Shortwave and longwave contributions to global warming under increased CO_2

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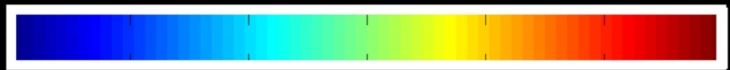
Energy imbalance and temperature change

Unperturbed

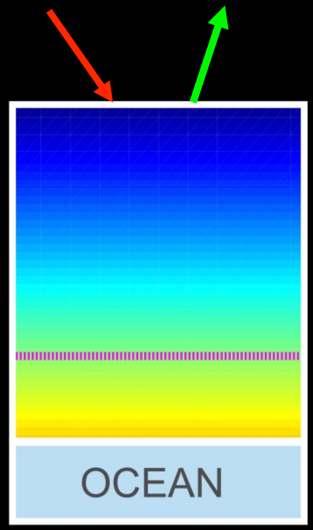
ASR = OLR

Atmospheric Emission Level

Atmospheric Temperature

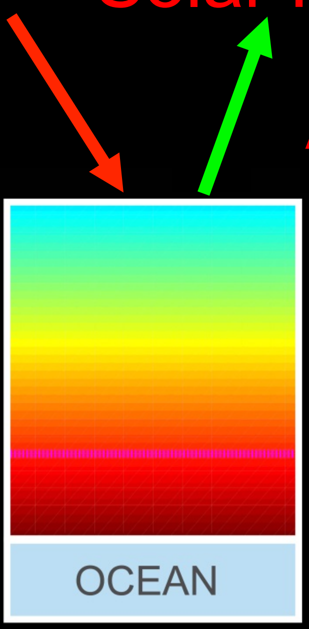


Cold Hot



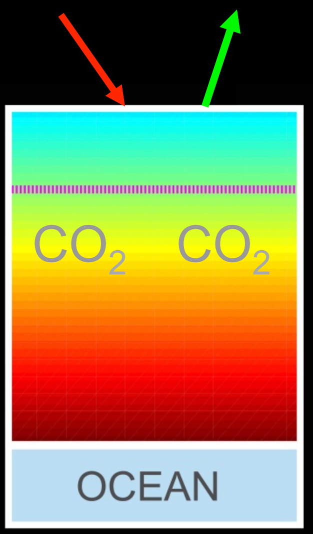
Solar Perturbation

ASR = OLR

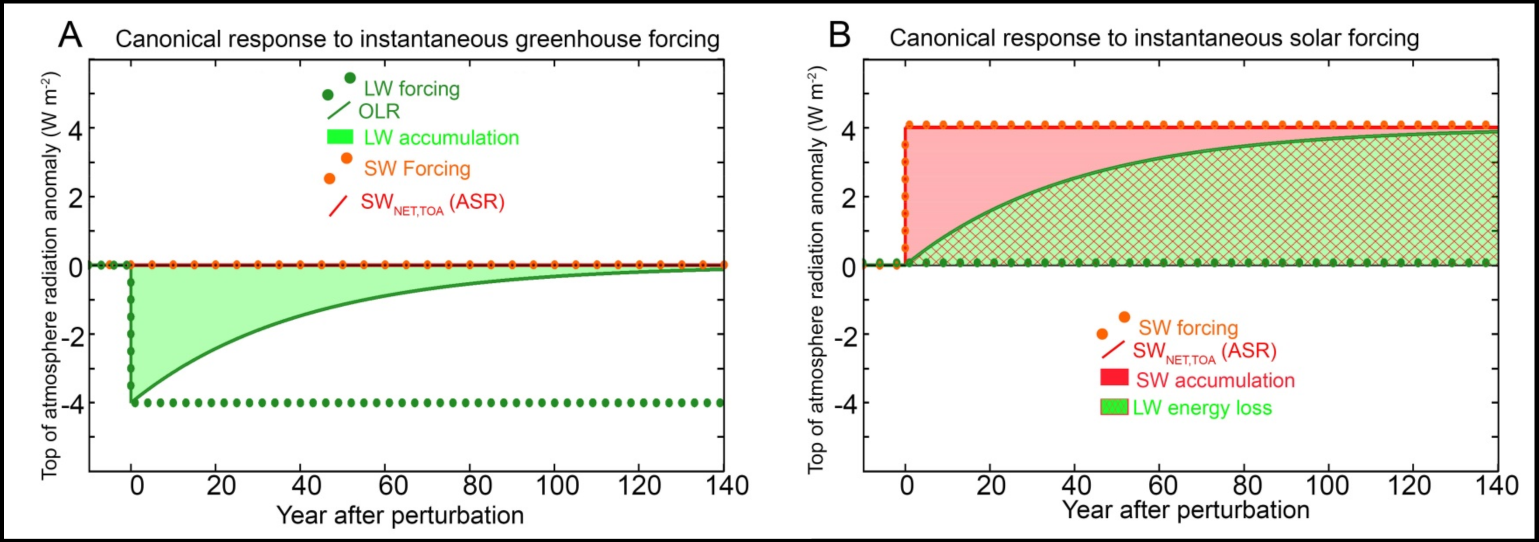


Greenhouse Perturbation

ASR = OLR

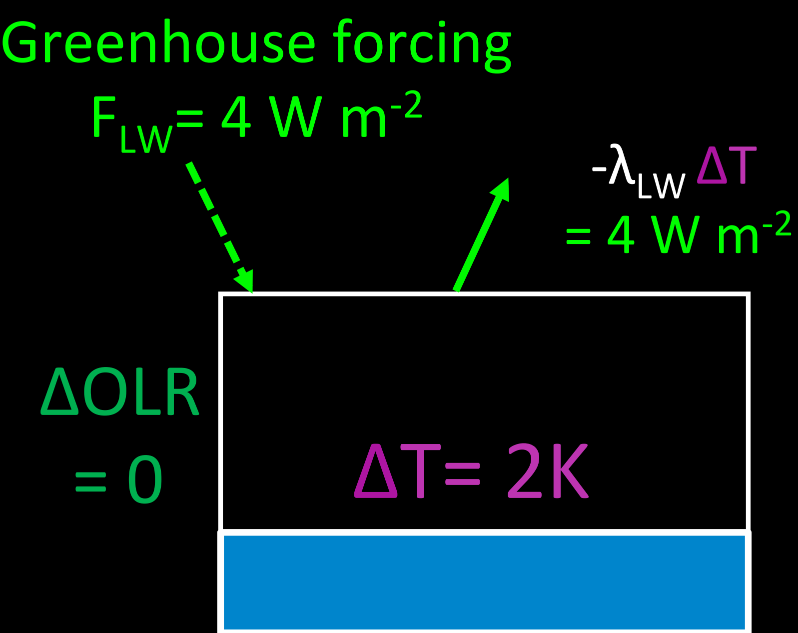


Top of Atmosphere Radiative response to greenhouse and shortwave forcing



How to reconcile this – response to greenhouse forcing with a shortwave feedback

LW feedback only



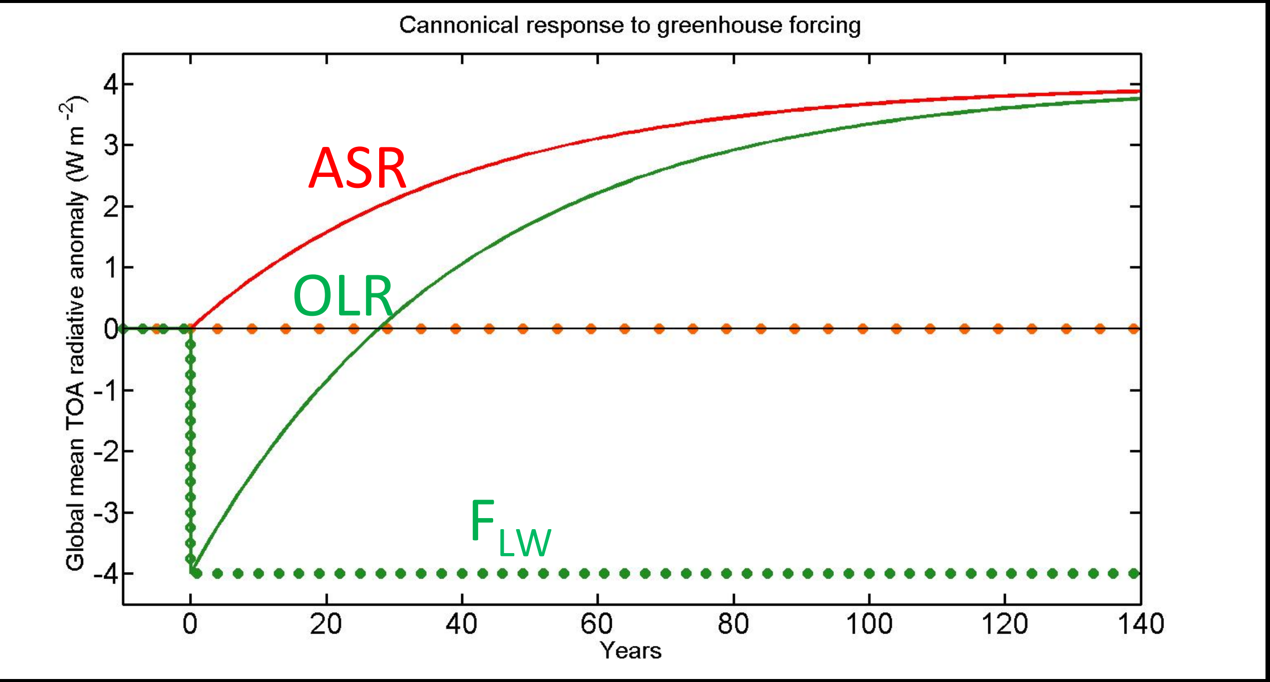
Forcing = response

$F_{LW} = -\lambda_{LW}\,\Delta T$

if $\lambda_{LW} = -2$ W m^{-2} K^{-1}

$\Delta T = F_{LW} / -\lambda_{LW} = 2$ K

Time evolution of OLR response to greenhouse forcing with SW feedback



OLR must go from –FLW at time 0 to FLW in the equilibrium response

→ OLR returns to unperturbed value *when half of the equilibrium temperature change occurs*

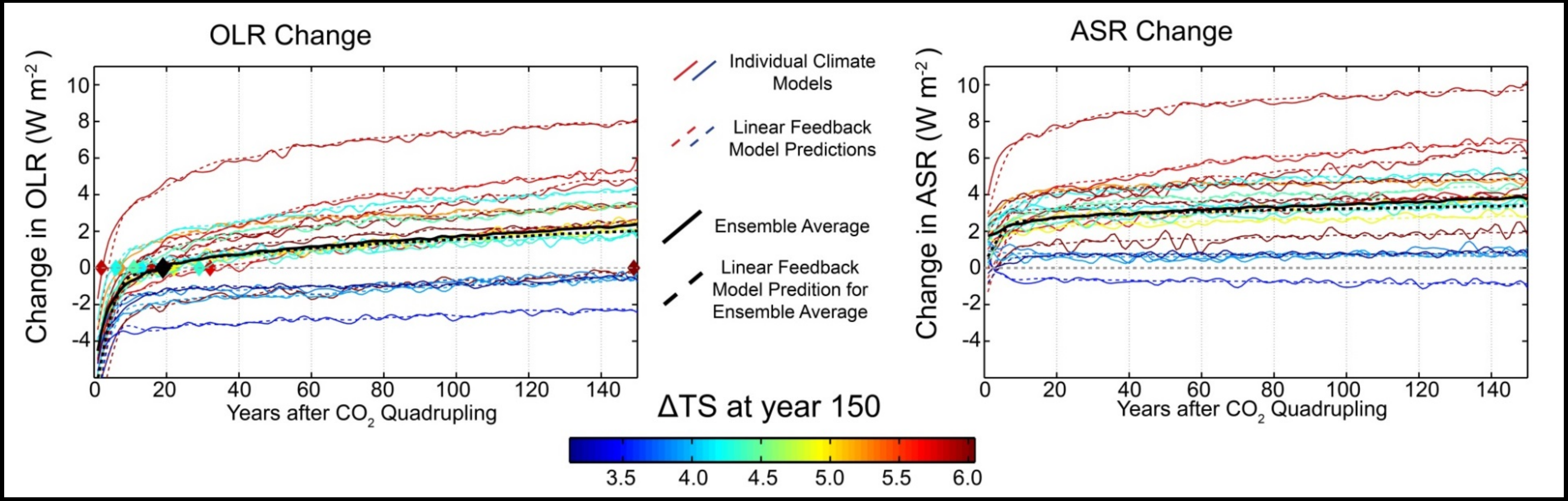
The energy imbalance equation:

Has the solution: T_S

With the characteristic timescale (τ)

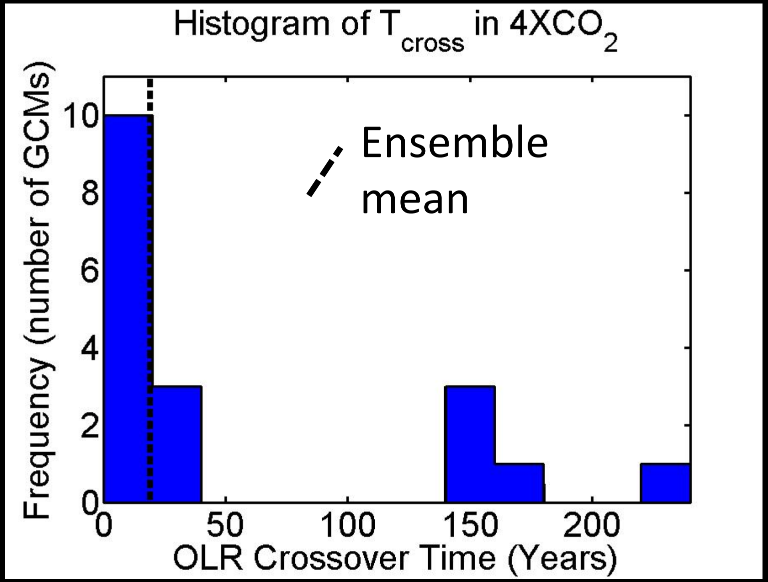
τ= = = 30 years (for 150 meter deep ocean)

