Climate sensitivity with a time dependent climate feedback parameter.

Robin Guillaume-Castel & **Benoit Meyssignac**

LEGOS, Toulouse University - robin.guillaume-castel@legos.obs-mip.fr

Perturbation theory provides a rigorous theoretical framework to develop energy balance models (EBM) with a time-dependent climate feedback parameter $\lambda(t)$, along with a robust definition of $\lambda(t)$ (**see companion poster by Meyssignac et al.**).
We evaluate $\lambda(t)$ following abrupt CO_2 increase in 10 climate models from the LongRunMIP experiments. New estimates of $\lambda(t)$ show much smaller time variations than previous published estimates.

Analysis of the asymptotic form of the radiative response with the new EBM yields a new expression of the climate sensitivity which explicitly depends on the **climate state before the forcing is applied** (λ_0), and on **temporal changes of λ** ($\Delta\lambda$). The spread in $\Delta\lambda/\lambda_0$ explains 83% of the spread in LongRunMIP effective climate sensitivity.

We confirm that the non-linear radiative response of the Earth across CO_2 increase scenarios is explained by the **temperature-dependence of λ** and thus the temperature-dependence of the climate sensitivity. However, we show that $\lambda(t)$ never becomes positive even in high CO_2 increase scenarios.

Theoretical Framework

The climate system is a **forced dynamical system**. The surface temperature follows

$$C\frac{dT_s}{dt} = F + R - H \quad (1)$$

Where:
- H the deep ocean heat exchange
- C is the heat capacity
- Ts the surface temperature
- F the radiative forcing
- R the radiative response

On interannual and longer timescales, **R is linear with T_s** (Budyko, 1969): $R = \lambda T_s$ (2)

- λ is the climate feedback parameter.

If λ varies with time, the energy budget reads:

$$C\frac{dT_s}{dt} = F + \lambda(t)T_s - H \quad (3)$$

A given forcing F_0 is associated with steady state variables T_{S0} and λ_0. On a steady state:

$$F_0 = \lambda_0 T_{S0} = R_0 \quad (4)$$

$$H = 0 \quad (5)$$

The preindustrial era/control experiments are considered to be on a **steady state**.

Perturbation theory

We assume a small deviation ΔF from F_0 induces $\Delta\lambda$. Following perturbation theory, we look for a solution to (3):

$$T_S = T_{S0} + \Delta T_S$$

Equation (2) gives $R = \lambda T_S = (\lambda_0 + \Delta\lambda)(T_{S0} + \Delta T_S)$

$$R = \lambda_0 T_{S0} + \lambda_0 \Delta T_S + T_{S0}\Delta\lambda + \Delta\lambda\Delta T_S$$

Using (4) and a first order approximation leads to the surface EBM in anomalies:

$$C\frac{d\Delta T_S}{dt} = \Delta F + \Delta\lambda T_{S0} + \lambda_0 \Delta T_S - \Delta H \quad (6)$$

More details on the theory can be found in companion poster by **Meyssignac et al.**

Data used

LongRunMIP
Rugenstein et al. (2020)

- Data from 10 different climate models in CMIP5 and CMIP6
- We use abrupt CO_2 runs from the LongRunMIP experiment
- Runs > 1000 years

Results

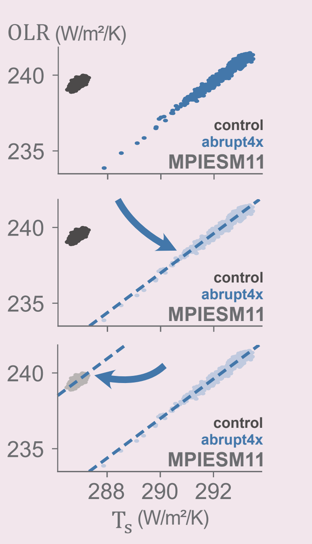
Evaluating $\lambda(t)$

To use (6), we must evaluate λ as $\lambda(t) = \dfrac{N - F_0 - \Delta F}{T_{S0} + \Delta T_S}$

Computing F_0 and λ_0

The challenge is to compute F_0. Two components:
- **Solar F_0** : absorbed solar radiation
- **"Longwave" (LW) F_0** due to atmospheric compositon: ?

