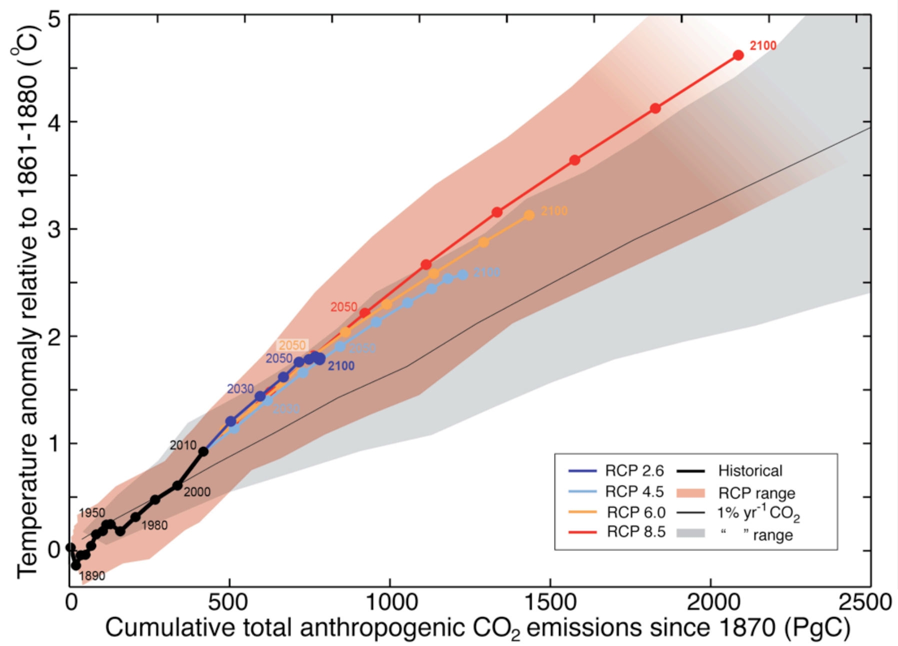
Climate impacts from the sequestration of heat & CO_2



IPCC (2013)

Allen et al. (2009) Nature
Peak warming link to cumulative carbon emissions

Explore the role of the ocean in affecting how warming relates to carbon emissions

Southern Ocean is potentially important player in affecting the anthropogenic heat and carbon uptake

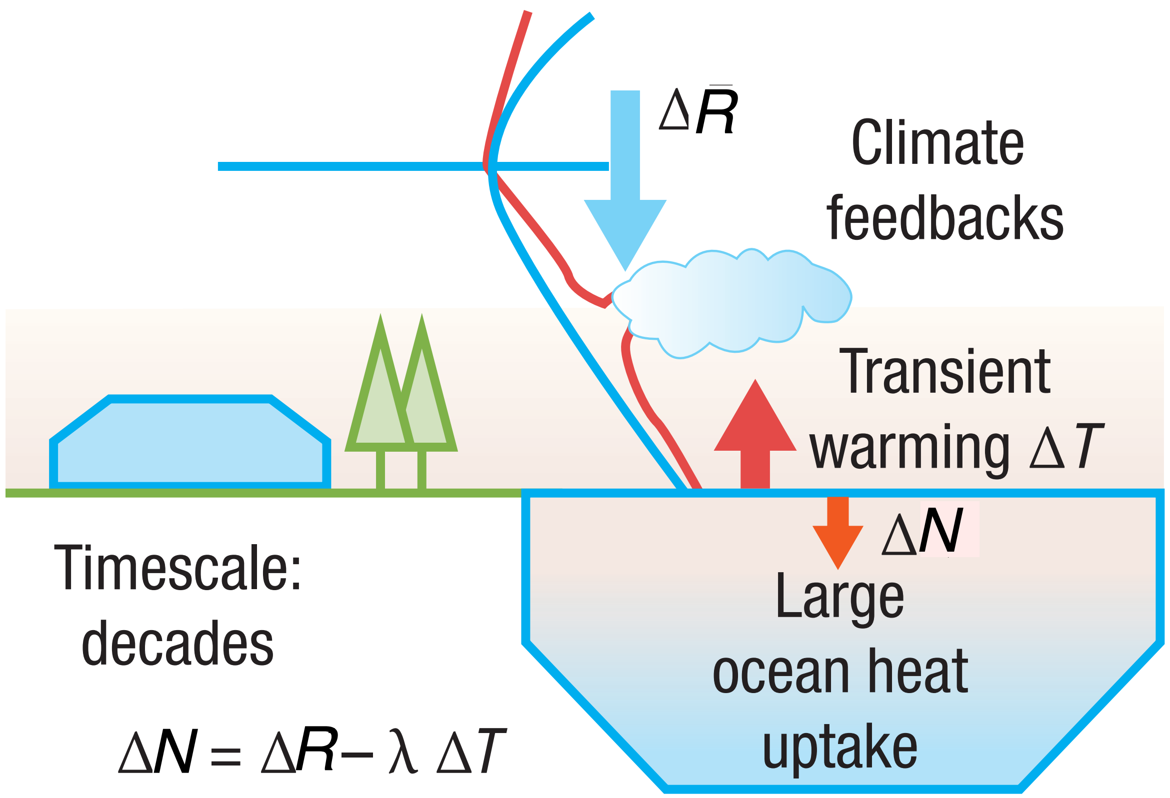
Talk plan:
1. Surface warming versus emissions
2. Response for long-term equilibrium
3. Response on multi-decadal timescale
4. Simplified atmosphere-ocean illustration

