Role of the AMOC in ocean heat storage and transient climate change

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Earth, Atmospheric and Planetary Sciences
Massachusetts Institute of Technology

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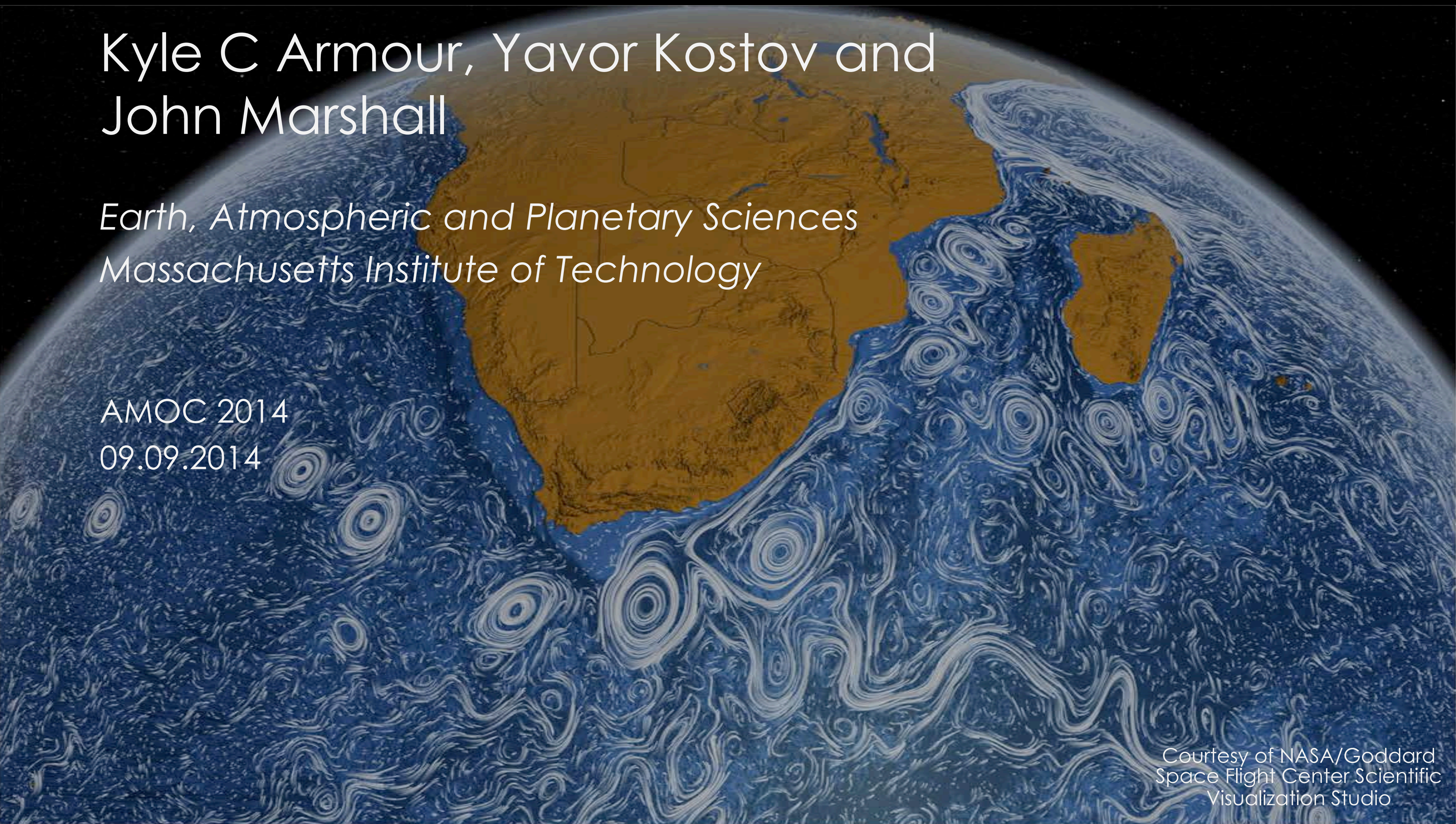
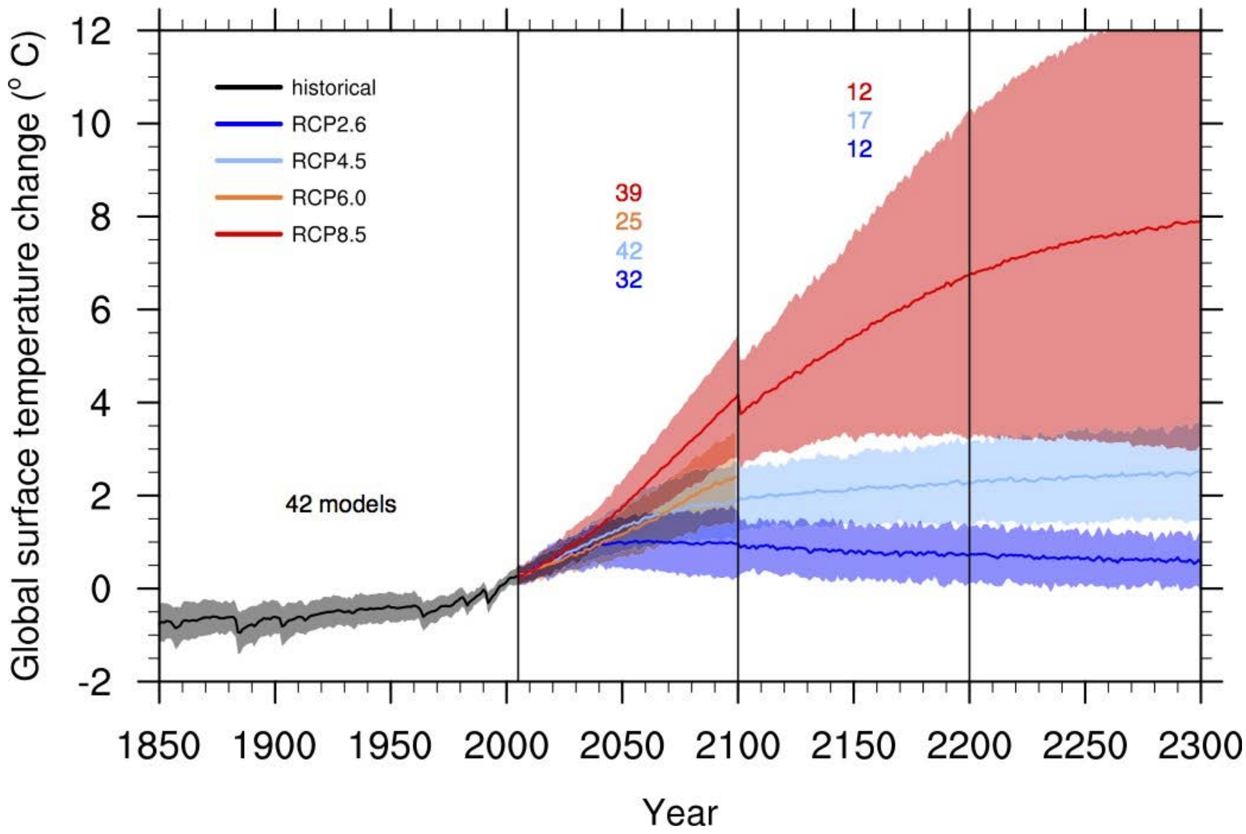
09.09.2014



Courtesy of NASA/Goddard Space Flight Center Scientific Visualization Studio

Projections of future global warming



(IPCC AR5)

Fully-coupled General Circulation Models (GCMs) from the Coupled Model Intercomparison Project, phase 5 (CMIP5)

Learning from climate models

- Consider single forcing simulations (e.g., CO_2 only)
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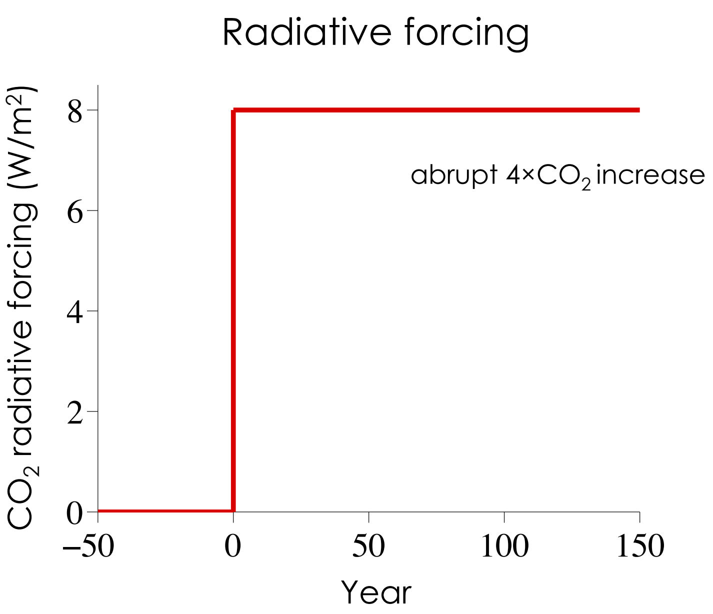
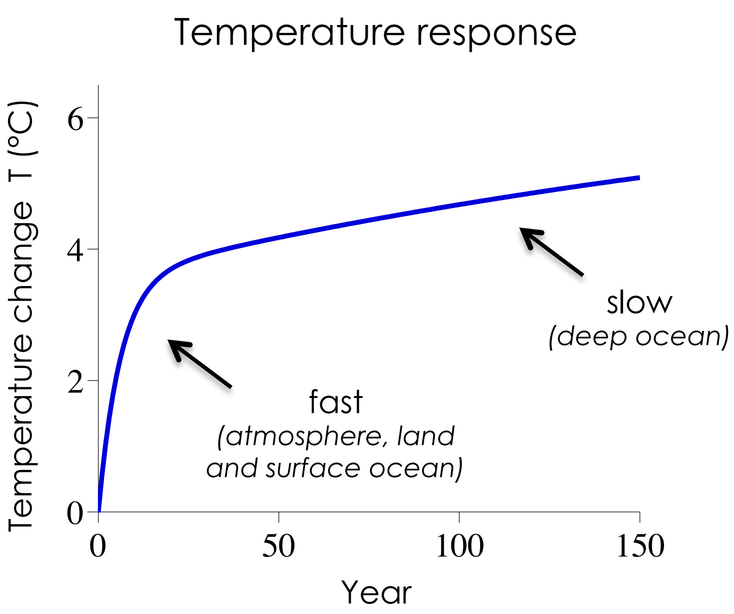
  - reveals the fundamental timescales of climate response





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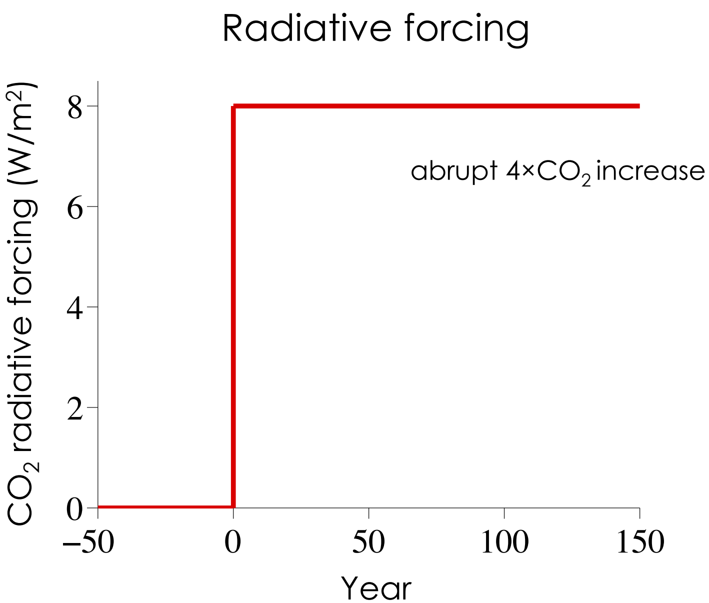

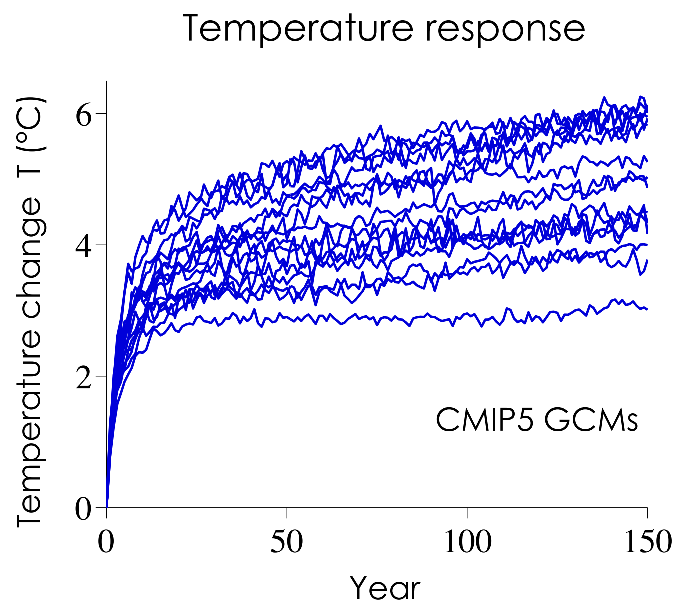

Global climate response to forcing

- Linearization of global top-of-atmosphere (TOA) energy budget

$$H = \lambda T + R$$

- H: global TOA radiation flux anomaly
- λT: global TOA radiative response
- R: global TOA radiative forcing

- Temperature anomaly T has units of K or °C
- H and R have units of W/m^2
- 'Global radiative feedback' λ is negative (stabilizing) and has units of $Wm^{-2}K^{-1}$

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- Transient warming:

$$H = c_{eff}\frac{dT}{dt} = \lambda T + R$$

c_{eff}: global effective heat capacity

$c_{eff}\frac{dT}{dt}$: Rate of global heat content change

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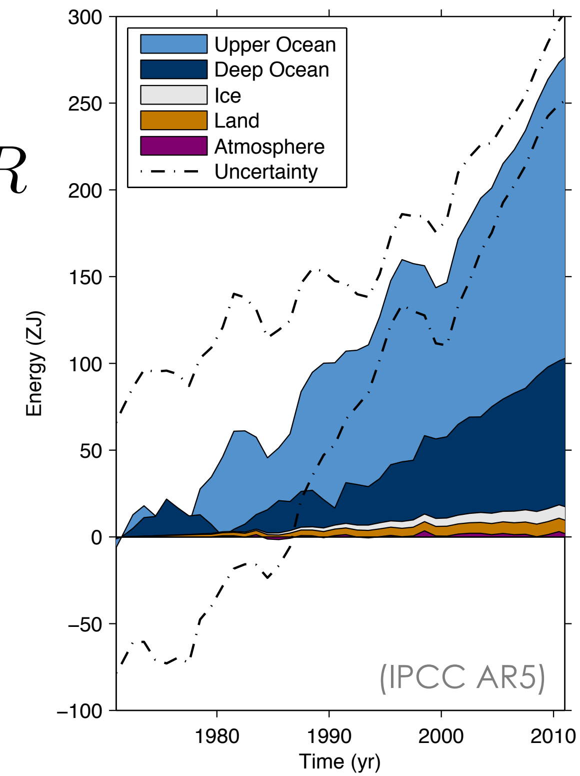
c_{eff}: global effective heat capacity

