Incorporating nonlinearities into the climate forcing & feedback framework

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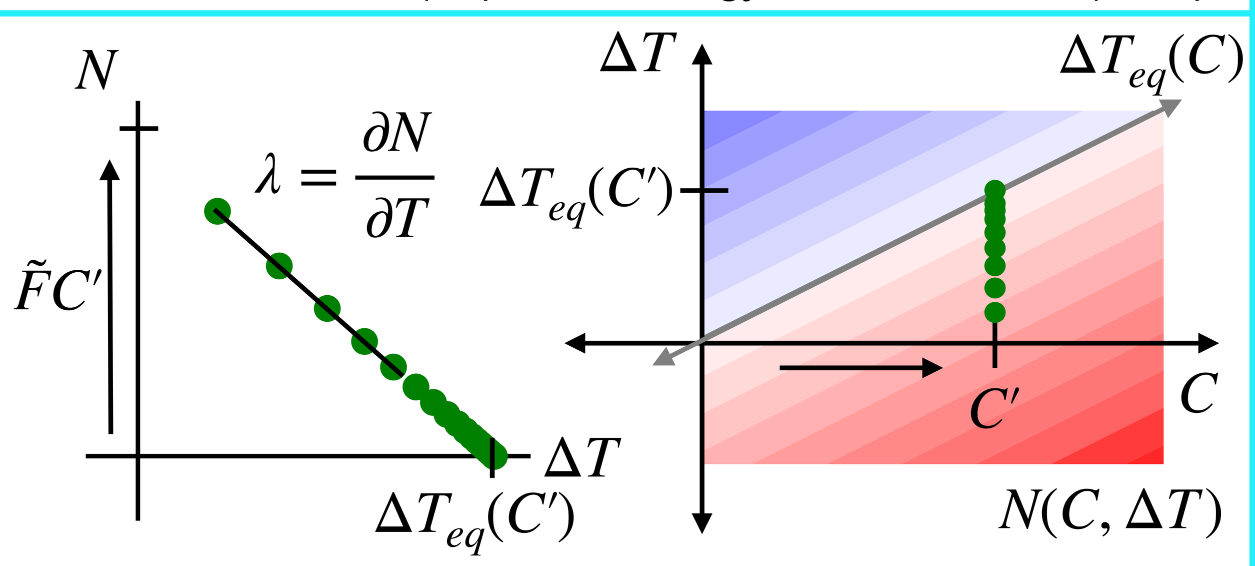
Finding: *Incorporating both spatial and state-dependent terms into the energy balance model of global warming allows us to recreate a GCM's nonlinear response to CO_2 forcing.*

$N \propto (C, \Delta T)$: the 0D linear energy balance model of global warming

A zero-dimensional (0D) linear energy balance model (EBM):



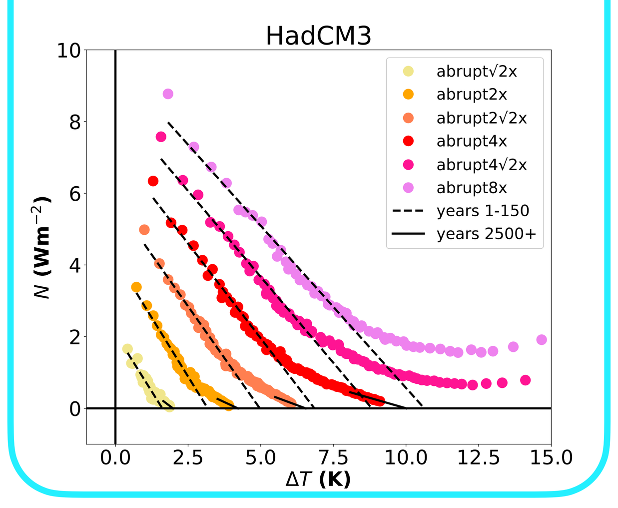
$$\Delta T_{eq}(C') = -\frac{\tilde{F}}{\lambda}C' = \Delta T_{2x}C'$$