Phil Goodwin (Southampton), Ric Williams (Liverpool) & Andy Ridgwell (Bristol)

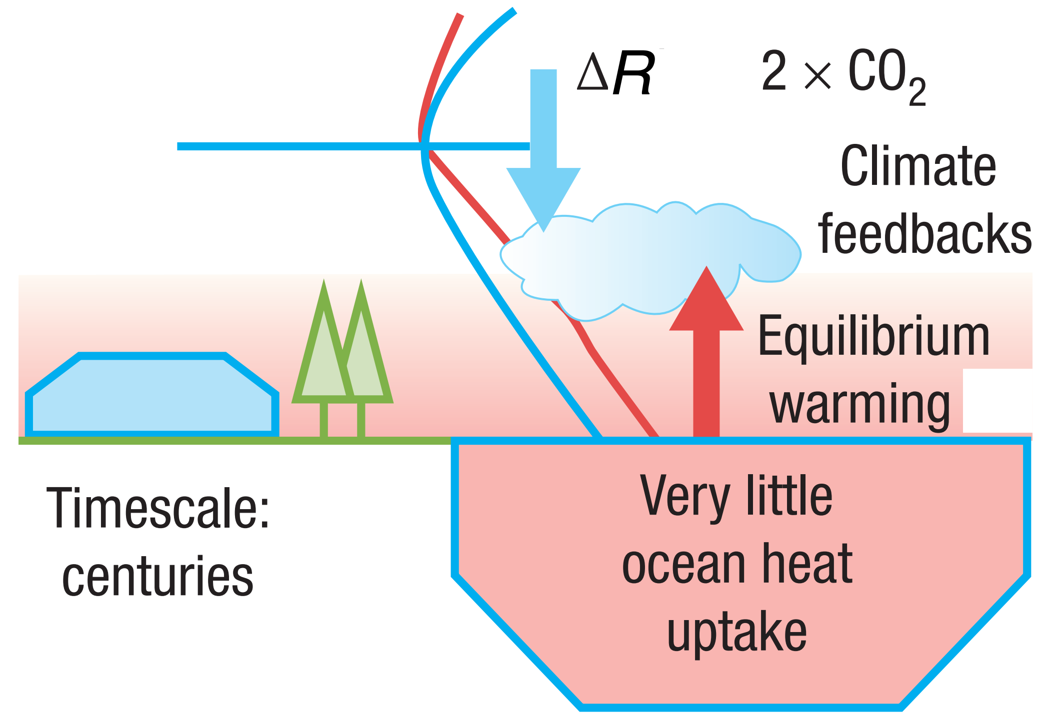
(Goodwin, Williams & Ridgwell, 2015, Nature Geoscience)

Climate response

climate response after decades



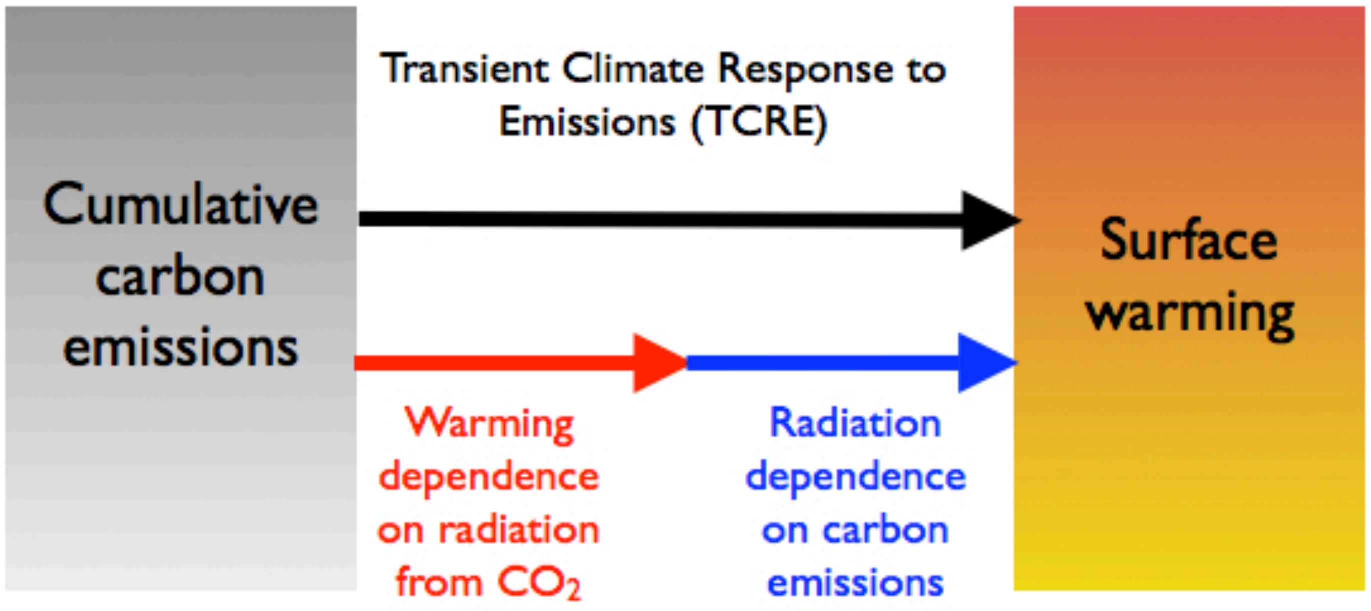
climate response after centuries



from Knutti and Hegerl (2008)

1. Surface warming versus cumulative carbon emissions

explore relationship between carbon emissions and warming



$$\Delta T = \left(\frac{\partial T}{\partial R}\right)\left(\frac{\partial R}{\partial I_{em}}\right)\Delta I_{em}$$

$$\Delta T = T(t) - T(t_o)$$

$$\Delta I_{em} = I_{em}(t) - I_{em}(t_o)$$

$$\Delta R = R(t) - R(t_o)$$

aim to reveal competing effects of ocean heat & carbon uptake

avoid many important processes, such as other greenhouse gases, aerosols ...