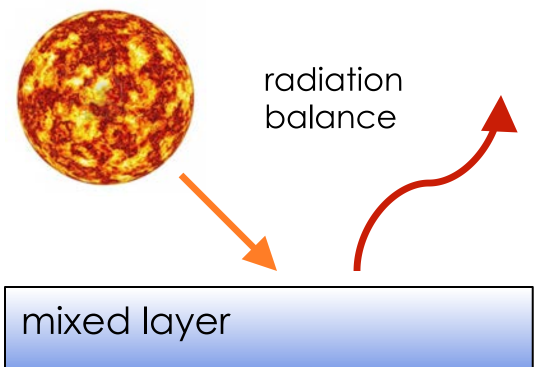
$c_{eff}\frac{dT}{dt}$: Rate of global heat content change (ocean heat uptake)



Global climate response to forcing

- Example: Climate response *without* a deep ocean

$$c_{ml}\frac{dT}{dt} = \lambda T + R$$



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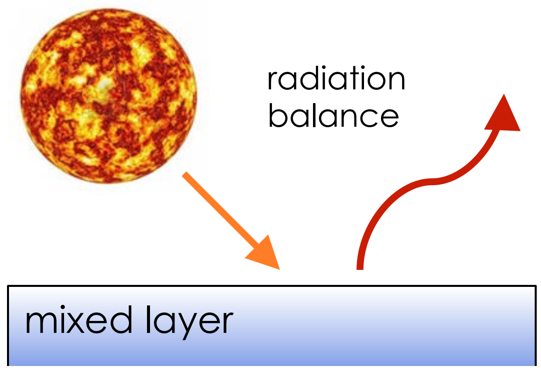
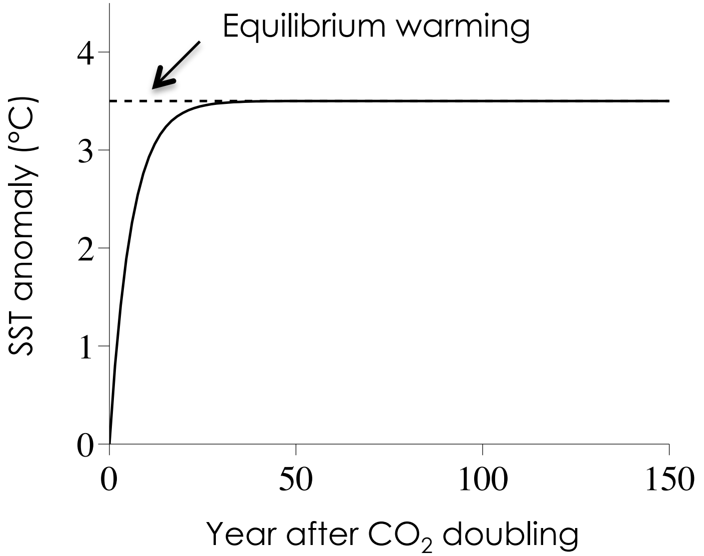


- One timescale
  - Adjustment of mixed layer (~decade)

$$\tau = -c_{ml}/\lambda$$

Sea-surface temperature response to CO_2 doubling



Global climate response to forcing

- Example: Climate response *with* a deep ocean

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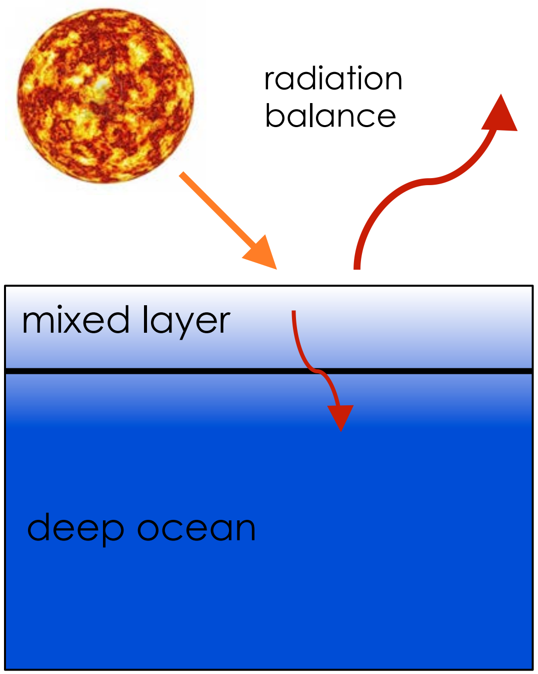

Gregory (2000), Held et al (2010)

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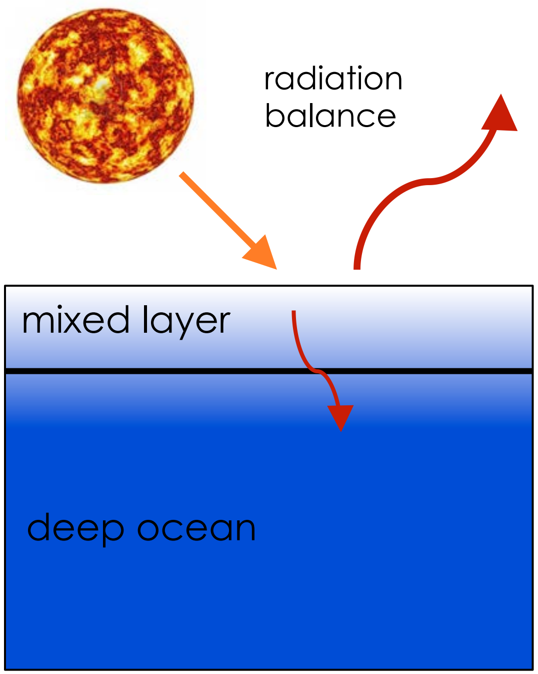

- Two timescales
  - Adjustment of mixed layer (~years)

$$\tau_{fast} \approx \frac{c_{ml}}{-\lambda + \beta}$$

  - Adjustment of deep ocean (~centuries)

$$\tau_{slow} \approx \frac{c_{deep}}{\beta}\frac{\lambda - \beta}{\lambda}$$

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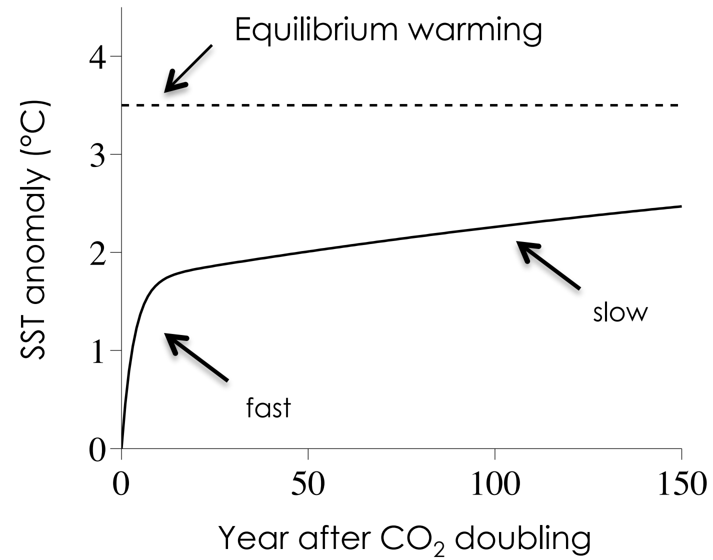

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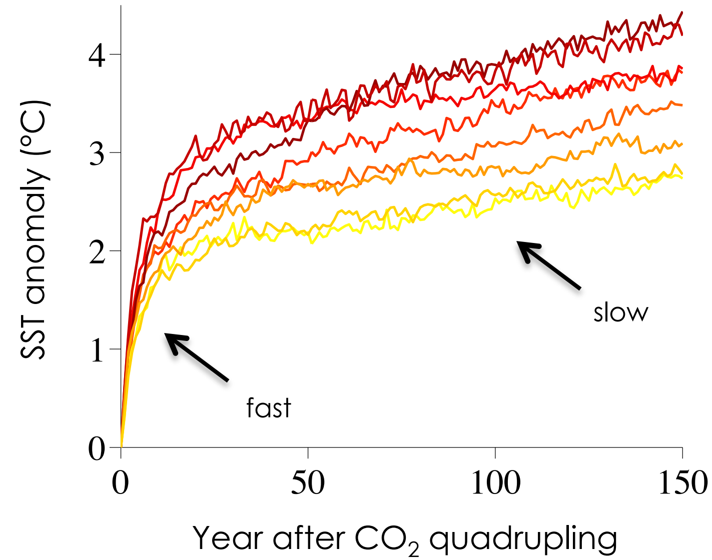
CMIP5 sea-surface temperature response to CO_2 quadrupling



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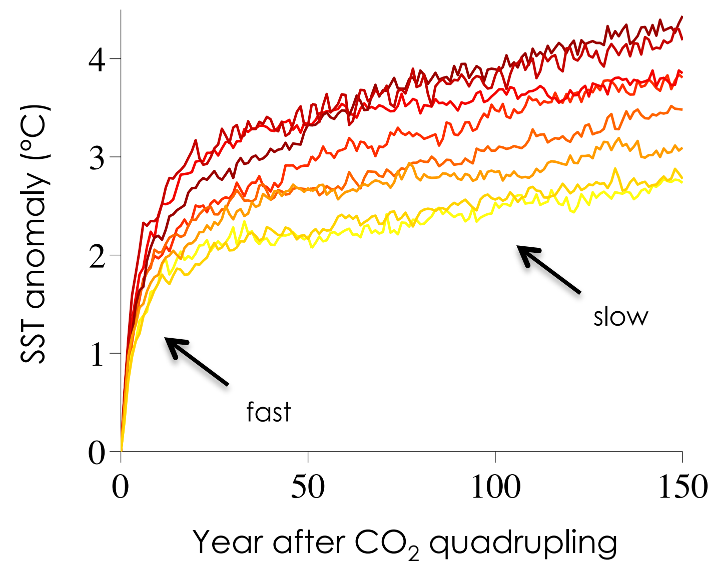
- Fit 2-layer model to surface response of CMIP5 models
  - c_{ml} = effective depth of 100 m
  - c_{deep} ranges from 590 to 1660 m
  - β ranges from 1.2 to 2.1 $Wm^{-2}K^{-1}$
  - λ ranges from -2.5 to -1.4 $Wm^{-2}K^{-1}$
  - R ranges from 8.8 to 11.0 Wm^{-2}

(first three: ocean; last two: atmos)

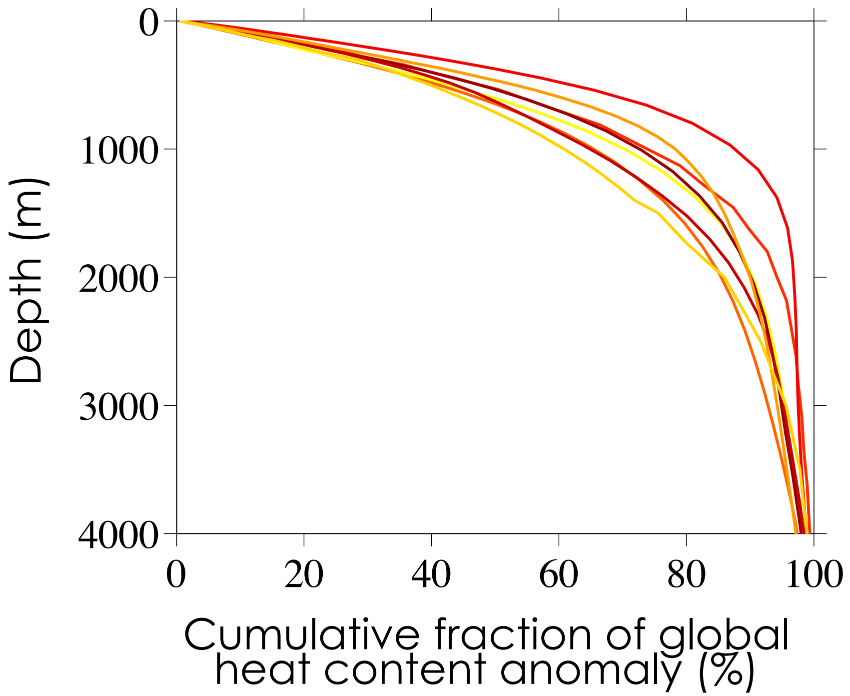
CMIP5 sea-surface temperature response to CO_2 quadrupling



Gregory (2000), Held et al (2010)

What sets the effective ocean heat capacity?

