TIPES
TIPPING POINTS IN THE EARTH SYSTEM

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Projections of the Transient State-Dependency of Climate Feedbacks

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Summary

Climate Feedbacks

Warming leads to change of internal process of climate system

- ☀ Planck radiation feedback
- Surface Albedo feedback
- 🌡 Lapse Rate feedback
- 💧 Water Vapour feedback
- ☁ Cloud Formation feedback

Problem:

Classic methods relate everything linearly to global warming

- ☹ Misses state-dependency and changes in feedback strength

Solution:

Decomposition of feedbacks as observables over time scales

- ☻ Captures temporal evolution & state-dependency of feedbacks

Climate Feedback Theory

Classic treatment of climate feedbacks (1)

Warming is due to net positive radiative imbalance

$$\Delta N = N_{SW,\downarrow} - N_{SW,\uparrow} - N_{LW,\uparrow}$$

incoming sunlight | reflected sunlight | Planck radiation

When $\Delta N = 0$ no more warming:

→ equilibrium warming $\Delta T_* = T_* - T_0$

Classic treatment of climate feedbacks (2)

Express imbalance as function of system state

$$\Delta N(t) = \Delta N(\, y(t)\,, \mu(t)\,)$$

Near equilibrium y_* (with $\mu = \mu_*$) a Taylor expansion gives

$$\Delta N(t) = \Delta N(y_*, \mu_*) + \left.\frac{\partial \Delta N}{\partial \mu}\right|_* \Delta\mu(t) + \left.\frac{\partial \Delta N}{\partial y}\right|_* \Delta y(t) + h.o.t.$$

Equals Zero

Radiative Forcing

Climate Response

Assumed to be small

$$\Delta N(t) = F(t) + \Delta R(t)$$

Implicit assumption: relevant climate dynamics are **approximately** a **linear** system

Classic treatment of climate feedbacks (3)

Climate Response ΔR is sum of *feedback contributions*:

$$\Delta R(t) = \sum_{j \in \mathcal{F}} \Delta R_j(t)$$

$\mathcal{F}$ is set of **Climate Feedbacks:**

- ☀ Planck radiation feedback
- Surface Albedo feedback
- Lapse Rate feedback
- Water Vapour feedback
- Cloud Formation feedback

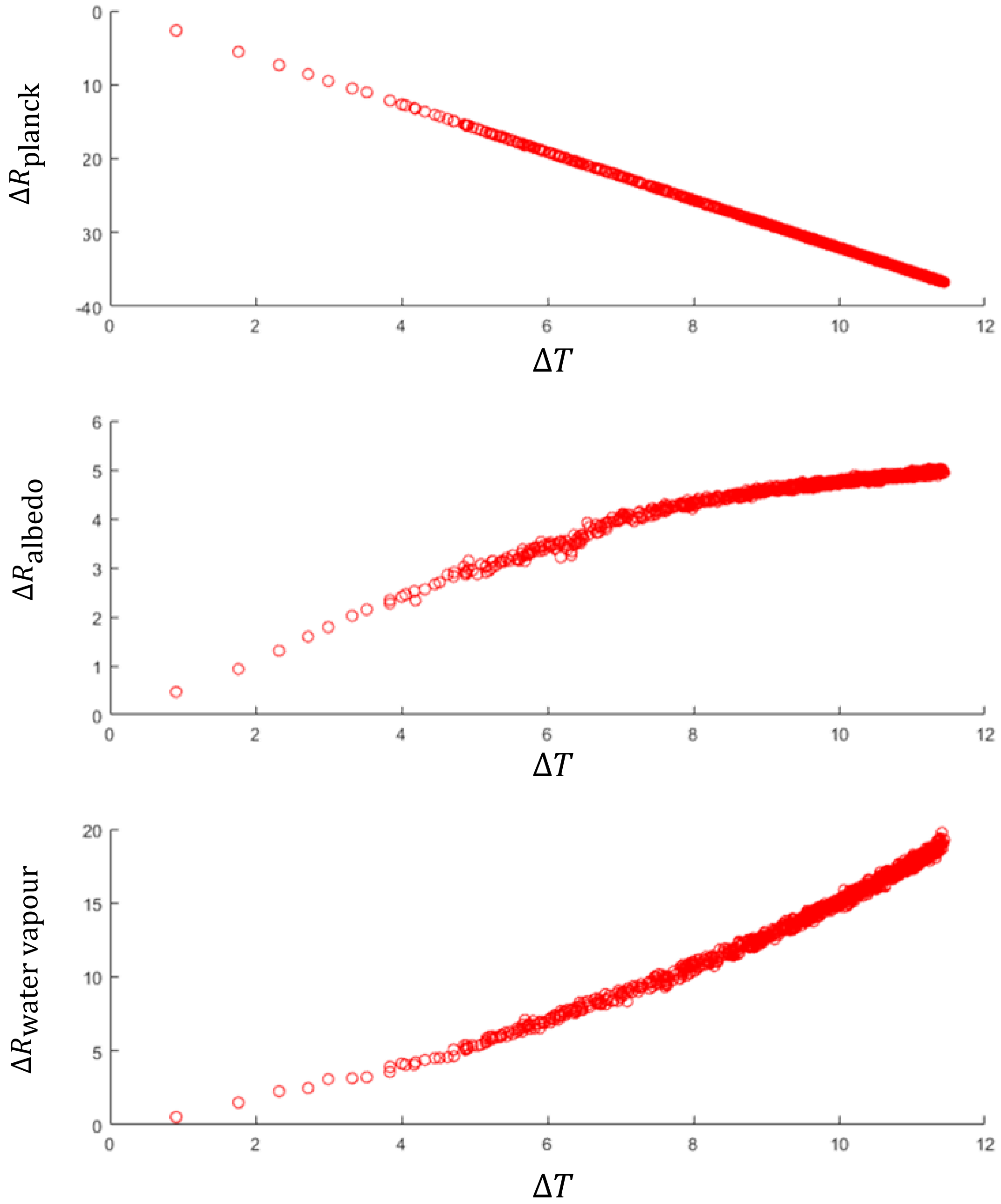
$$\Delta R_j(t) \coloneqq \left.\frac{\partial \Delta N}{\partial y_j}\right|_* \Delta y_j(t)$$