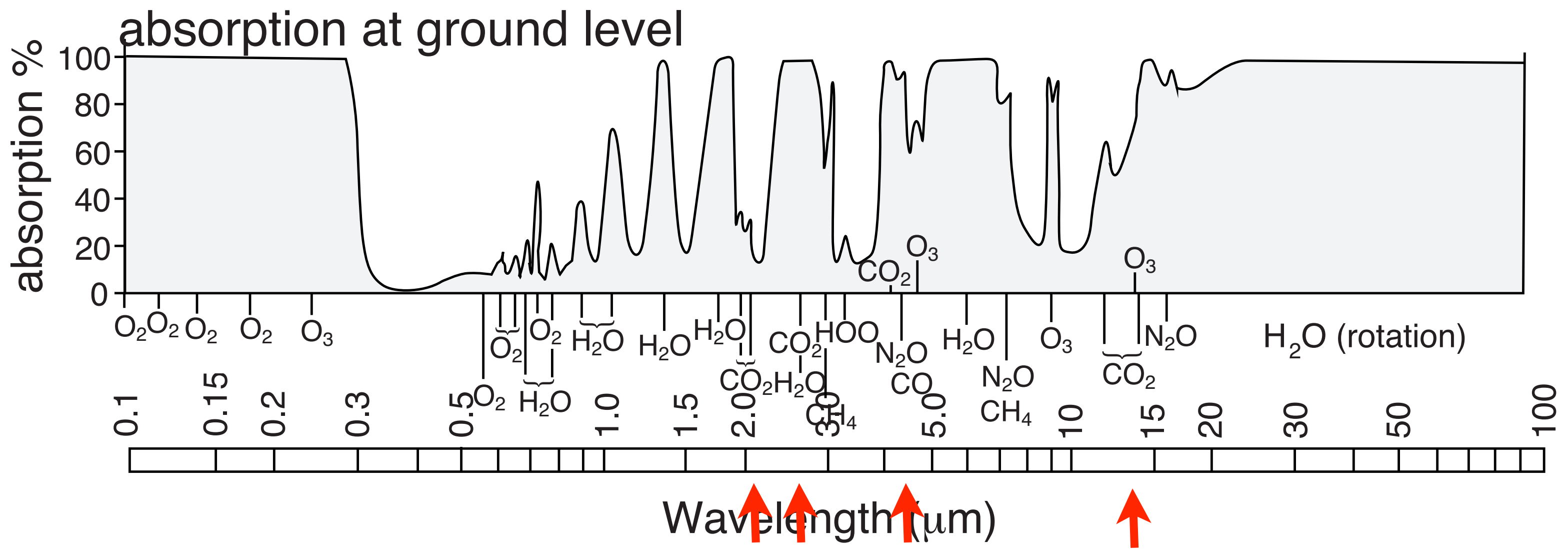
Temperature links to radiative forcing from CO_2