- Depth of ocean heat storage in CMIP5 models, 100 years after a CO_2 quadrupling



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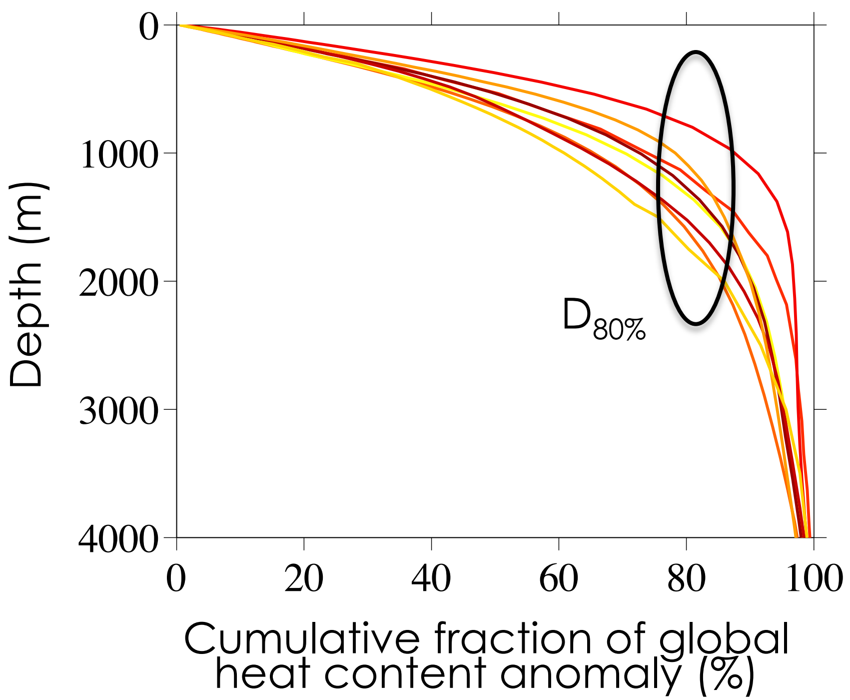

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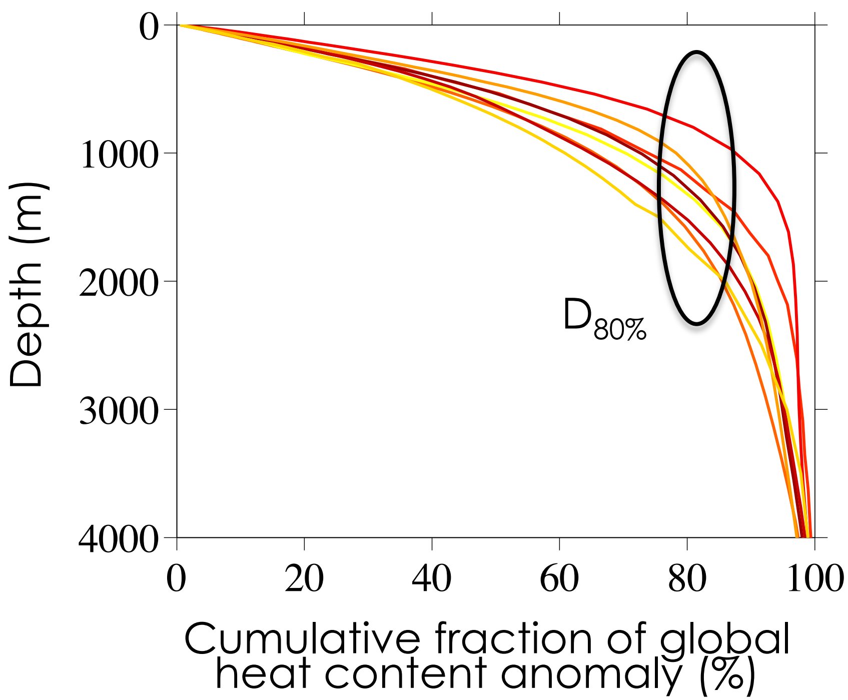

- $D_{80\%}$ is a metric for the depth of ocean heat storage, defined as the depth above which 80% of global heat content anomaly resides
- $D_{80\%}$ ranges from 780 m to 1800 m, similar to effective deep ocean depth (c_{deep}) in 2-layer model

$$c_{ml}\frac{dT}{dt} = \lambda T + R + \beta(T_{deep} - T)$$

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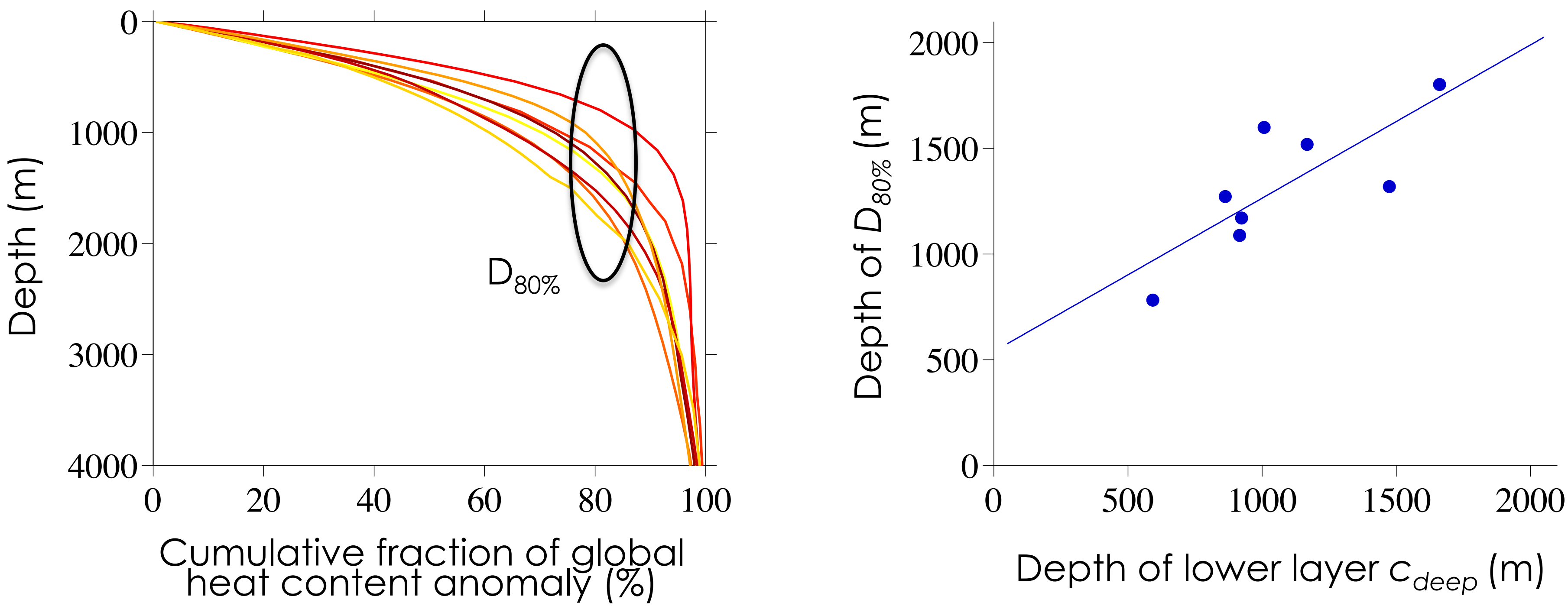

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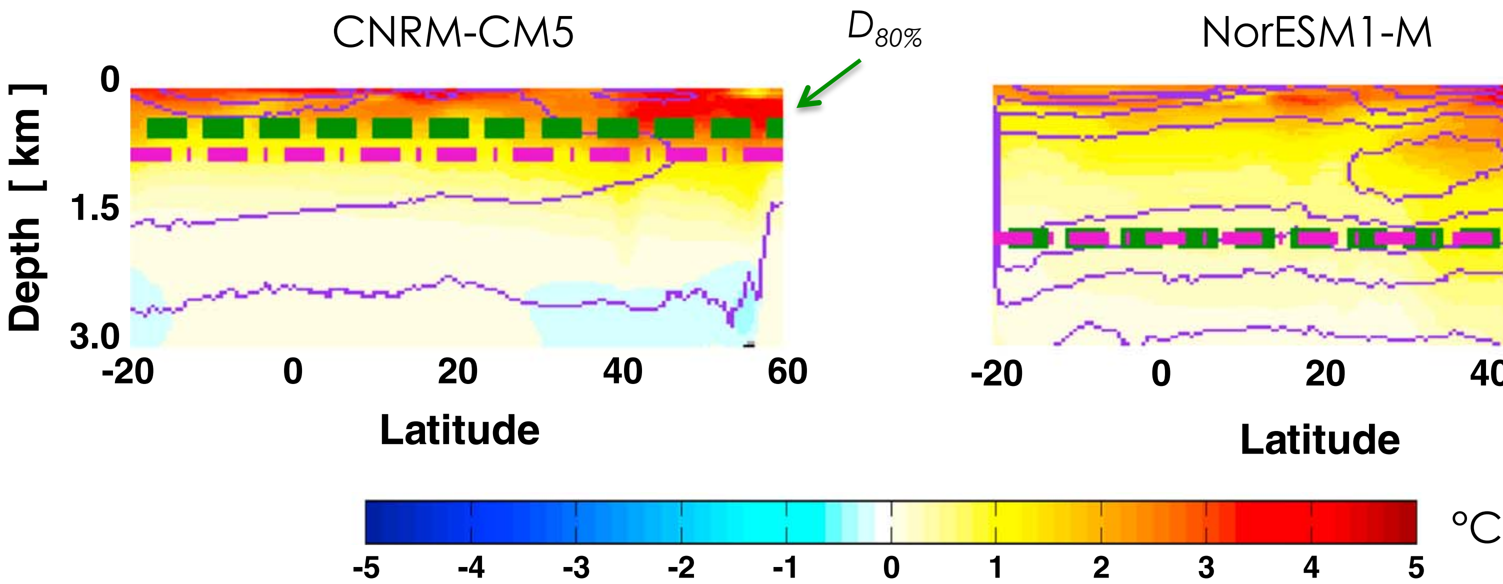

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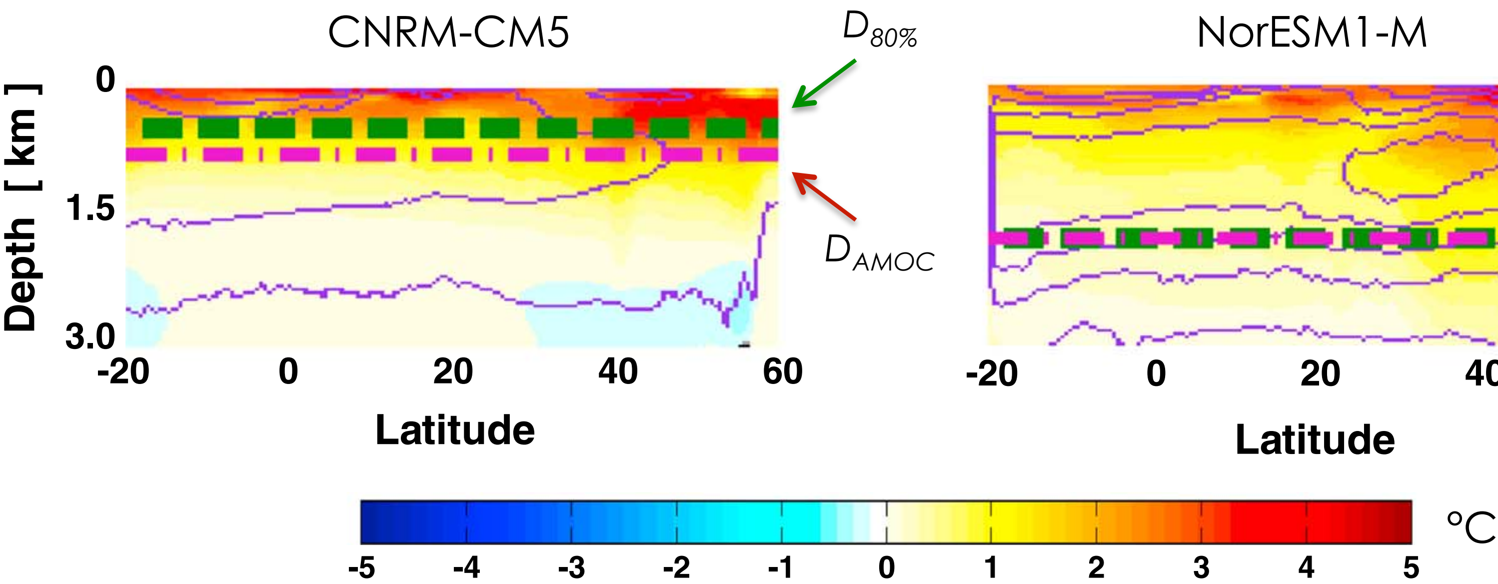
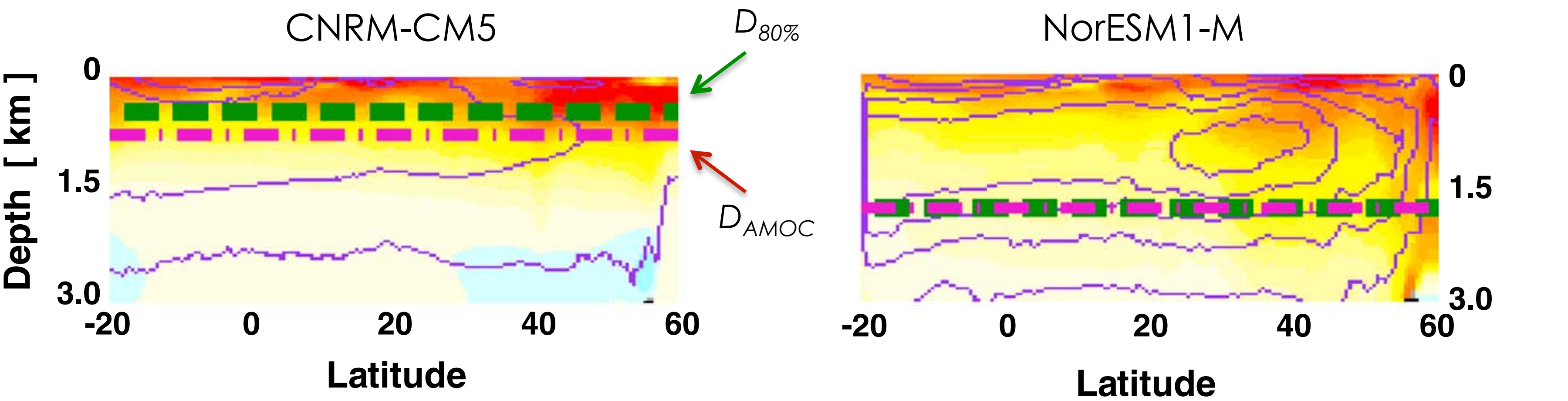
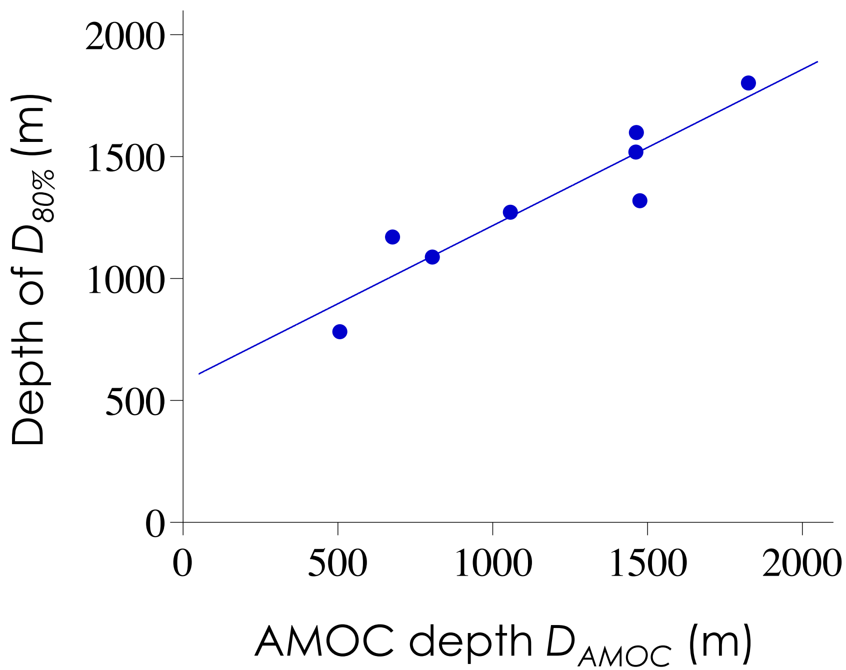


- D_{AMOC} is a metric for the depth of the AMOC, defined as the average depth of 5 and 10 Sv streamlines over the simulation
- D_{AMOC} ranges from 500 m to 1800 m, similar to $D_{80\%}$

What sets the effective ocean heat capacity?