Glossary

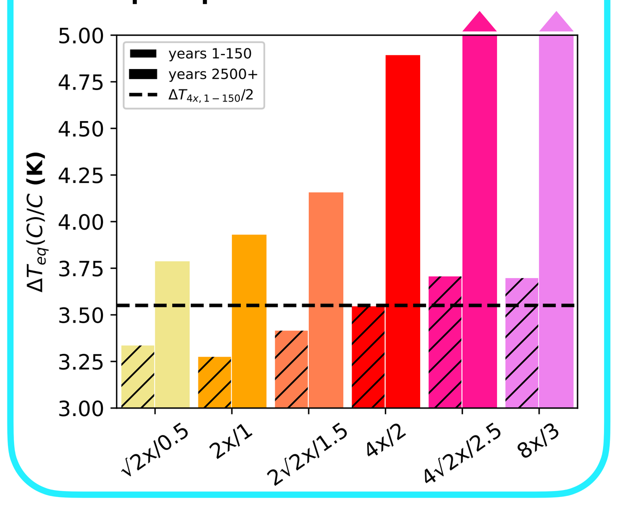
C - # of CO_2 doublings
$F \equiv N(C,0)$ - forcing
ΔT - surface warming
$\lambda \equiv \partial N/\partial T$ - feedback
ΔT_{eq} - equilibrium warming
$\tilde{F} \equiv \partial N/\partial C$ - F per doubling
N - net TOA radiative flux (↓+)
$\Delta T_{2x} \equiv \Delta T_{eq}(C)/C$ - ECS

The 0D linear EBM is the basis of two common assumptions.