$$\Delta T = \frac{\Delta R}{\lambda}$$

ΔT surface warming change

ΔR radiative forcing change

λ climate feedback paramet



CO_2 bands

radiative forcing from CO_2

$$\Delta R = a \ln(CO_2(t)/CO_2(t_o))$$

$$a = 5.35 W m^{-2}$$

climate sensitivity from CO_2

$$\Delta T = \Delta T_{2\times CO_2} \frac{\ln(CO_2(t)/CO_2(t_o))}{\ln 2}$$

$\Delta T_{2\times CO_2}$ =1.5 to 4.5 K

climate feedback parameter

$$\lambda^{-1} = \frac{\Delta T_{2\times CO_2}}{a \ln 2}$$

λ^{-1} =0.5 to 1.2 K(W m^{-2})$^{-1}$

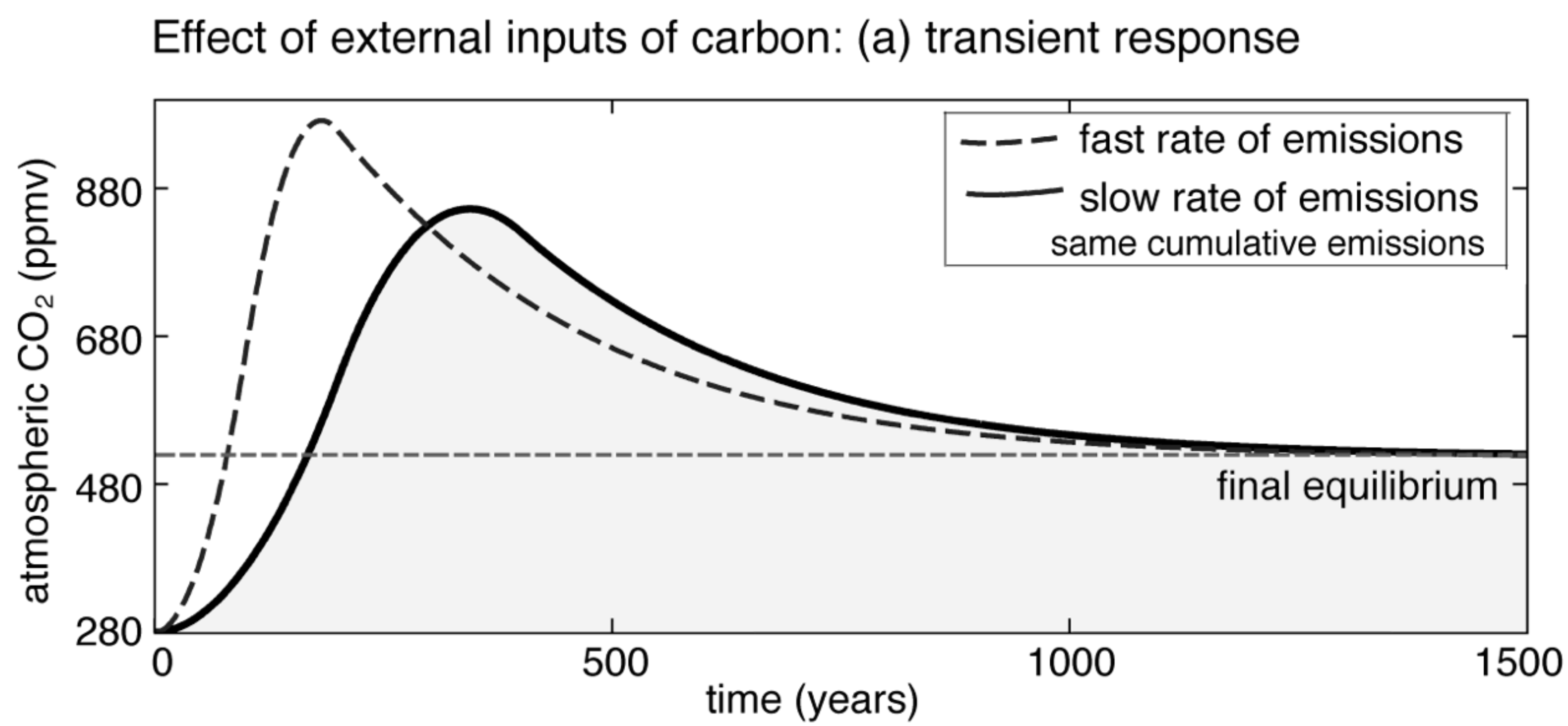
Atmospheric CO_2 response to carbon emissions

What is the effect of more CO_2?

oceans become more acidic
inhibits further ocean uptake

reactions in seawater

$$CO_2^* + H_2O = HCO_3^- + H^+$$
$$HCO_3^- = CO_3^{2-} + H^+$$



$$CO_2(t_{equilib}) = CO_2(t_o)\exp(\Delta I_{em}/I_B)$$

$$\Delta I_{em} = I_{em}(t) - I_{em}(t_o)$$

$$I_B = I_{Atmos} + C_{sat}/B$$

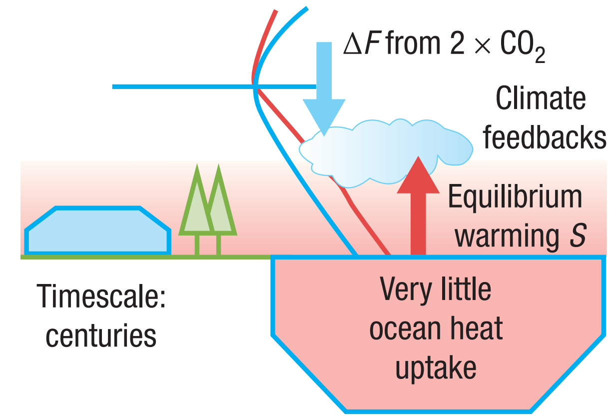
is 3500 PgC

$$\Delta \ln CO_2 = \frac{\Delta I_{em}}{I_B}$$

Goodwin et al. (2007) GBC
Goodwin et al. (2009) Nature Geoscience

2. Climate response as air-sea equilibrium is approached

$$\Delta T = \left(\frac{\partial T}{\partial R}\right)\left(\frac{\partial R}{\partial I_{em}}\right)\Delta I_{em}$$