Inter-model spread in TOA response



The TOA response to greenhouse forcing differs a lot between GCMs

- OLR returns to unperturbed values (T_{CROSS}) within 5 years for some GCMs and not at all for others (bi-modal)
- On average, T_{CROSS} = 19 years



Linear Feedback model

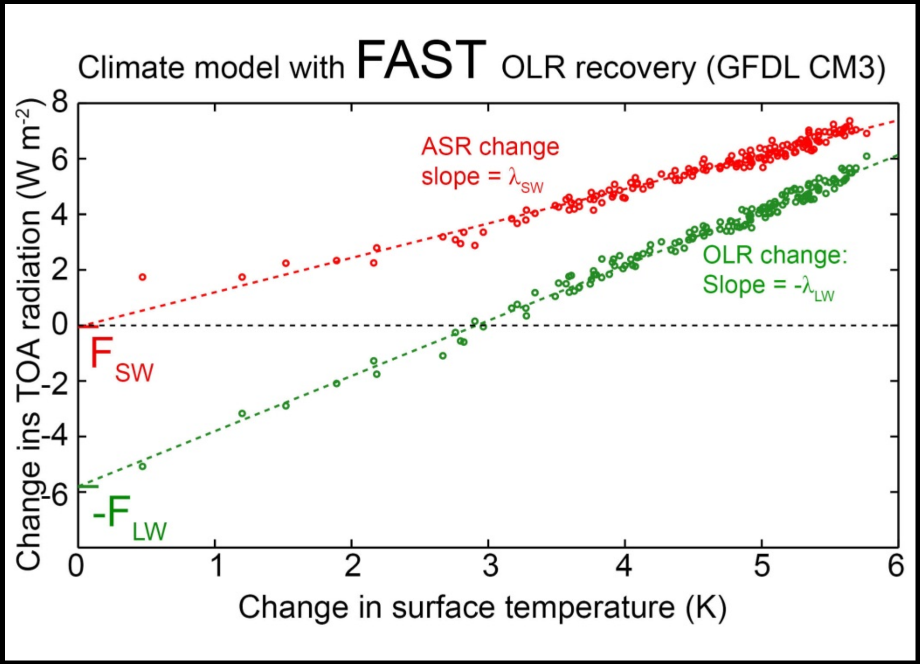
$$\overbrace{C(t)\frac{d}{dt}T_S}^{\text{Energy Change}} = \overbrace{\overbrace{F_{SW} + F_{LW}}^{\text{Forcing}} + \overbrace{(\lambda_{LW} + \lambda_{SW})T_S(t)}^{\text{Feedbacks}}}^{\text{Top of atmosphere (TOA) radiation}}.$$

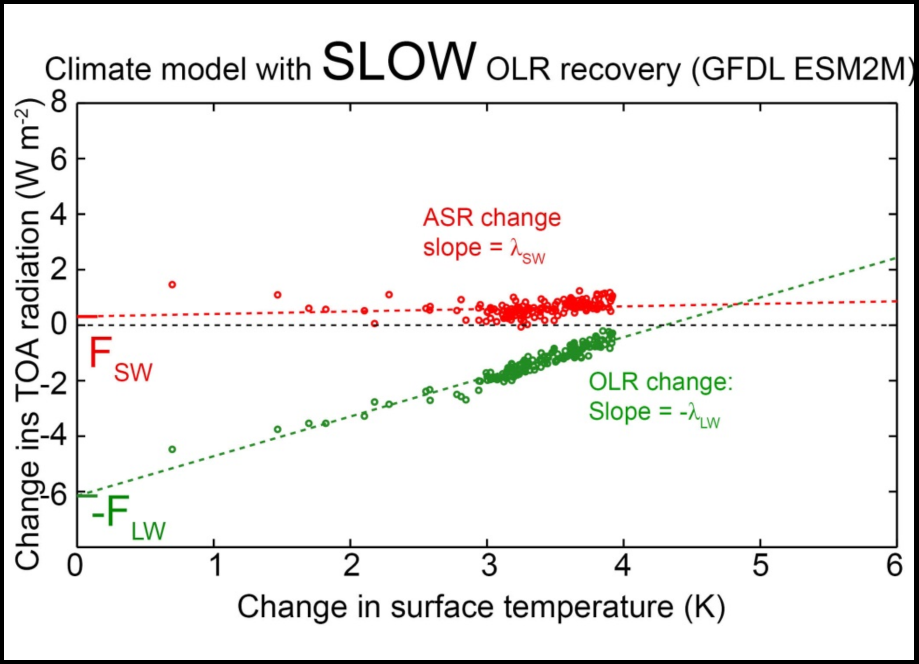
- C = heat capacity of climate system. Time dependent – meters of ocean
- T_S = Global mean surface temperature change
- F_{SW} and F_{LW} are the SW and LW radiative forcing (including fast cloud response to radiative forcing – W m^{-2})
- λ_{LW} and λ_{SW} are the LW and SW feedback parameters. W m^{-2} K^{-1}

- Given above parameters and T_S , we can predict the TOA response

$$OLR(t) = -F_{LW} - \lambda_{LW} T_S(t)$$
$$ASR(t) = F_{SW} + \lambda_{SW} T_S(t)\ .$$

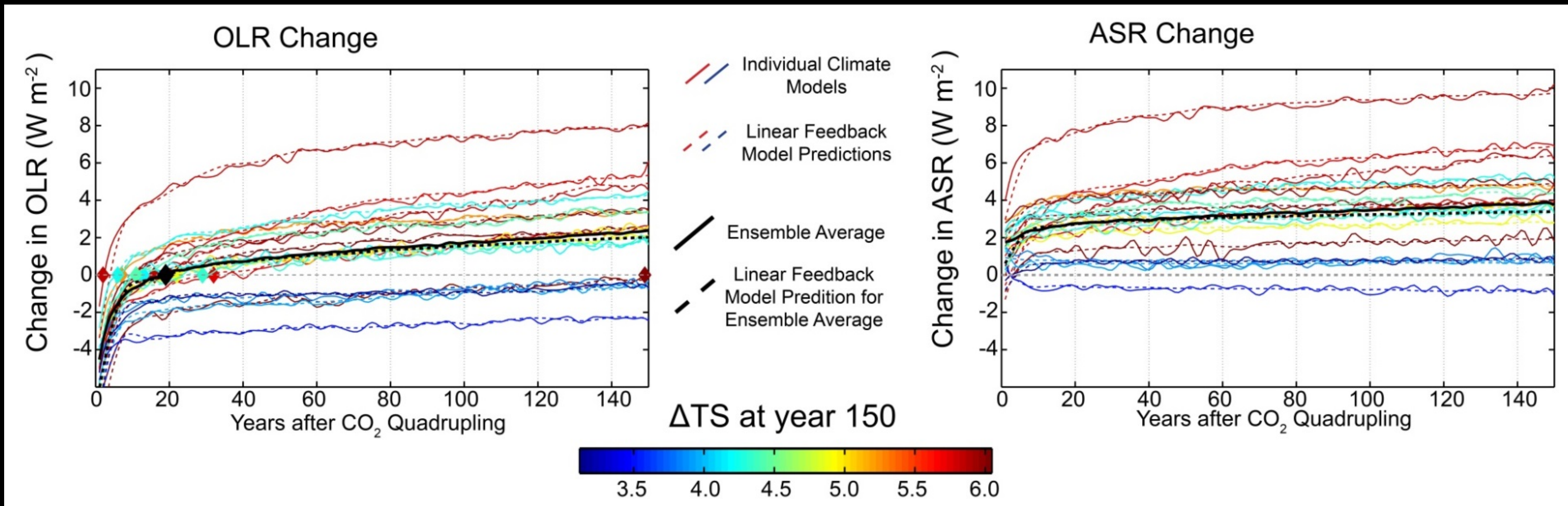
Backing out Forcing and feedbacks from instantaneous 4XCO2 increase runs





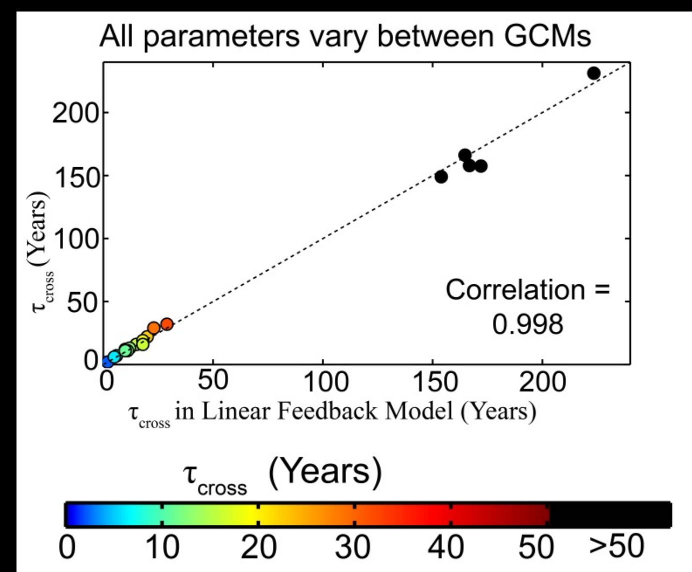
- Feedbacks parameters (λ_{LW} and λ_{SW}) are the slope of –OLR and ASR vs. T_S (W m^{-2} K^{-1})
- Forcing (F_{SW} and F_{LW}) is the intercept (W m^{-2}) . Includes rapid cloud response to CO_2 (Gregory and Webb)

Linear Feedback model works



The TOA response in each model (and ensemble average) – solid lines– is well replicated by the linear feedback model

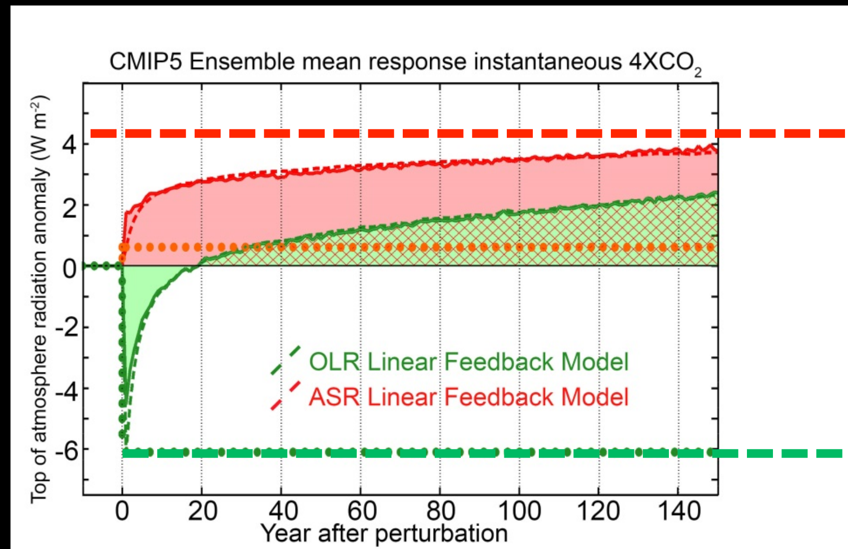
- What parameters (forcing, feedbacks, heat capacity) set the mean radiative response and its variations across models?



Ensemble average OLR recovery timescale

Ensemble average forcing and feedbacks

- $\lambda_{LW} = -1.7\ W\ m^{-2}\ K^{-1}$
- $\lambda_{SW} = +0.6\ W\ m^{-2}\ K^{-1}$
- $F_{LW} = +\ 6.1\ W\ m^{-2}$



OLR at equilibrium

OLR at time = 0

equilibrium temperature change

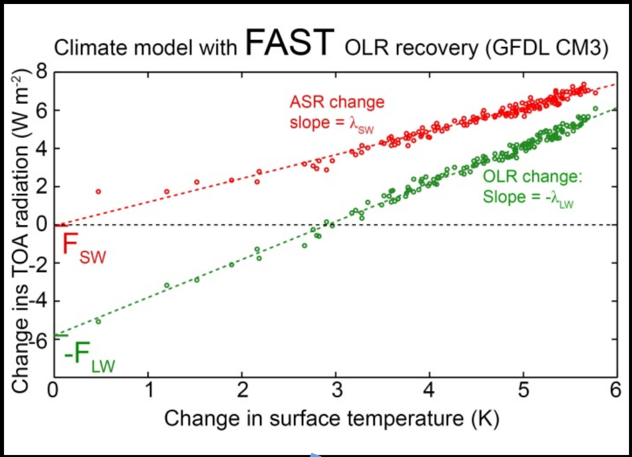
T_{EQ}

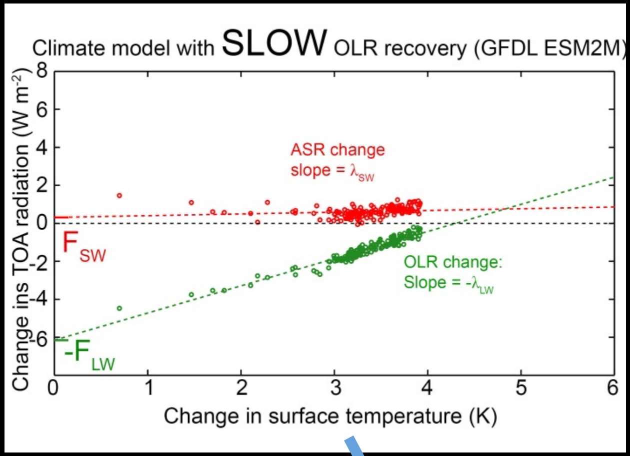
ASR in new equilibrium = $T_{EQ}\lambda_{SW} = 4\ W\ m^{-2}$