Classic: define feedback strength λ_j via

$$\Delta R_j(t) = \lambda_j \, \Delta T(t)$$

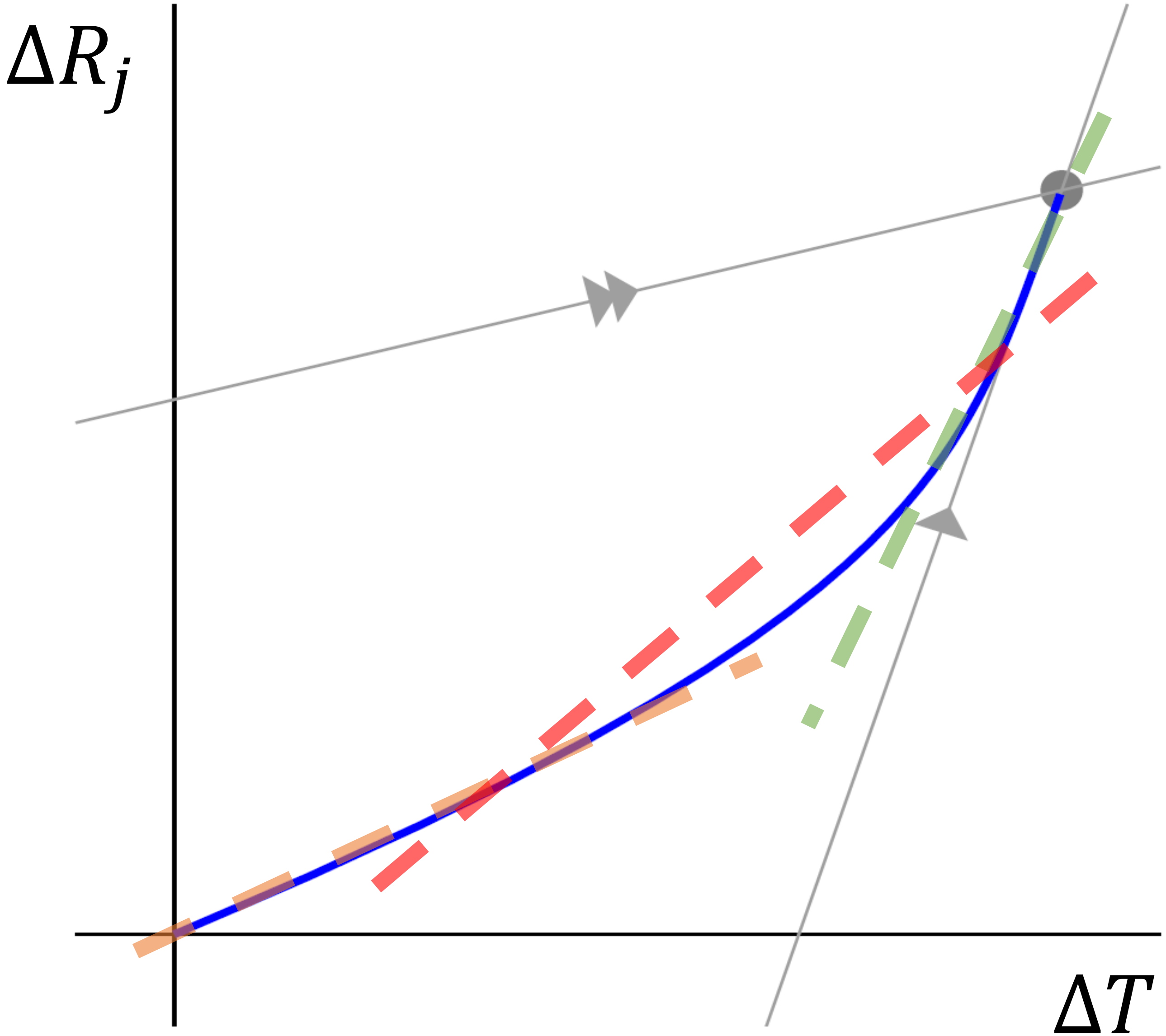
Implicit assumption: relevant climate dynamics play on **approximately one mode**

The problem with the classic treatment (1)



Data: CESM2, abrupt4xCO2 experiment (1,000 y) in CMIP6

The problem with the classic treatment (2)



Evolution of Observables

$$\frac{dO}{dt} = \mathcal{L}O + g(t)$$

Linear Response Theory (& Koopman Theory):

$$\Delta O(t) = \left(G^{[O]} * g\right)(t) = \int_0^t G^{[O]}(s)\, g(t-s)\, ds$$

Approximation of Green Function:

$$G^{[O]}(t) = \sum_{m=1}^{M} \beta_m^{[O]}\, e^{-t/\tau_m}$$

So:

$$\Delta O(t) = \sum_{m=1}^{M} \beta_m^{[O]}\, \mathcal{M}_m^{g}(t)$$

$$\mathcal{M}_m^{g}(t) = \int_0^t e^{-s/\tau_m}\, g(t-s) ds$$

all observable dependency (↑ $\beta_m^{[O]}$)

all forcing (and time) dependency (↑ $\mathcal{M}_m^{g}(t)$)