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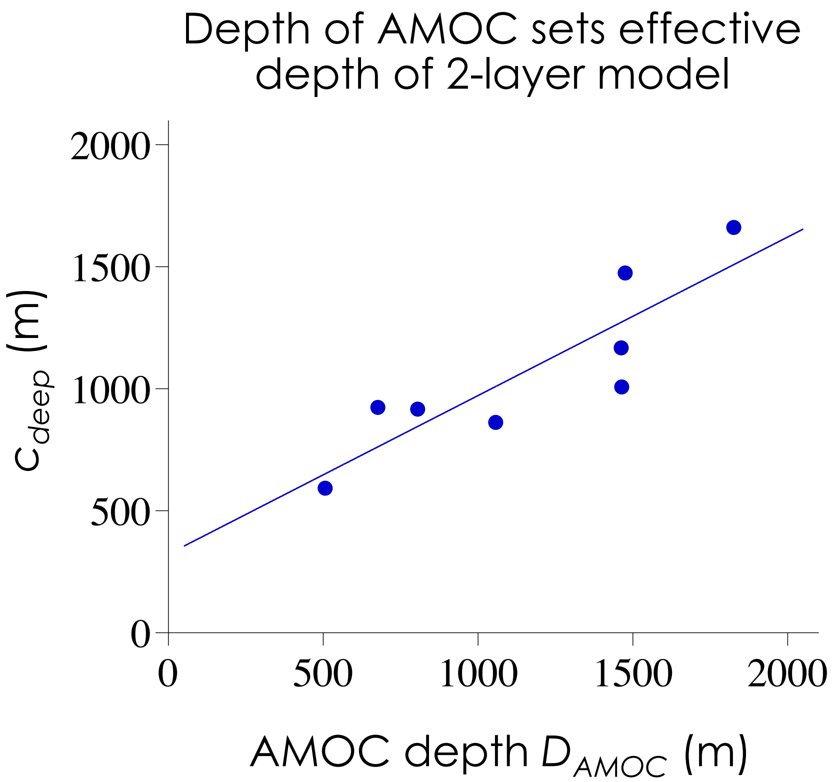

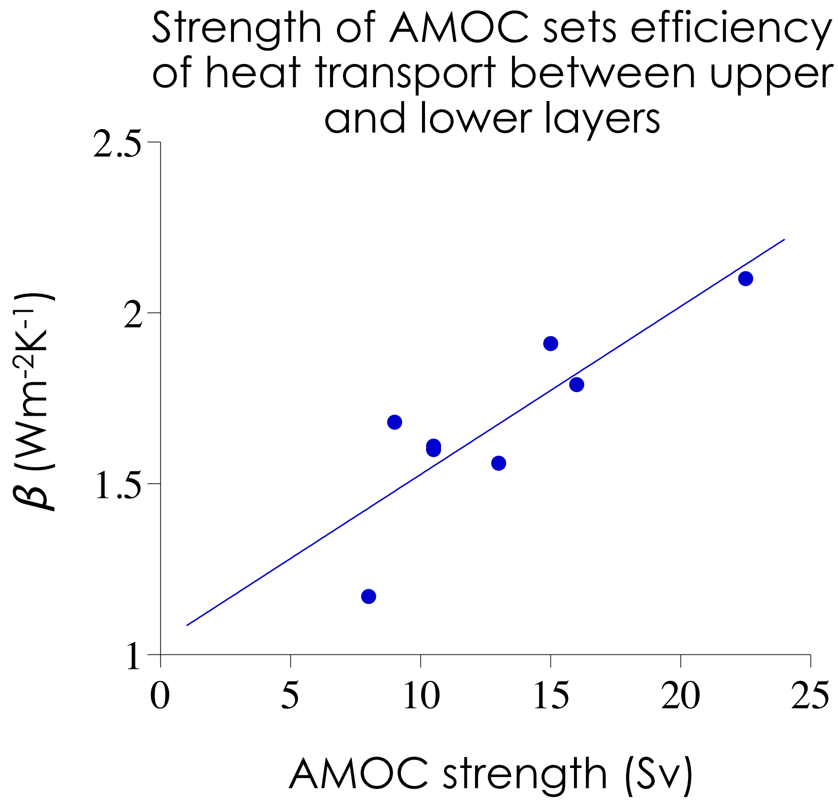

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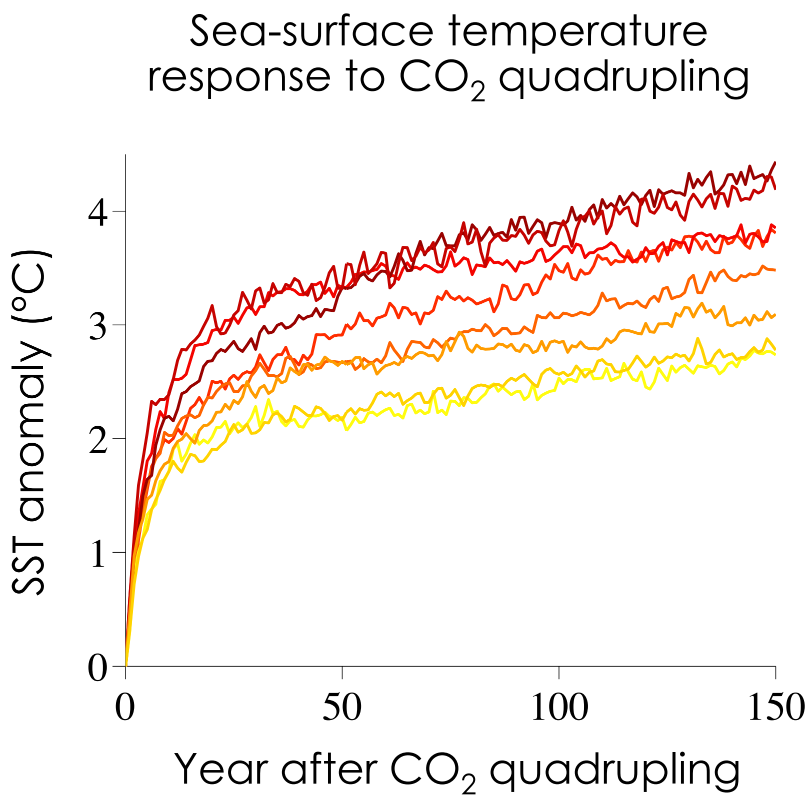
Role of the ocean in SST response



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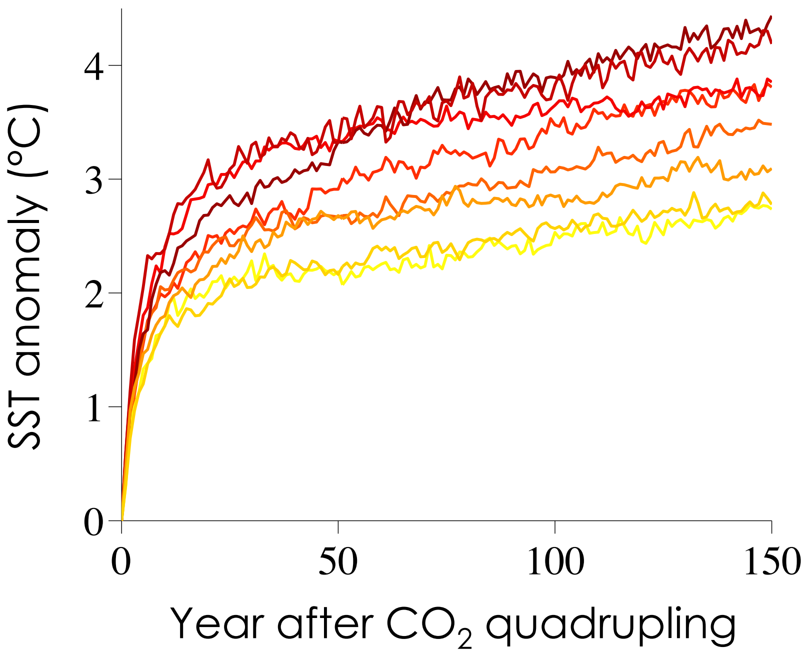
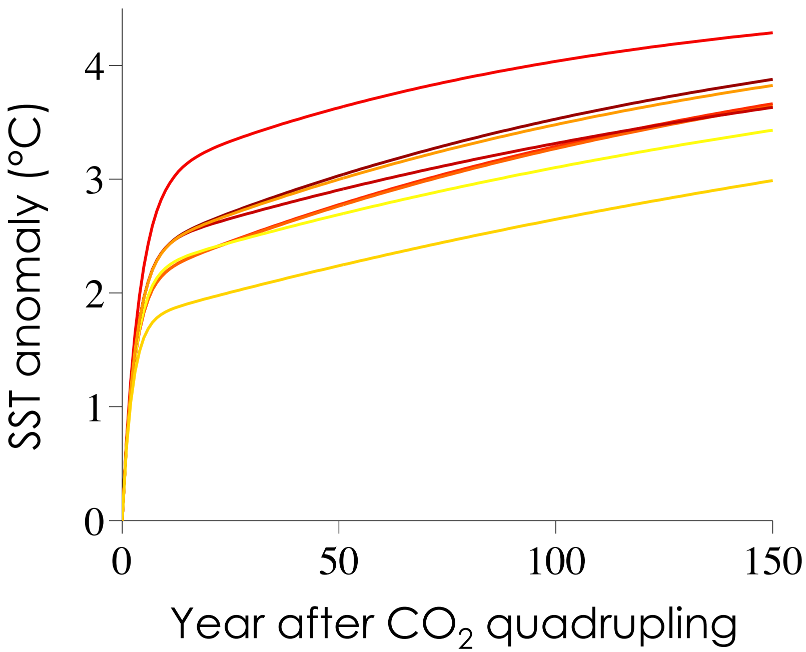
Role of the ocean in SST response

Sea-surface temperature response to CO_2 quadrupling



Sea-surface temperature response in 2-layer model, with ensemble mean atmospheric properties (λ and R)



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Role of feedbacks and forcing in SST response

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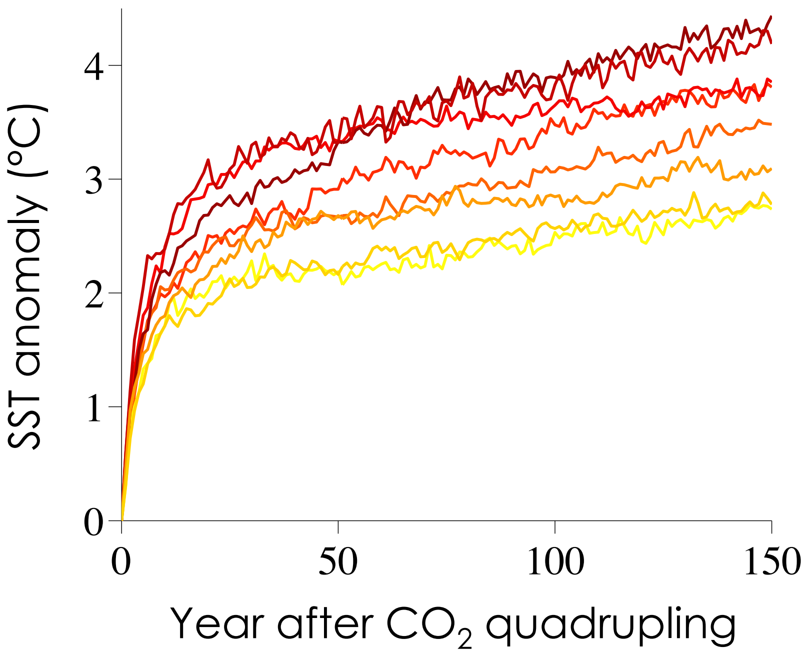
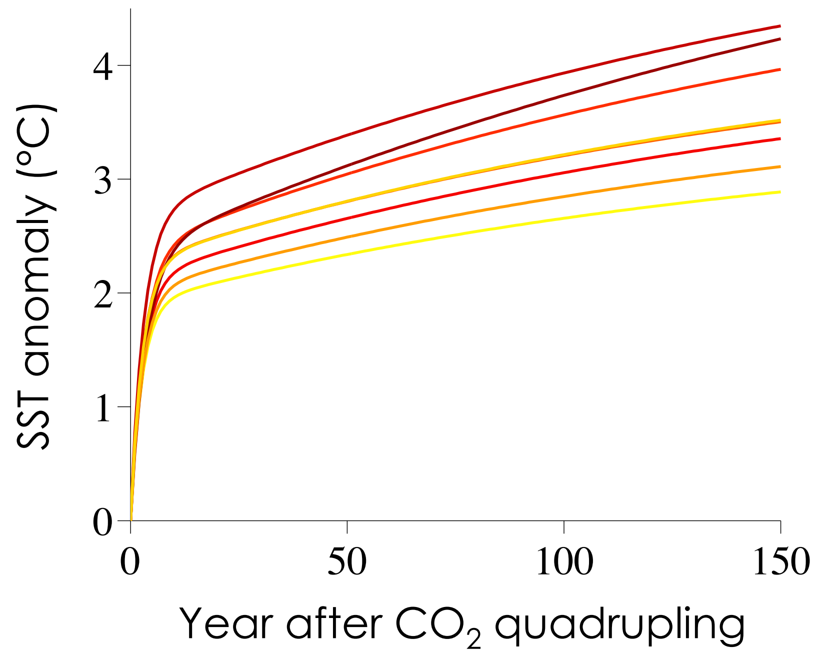


Sea-surface temperature response in 2-layer model, with ensemble mean ocean properties (c_{deep} and β)



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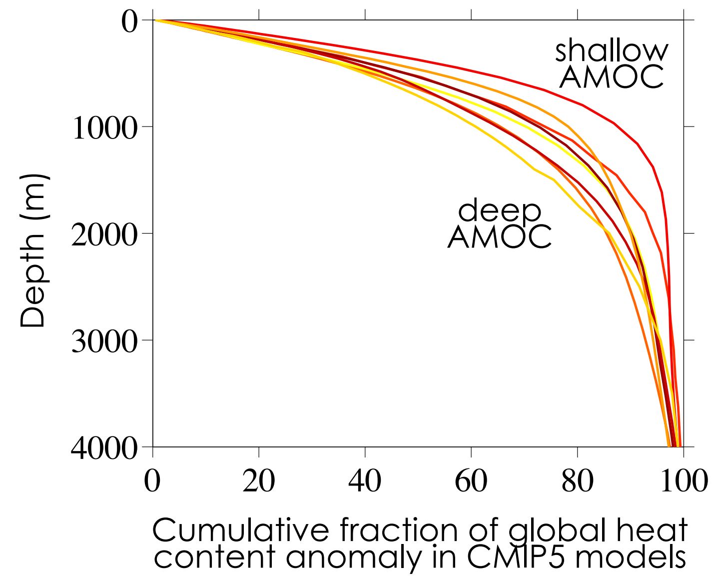
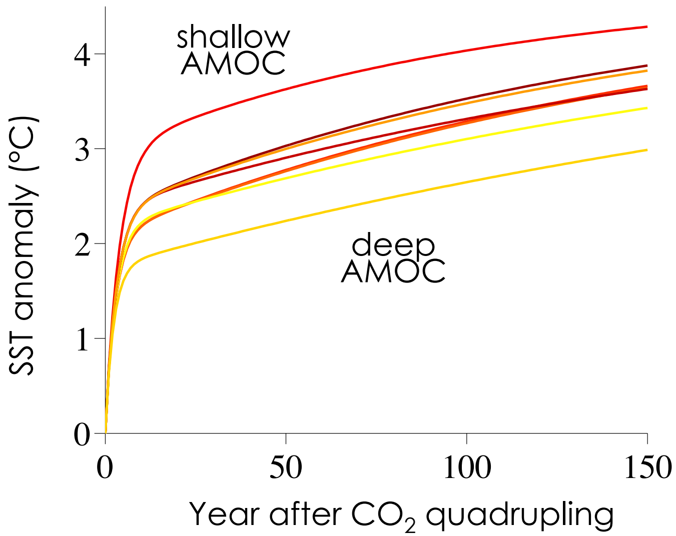
Role of AMOC in transient global warming