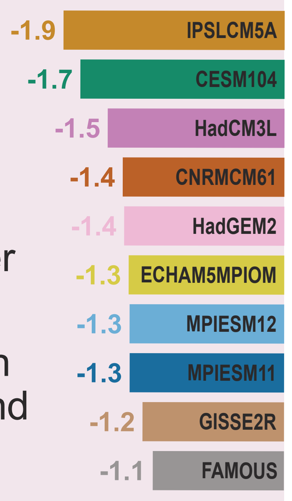
Computing LW F_0



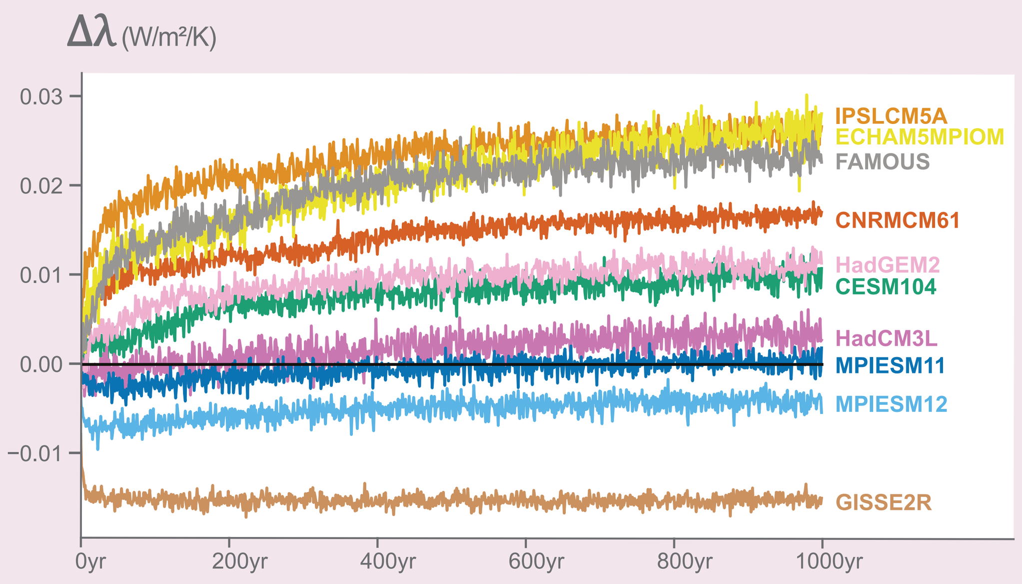
I Budyko (1969): $OLR = A(F) + BT_s$

II Regress OLR over T_s in **abrupt4x CO_2** for better signal/noise

III Regress in **control** with the **same slope** and find the intercept: **LW F_0**