New feedback metrics

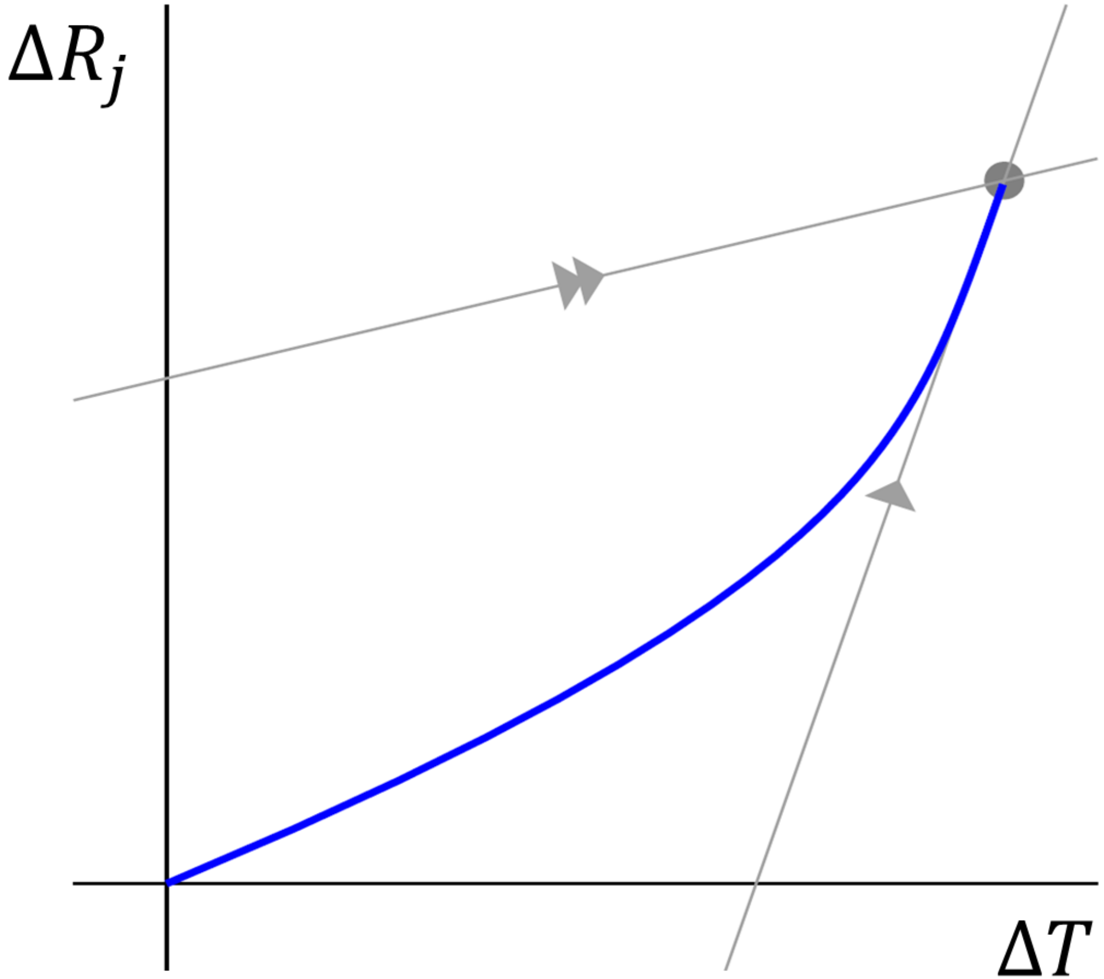
$$\Delta O(t) = \sum_{m=1}^{M} \beta_m^{[O]} \, \mathcal{M}_m^g(t)$$

Feedback strength per mode:

$$\lambda_j^m := \frac{\beta_m^{[R_j]}}{\beta_m^{[T]}}$$

Instantaneous feedback strength:

$$\lambda_j^{inst}(t) := \frac{\frac{d}{dt}\Delta R_j(t)}{\frac{d}{dt}\Delta T(t)}$$



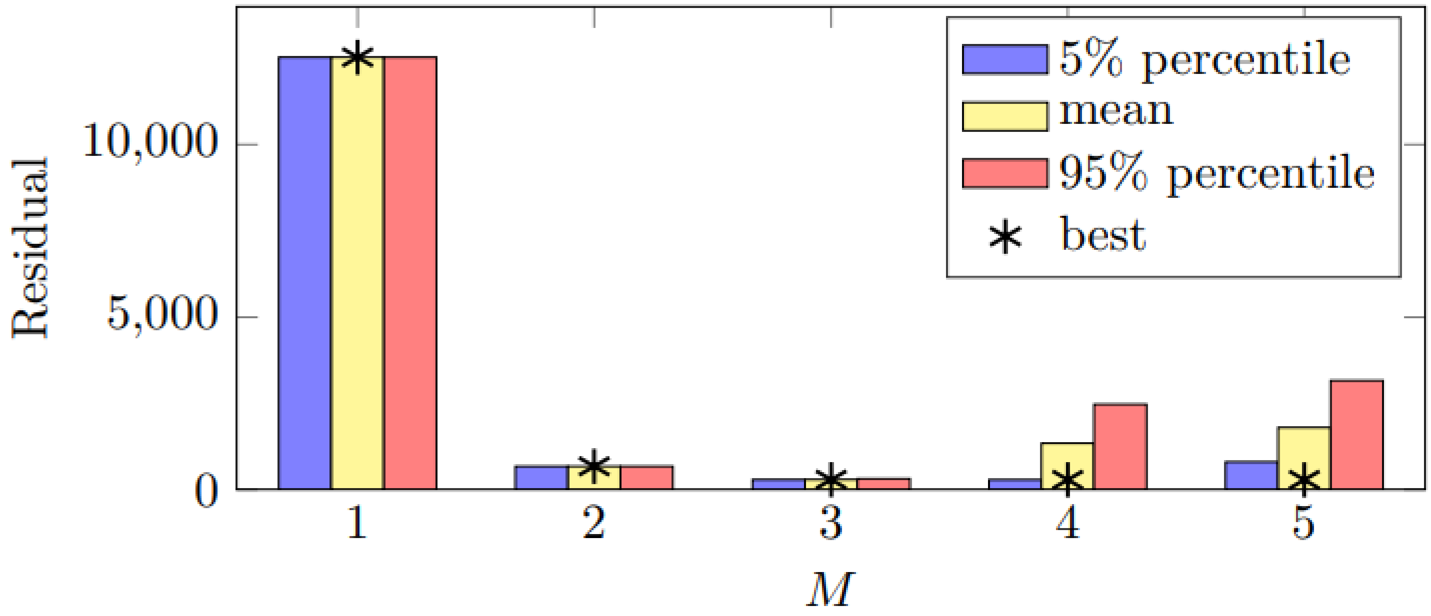
Application to CESM2 runs

Application to CESM2's abrupt4xCO2 run in CMIP6 (1)