- Depth of heat storage is strongly influenced by the depth of AMOC



- In those models with a deeper and stronger AMOC, a smaller portion of the heat anomaly remains in the upper ocean, delaying surface warming

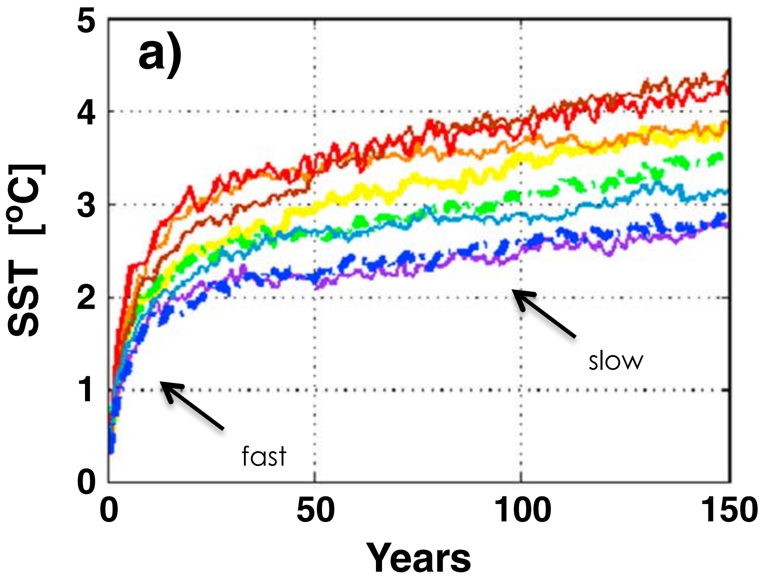
- Variations in climate feedbacks is the other large source of inter-model spread in transient surface warming

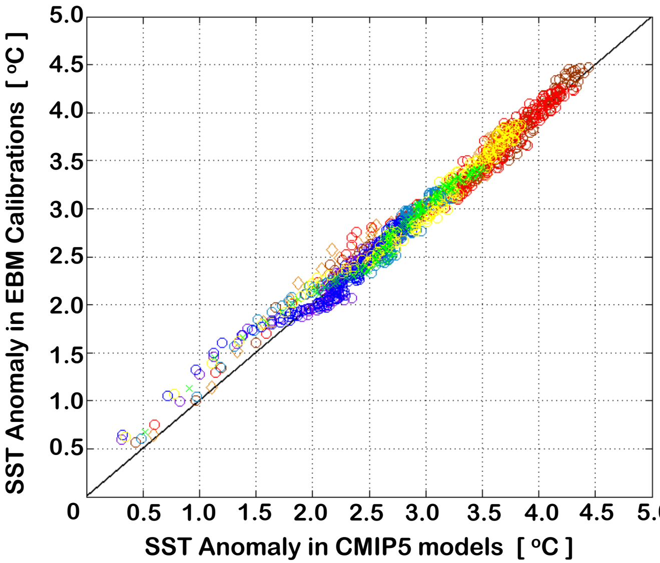


Y Kostov, KC Armour and J Marshall (2014), Impact of the Atlantic meridional overturning circulation on ocean heat storage and transient climate change, *Geophys. Res. Lett.*, 41, doi: 10.1002/2013GL058998.

Bonus slides

What sets the effective ocean heat capacity?





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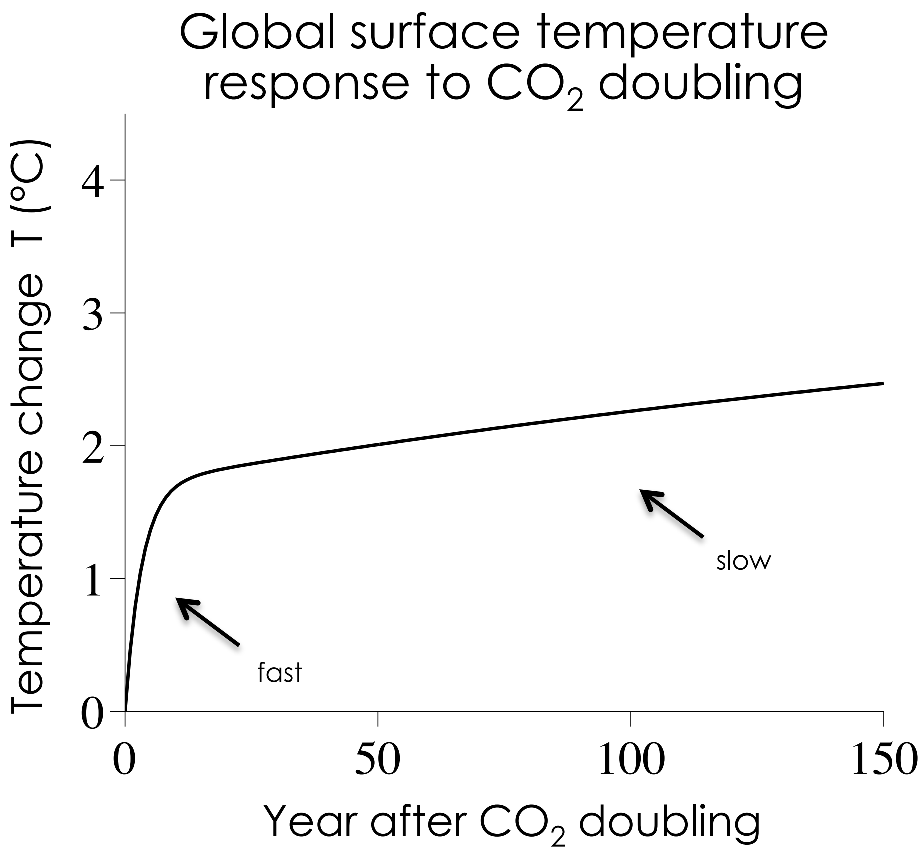
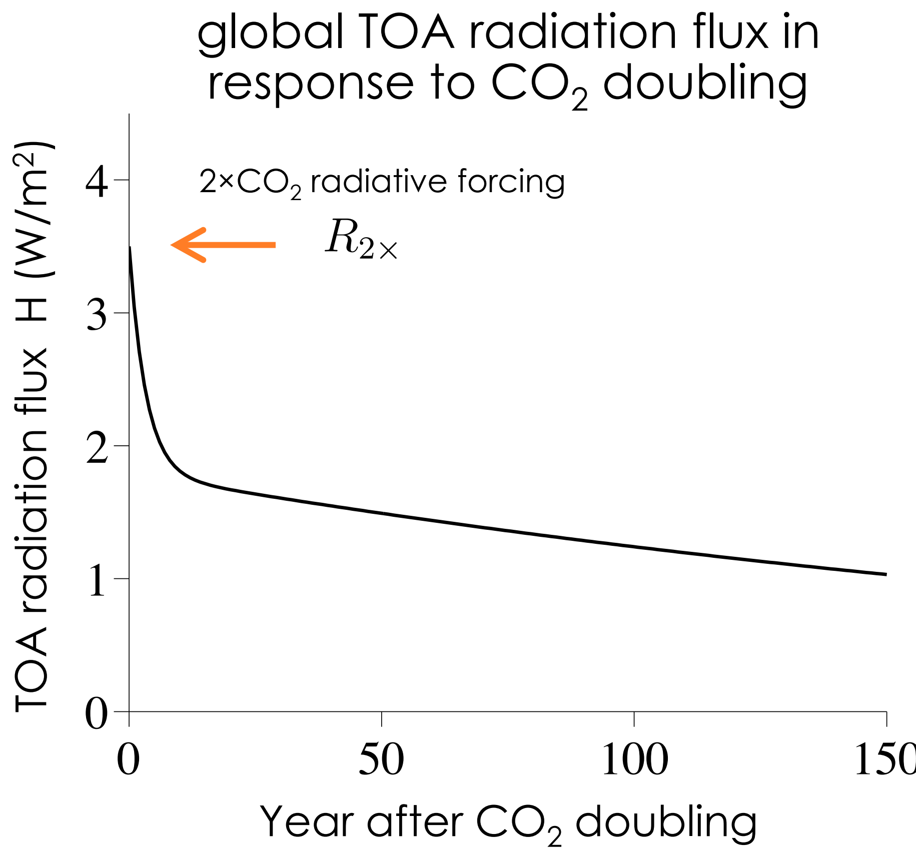
Kostov, Armour and Marshall (2014)

Global climate response to forcing

$$H = c_{eff}\frac{dT}{dt} = \lambda T + R$$





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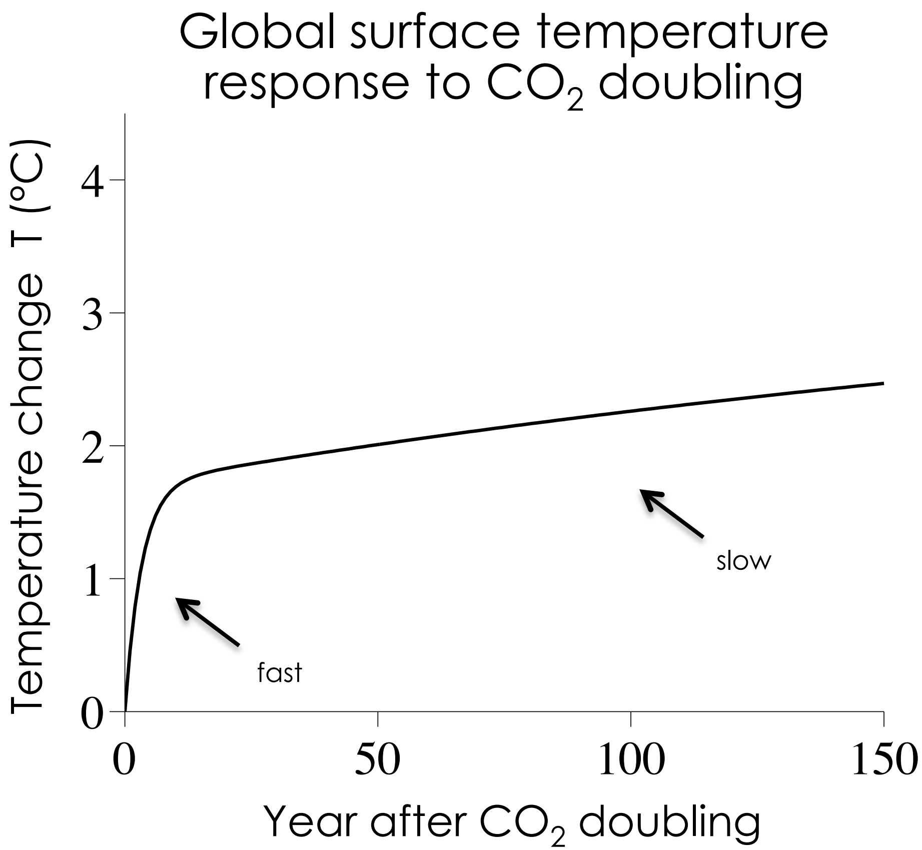

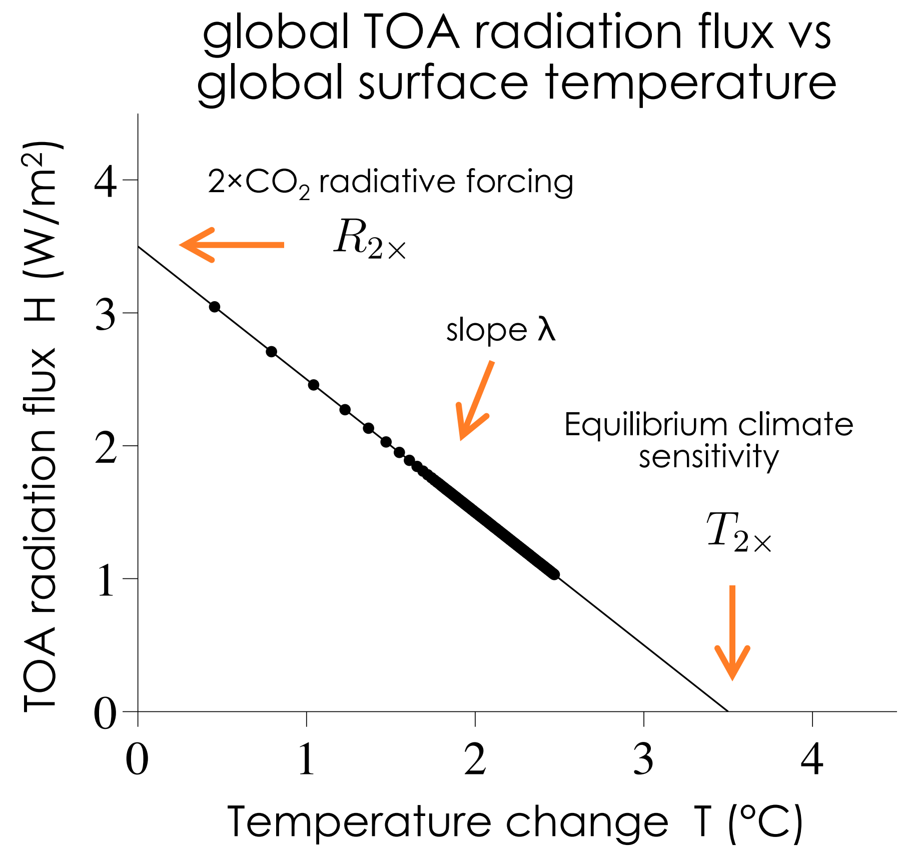

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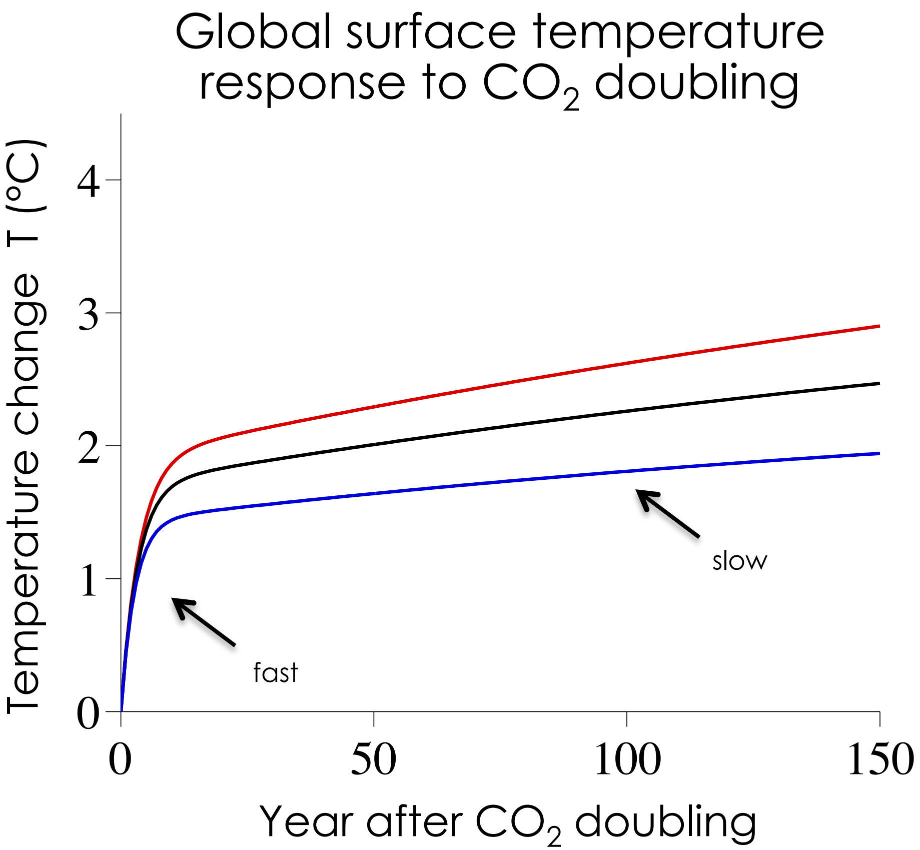

