Controls on the Transient Climate Response to Emissions

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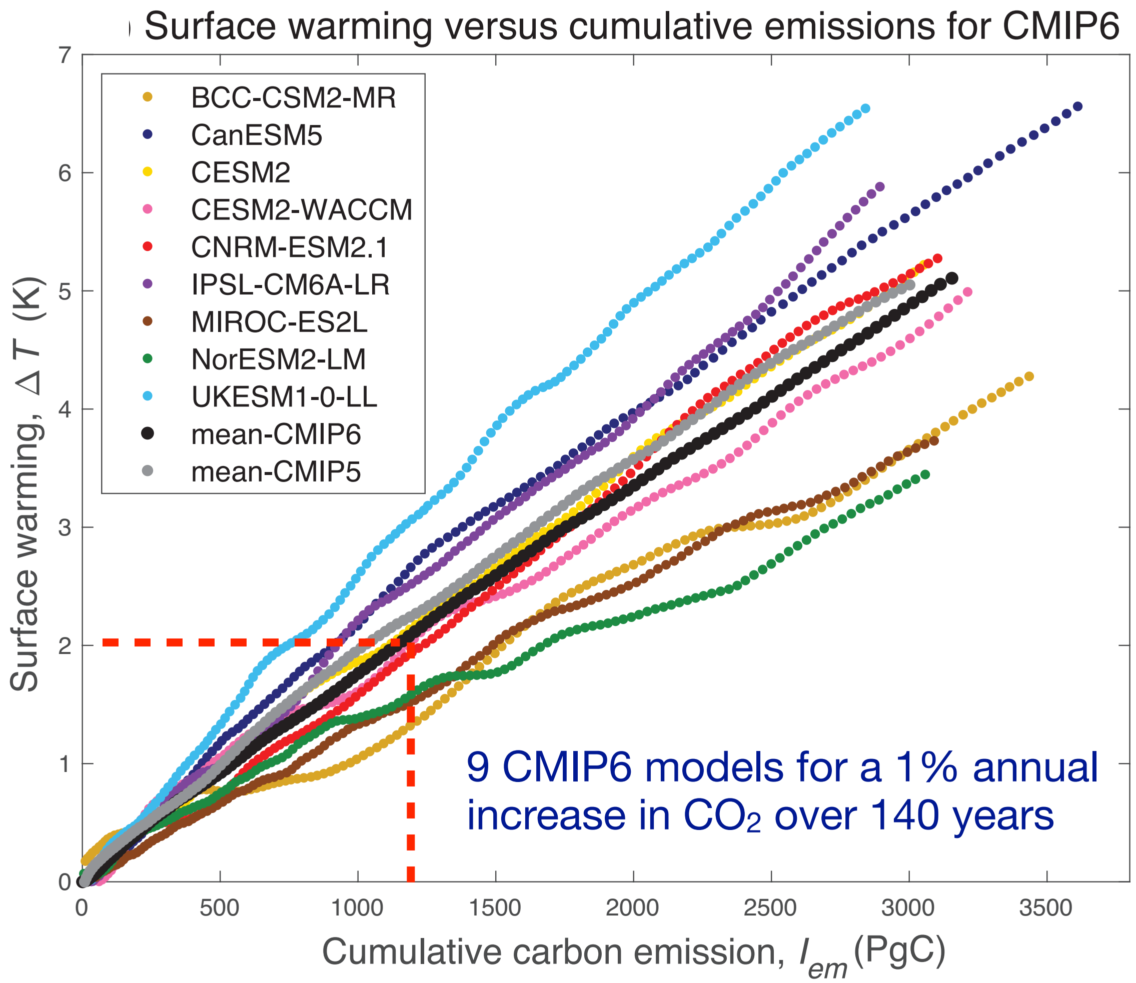
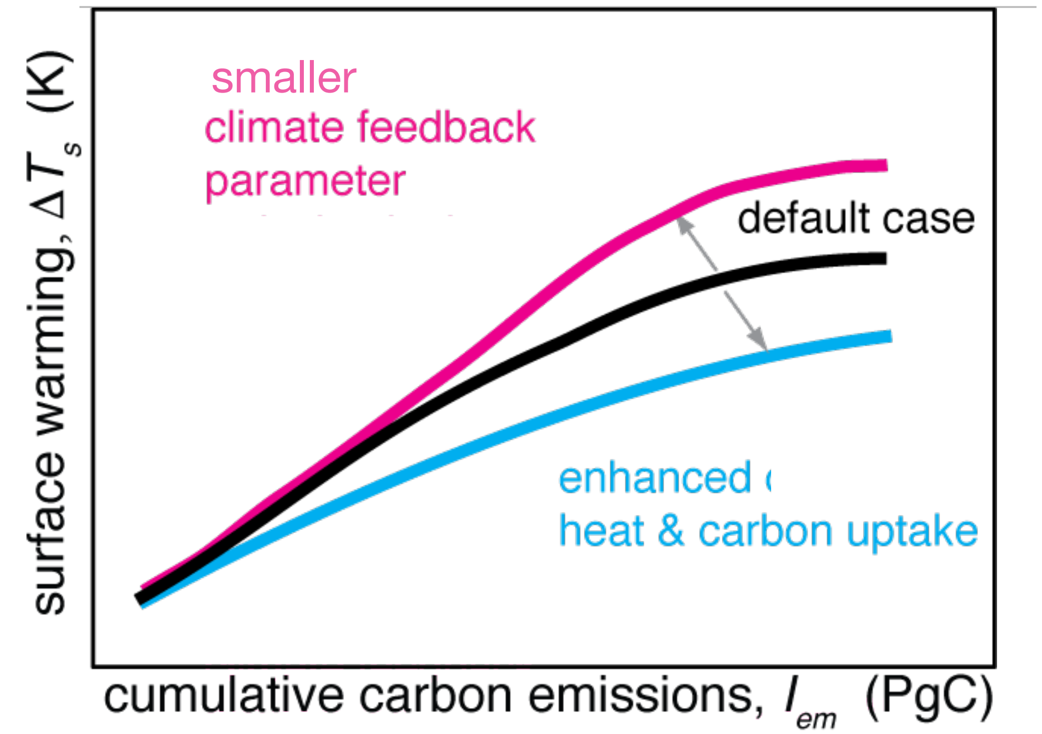