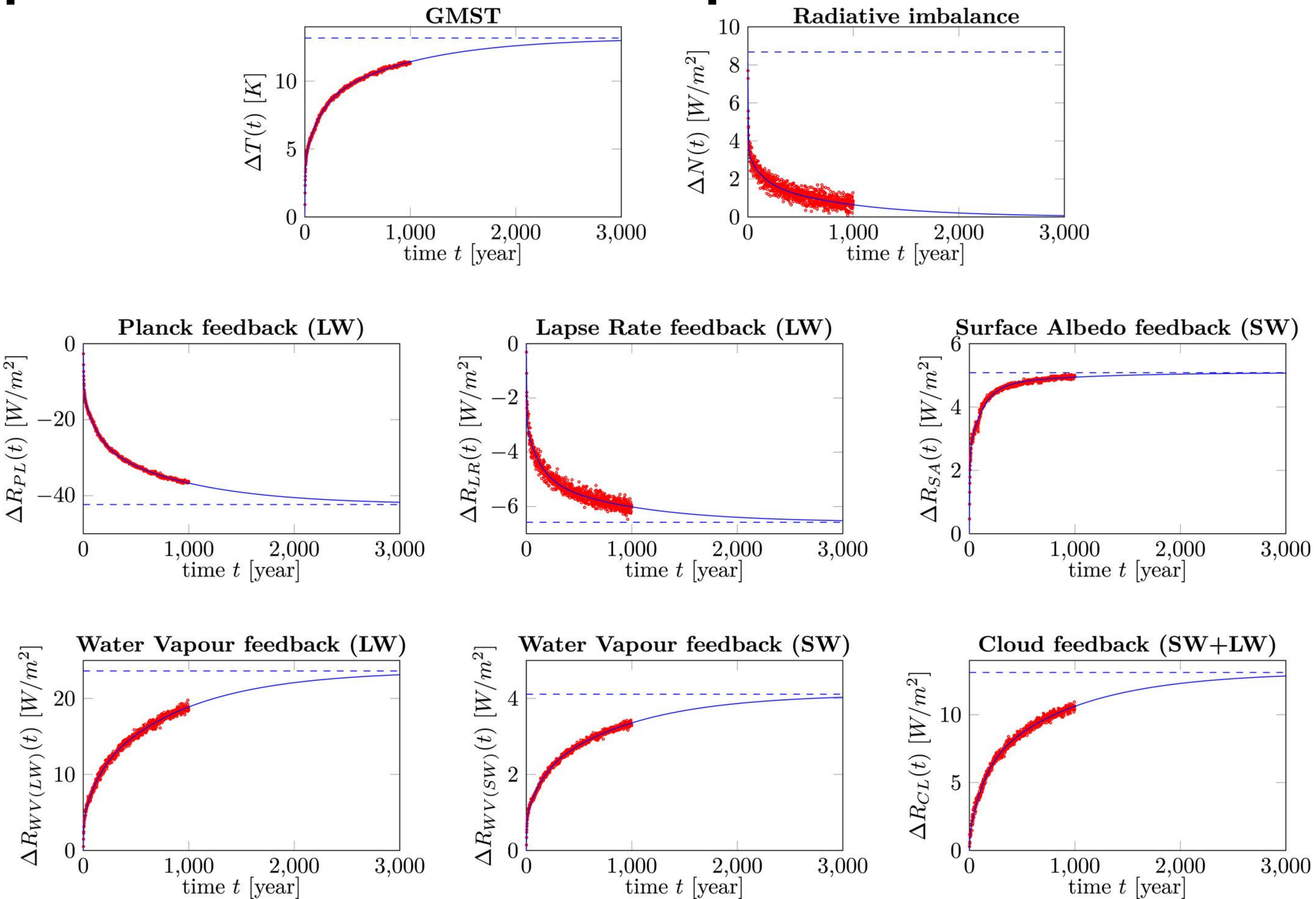
Radiative kernel: CESM-CAM5 from [Pendergrass et al, 2017]

Procedure:

1. Compute $\langle \Delta R_j \rangle(\mathrm{t}) = \left\langle \frac{\partial \Delta N}{\partial y_j}\left(\vec{y}_* \ ; \mu_* \right) \Delta y_j \right\rangle(t)$
2. Fit $\langle \Delta R_j \rangle(\mathrm{t}) = \sum_{n=1}^{M} \beta_n^{[R_j]} \mathcal{M}_n^g(t)$ (and similar for ΔT and N)
3. Compute feedback strengths