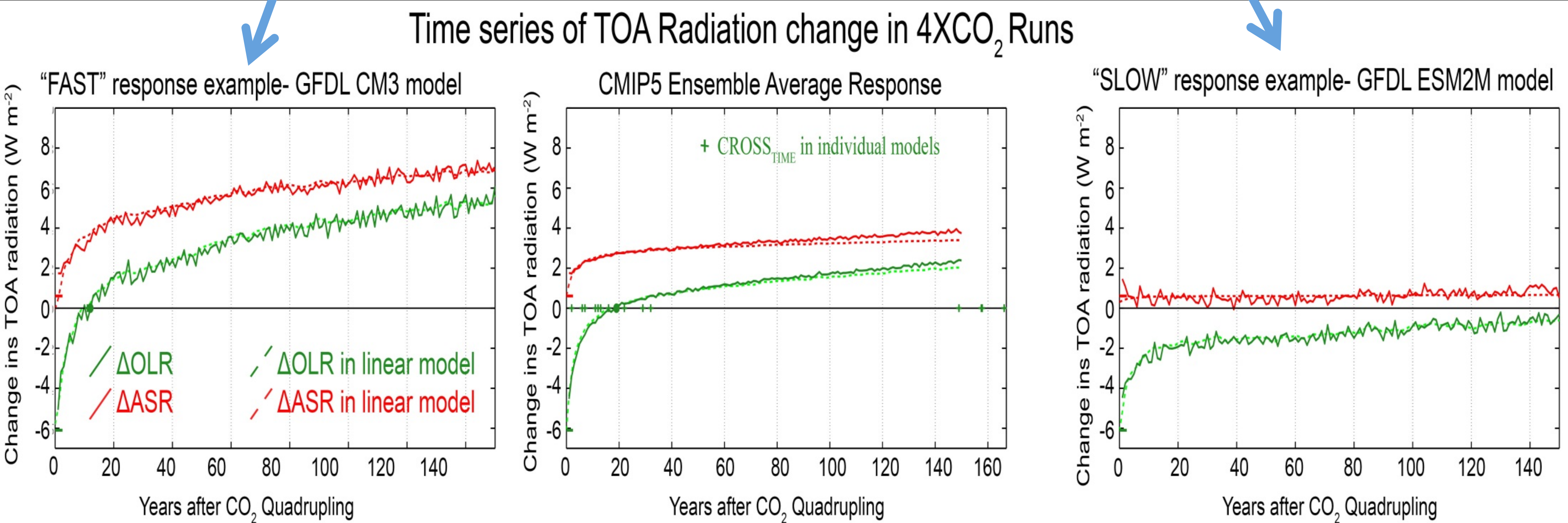
- To come to equilibrium, OLR must go from $-\ F_{LW} = -\ 6.1\ W\ m^{-2}$ to $T_{EQ}\lambda_{LW} = +4\ W\ m^{-2}$
- OLR must change by $10\ W\ m^{-2}$ to come to equilibrium

→ OLR crosses zero about 60% of the way the equilibrium

Climate model differences in OLR response time







Sensitivity of τ_{CROSS} to feedback parameters

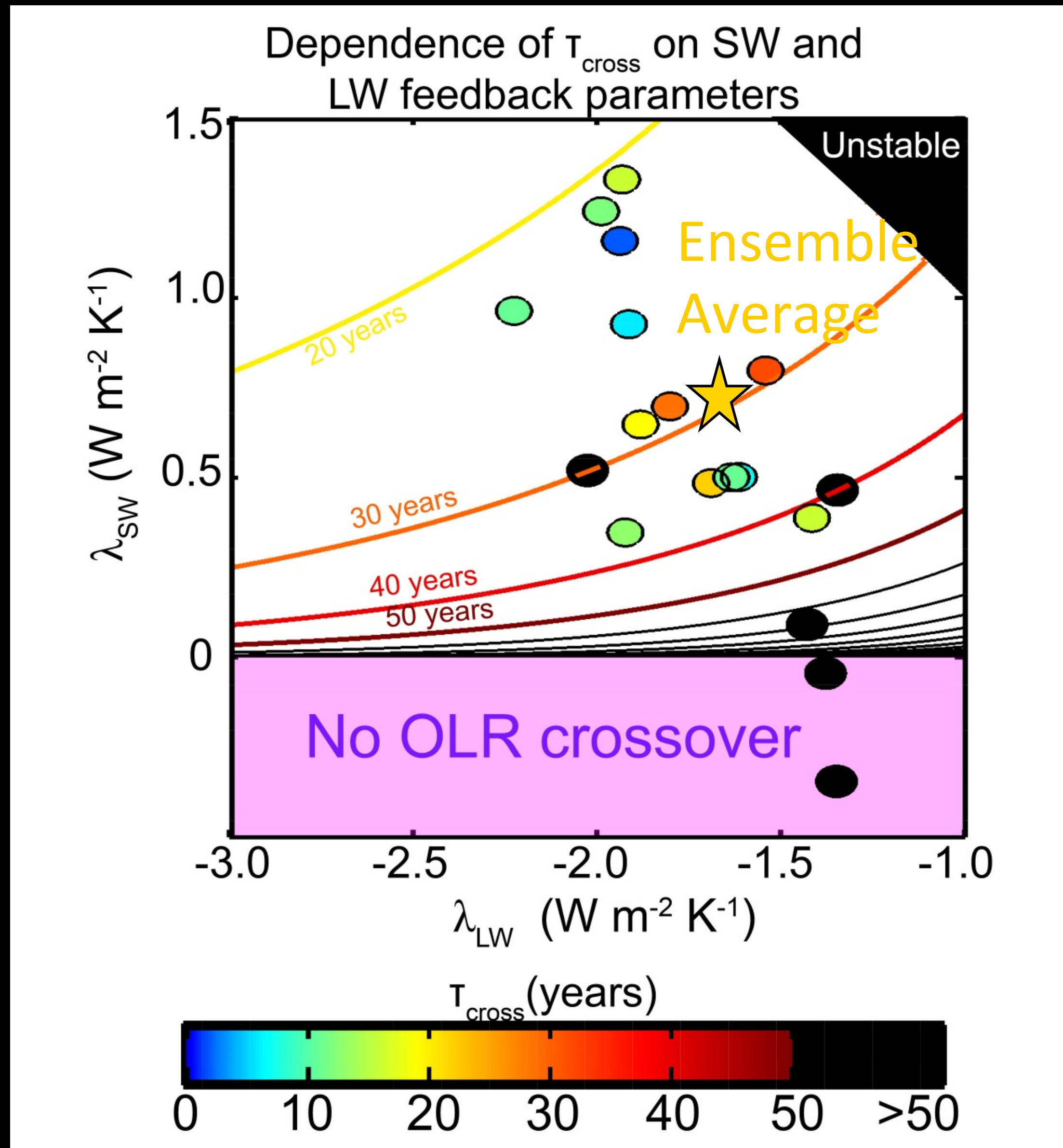
If $F_{SW} = 0$ (simplification):

$$\tau_{CROSS} = \tau \ln(-\lambda_{LW} / \lambda_{SW})$$

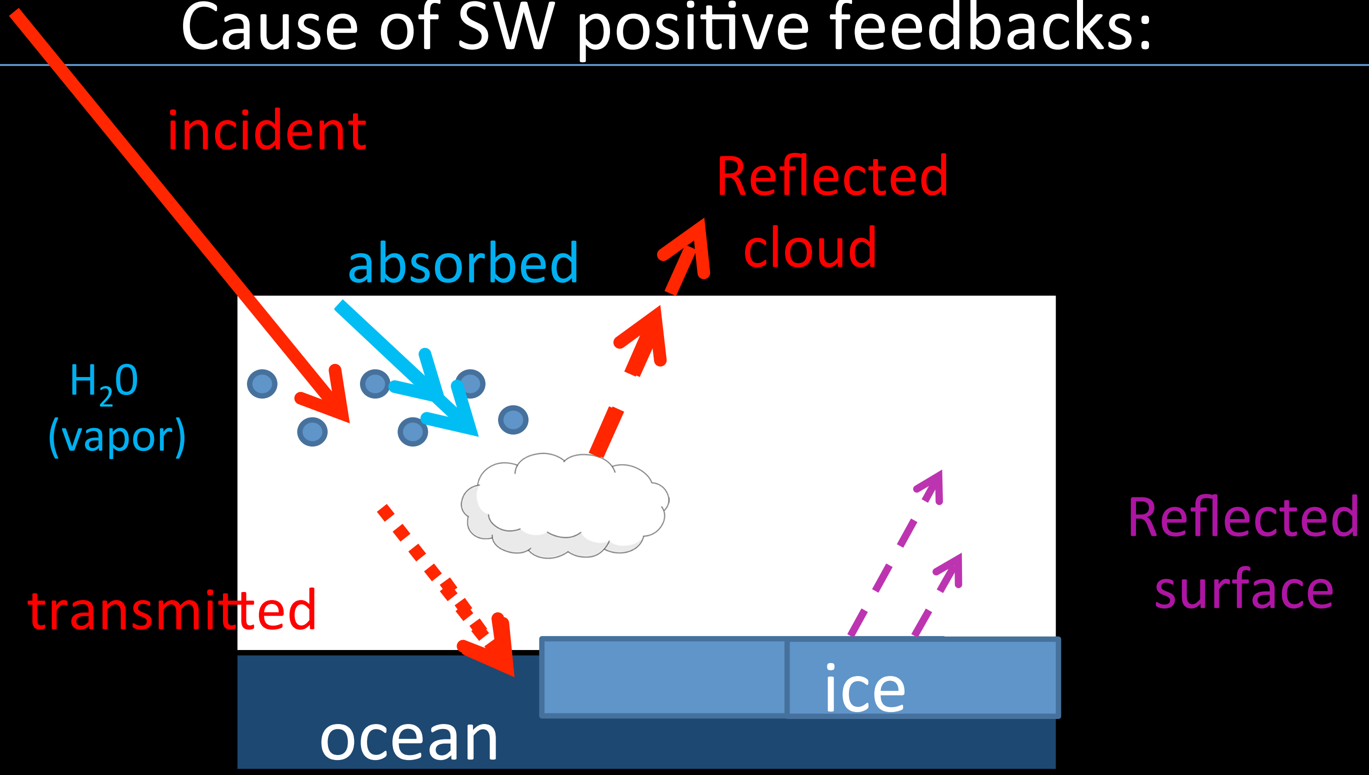
τ_{cross} is determined by the OLR value demanded in the new equilibrium

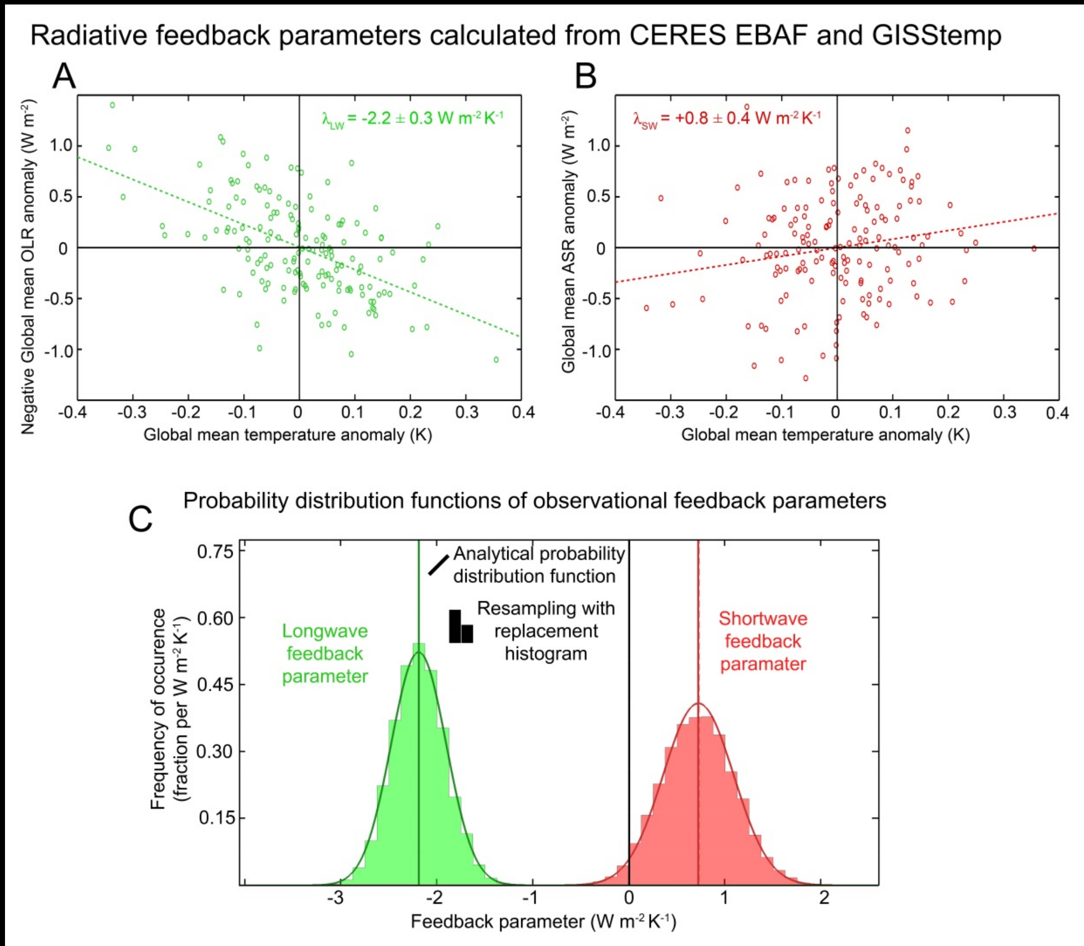
→ Set by relative magnitudes of λ_{LW} and λ_{SW}

→ HAS STEEP GRADIENTS IN VICINITY OF $\lambda_{SW}=0$



Cause of SW positive feedbacks:





- Observations of the co-variability of global mean surface temperature and ASR/OLR give statistically significant estimates of λ_{SW} and λ_{LW}

- $\lambda_{SW} = 0.8 \pm 0.4$ W m^{-2} K^{-1}
- $\lambda_{LW} = -2.0 \pm 0.3$ W m^{-2} K^{-1}