Transient linearity:
assume feedback (λ) is constant across time

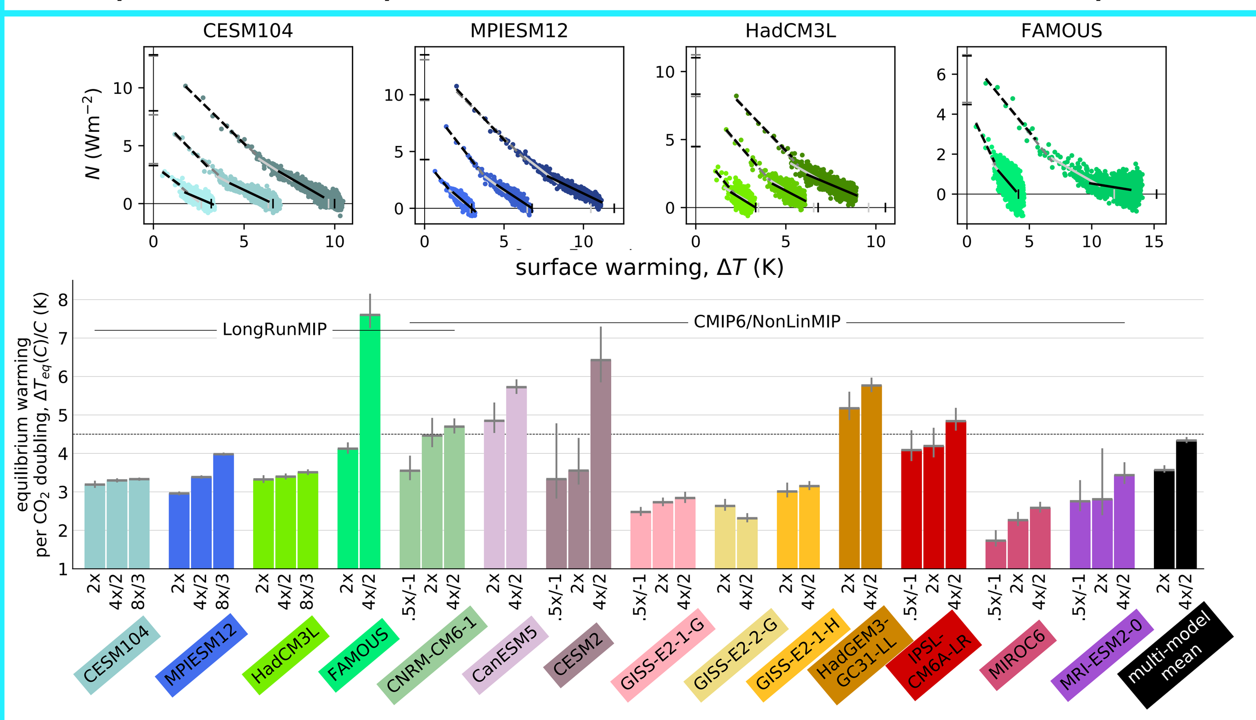


Equilibrium linearity:
assume ΔT_{eq} is proportional to C



Transient linearity allows one to use obs. to estimate λ, or the first 150 years of an abrupt2^Cx run to estimate $\Delta T_{eq}(C)$. *Equilibrium linearity* allows us to use the equilibrium response of any CO_2 forcing (i.e. abrupt4x) to estimate ΔT_{2x}. HadCM3 appears to have transient and equilibrium linearity after 150 years, but has neither after 1000s of years.

Abruptnx GCM experiments violate both linear assumptions.



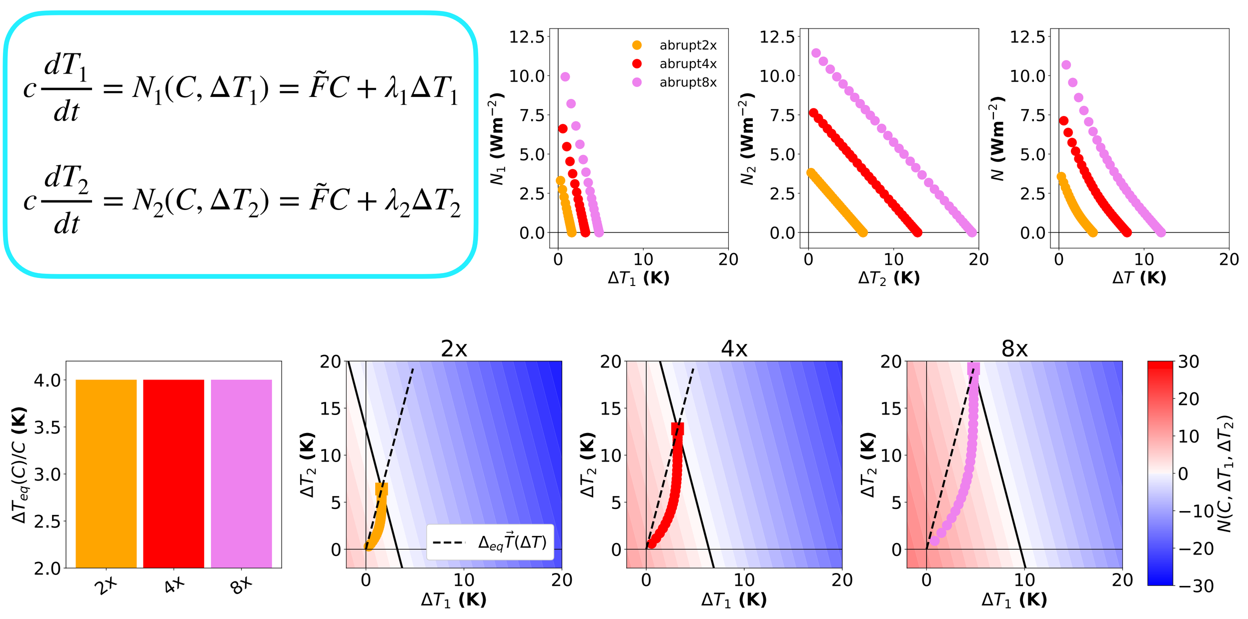
Abrupt*n*x simulations from LongRunMIP (Rugenstein et al. 2019) and the NonLinMIP (Good et al. 2016) experiments of CMIP6 typically show increases in λ with time (transient nonlinearity) and increases in $\Delta T_{eq}(C)/C$ with C (equilibrium nonlinearity) (Bloch-Johnson et al, 2021). In order to model this behavior, we have to extend the 0D linear EBM.