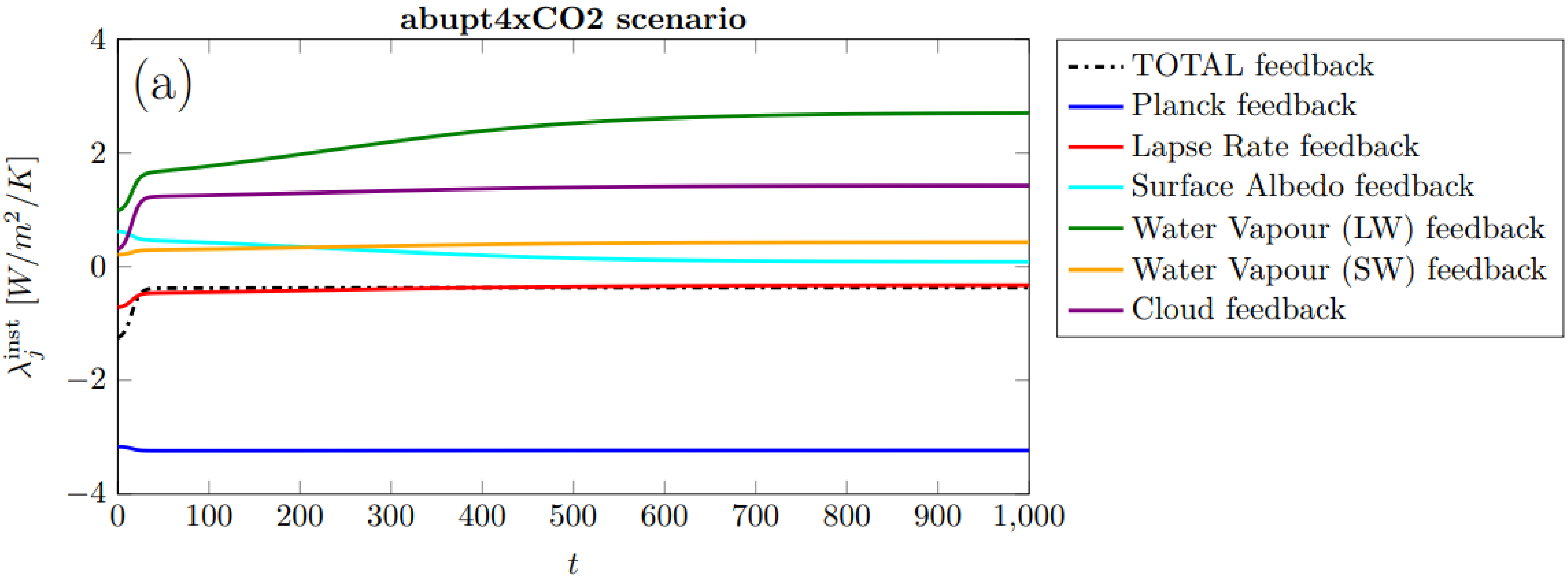
Application to CESM2's abrupt4xCO2 run in CMIP6 (2)



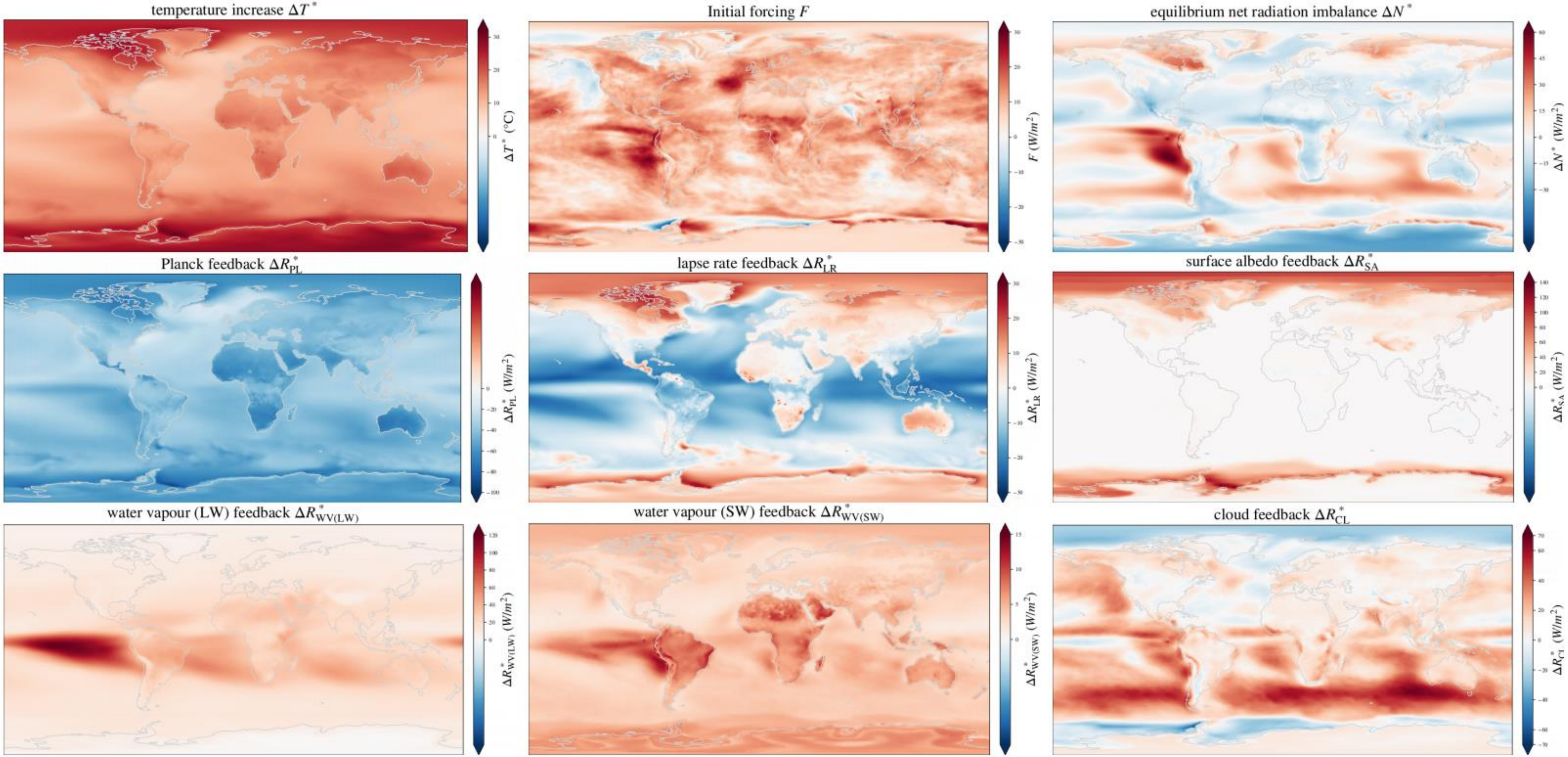
Application to CESM2's abrupt4xCO2 run in CMIP6 (3)