$$\Delta T = \frac{1}{\lambda}\Delta R$$

$$\Delta R = a\Delta \ln CO_2$$

$$\Delta \ln CO_2 = \frac{\Delta I_{em}}{I_B}$$

$$a = 5.35 \mathrm{W\ m}^{-2}$$

$$\Delta \ln CO_2 = \ln CO_2(t) - \ln CO_2(t_o)$$

$$I_B = 3500 \ \mathrm{PgC}$$

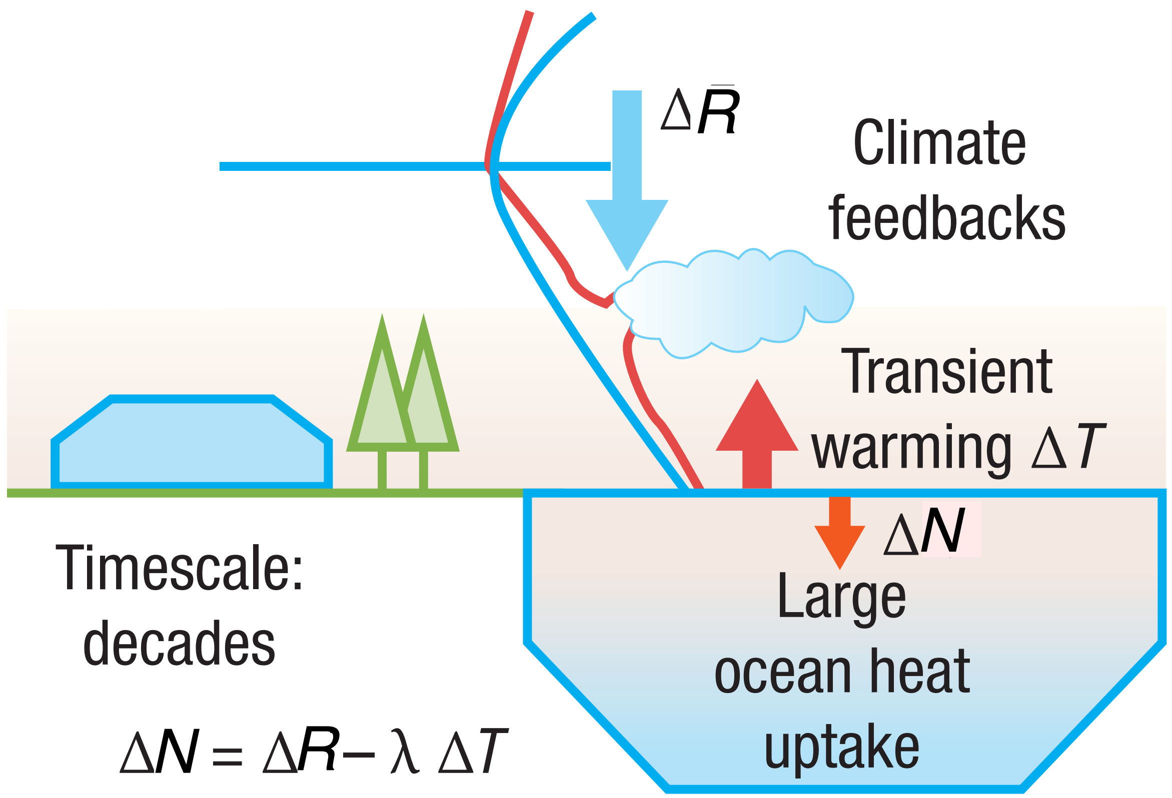
$$\Delta T = \left(\frac{1}{\lambda}\right)\left(\frac{a}{I_B}\right)\Delta I_{em}$$