$N \propto (C, \Delta \vec{T})$: adding a spatial dimension to the linear EBM

Spatial terms can add transient nonlinearity.

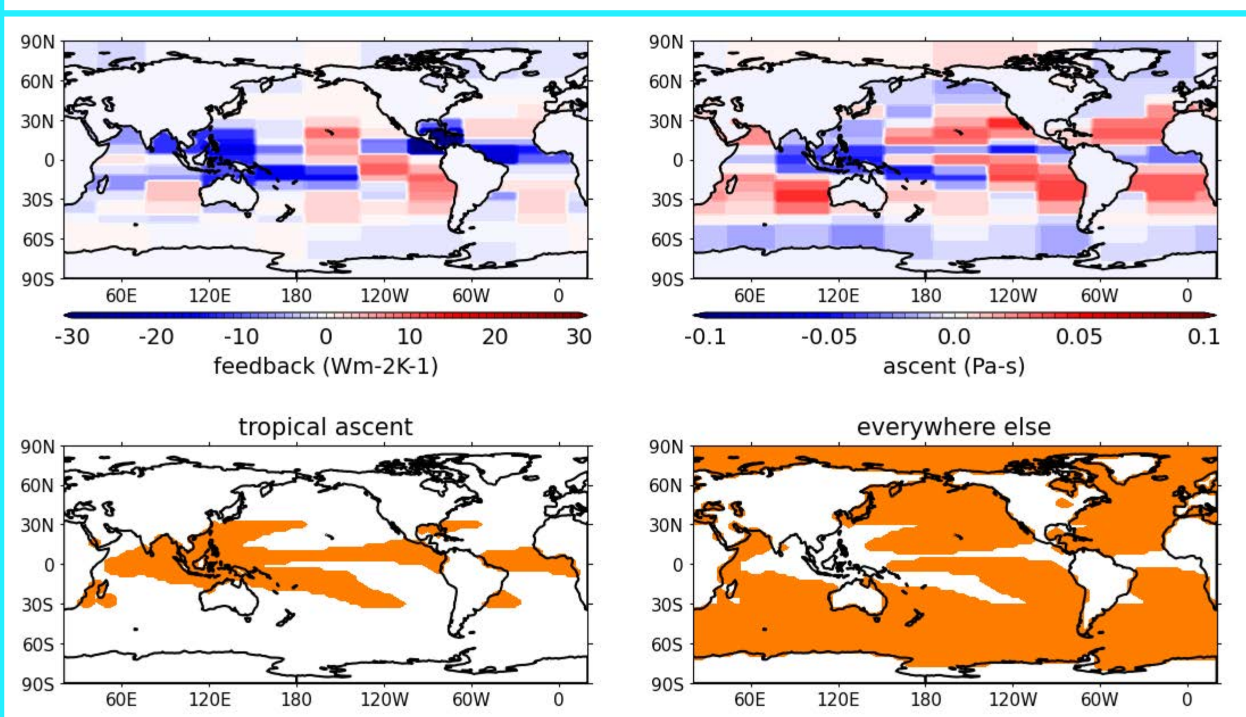
$$c\frac{dT_1}{dt} = N_1(C, \Delta T_1) = \tilde{F}C + \lambda_1 \Delta T_1$$