	Mode 1	Mode 2	Mode 3	Equilibrium
τ_m	4.5 (± 0.1)	127 (± 3.8)	889 (± 50)	-
λ_m	−1.28 (± 0.08)	−0.38 (± 0.03)	−0.37 (± 0.02)	−0.66 (± 0.03)
Planck (LW)	−3.16 (± 0.02)	−3.24 (± 0.02)	−3.23 (± 0.01)	−3.21 (± 0.05)
Lapse Rate (LW)	−0.73 (± 0.03)	−0.50 (± 0.03)	−0.32 (± 0.03)	−0.50 (± 0.01)
Surface Albedo (SW)	+0.62 (± 0.04)	+0.56 (± 0.02)	+0.08 (± 0.10)	+0.39 (± 0.01)
Water Vapour (LW)	+0.97 (± 0.03)	+1.38 (± 0.02)	+2.71 (± 0.01)	+1.79 (± 0.04)
Water Vapour (SW)	+0.21 (± 0.09)	+0.26 (± 0.05)	+0.43 (± 0.02)	+0.31 (± 0.01)
Clouds (SW + LW)	+0.27 (± 0.36)	+1.19 (± 0.02)	+1.43 (± 0.01)	+1.00 (± 0.03)
sum	−1.82 (± 0.37)	−0.36 (± 0.07)	+1.09 (± 0.11)	−0.22 (± 0.08)
missing	+0.54 (± 0.38)	−0.02 (± 0.08)	−1.46 (± 0.11)	−0.43 (± 0.08)

Application to CESM2's abrupt4xCO2 run in CMIP6 (3)



Spatial Response – Equilibrium Estimates



Projections for other forcings

$$\Delta O(t) = \sum_{m=1}^{M} \beta_m^{[O]} \, \mathcal{M}_m^{g}(t)$$

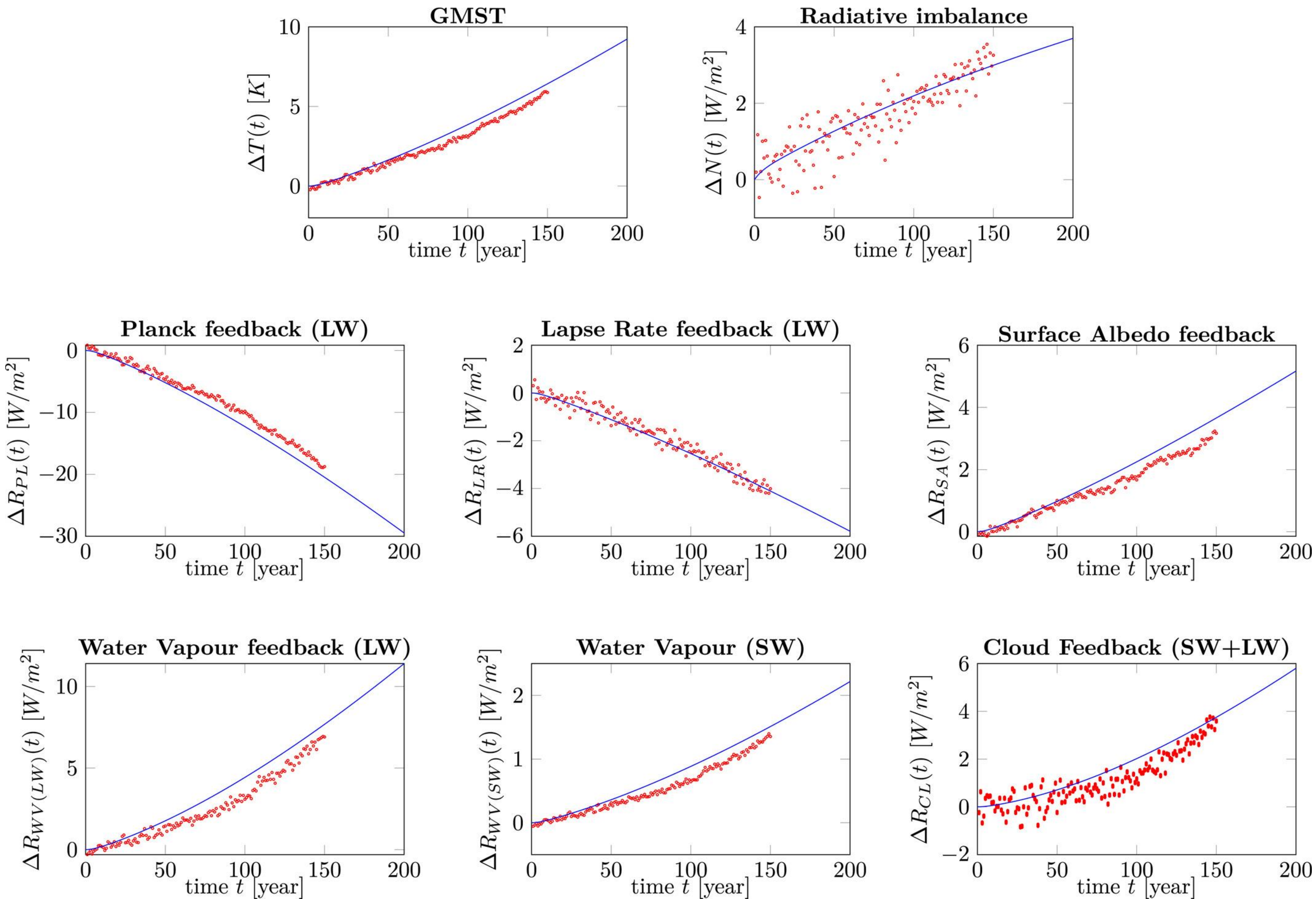
only this gets changed!