$\Delta T/\Delta I_{em} \sim$ 1.2 +/- 0.7 K per 1000 PgC

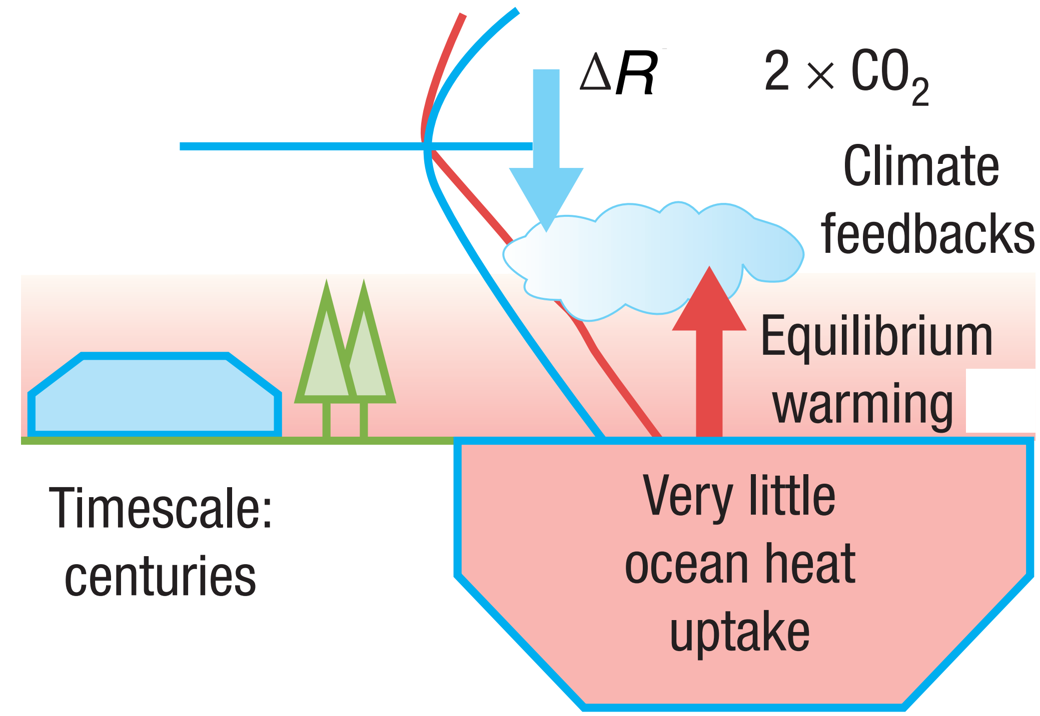
Williams et al. (2012) GRL

Climate response

climate response after decades

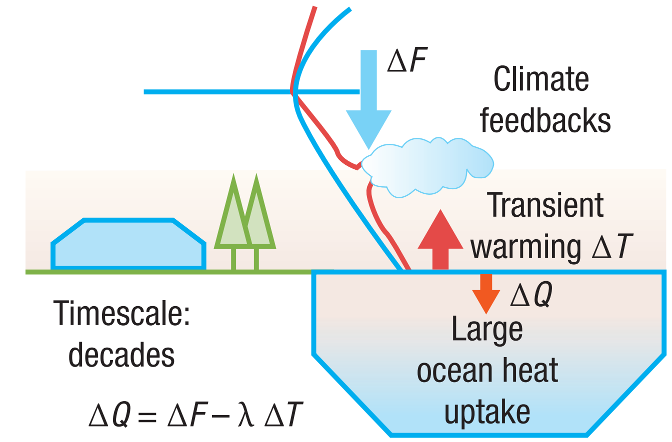


climate response after centuries



from Knutti and Hegerl (2008)

3. Climate response on multi-decadal timescales



$$\Delta T = \left(\frac{\partial T}{\partial R}\right)\left(\frac{\partial R}{\partial I_{em}}\right)\Delta I_{em}$$

warming dependence on radiative forcing from CO_2

$$\Delta T = \frac{1}{\lambda}(\Delta R - \epsilon N)$$

N ocean heat uptake

ϵ efficacy

$$\Delta T = \frac{1}{\lambda}\left(1 - \frac{\epsilon N}{\Delta R}\right)\Delta R$$

normalised ocean heat uptake

$$N* = \frac{\epsilon N}{\Delta R}$$

$$\Delta T = \frac{1}{\lambda}(1 - N^*)\,\Delta R$$

surface temperature change

normalised ocean heat uptake

radiative forcing from CO2

3. Climate response on multi-decadal timescales for atmosphere-ocean system

$$\Delta T = \left(\frac{\partial T}{\partial R}\right)\left(\frac{\partial R}{\partial I_{em}}\right)\Delta I_{em}$$

radiative forcing dependence on cumulative carbon emissions

$$\Delta R = a\Delta \ln CO_2$$

$$\Delta \ln CO_2(t) = \frac{\Delta I_{em}(t) + I_{Usat}(t)}{I_B}$$

I_{Usat} ocean carbon undersaturation

$$\Delta R = \frac{a}{I_B}\left(1 + \frac{I_{Usat}}{\Delta I_{em}}\right)\Delta I_{em}$$

normalised ocean carbon undersaturation

$$I^*_{Usat} = \frac{I_{Usat}}{\Delta I_{em}}$$

$$\Delta R = \frac{a}{I_B}(1 + I^*_{Usat})\Delta I_{em}$$

radiative forcing from CO2

normalised ocean carbon undersaturation

cumulative emissions

(Goodwin et al. 2015, Nature Geoscience)

3. Climate response on multi-decadal timescales for atmosphere-ocean system

$$\Delta T = \left(\frac{\partial T}{\partial R}\right)\left(\frac{\partial R}{\partial I_{em}}\right)\Delta I_{em}$$

$$\Delta T = \frac{1}{\lambda}\left(1 - N^*\right)\Delta R$$

surface temperature change; normalised ocean heat uptake; radiative forcing from CO2

$$\Delta R = \frac{a}{I_B}\left(1 + I^*_{Usat}\right)\Delta I_{em}$$

radiative forcing from CO2; normalised ocean carbon undersaturation; cumulative emissions

normalised ocean heat uptake

$$N* = \frac{\epsilon N}{\Delta R}$$

normalised ocean carbon undersaturation

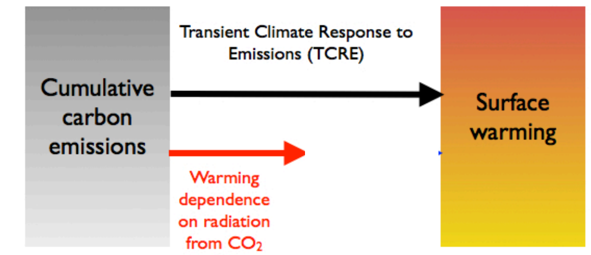
$$I^*_{Usat} = \frac{I_{Usat}}{\Delta I_{em}}$$

$$\Delta T = \frac{1}{\lambda}\left(1 - N^*\right)\frac{a}{I_B}\left(1 + I^*_{Usat}\right)\Delta I_{em}$$