A climate metric: *the Transient Climate Response to Emissions*

$$\boxed{\mathrm{TCRE} \equiv \frac{\Delta T(t)}{I_{em}(t)}}$$

$\Delta T(t)$ = change in global-mean surface air temperature

$I_{em}(t)$ = cumulative carbon emission (PgC)

$\Delta F(t)$ = change in radiative forcing

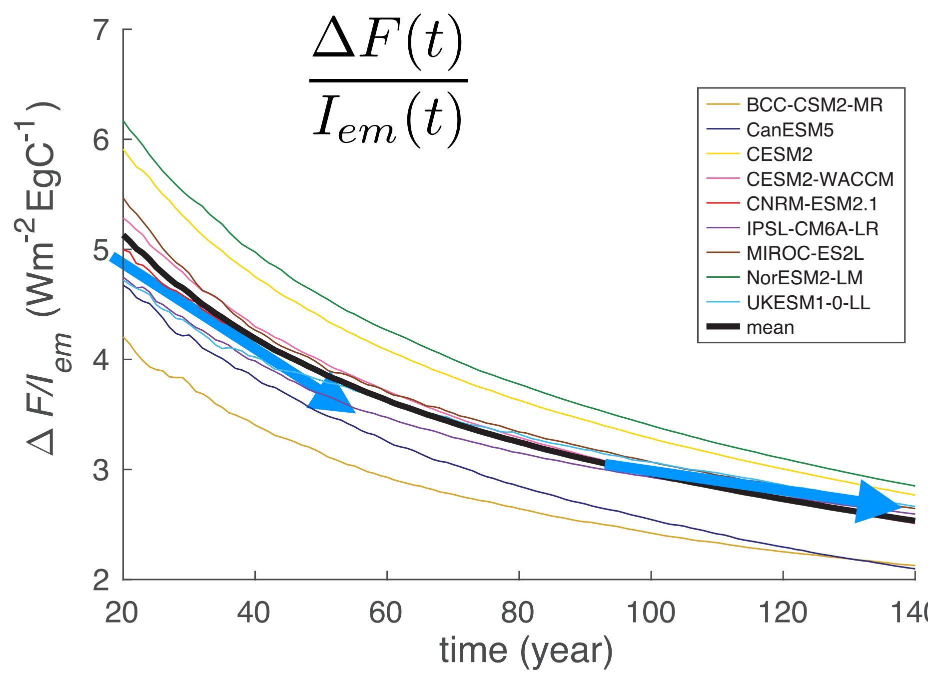
to gain insight ,connect to radiative forcing