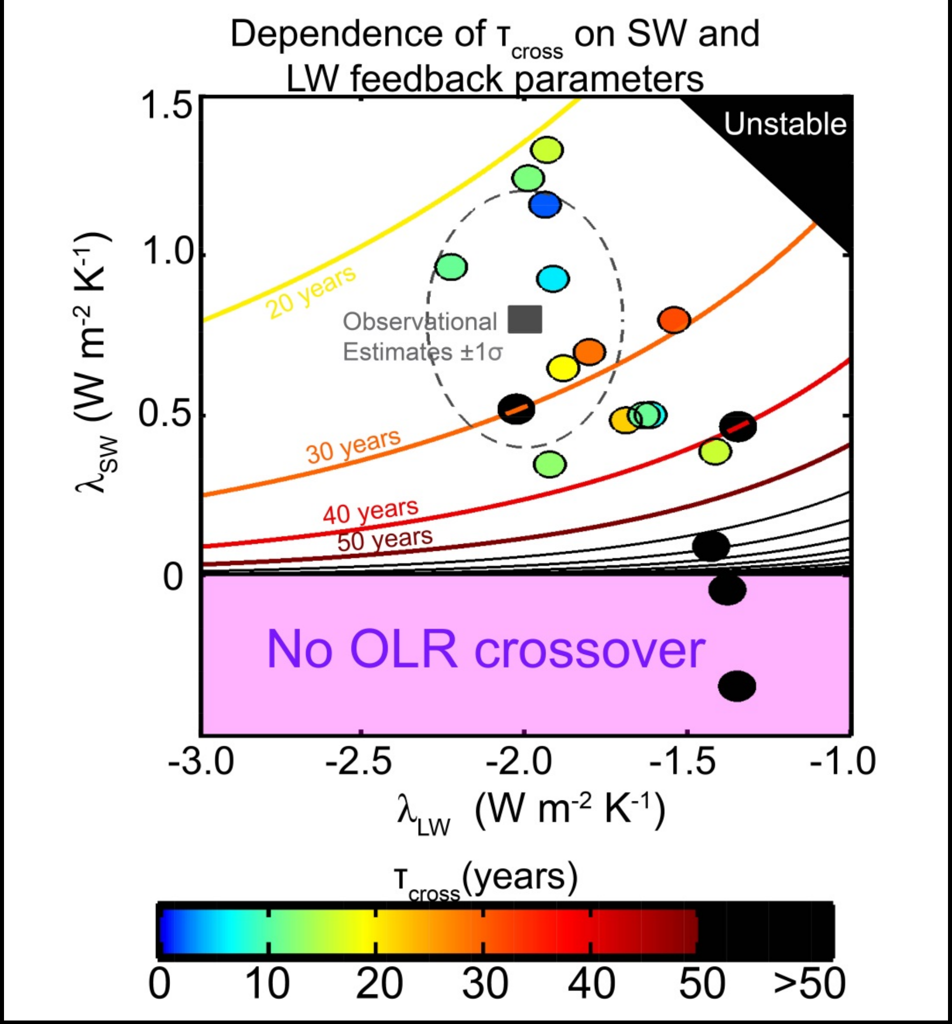
Temperature Data	λ_{SW}	λ_{LW}	λ
NCEP Reanalysis TAS	0.7 ± 0.4	-1.7 ± 0.2	-1.0 ± 0.3
GIS TEMP	0.8 ± 0.4	-2.2 ± 0.3	-1.4 ± 0.4
CW HadCRUT4	0.9 ± 0.5	-2.0 ± 0.4	-1.1 ± 0.4
Average	0.8 ± 0.4	-2.0 ± 0.3	-1.2 ± 0.4

Implications for OLR recovery timescale

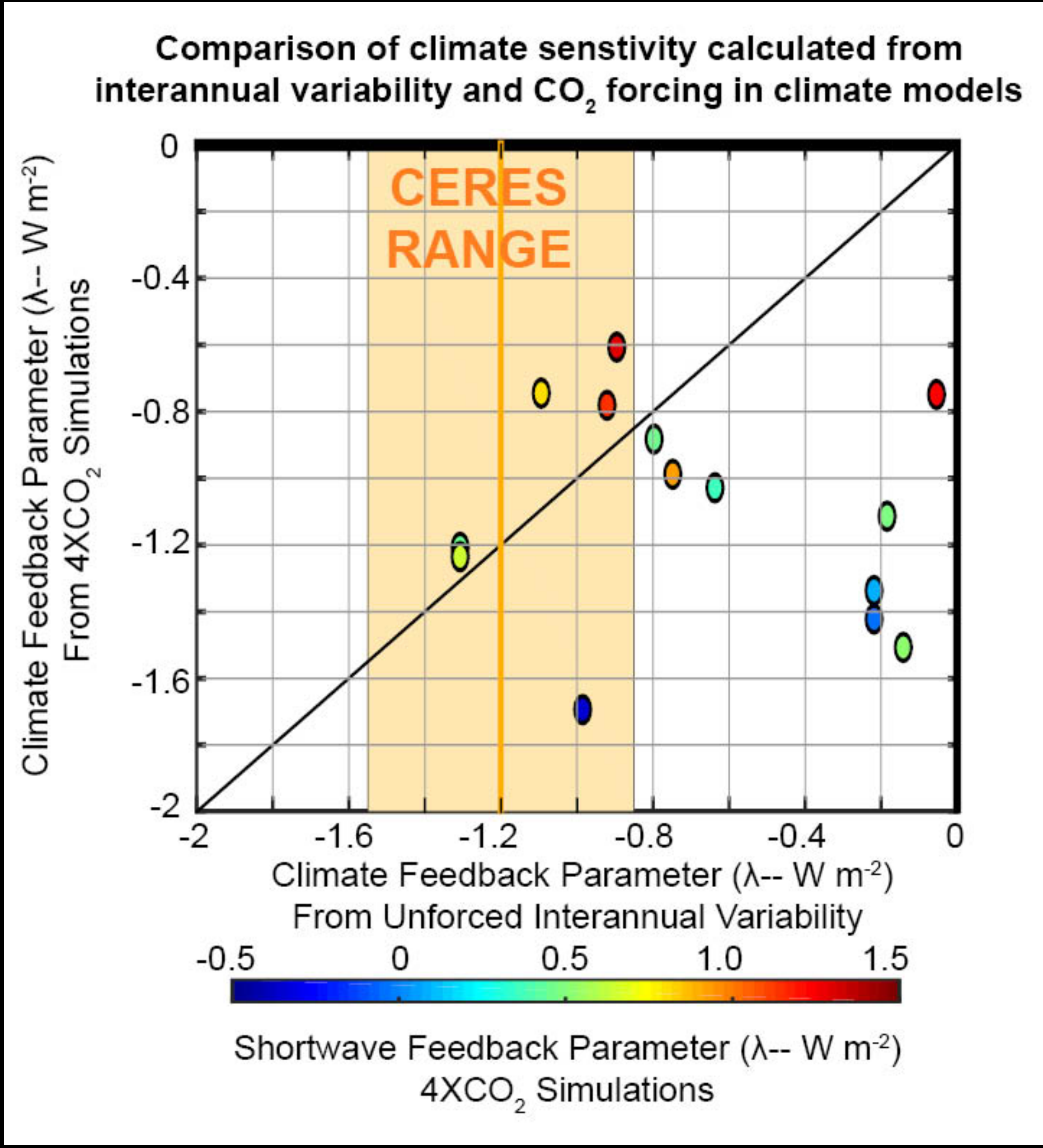
- Observational constraints suggest that τ_{cross} is of order decades IN RESPONSE TO LW FORCING ONLY

- Assumes an (CMIP5 ensemble average) radiative relaxation timescale (τ) of 27 years

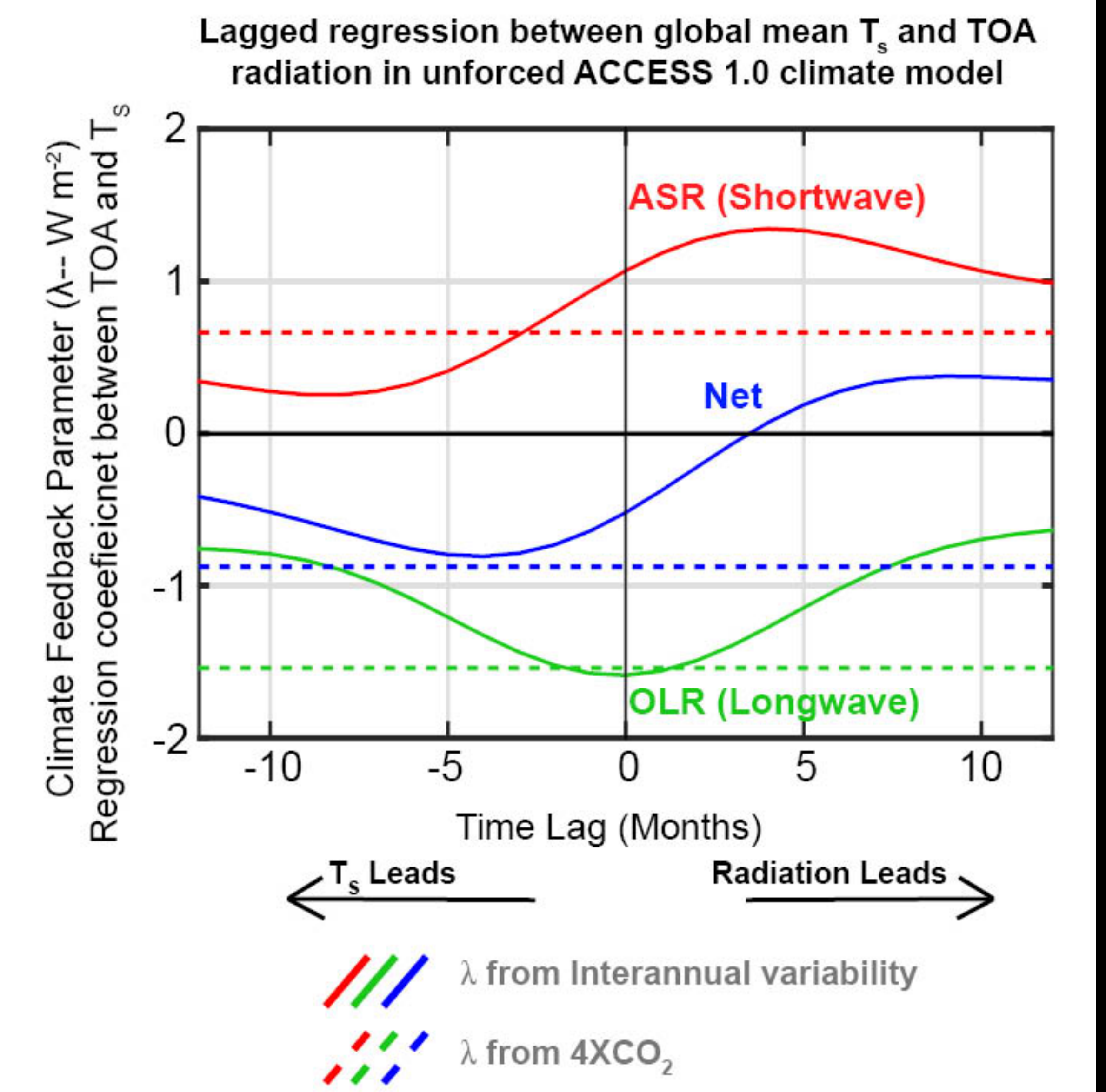
$$\tau_{CROSS} = \tau \ln(-\lambda_{LW} / \lambda_{SW})$$



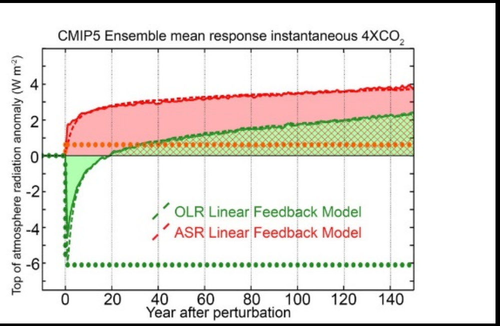
Can we get climate feedbacks from interannual variability of CERES (and surface temperature)?



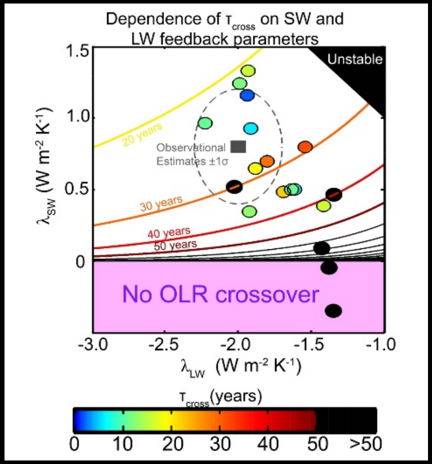
Radiation causes surface temperature anomalies as well as responds to it– potential to confuse the non-feedback forcing with the feedback.