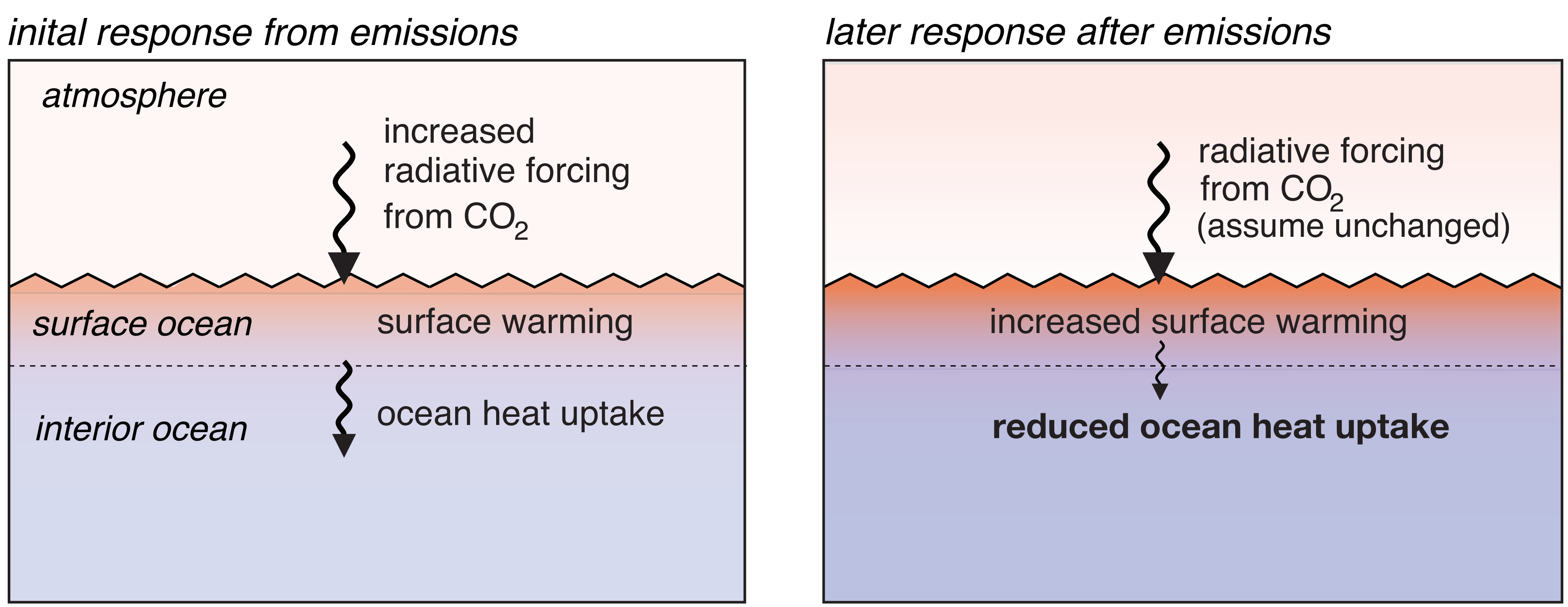
(Goodwin et al. 2015, Nature Geoscience)

3. Climate response on multi-decadal timescales

$$\Delta T(t) = \frac{1}{\lambda}\left(1 - N^*(t)\right) \frac{a}{I_B}\left(1 + I^*_{Usat}(t)\right) \Delta I_{em}(t)$$



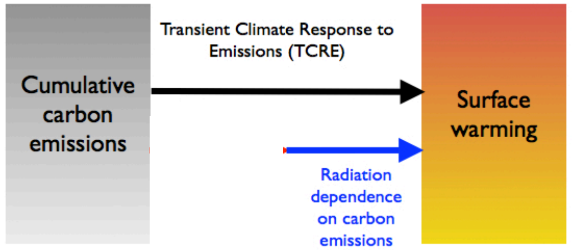
how does surface warming vary in time?



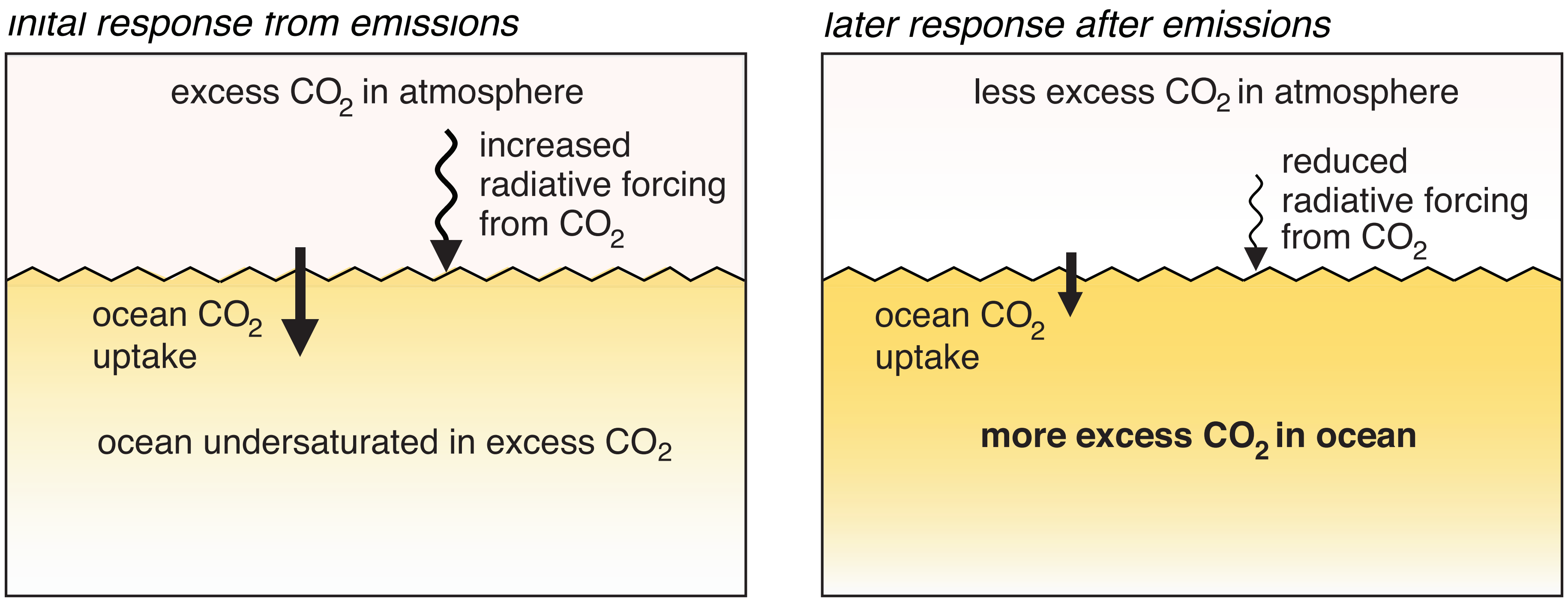
surface warming *increases* in time
due to weakening ocean heat uptake