Time series of λ



- **The variations of $\Delta\lambda$ are very small compared to λ_0**

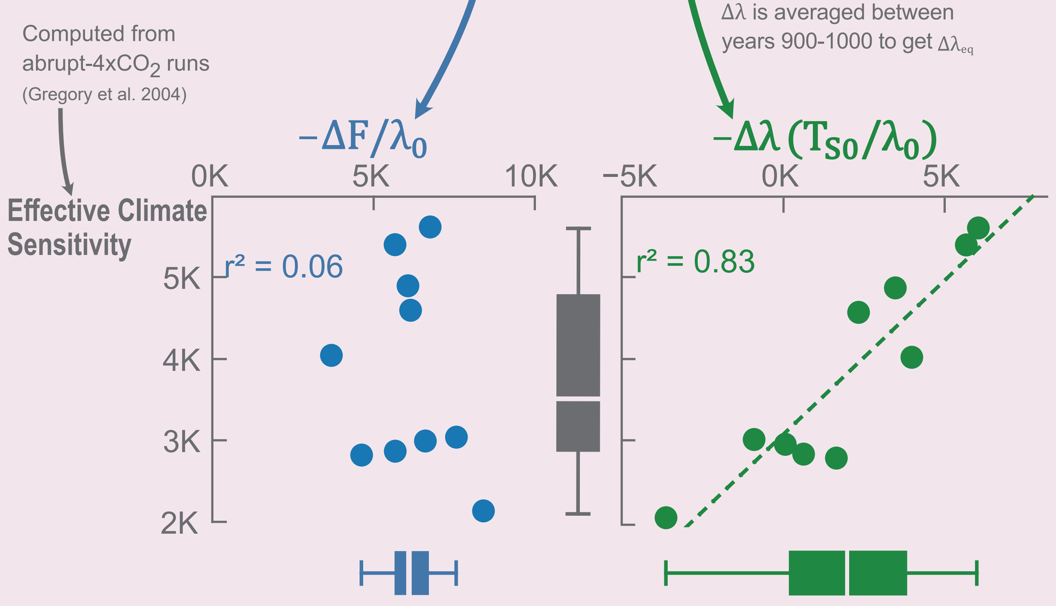
Climate sensitivity with $\lambda(t)$

The climate sensitivity is obtained by equilibrating (6):

$$C\frac{d\Delta T_S}{dt} = 0 \qquad H = 0$$

Climate sensitivity with $\lambda(t)$

$$ECS = -\frac{\Delta F}{\lambda_0} - \frac{\Delta\lambda_{eq}}{\lambda_0} T_{S0}$$