$$\boxed{\frac{\Delta T(t)}{I_{em}(t)} = \underbrace{\left(\frac{\Delta T(t)}{\Delta F(t)}\right)}_{\text{dependence of surface warming on radiative forcing}} \underbrace{\left(\frac{\Delta F(t)}{I_{em}(t)}\right)}_{\text{dependence of radiative forcing on carbon emissions}}}$$

For further details, see Williams, Ceppi & Katavouta (2020) Controls of the Transient Climate Response to Emissions by physical feedbacks, heat uptake and carbon cycling. Environ. Res. Letters, in press.

Dependence of radiative forcing on carbon emissions *decreases in time*

$$\mathrm{TCRE} = \frac{\Delta T(t)}{I_{em}(t)} = \left(\frac{\Delta T(t)}{\Delta F(t)}\right)\left(\frac{\Delta F(t)}{I_{em}(t)}\right)$$



dependence of radiative forcing on carbon emissions

$$\frac{\Delta F(t)}{I_{em}(t)} = \left(\frac{\Delta F(t)}{\Delta I_{atmos}(t)}\right)\left(\frac{\Delta I_{atmos}(t)}{I_{em}(t)}\right)$$

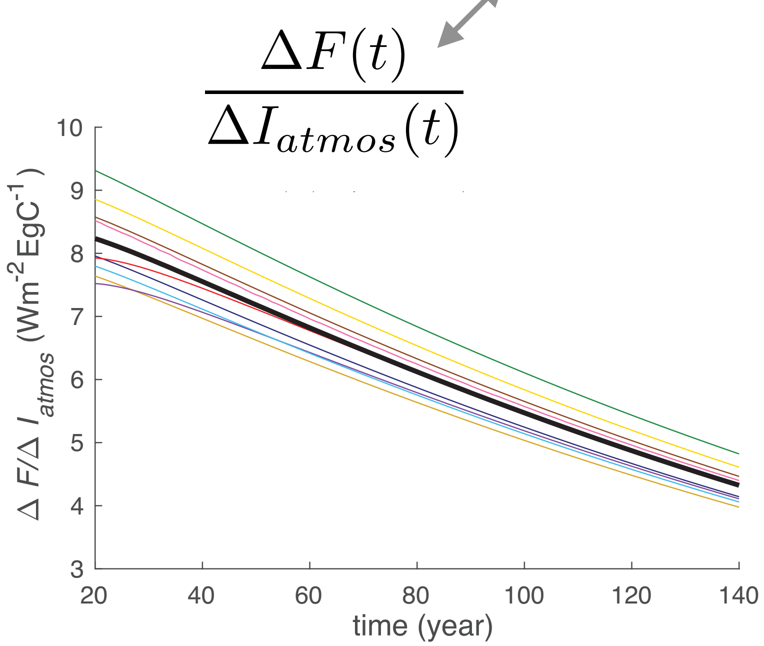
saturation of radiative forcing with atmospheric CO_2