Linear Response Theory – CAVEATS:

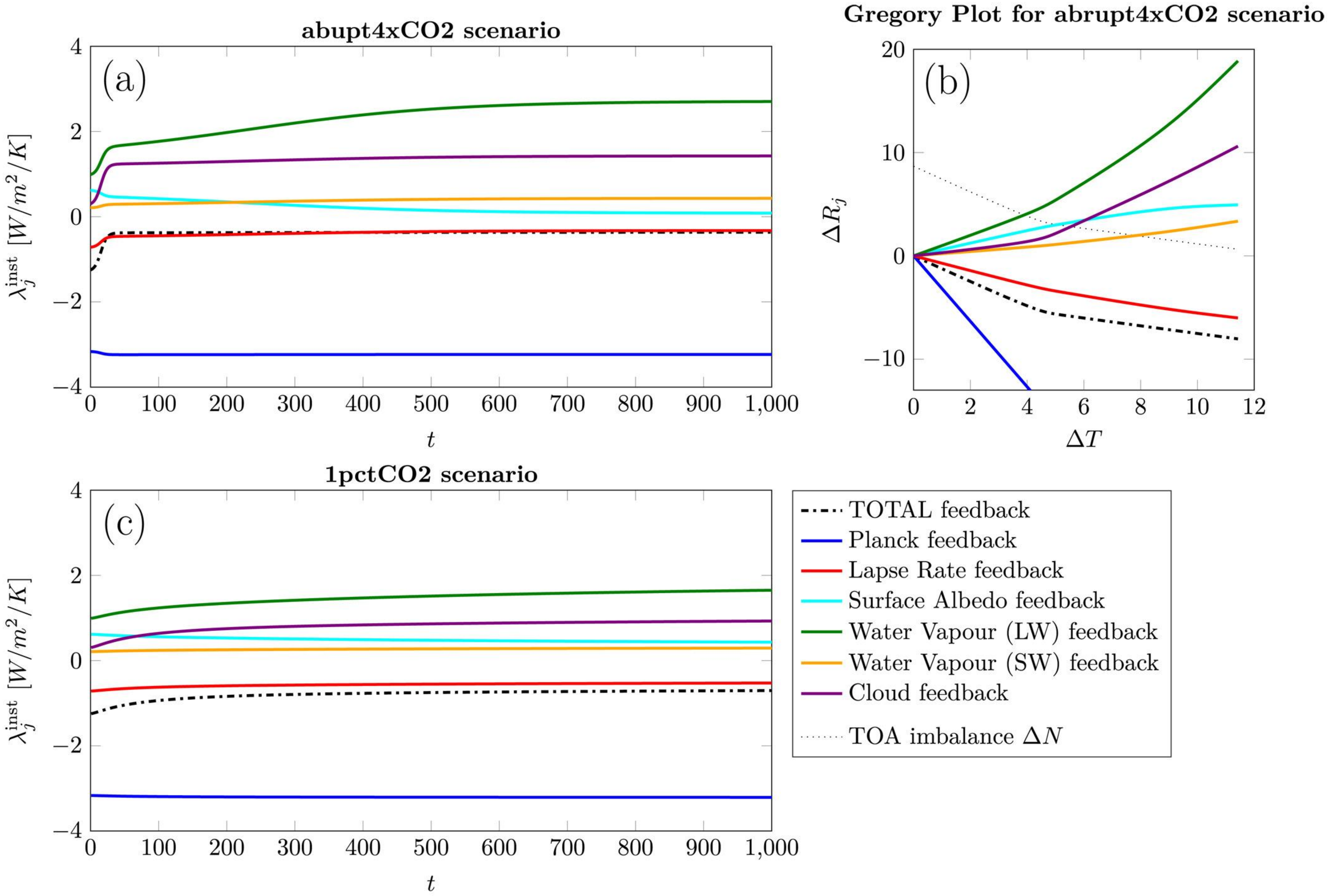
i. forcings & responses should be ‘small enough’