$$c\frac{dT_2}{dt} = N_2(C, \Delta T_2) = \tilde{F}C + \lambda_2 \Delta T_2$$



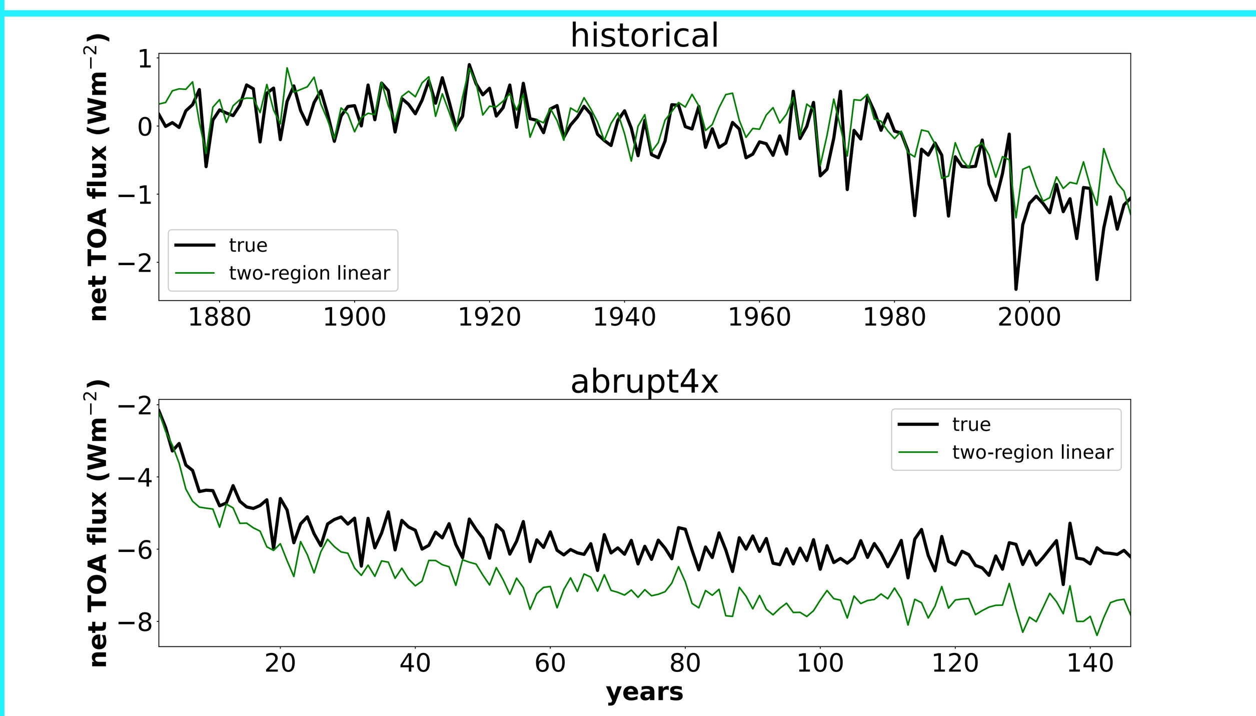
Adding a region with a different feedback causes warming to occur at different time scales, so that globally averaged λ changes with time. We can also add spatial thermal inertia, heat transport, and nonlocal feedbacks, but as long as F is proportional to C and feedbacks and transport are proportional to ΔT, the EBM will have equilibrium linearity.

GCMs have two distinct regions (tropical ascent, elsewhere).



Spatial feedbacks for HadCM3, estimated by running fixed-SST experiments, are similar to the map of vertical velocity at 700hPa, with strong negative feedbacks in regions of tropical ascent and modest feedbacks elsewhere (Zhou et al. 2017). Based on this, we divide the Earth into tropical ascent ("ta") and everywhere else ("ee") regions.

A linear two-region EBM recreates HadCM3's historical N.