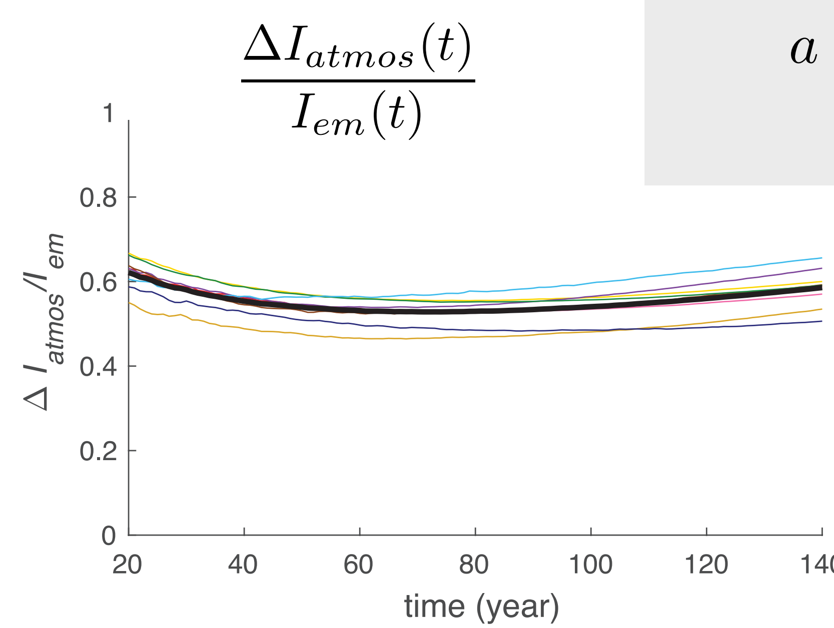
airborne fraction

radiative forcing

$$\Delta F(t) = a \ln(\mathrm{CO_2}(t)/\mathrm{CO_2}(t_0))$$

a from abrupt 4xCO_2 experiment regression of planetary heat uptake vs temperature

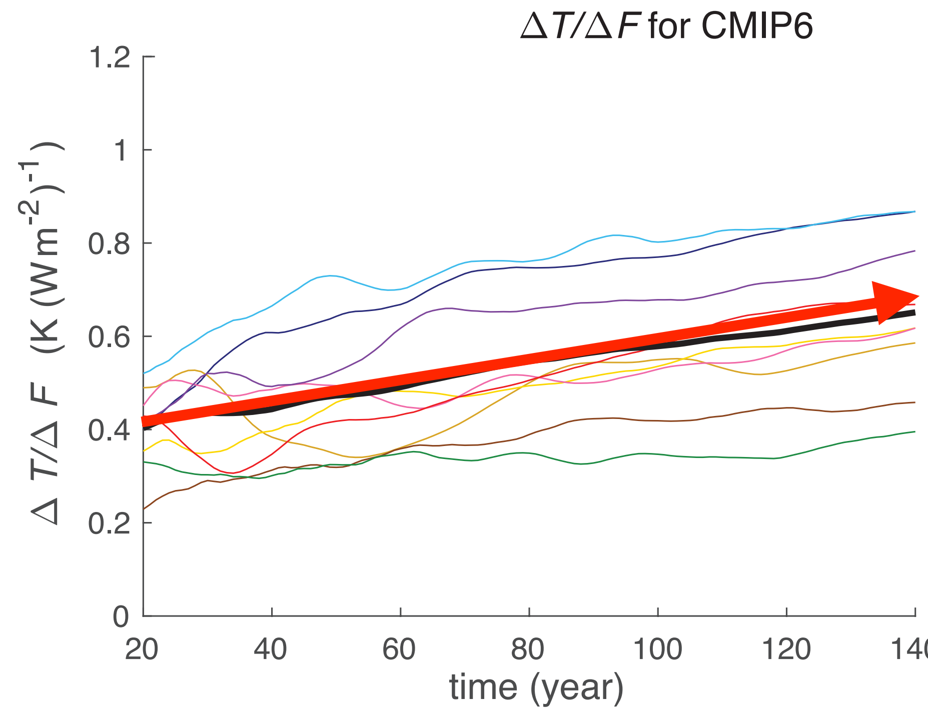




Intermodel differences from *radiative forcing dependence* and *airborne fraction*