ii. should look at ensemble means

Projections for CESM2’s 1pctCO2 experiment

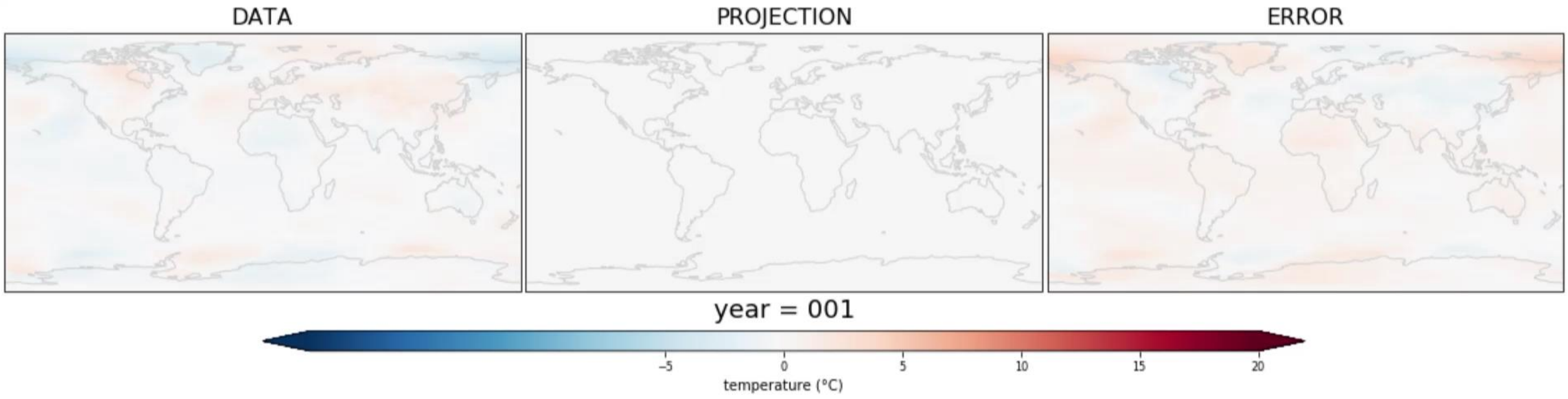


Instantaneous feedback strengths for abrupt4xCO2 & 1%CO2



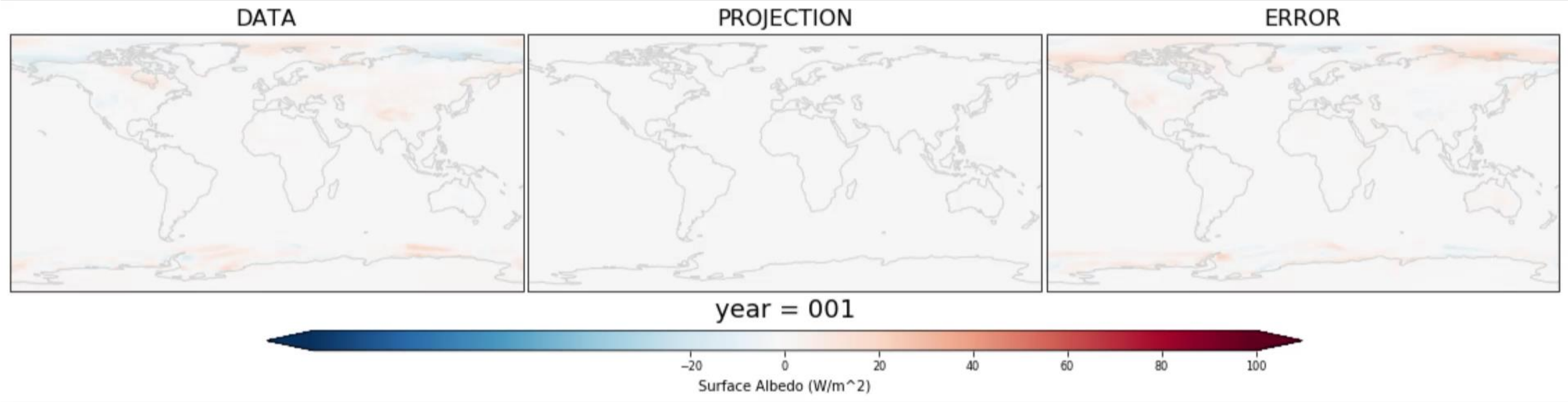
Spatial projections for 1%CO2 experiment

TEMPERATURE



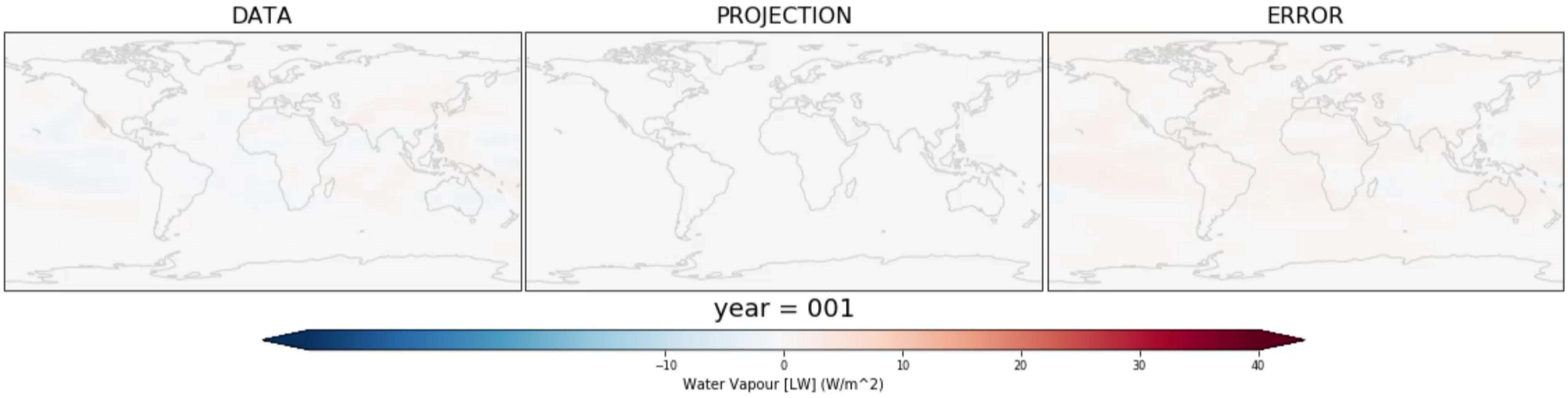
Spatial projections for 1%CO2 experiment

SURFACE ALBEDO FEEDBACK CONTRIBUTION



Spatial projections for 1%CO2 experiment

WATER VAPOUR (LW) FEEDBACK CONTRIBUTION



Projections of Climate Feedbacks

SUMMARY OF METHOD

Evolution of observable

$$\Delta O(t) = \sum_{m=1}^{M} \beta_m^{[O]} \mathcal{M}_m^g(t)$$

$$\mathcal{M}_m^g(t) = \int_0^t e^{-s/\tau_m} g(t-s)ds$$

- Allows dissecting feedback contributions over time and space
  - Feedback strength per mode
  - Feedback missing on long time scale?
- Projections for other forcings seem possible
  - Tests presented are promising

Paper out in Geophysical Research Letters:

Projections of the transient state-dependency of climate feedbacks

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