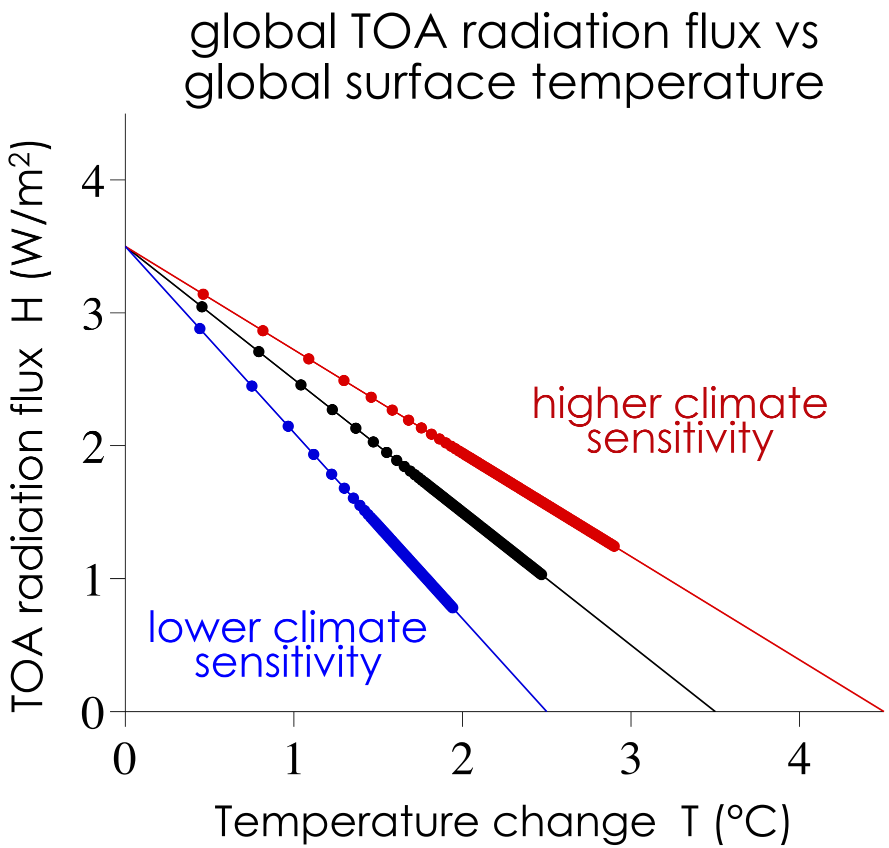

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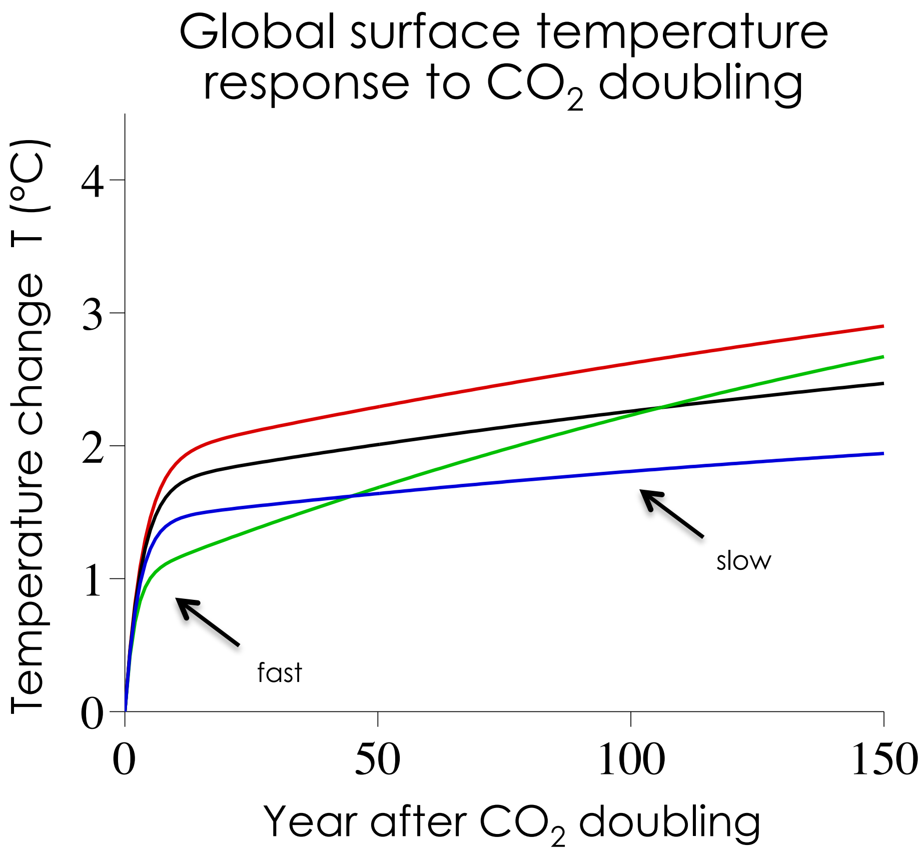

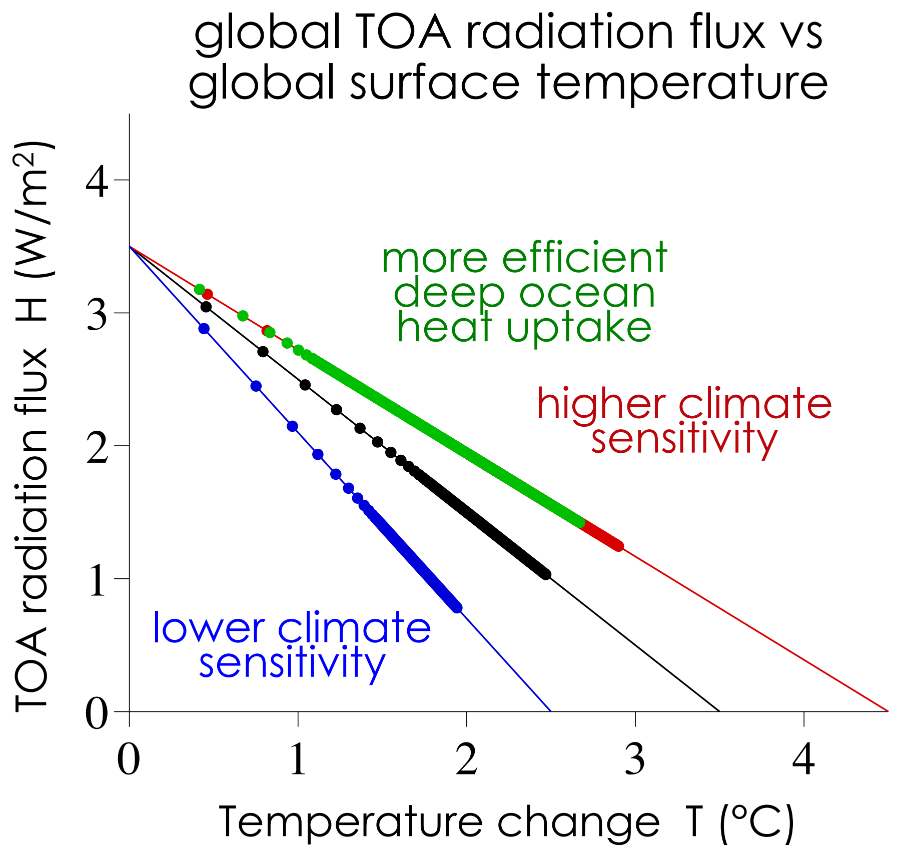

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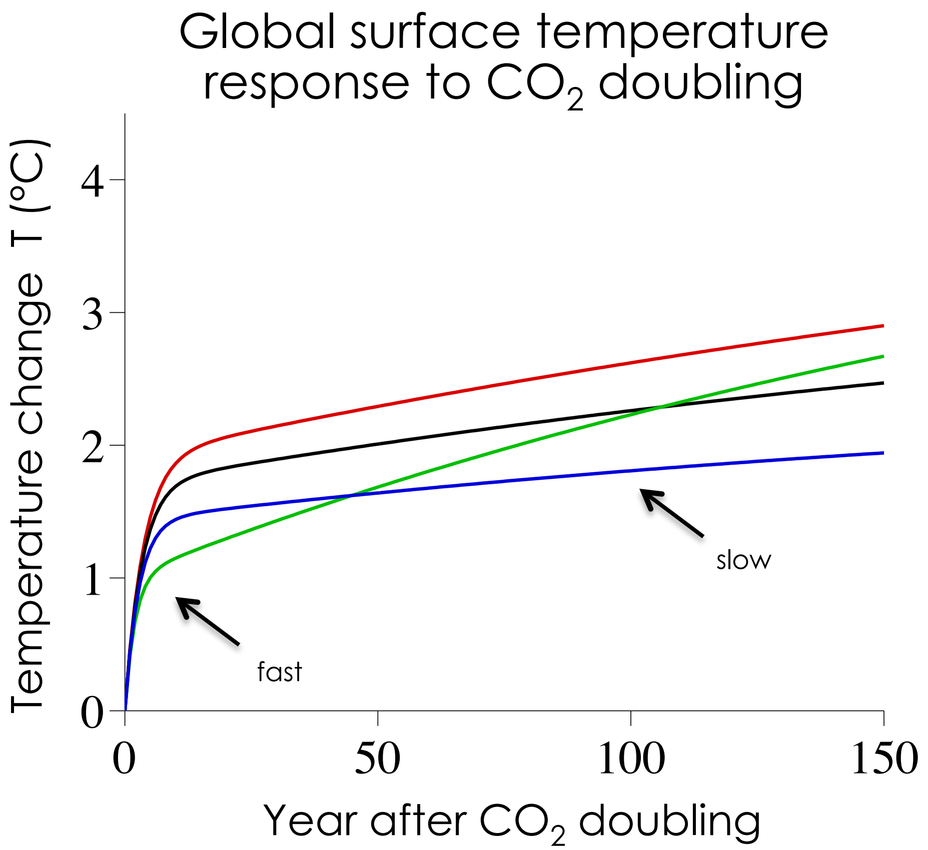
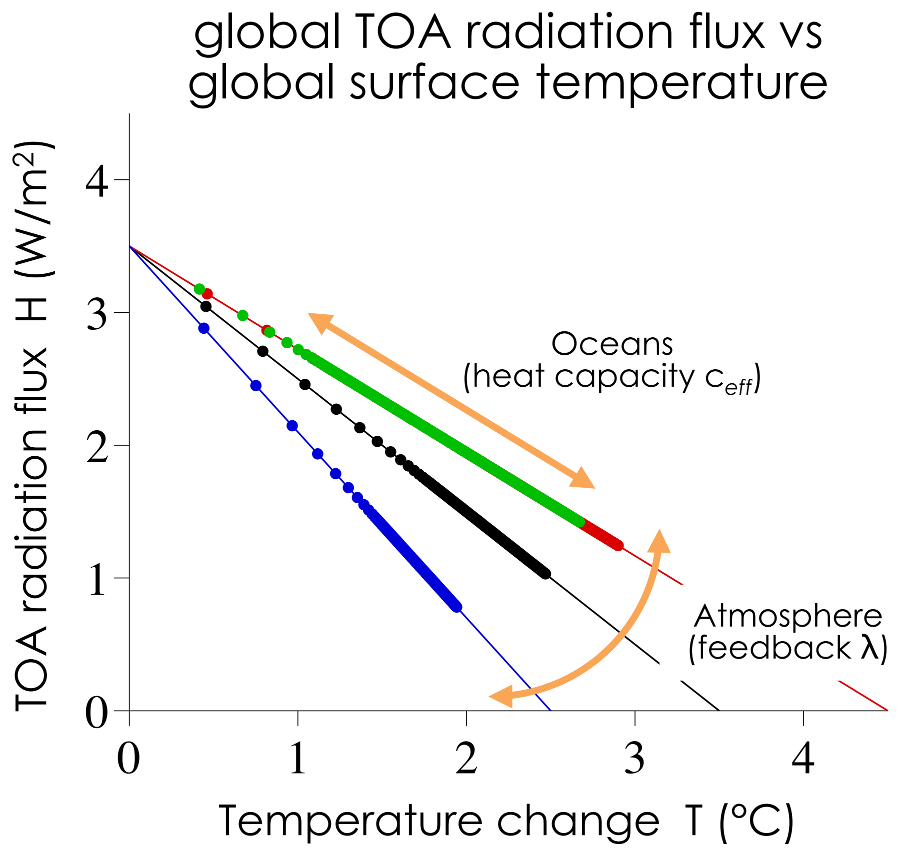
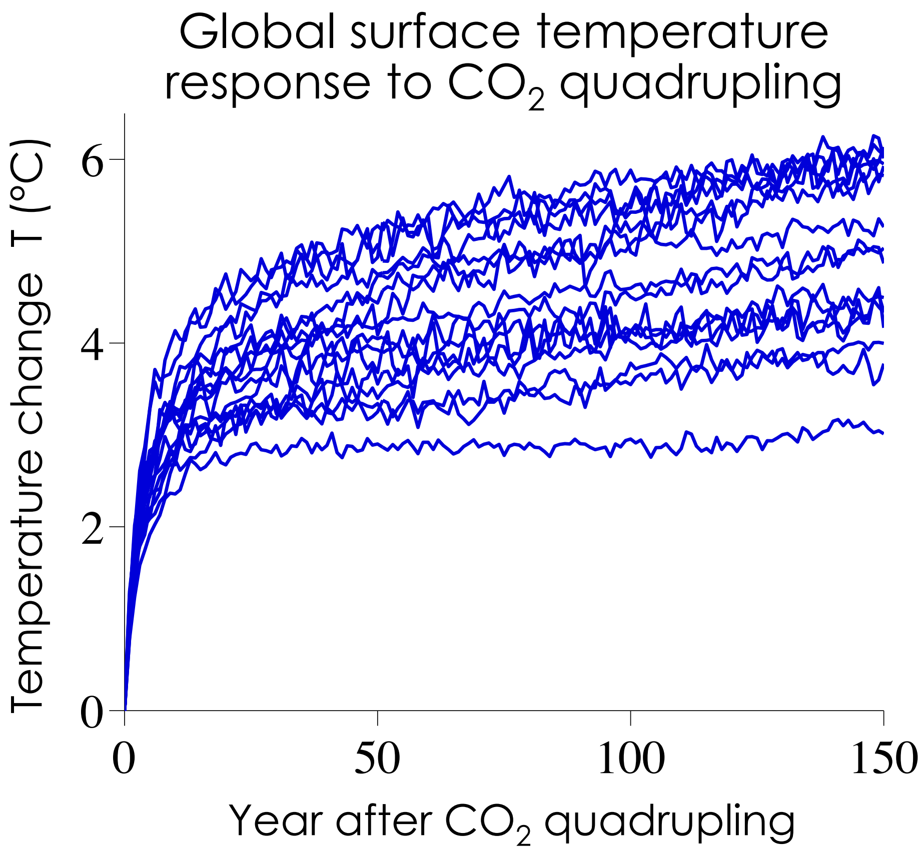