Dependence of surface warming on radiative forcing *increases in time*

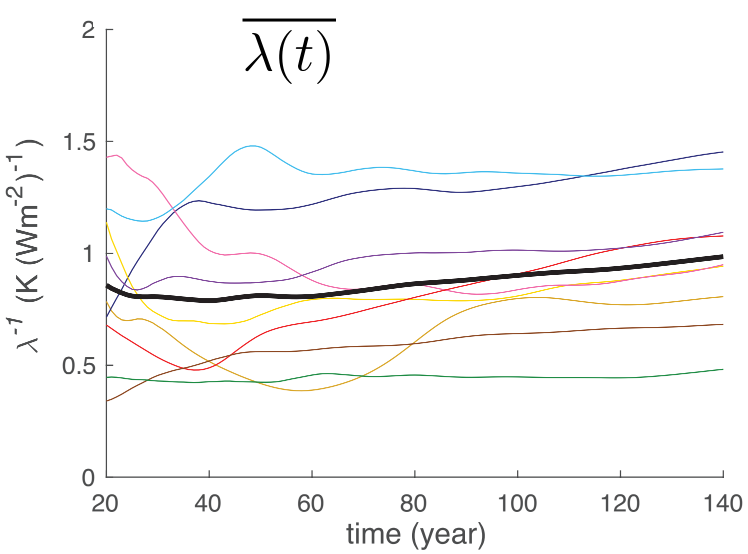
$$\mathrm{TCRE} = \frac{\Delta T(t)}{I_{em}(t)} = \left(\frac{\Delta T(t)}{\Delta F(t)}\right)\left(\frac{\Delta F(t)}{I_{em}(t)}\right)$$



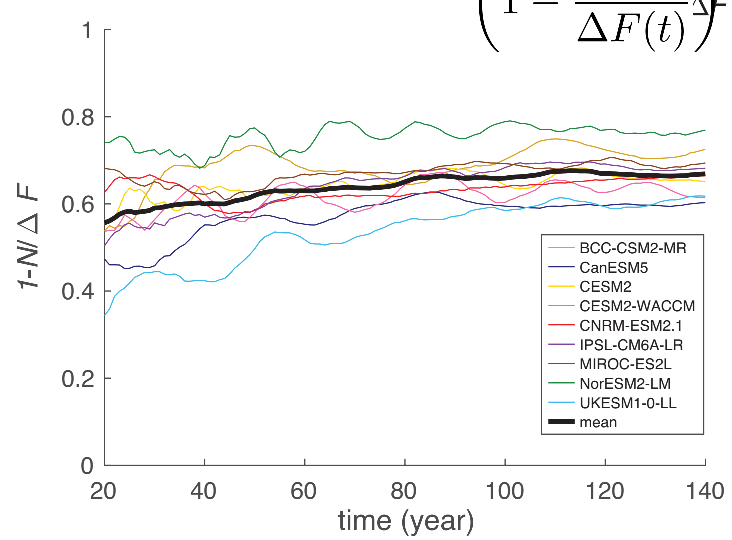
dependence of surface warming on radiative forcing

$$\frac{\Delta T(t)}{\Delta F(t)} = \underbrace{\frac{1}{\lambda(t)}}_{\text{(climate feedback parameter)}^{-1}} \underbrace{\left(1 - \frac{N(t)}{\Delta F(t)}\right)}_{\text{fraction of radiative forcing warming the surface}}$$