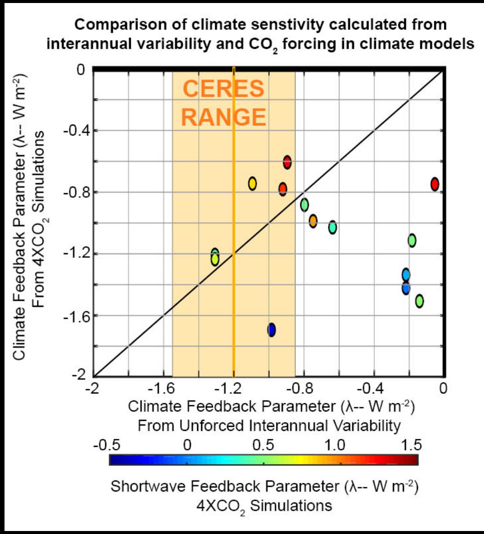
Conclusions



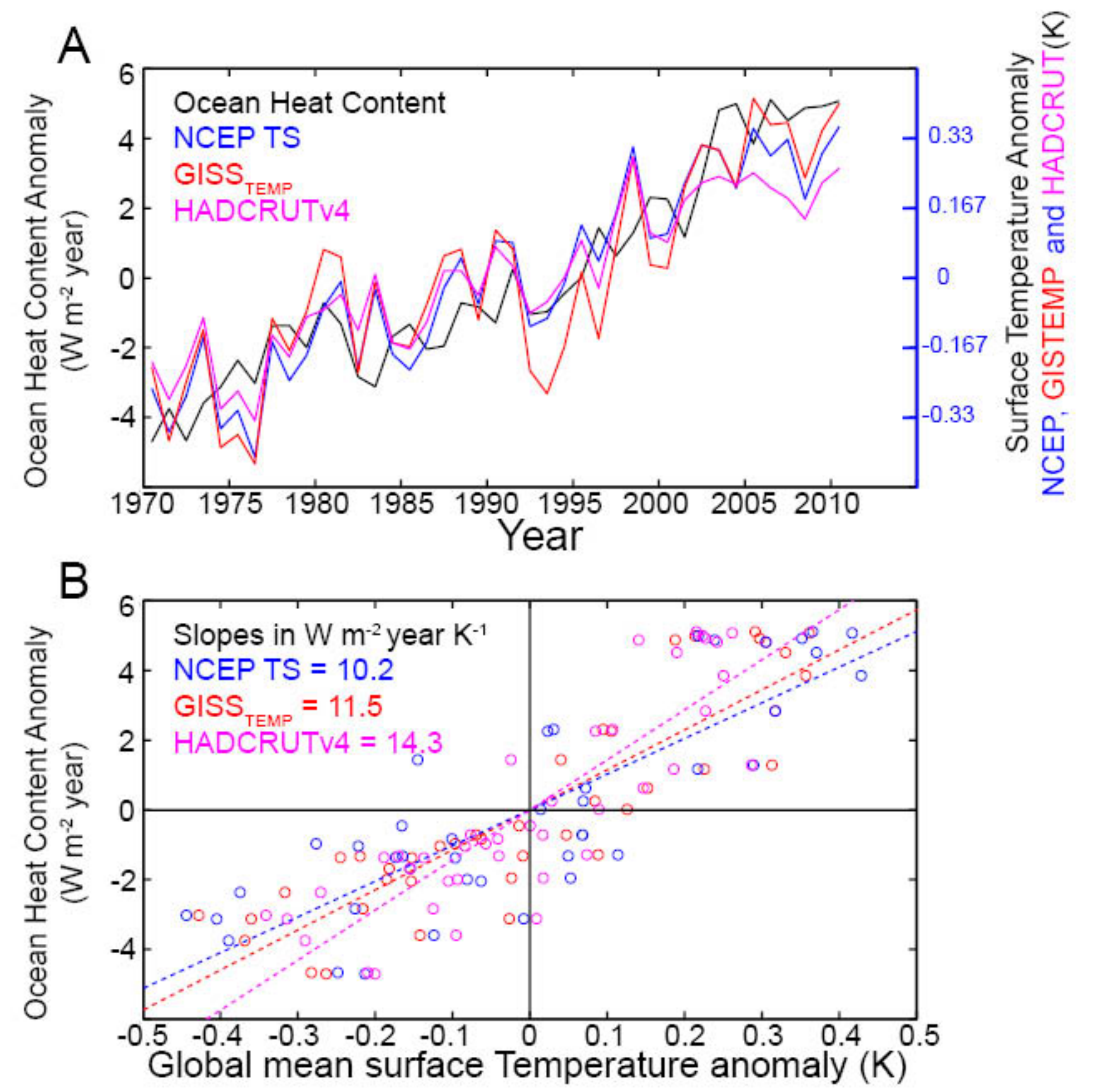
CO2 initiates global warming by decreasing OLR but the TOA energy imbalance is dominated by increased absorbed solar radiation in most climate models – associated with surface albedo and SW water vapor feedbacks



CERES data also suggest a positive shortwave feedback → global warming will most likely result in enhanced ASR and we should not expect to see reduced OLR from the forcing

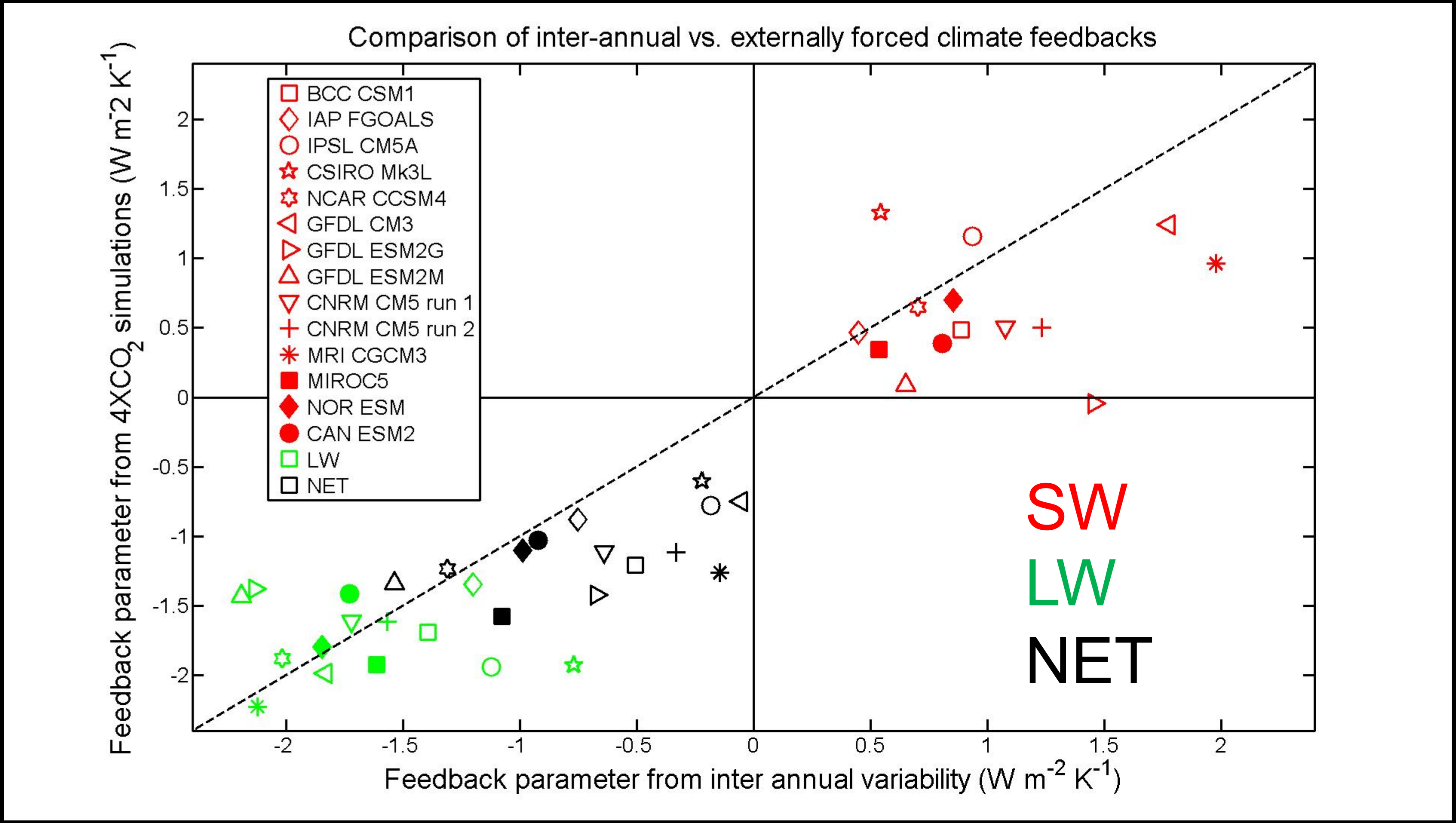


Can interannual variability in CERES tell us anything about climate feedbacks?

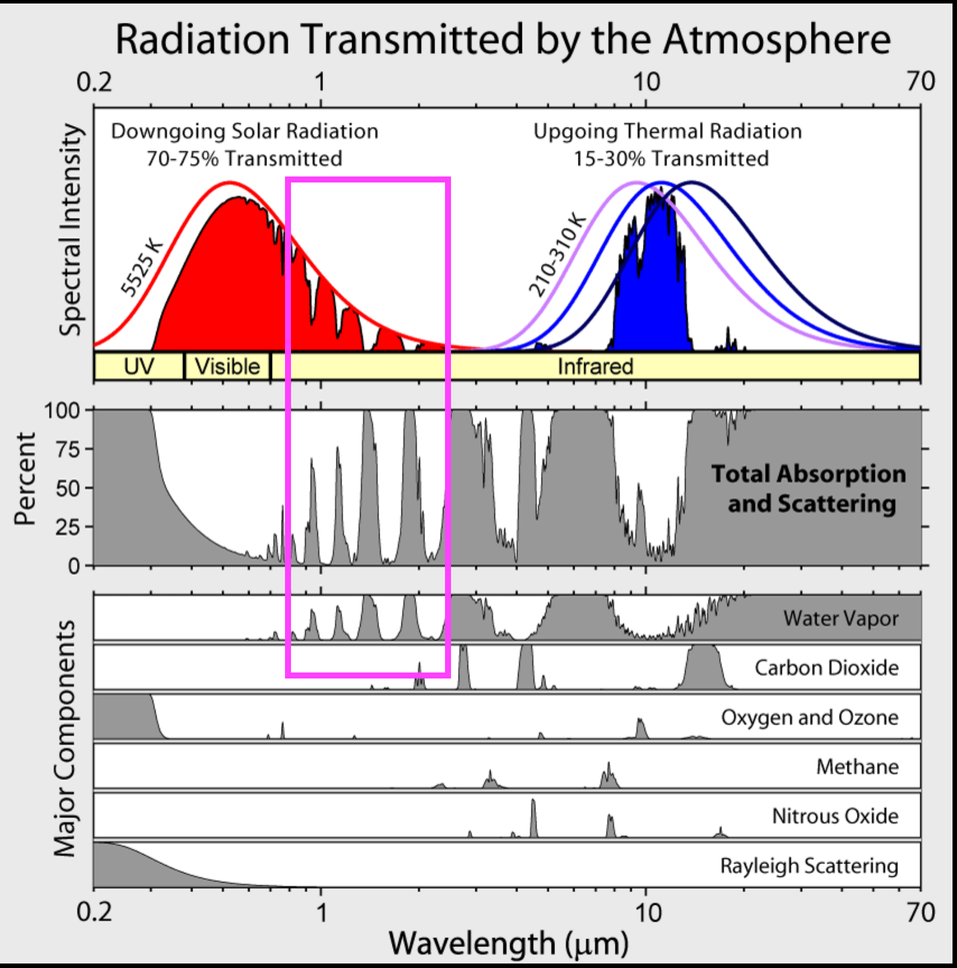


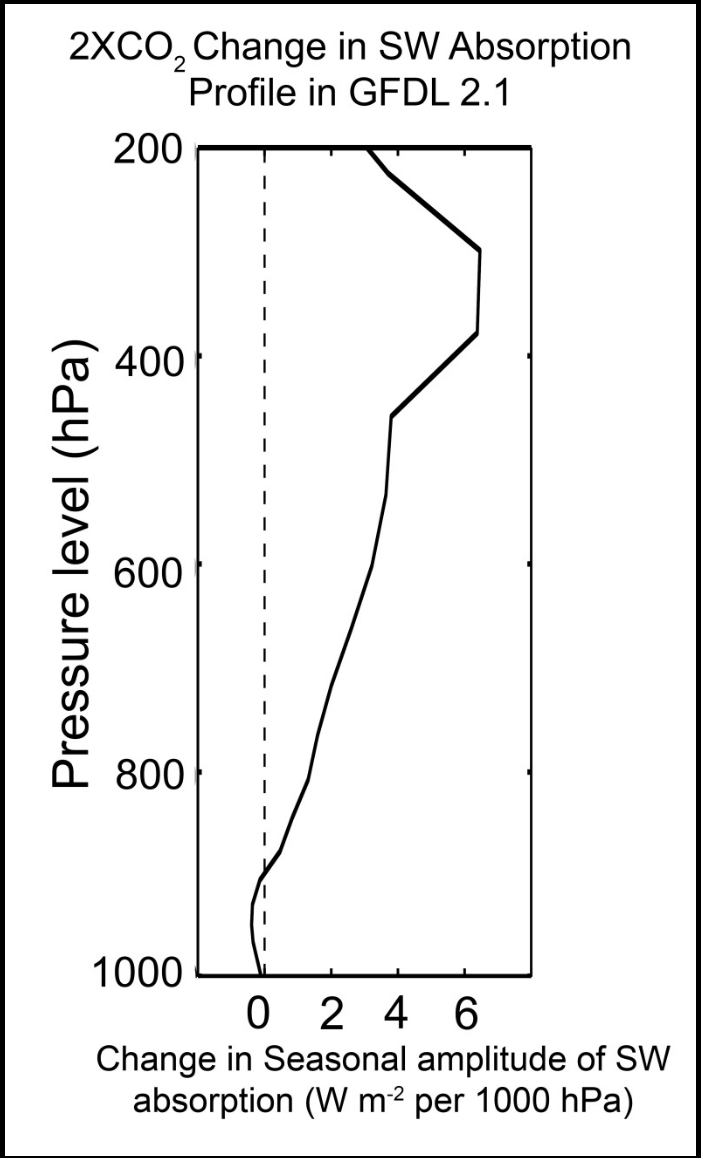
A
Ocean Heat Content
NCEP TS
GISS$_{TEMP}$
HADCRUTv4
Ocean Heat Content Anomaly (W m^{-2} year)
Surface Temperature Anomaly
NCEP, GISTEMP and HADCRUT(K)
Year
B
Slopes in W m^{-2} year K^{-1}
NCEP TS = 10.2
GISS$_{TEMP}$ = 11.5
HADCRUTv4 = 14.3
Ocean Heat Content Anomaly (W m^{-2} year)
Global mean surface Temperature anomaly (K)

Are the radiative feedbacks that operate on inter-annual timescales equivalent to equilibrium feedbacks?