Climate response to an abrupt CO_2 change

- 16 CMIP5 fully-coupled GCMs forced by abrupt CO_2 quadrupling



16 fully-coupled General Circulation Models (GCMs) from the Coupled Model Intercomparison Project, phase 5 (CMIP5)

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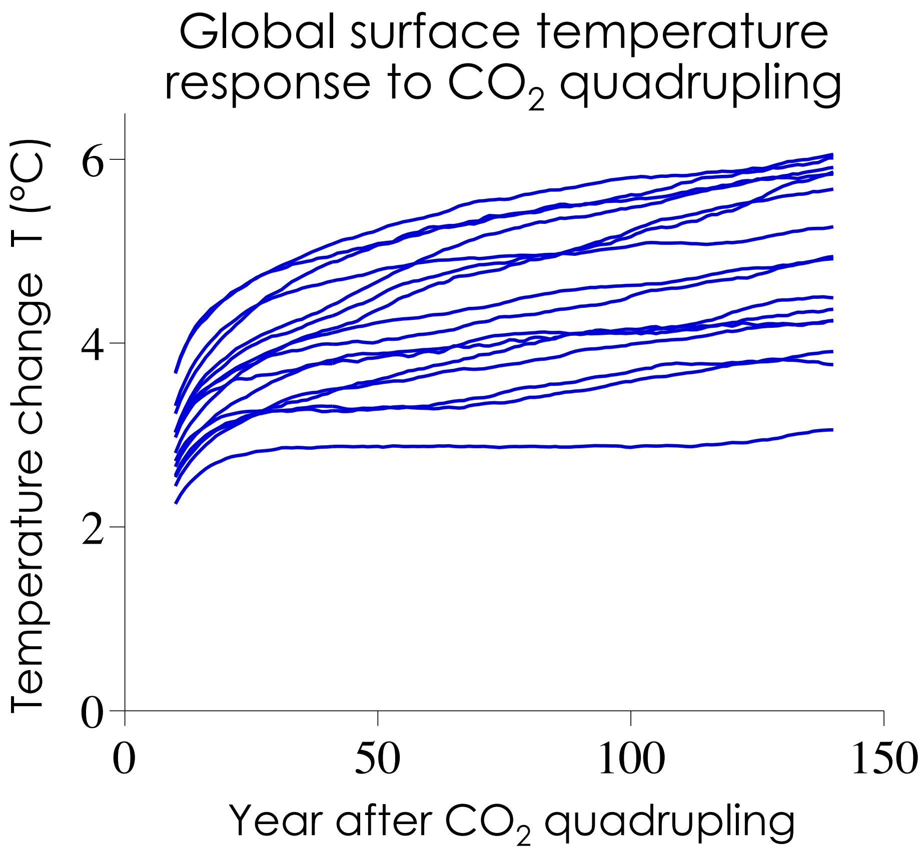

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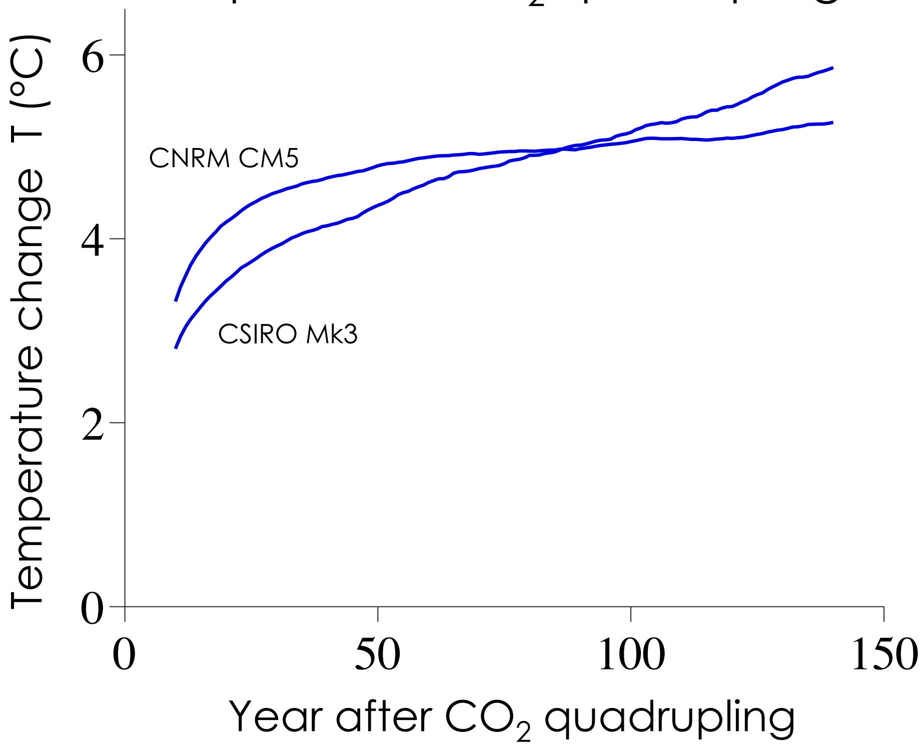
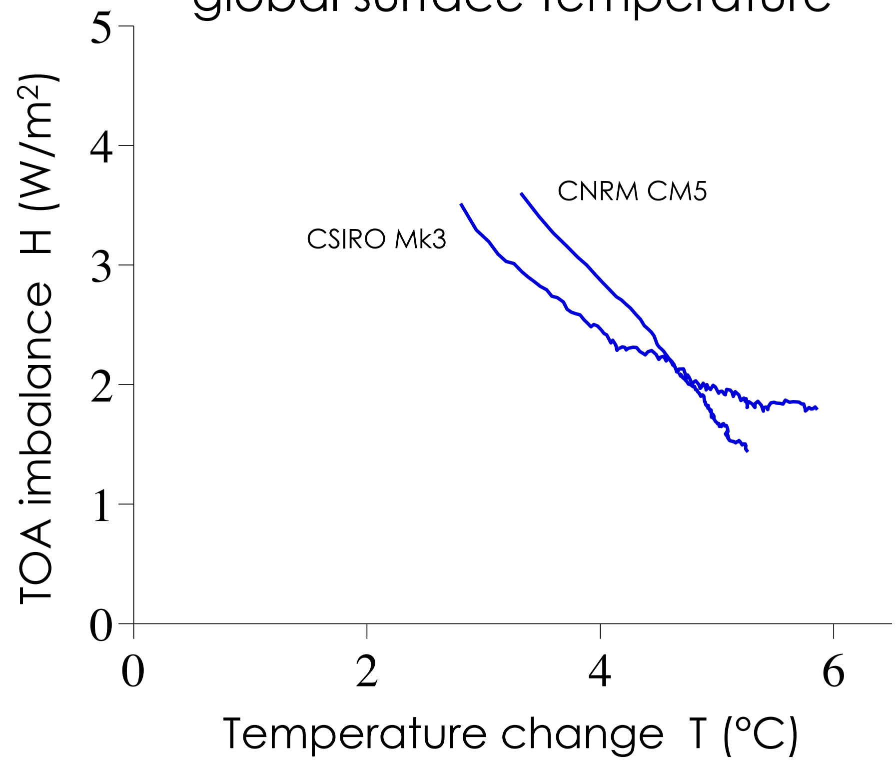


Global TOA radiation flux vs global surface temperature

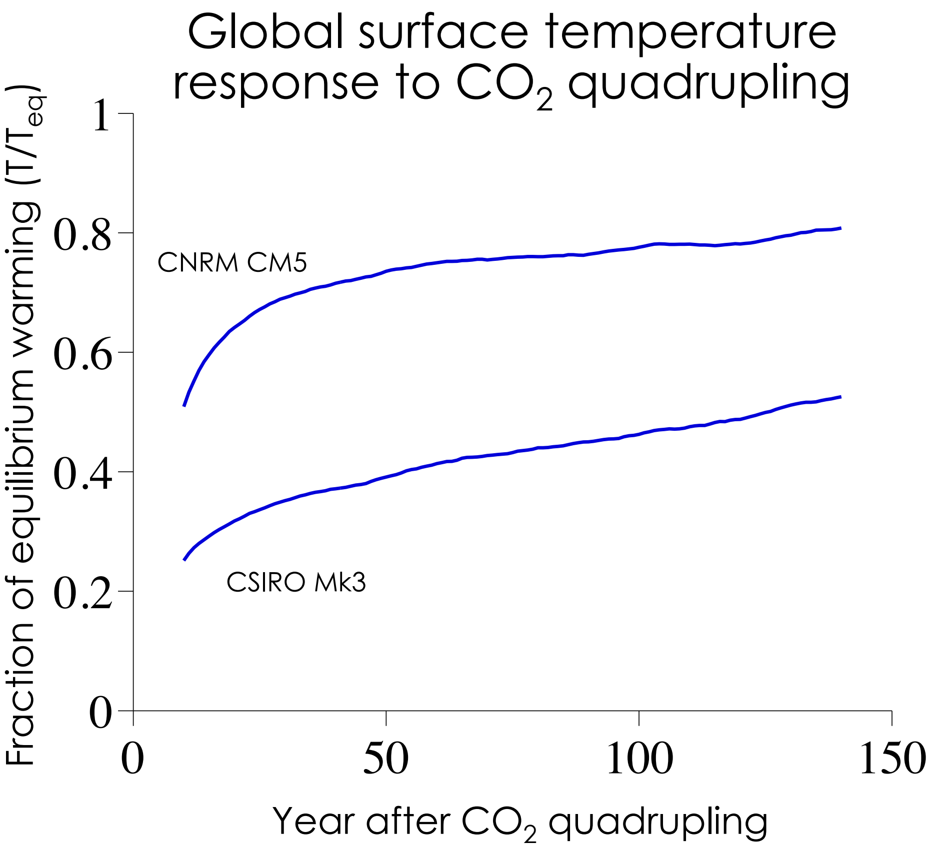


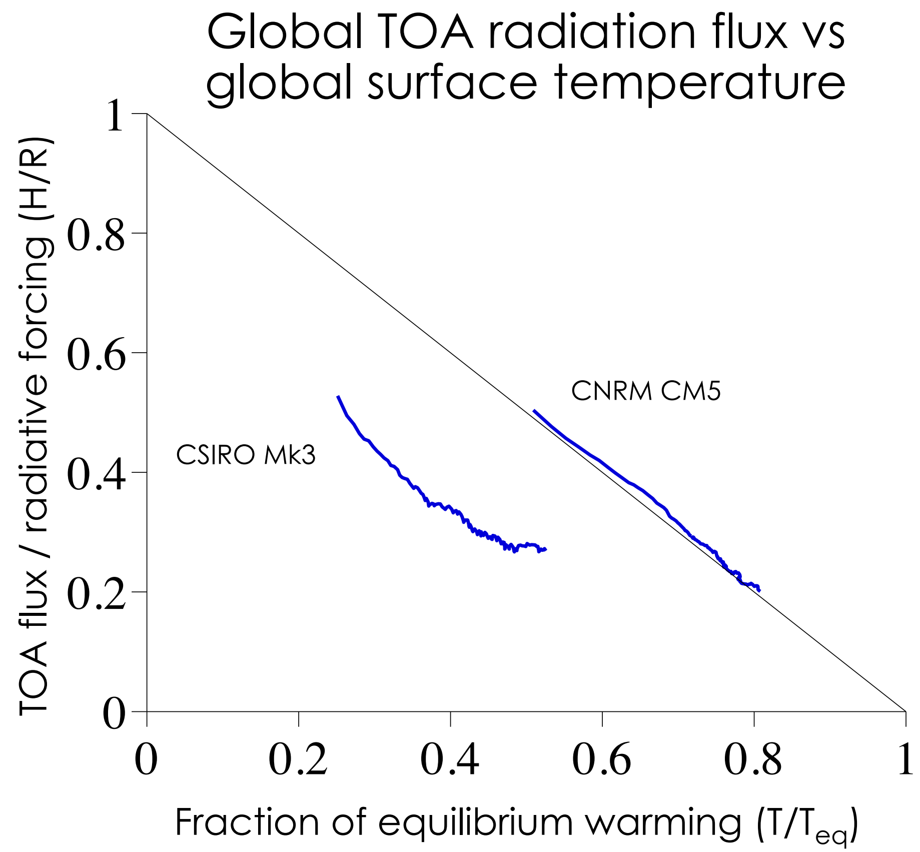
$$H = \lambda_{eff}(t)T + R \longrightarrow T_{eff}(t) = -\frac{R_{2\times}}{\lambda_{eff}(t)}$$

"Effective climate sensitivity"

Climate response to an abrupt CO_2 change

- 16 CMIP5 fully-coupled GCMs forced by abrupt CO_2 quadrupling





$$H = \lambda_{eff}(t)T + R \quad \longrightarrow \quad T_{eff}(t) = -\frac{R_{2\times}}{\lambda_{eff}(t)}$$