$$\frac{1}{\lambda(t)}$$



$$\left(1 - \frac{N(t)}{\Delta F(t)}\right)$$



$$\Delta F(t) = \lambda(t)\Delta T(t) + N(t),$$

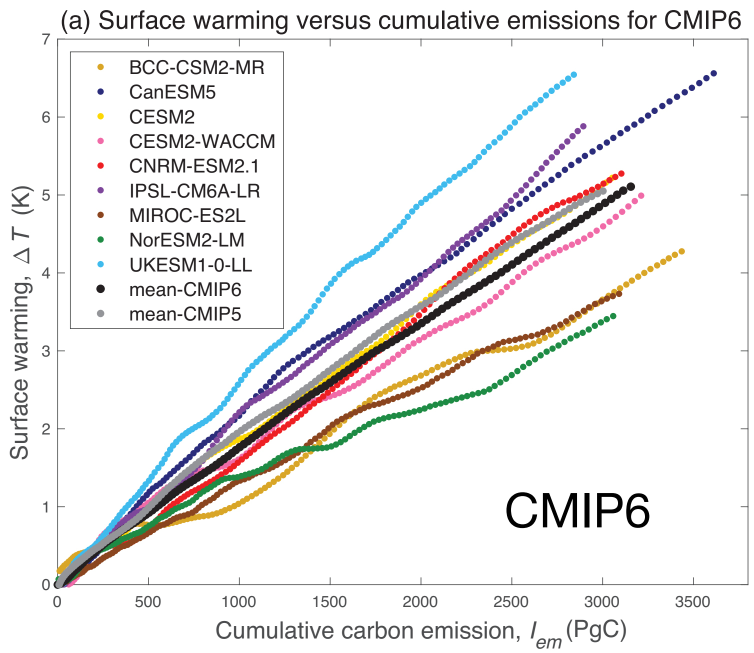
radiative forcing	radiative response	planetary heat uptake

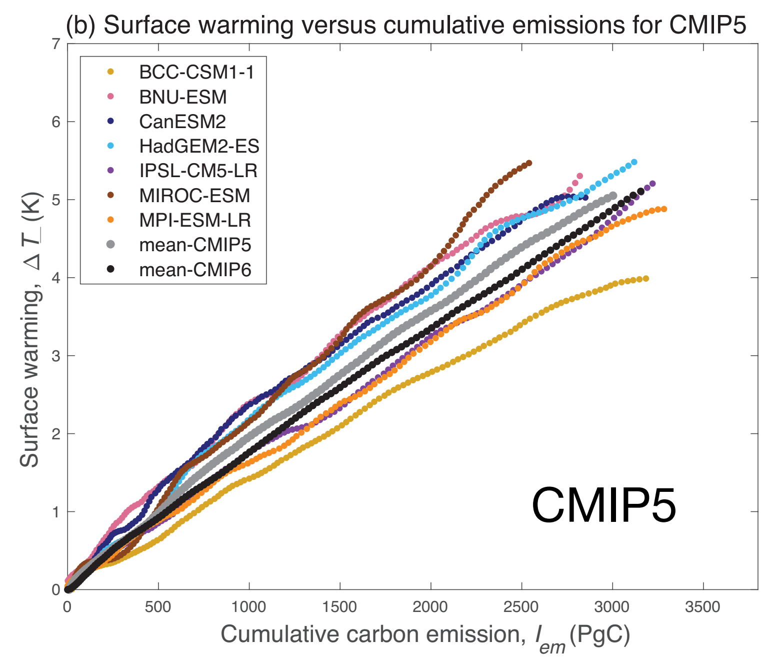
$\lambda(t)$ = climate feedback parameter from regression of radiative response vs temperature

$N(t)$ = planetary heat uptake from 1% annual CO_2 experiment

Intermodel differences mainly from *climate feedback parameter* and *ocean heat uptake*