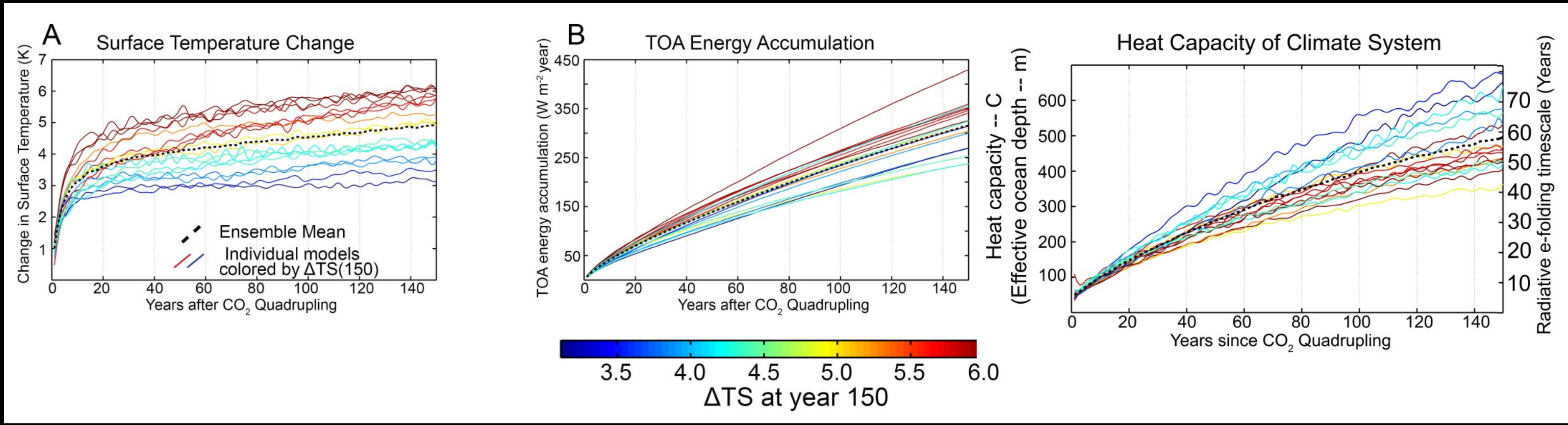


Water Vapor as a SW Absorber





Heat capacity: $4XCO_2$

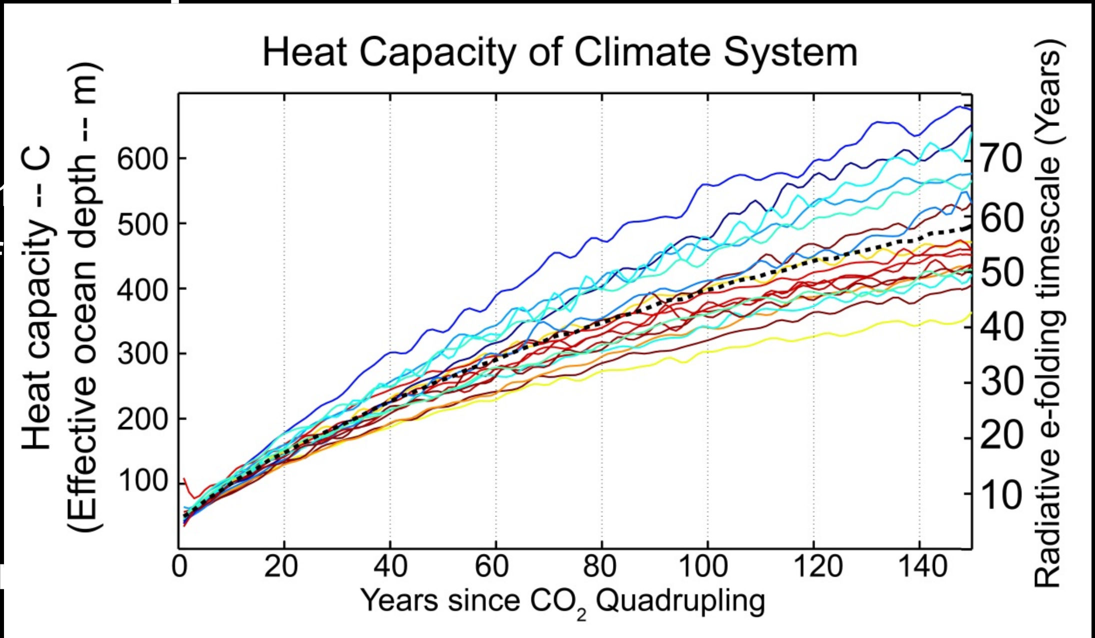


- Heat capacity increases with time as energy penetrates into the ocean
- In first couple decades, energy is within the first couple 100 m of ocean and system e-folds to radiative equilibrium in about a decade

How fast does the system approach equilibrium?

Ensemble average
forcing and feedbacks

- C = 250 m (30 W m^{-2}year K^{-1} the ensemble average for f century after forcing
- λ_{LW} = -1.7 W m^{-2} K^{-1}
- λ_{SW} = +0.6 W m^{-2} K^{-1}



The energy imbalance equatio

Has the solution:

T_S

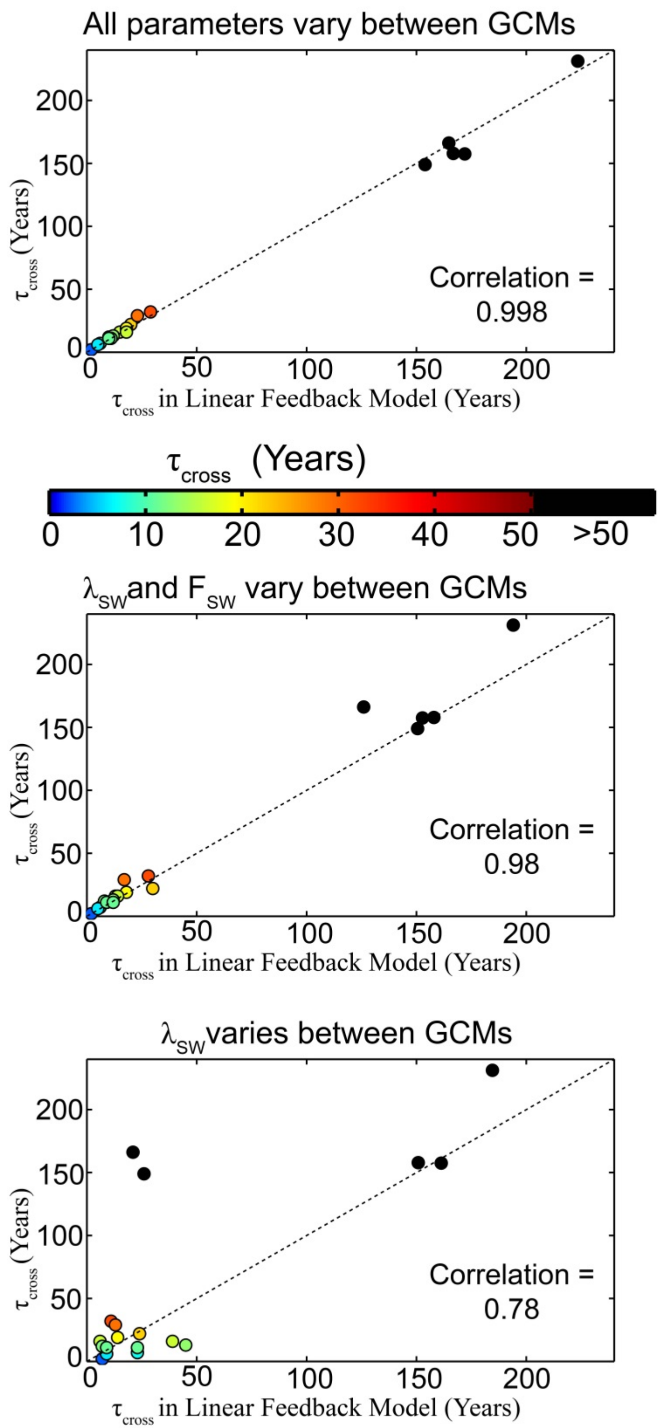
With the characteristic timescale (τ)

τ= =

=

= 27 years

Key point:
OLR returns to unperturbed value in of order the radiative relaxation timescale of the system → decades



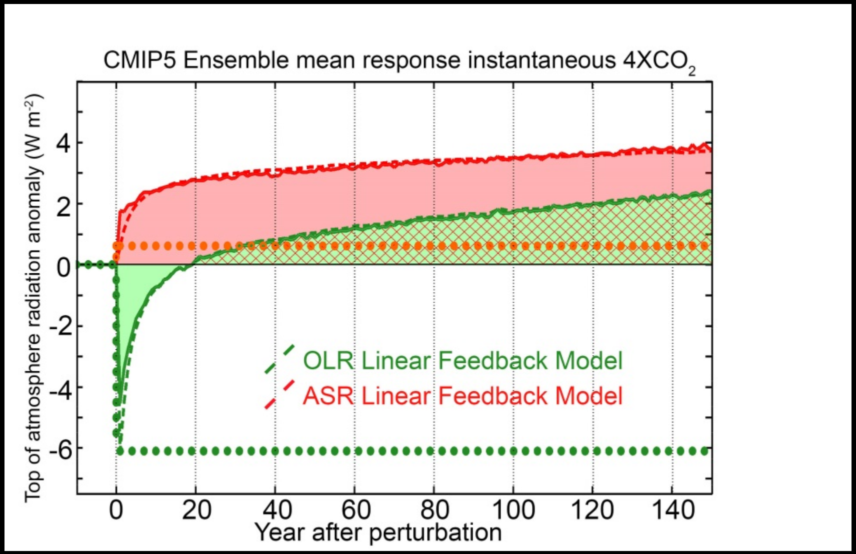
What parameter controls inter-GCM spread in TOA response?

- Using all GCM specific parameters gets the inter-model spread in τ_{cross}

- Varying just λ_{SW} and F_{SW} between GCMS captures inter-model spread in τ_{cross}
- λ_{LW} , F_{LW} and heat capacity differences between GCMs less important for determining the radiative response

- Varying just λ_{SW} gives bi-modal distribution of τ_{cross} with exception of two models (F_{SW} plays a role here)

τ_{cross} dependence on feedback parameters



Ensemble average forcing and feedbacks

- λ_{LW} = -1.7 W m^{-2} K^{-1}
- λ_{SW} = +0.6 W m^{-2} K^{-1}
- F_{LW} = + 6.1 W m^{-2}

equilibrium temperature change

T_{EQ}

T_{EQ}

Feedback gain: Amplification of response due to

G_{FEED}

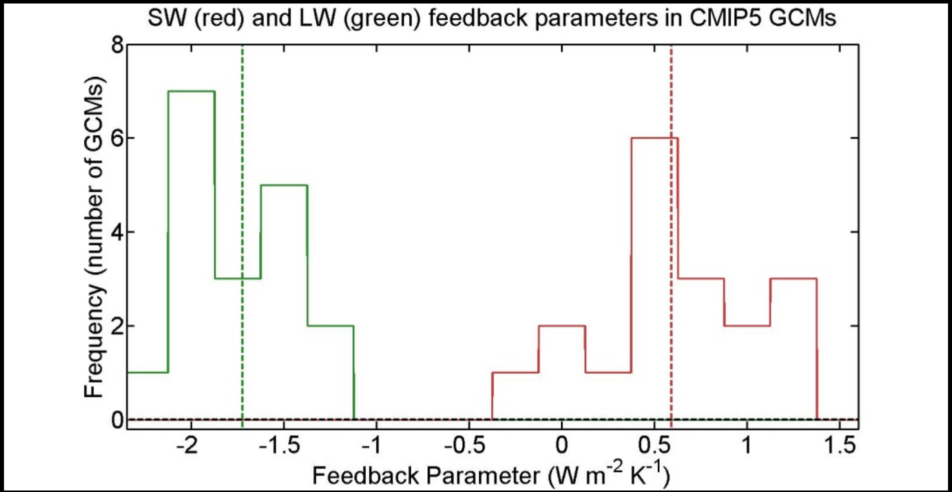
T_S

OLR

initial final transition

OLR =0 at $\tau=\tau_{cross}$

How far from equilibrium OLR =0



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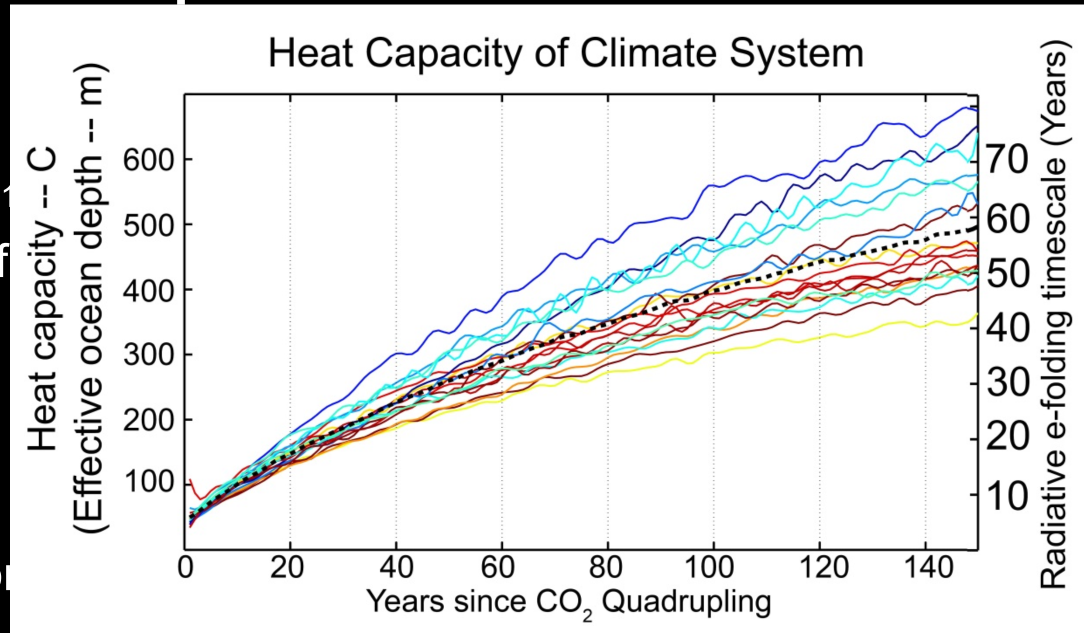