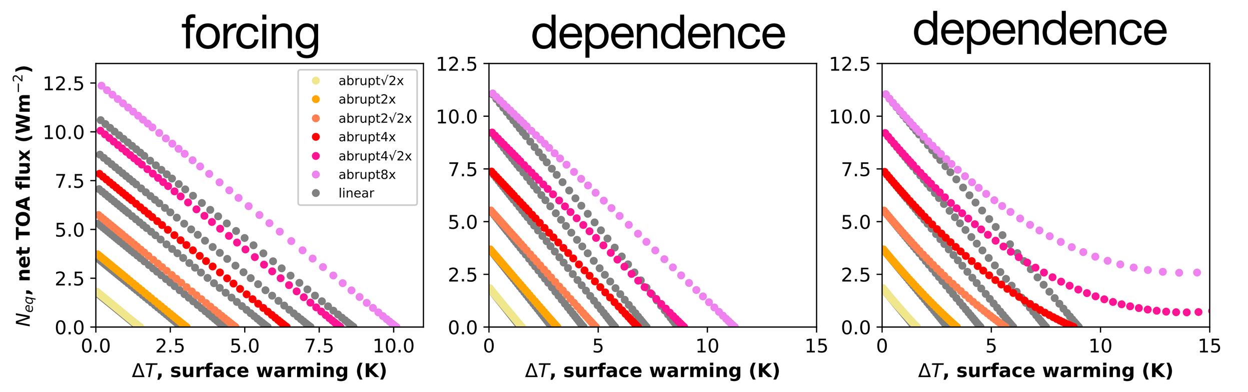
We use estimates of λ_{ta} and λ_{ee} from fixed-sst experiments multiplied by time series of ΔT_{ta} and ΔT_{ee} to estimate the N created by amip experiments with historical and abrupt4x warming patterns. This two linear two-region EBM estimates the historical N well, but not the abrupt4x N. For larger forcings, we need to include nonlinear terms.

$N \not\propto (C, \Delta \vec{T})$: adding nonlinear terms to the spatial linear EBM

A 0D quadratic EBM to analyze equilibrium nonlinearity:

$$N_{eq}(C, \Delta T) \equiv N(C, \Delta \vec{T}_{eq}(\Delta T)) \approx$$

$$\tilde{F}_{pi}C + \lambda_{pi}\Delta T + \underbrace{\frac{1}{2}\partial_C \tilde{F}C^2}_{\text{nonlinear forcing}} + \underbrace{\partial_C \lambda C \Delta T}_{\text{feedback } CO_2 \text{ dependence}} + \underbrace{\frac{1}{2}\partial_T \lambda \Delta T^2}_{\text{feedback temperature dependence}}$$

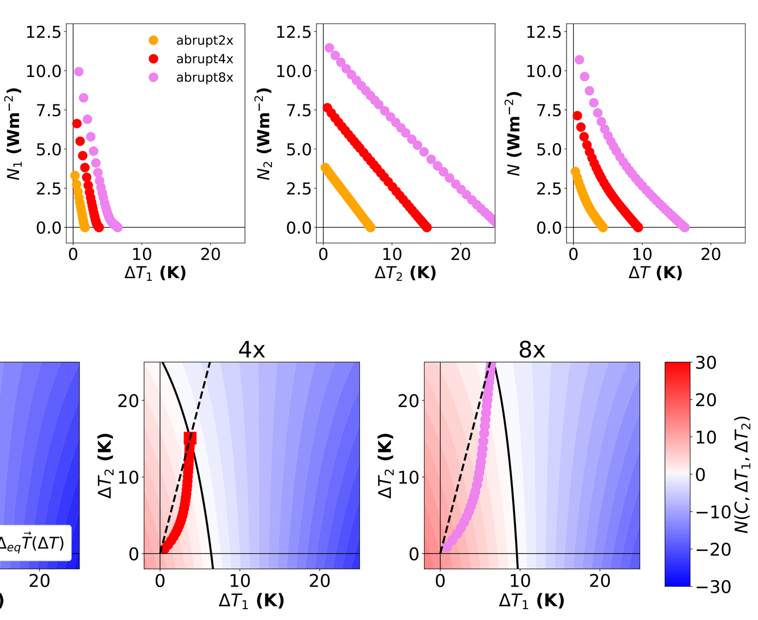


If we define N_{eq} using the equilibrium pattern of warming, then it has $\Delta T_{eq}(C)$ as its zero contour, and its quadratic approximation partitions equilibrium nonlinearity between three terms: nonlinear forcing, feedback CO_2 dependence, and feedback temperature dependence. The latter has the strongest effect on sensitivity (Bloch-Johnson et al. 2021).