Intermodel differences in the Transient Climate Response to Emissions for CMIP6
mainly from the thermal response involving physical feedbacks





$$\mathrm{TCRE} = \frac{\Delta T(t)}{I_{em}(t)}$$

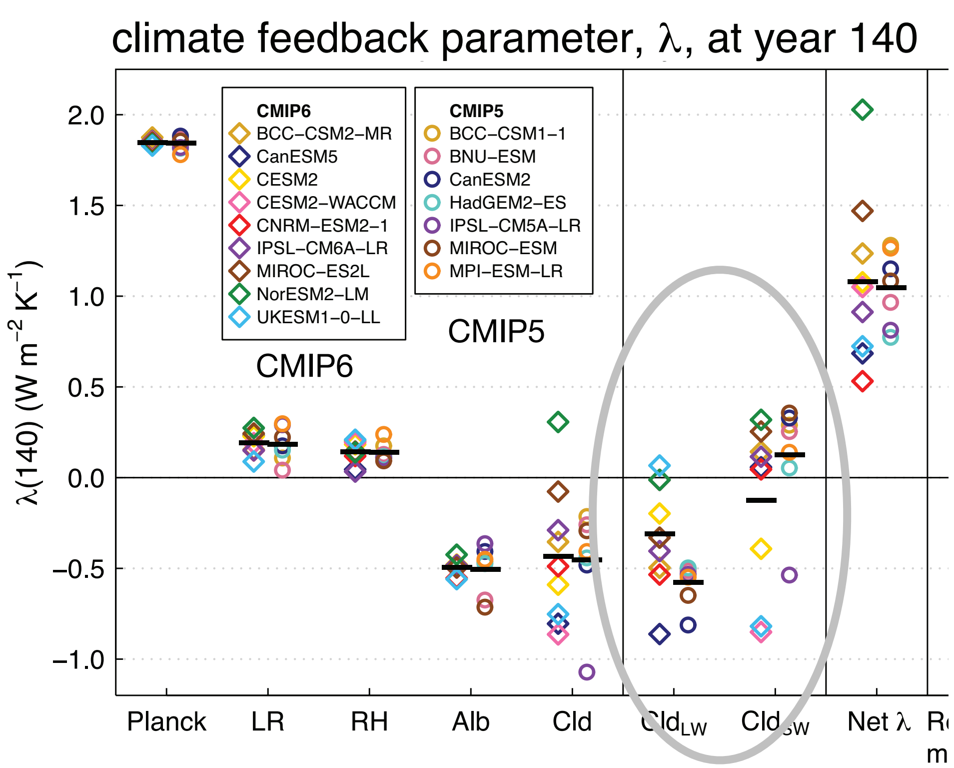
$$= \underbrace{\left(\frac{\Delta T(t)}{\Delta F(t)}\right)}_{\text{dependence of surface warming on radiative forcing}} \underbrace{\left(\frac{\Delta F(t)}{I_{em}(t)}\right)}_{\text{dependence of radiative forcing on carbon emissions}}$$

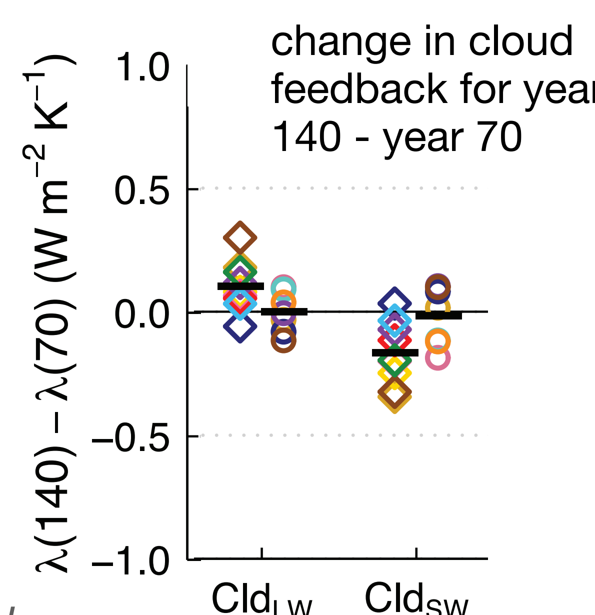
Larger spread in thermal response in CMIP6 due to climate feedback & ocean heat uptake

Table of relative standard deviation

$\sigma_x/\overline{x}$	$\Delta T/\Delta F$	$\Delta F/I_{em}$
CMIP6	**0.26**	0.10
CMIP5	**0.16**	0.21

Wider range in cloud feedbacks for CMIP6





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