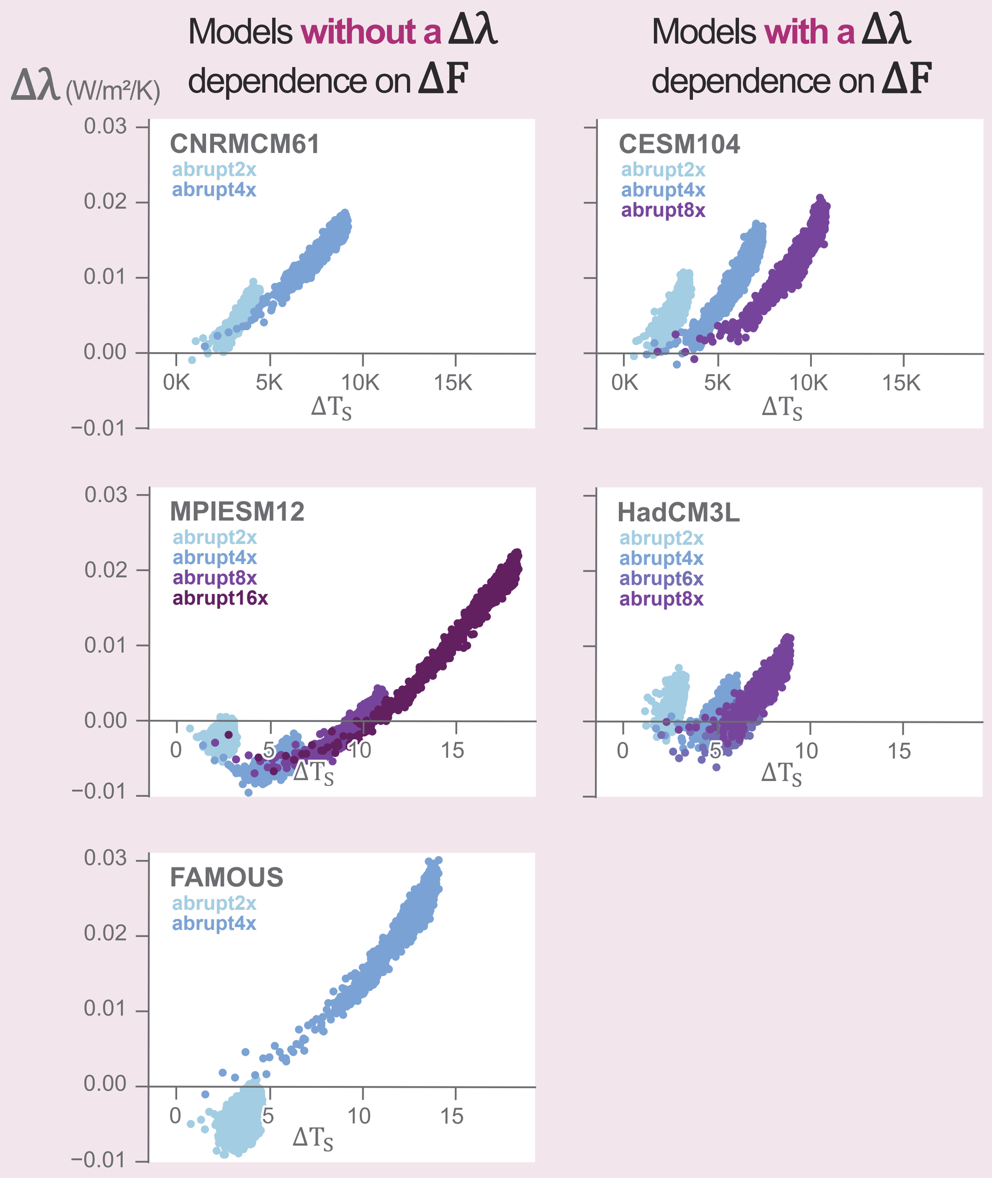


- There is little spread in $\Delta F/\lambda_0$
- **The spread in ECS is mostly explained by $\Delta\lambda\,(T_{S0}/\lambda_0)$**
- **This shows an explicit link between the pattern effect in $\Delta\lambda$ and the climate sensitivity.**

ΔT_s dependence of $\lambda(t)$

We search for dependences of $\Delta\lambda$ on ΔF and ΔT_S

We use models with more than 2 abrupt experiments to get different ΔF and ΔT_S ranges



- **$\Delta\lambda$ increases with ΔT_S in all models but remains close to its initial value: never positive**

  ➡ **no runaway greenhouse gases effect due to temperature dependence of λ**

- **Some models show a positive dependence on ΔF**

Conclusion

- **Using perturbation theory, we derive an energy balance model with a variable λ**
- **We evaluate the dynamic evolution of λ in 10 climate models from the LongRunMIP experiment as:** $\lambda(t) = \dfrac{N - F_0 - \Delta F}{T_{S0} + \Delta T_S}$
- **We show that variations of λ are two orders of magnitude smaller than its initial value**
- **This formulation allows for a continuous λ from control to abrupt expriments**
- **From our EBM, we derive a new formula for the climate sensitivity, with an explicit dependence on the base state of the climate and on the variations of λ** $ECS = -\dfrac{\Delta F}{\lambda_0} - \dfrac{\Delta\lambda_{eq}}{\lambda_0} T_{S0}$
- **We find that the relative variations of λ explain the spread in effective climate sensitivity**
- **We confirm that the temperature dependence of λ increases the climate sensitivity for high CO_2 forcing**
- **We show that λ never becomes positive even under high CO_2 forcing: no runaway greenhouse effect**

Future work

- **Applying the formalism to non constant forcing simulations : 1%CO2 – Historical**
- **Applying the formalism to obervations**
- **Physical understanding of $\Delta\lambda$**

Budyko (1969). The effect of solar radiation variations on the climate of the Earth. tellus, 21(5), 611-619.

Gregory et al. (2004). (2004). A new method for diagnosing radiative forcing and climate sensitivity. Geophysical research letters, 31(3).

Rugenstein et al. (2020). LongRunMIP: motivation and design for a large collection of millennial-length AOGCM simulations. Bulletin of the American Meteorological Society, 100(12), 2551-2570.

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