Cross terms can cause feedback temperature dependence.

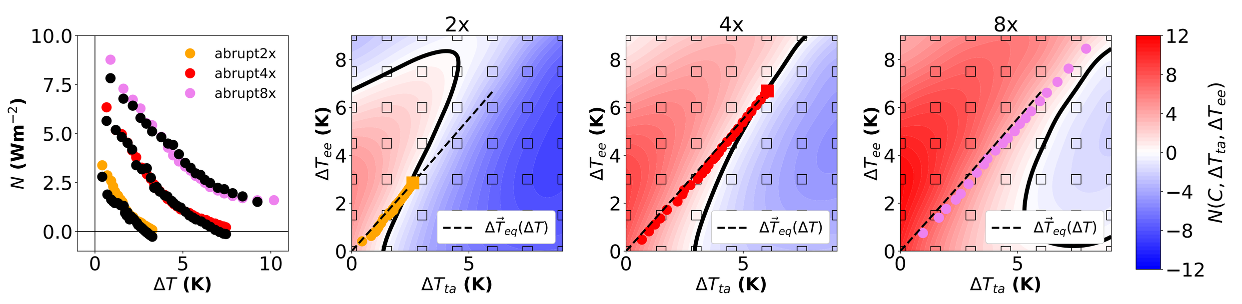
$$c\frac{dT_1}{dt} = N_1(C, \Delta T_1) = \tilde{F}C + \lambda_1 \Delta T_1 + \partial_{T_1,T_2}N\Delta T_1 \Delta T_2$$

$$c\frac{dT_2}{dt} = N_2(C, \Delta T_2) = \tilde{F}C + \lambda_2 \Delta T_2 + \partial_{T_1,T_2}N\Delta T_1 \Delta T_2$$



Many different nonlinear spatial EBMs can have the same N_{eq}. In this example, we add cross terms to the spatial example from above left, which creates positive global $\partial_T \lambda$, even though neither region has temperature dependence on its own. This motivates us to add both temperature dependence and cross terms to our two-region model.

A nonlinear two-region EBM recreates HadCM3's abrupt N.



We use fixed-sst experiments to estimate $N(C, \Delta T_{ta}, \Delta T_{ee})$ over a grid of ΔT_{ta} and ΔT_{ee}. Interpolation between estimated values of N at grid points (squares) allows us to fully recreate the abrupt2x, abrupt4x, and abrupt8x N (black dots in first panel), with cross-terms providing positive feedback temperature dependence. 2x and 4x simulations reach equilibrium value approximately at the estimated zero contour of N (solid black lines). The lack of intersection between estimated $\Delta \vec{T}_{eq}(\Delta T)$ (dashed black line) and 8x's zero contour successfully predicts runaway warming.

Implications

150 years of an abrupt4x may not be enough to estimate ΔT_{eq} • abrupt4x experiments may not give us ΔT_{2x} • Some of the high sensitivity models of CMIP6 may have reasonable historical sensitivity but high ΔT_{4x}, and therefore might not be "too hot." • Warming projections beyond 2100 that use an equilibrium linear EBM (e.g., those in AR6) may underestimate the risk of high warming. · A two-region nonlinear EBM with regions simply defined by tropical ascent can recreate both transient and equilibrium nonlinearity.

References

Rugenstein et al., 2019: LongRunMIP - motivation and design for a large collection of millennial-length GCM simulations, *BAMS*

Good, et al. 2016: nonlinMIP contribution to CMIP6: model intercomparison project for non-linear mechanisms: physical basis, experimental design and analysis principles, *GMD*

Bloch-Johnson et al, 2020: Climate Sensitivity Increases Under Higher CO2 Levels Due to Feedback Temperature Dependence, *GRL*

Zhou et al., 2017: Analyzing the dependence of global cloud feedback on the spatial pattern of sea surface temperature change with a Green's function approach, *JAMES*

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