The energy imbalance equatio

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T_S

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τ= =

=

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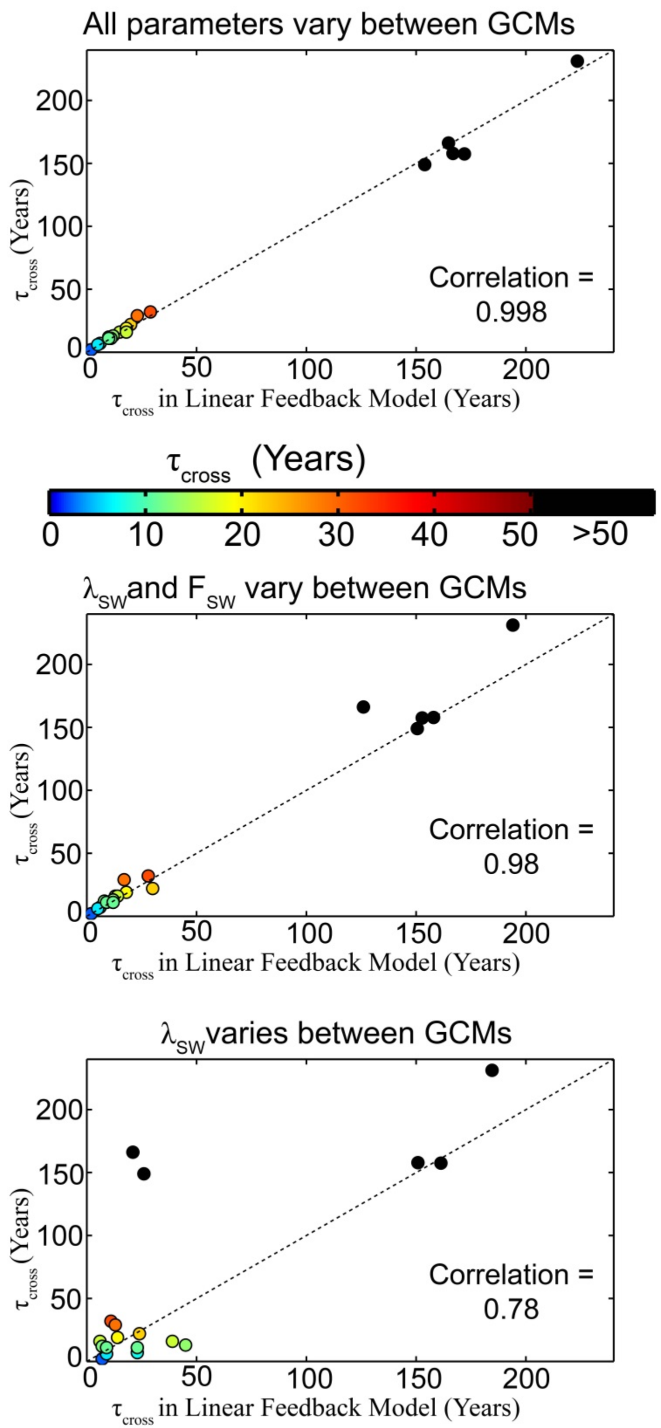

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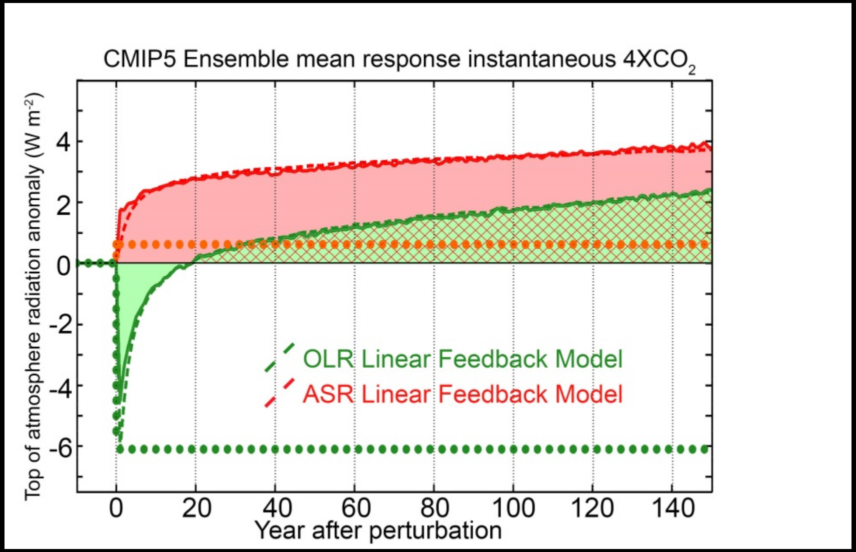

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equilibrium temperature change

T_{EQ}

T_{EQ}

Feedback gain: Amplification of response due to

G_{FEED}

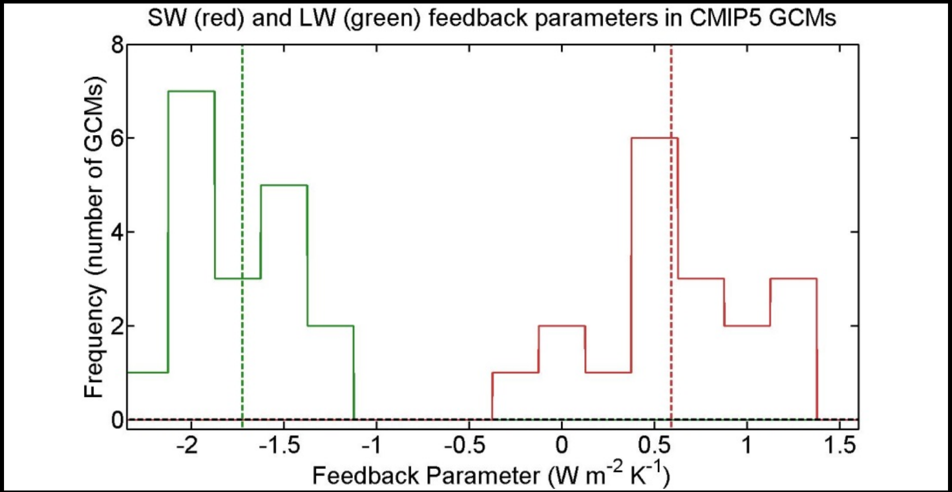
T_S

OLR

initial final transition

OLR =0 at $\tau=\tau_{cross}$

How far from equilibrium OLR =0



Sensitivity of τ_{CROSS} to feedback parameters

If $F_{SW} = 0$ (simplification):

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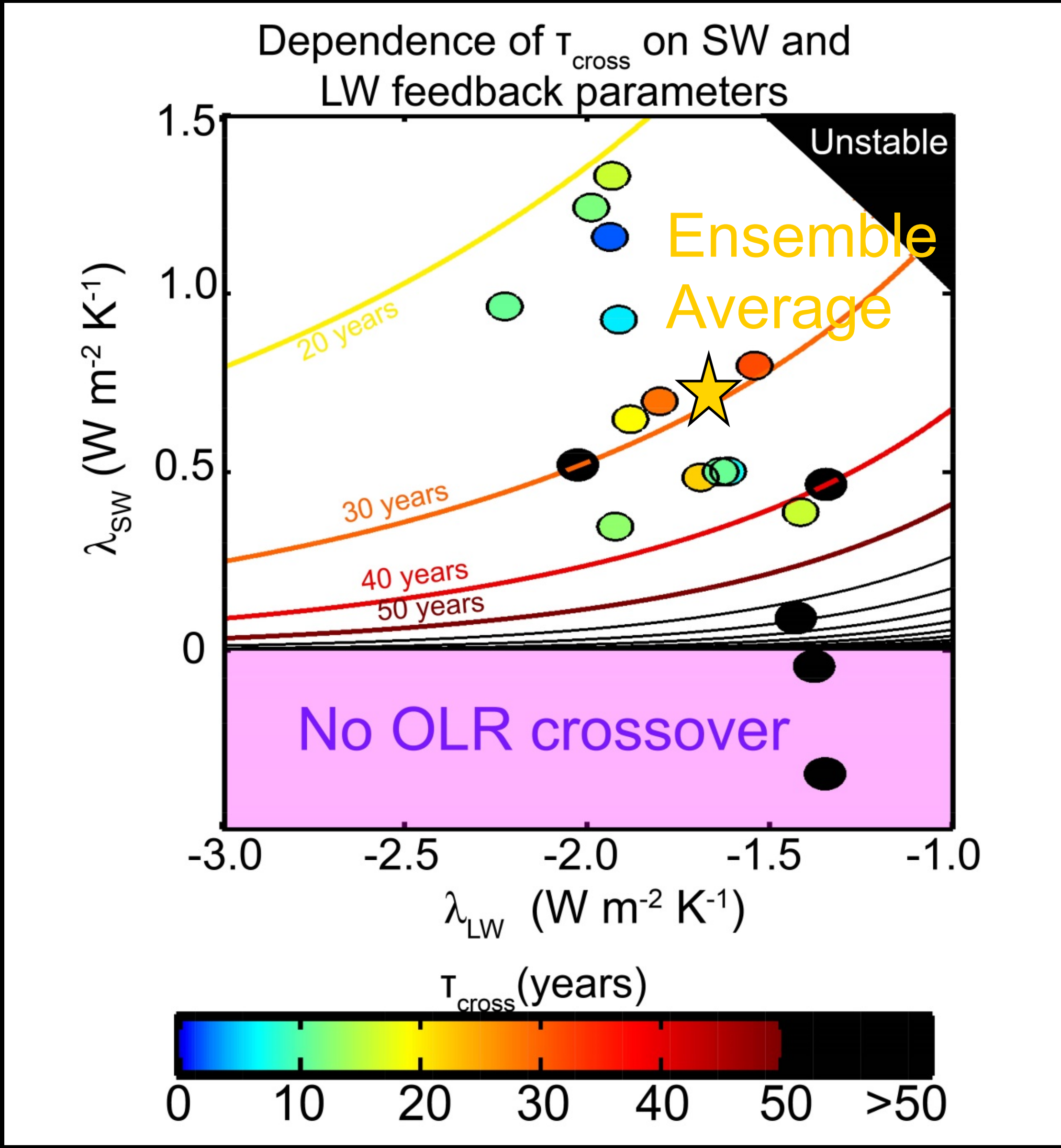
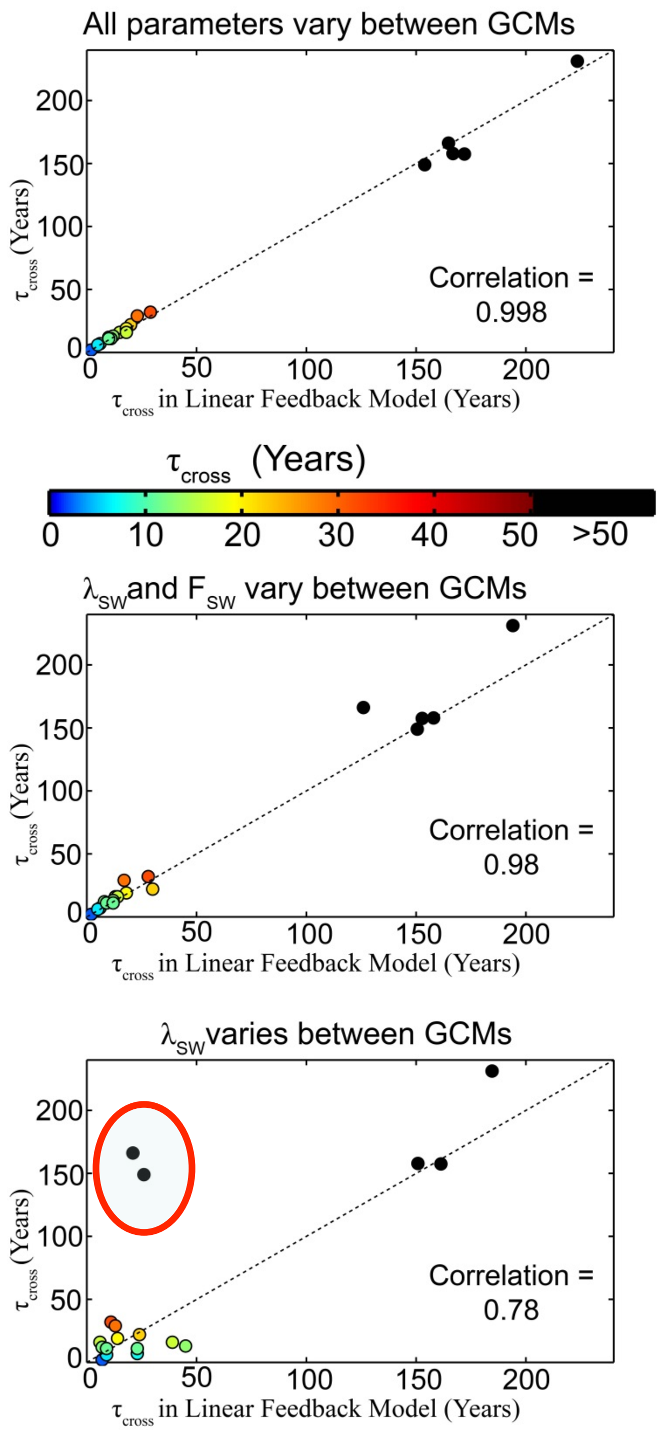




What parameter controls inter-GCM spread in TOA response?

