



The intermodel spread in climate sensitivity in the LongRunMIP experiment is due to different variations of λ among models.

Conclusions

1. A simple theory is developed to account for the time dependency of λ in the global energy budget.
2. The resulting differential equation accurately reproduces the response of the climate under abrupt changes in CO2 concentrations **at all time scales** as simulated in a mulitmillenia earth system model.
3. Analysis of the asymptotic form of the differential equation yields a new expression of the climate sensitivity which explicitely depends on the temporal variations of the climate feedback parameter.
4. We find that **the spread in climate sensitivity among climate models of the LongRunMip experiment is essentially due to different temporal changes in λ** (and thus different pattern effect) among models.

References

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