"Effective climate sensitivity"

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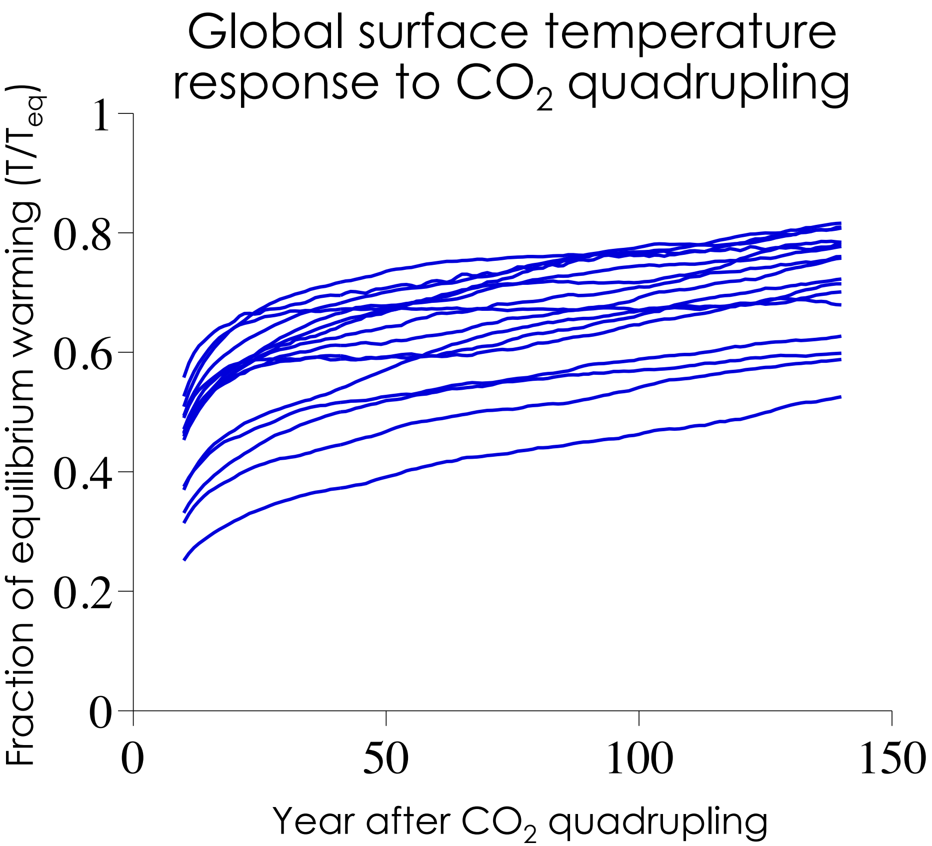

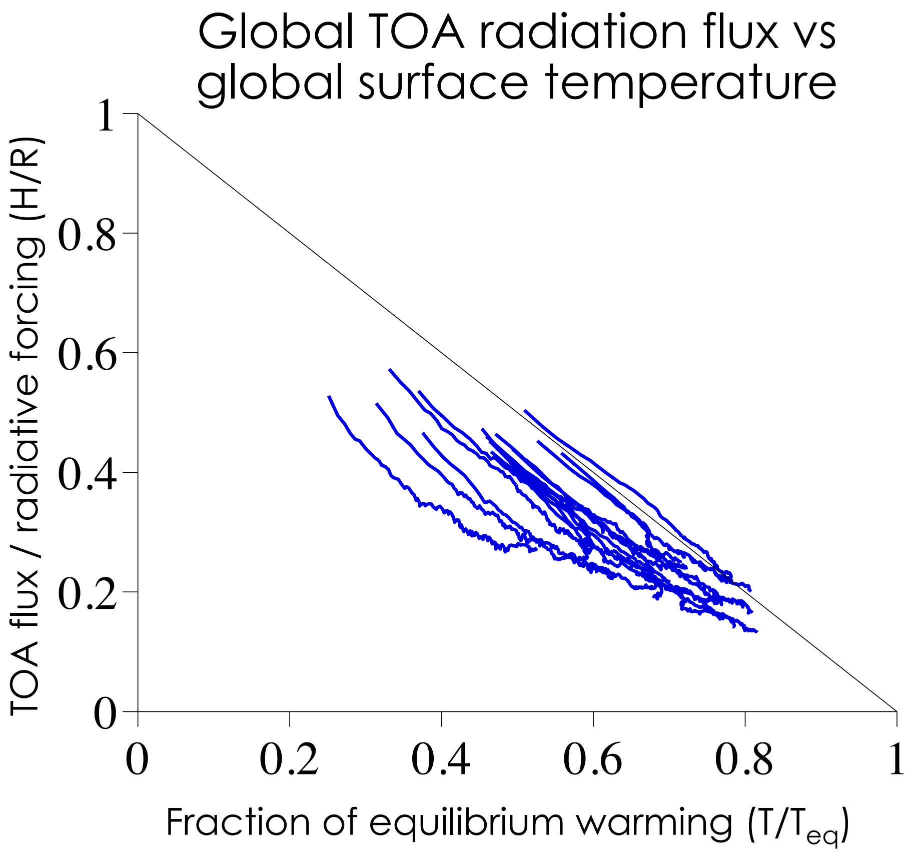

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"Effective climate sensitivity"

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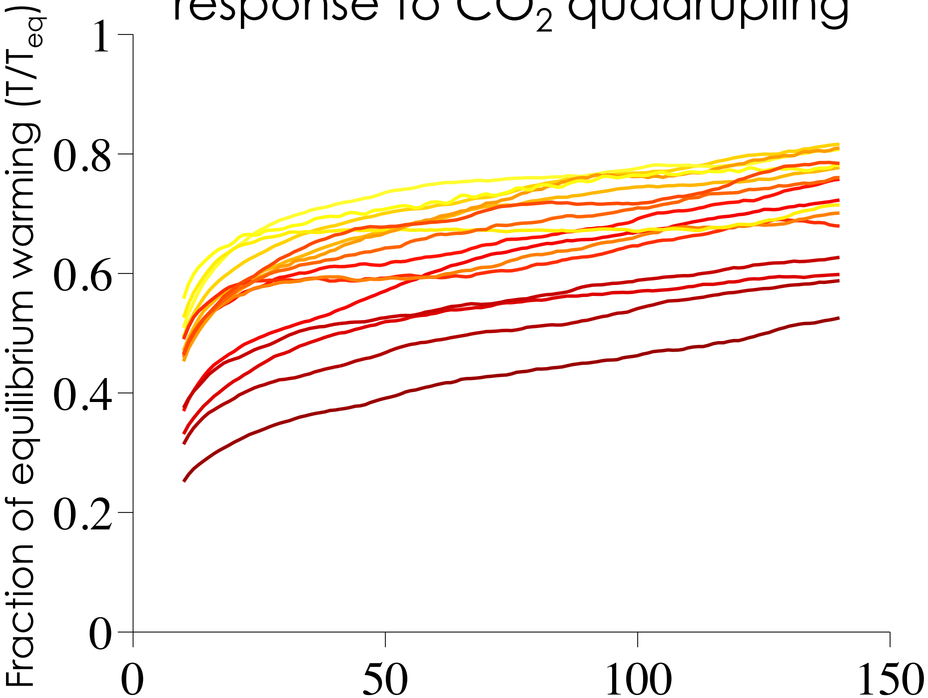
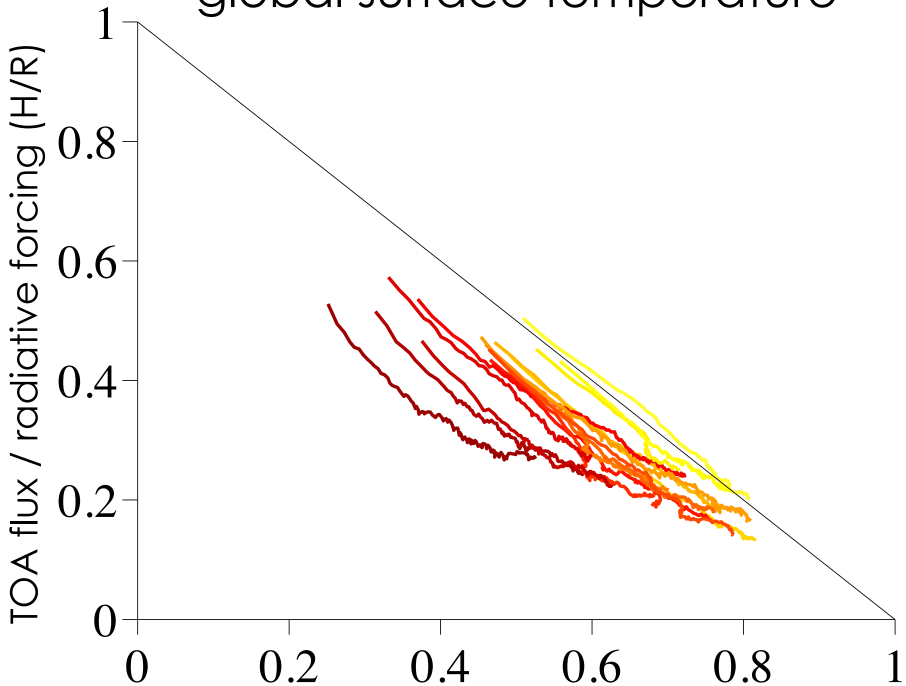
Global surface temperature response to CO_2 quadrupling



Global TOA radiation flux vs global surface temperature

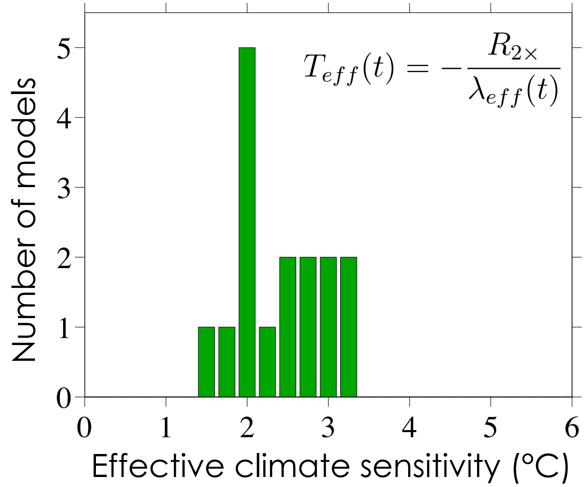


$$H = \lambda_{eff}(t)T + R \quad \rightarrow \quad T_{eff}(t) = -\frac{R_{2\times}}{\lambda_{eff}(t)}$$

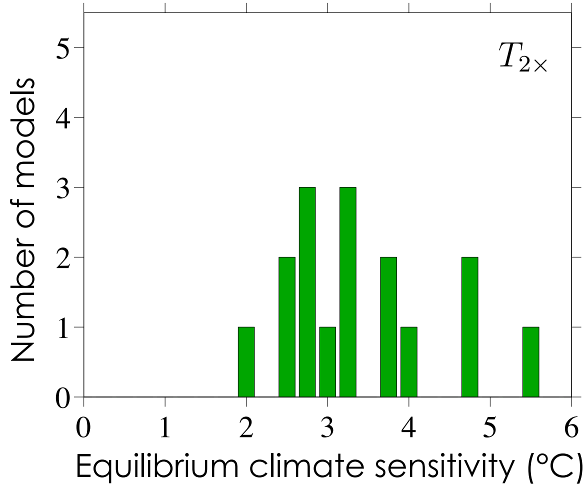
"Effective climate sensitivity"

Are we underestimating long-term global warming?

Effective climate sensitivity at the time of CO_2 doubling (year 70) in transient 1%/yr CO_2 ramping simulations



Equilibrium climate sensitivity estimated from abrupt 4×CO_2 simulations

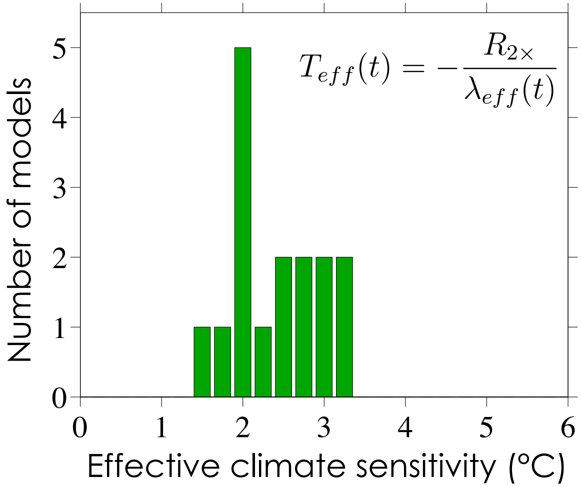


Apparent climate sensitivity (estimated long-term warming) before the emergence of SH polar amplification

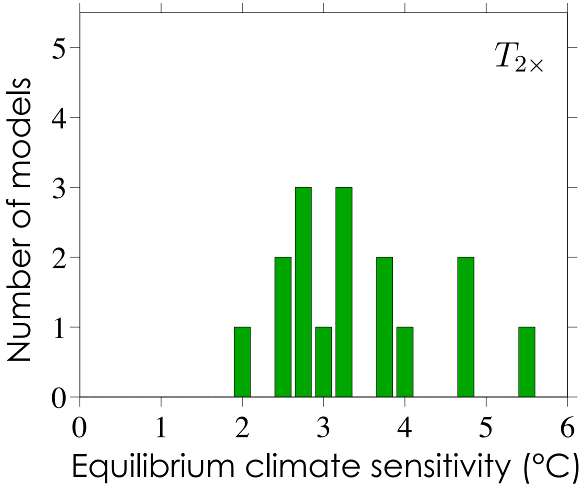
Actual (equilibrium) climate sensitivity

Are we underestimating long-term global warming?

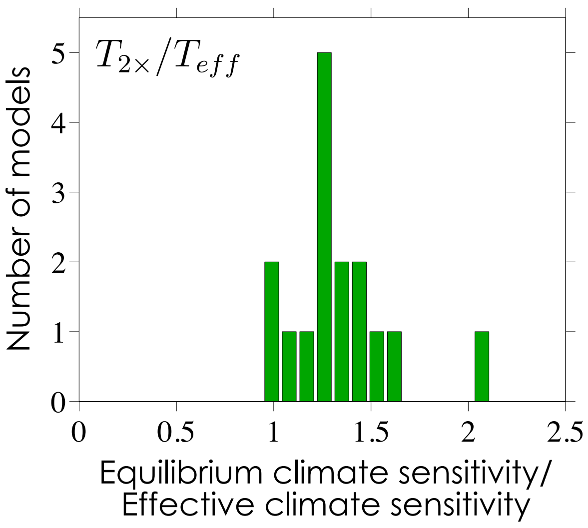
Effective climate sensitivity at the time of CO_2 doubling (year 70) in transient 1%/yr CO_2 ramping simulations



Equilibrium climate sensitivity estimated from abrupt 4×CO_2 simulations



Ratio of equilibrium to effective climate sensitivity:



Active vs passive role of ocean heat uptake