- While the relative magnitudes of λ_{SW} and λ_{LW} explain the vast majority of the spread in τ_{cross} there are several model outliers

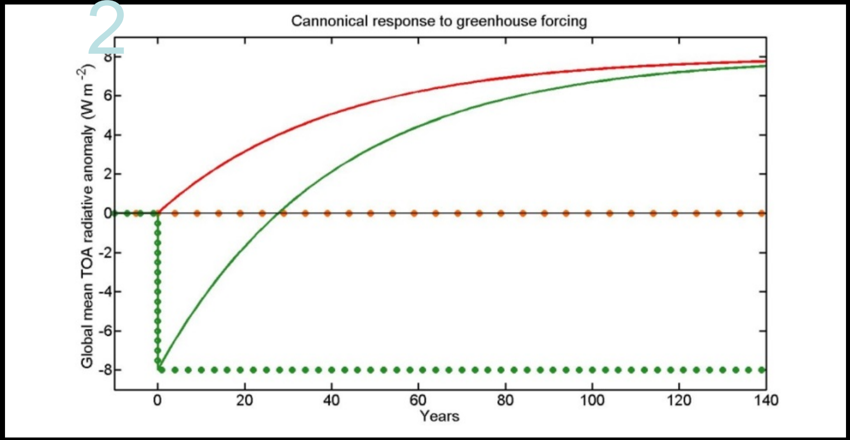
- A more complete analysis includes inter-model differences in F_{SW}

  → F_{SW} includes both direct radiative forcing by CO2 (small) and the rapid response of clouds to the forcing

From before, if F_{SW} =0 then:

G_{FEED}

Feedback Gain = 2



If $|\lambda_{SW}| = ½ |\lambda_{LW}|$ → T_{EQ} is doubled

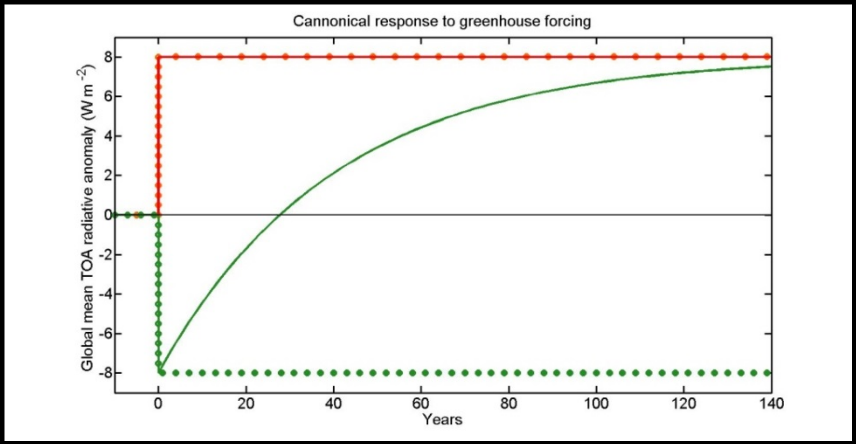
The OLR change to get to equilibrium is:
$(2*F_{LW}/ |\lambda_{LW}|) * |\lambda_{LW}| = 2F_{LW}$

→ OLR = 0 occurs half way to equilibrium
→ T_{CROSS} = T ln(2)

If $F_{SW} \neq 0$ then:

G_{FORCE}

Forcing Gain = 2

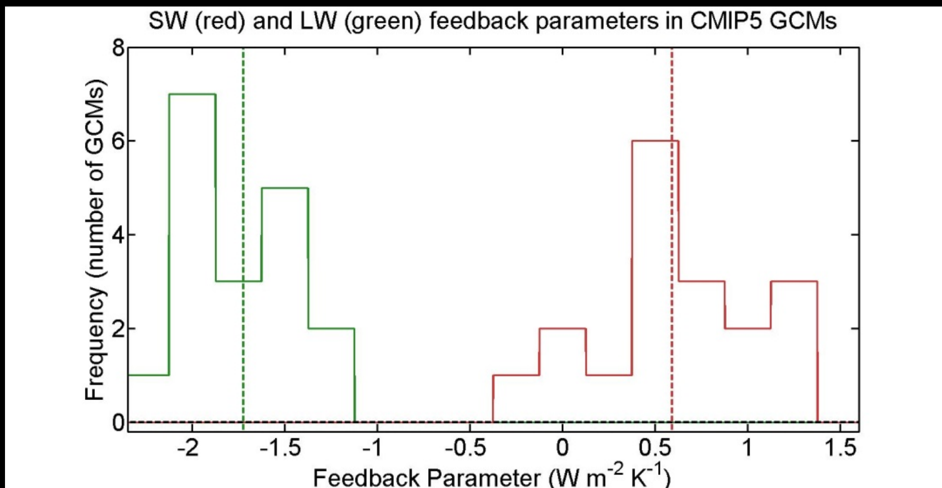


If $F_{LW} = F_{SW}$ → T_{EQ} is doubled and OLR asymptotes to $+F_{LW}$

→ OLR = 0 occurs half way to equilibrium
→ T_{CROSS} = T ln(2)

SW and LW Feedbacks and Forcing: $4XCO_2$

Feedbacks

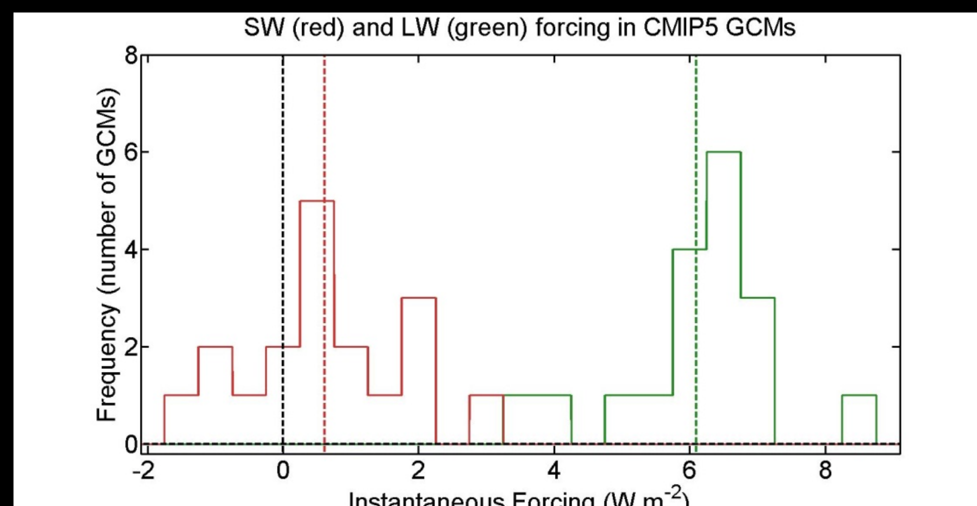


LW

SW

Ensemble Average

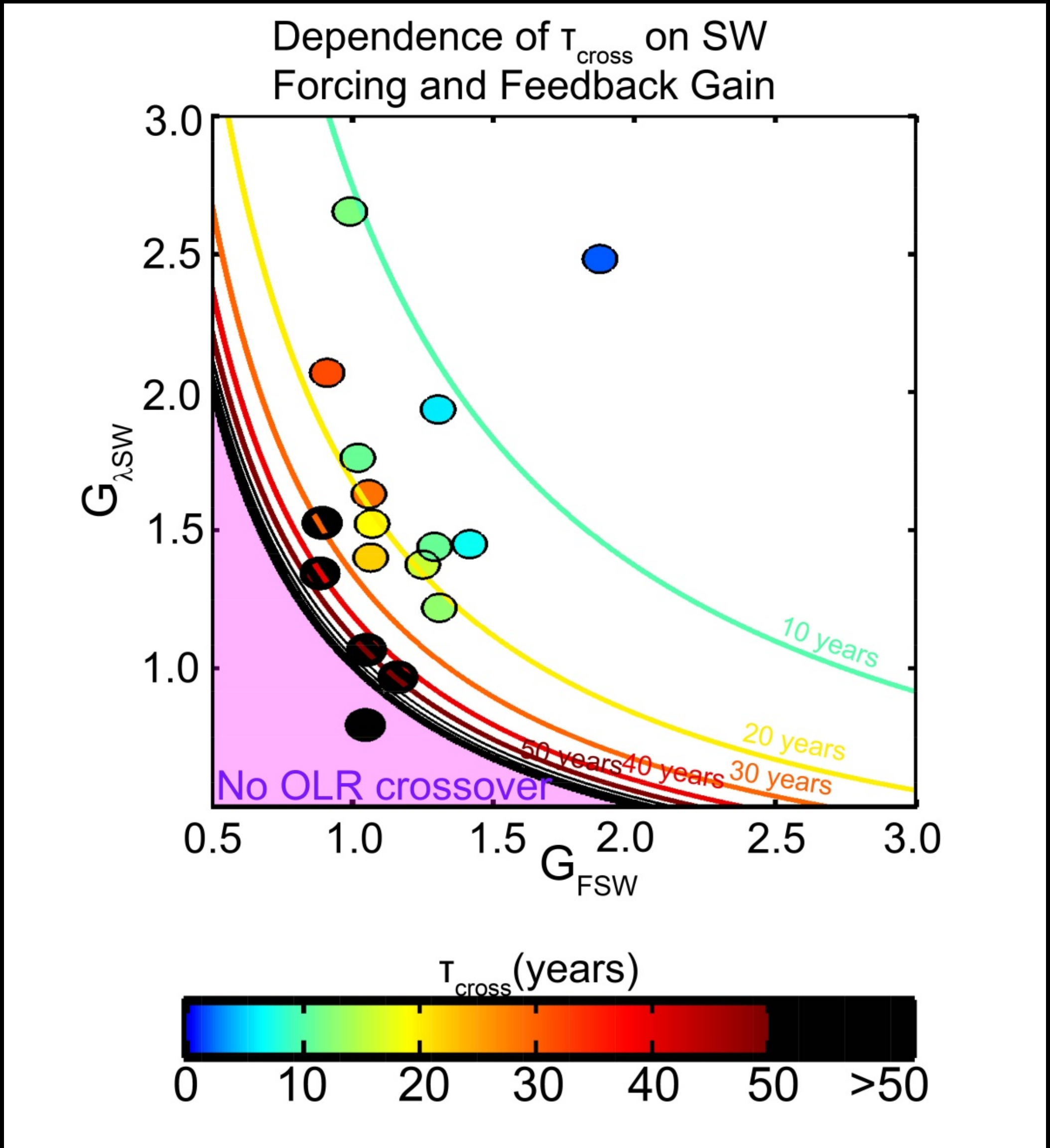
Forcing



- LW feedback is negative (stabilizing) and has small inter-GCM spread
- SW feedback is mostly positive and has large inter-GCM spread
- Forcing is mostly in LW (greenhouse)
- SW forcing has a significant inter-GCM spread

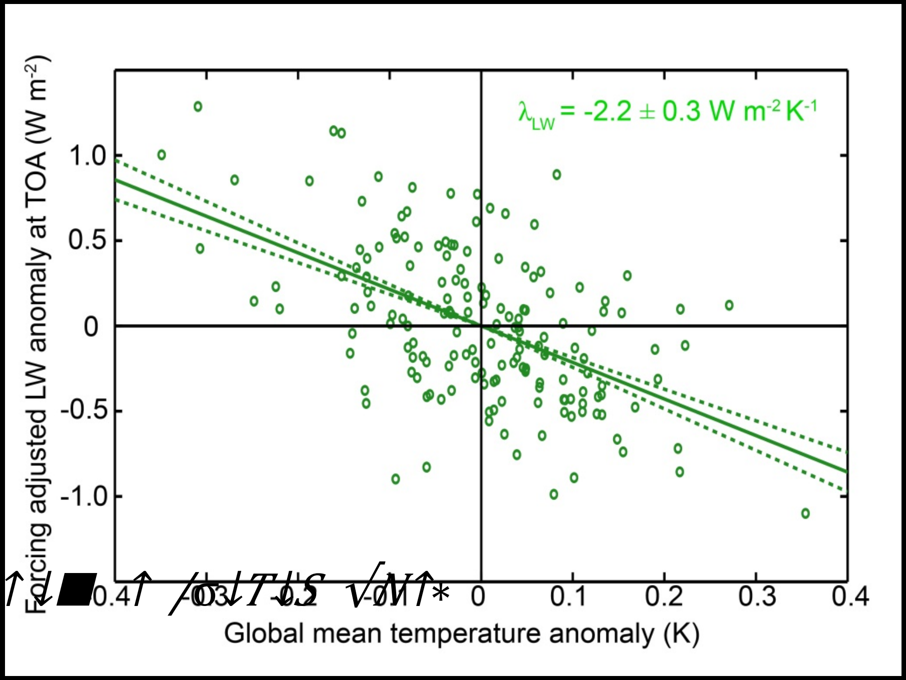
Sensitivity of τ_{CROSS} to feedback parameters

- Positive SW forcing and feedbacks favor a short OLR recovery timescale with a symetric dependence on the “gain” factors
- Explains the majority (R= 0.88) of inter- model spread
- Assumes a time and model invariant heat capacity (250m ocean depth equivalent)



LW Feedback parameter from observations

- Surface temperature explains a small fraction of OLR' variance (R=0.52)
- Error bars on regression coefficient (1σ) are small, why?
- Weak 1 month auto-correlation in OLR' – r_{OLR} (1month) = 0.3 → lots of DOF (N*= 113)



Unexplained amplitude

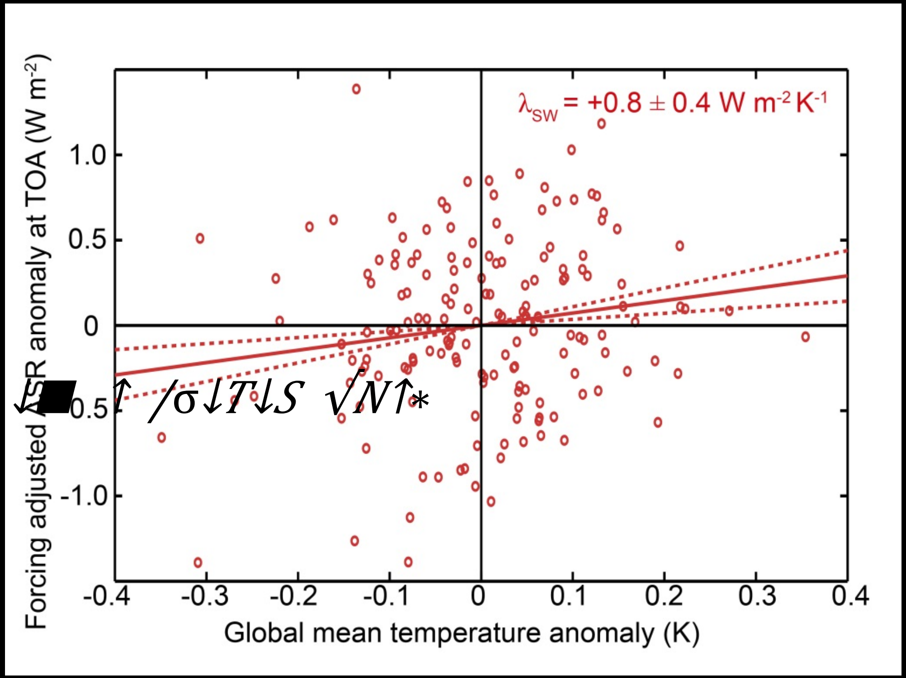
Independent realizations

Even if none of the OLR' variance was explained, the regression slope is still significant

→ Given the number of realizations, you would seldom realize such a large regression coefficient in a random sample – in the absence of a genuine relationship between T_S and OLR

SW Feedback parameter from observations

- Very weak correlation (r=0.16)
- Almost no memory in ASR' – r_{OLR} (1month) = 0.1 – mean we have lots of DOF (N*= 143)



The significance of the regression slope is not a consequence of the variance explained but, rather, the non-zero of the slope despite the number of realizations

→ The feedback has emerged from the non-feedback radiative processes in the record