3. Climate response on multi-decadal timescales

$$\Delta T(t) = \frac{1}{\lambda}\left(1 - N^*(t)\right)\frac{a}{I_B}\left(1 + I^*_{Usat}(t)\right)\Delta I_{em}(t)$$



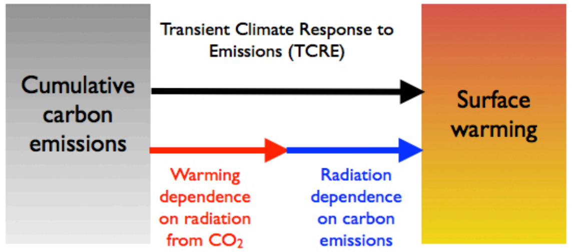
how does radiative forcing vary in time?



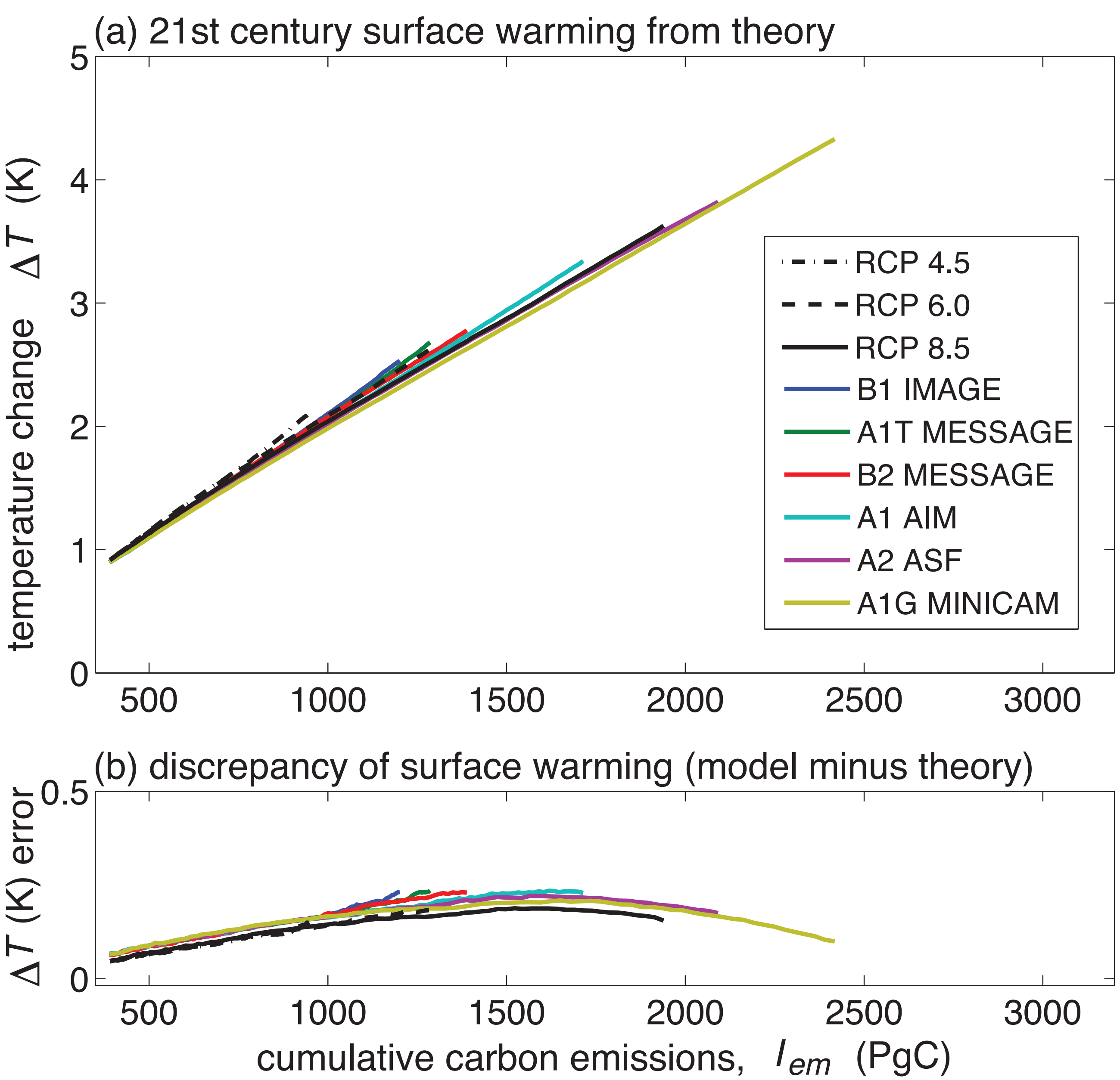
radiative forcing *decreases* in time
due to ocean carbon uptake

3. Climate response on multi-decadal timescales

$$\Delta T(t) = \frac{1}{\lambda}(1 - N^*(t)) \frac{a}{I_B}(1 + I^*_{Usat}(t)) \Delta I_{em}(t)$$

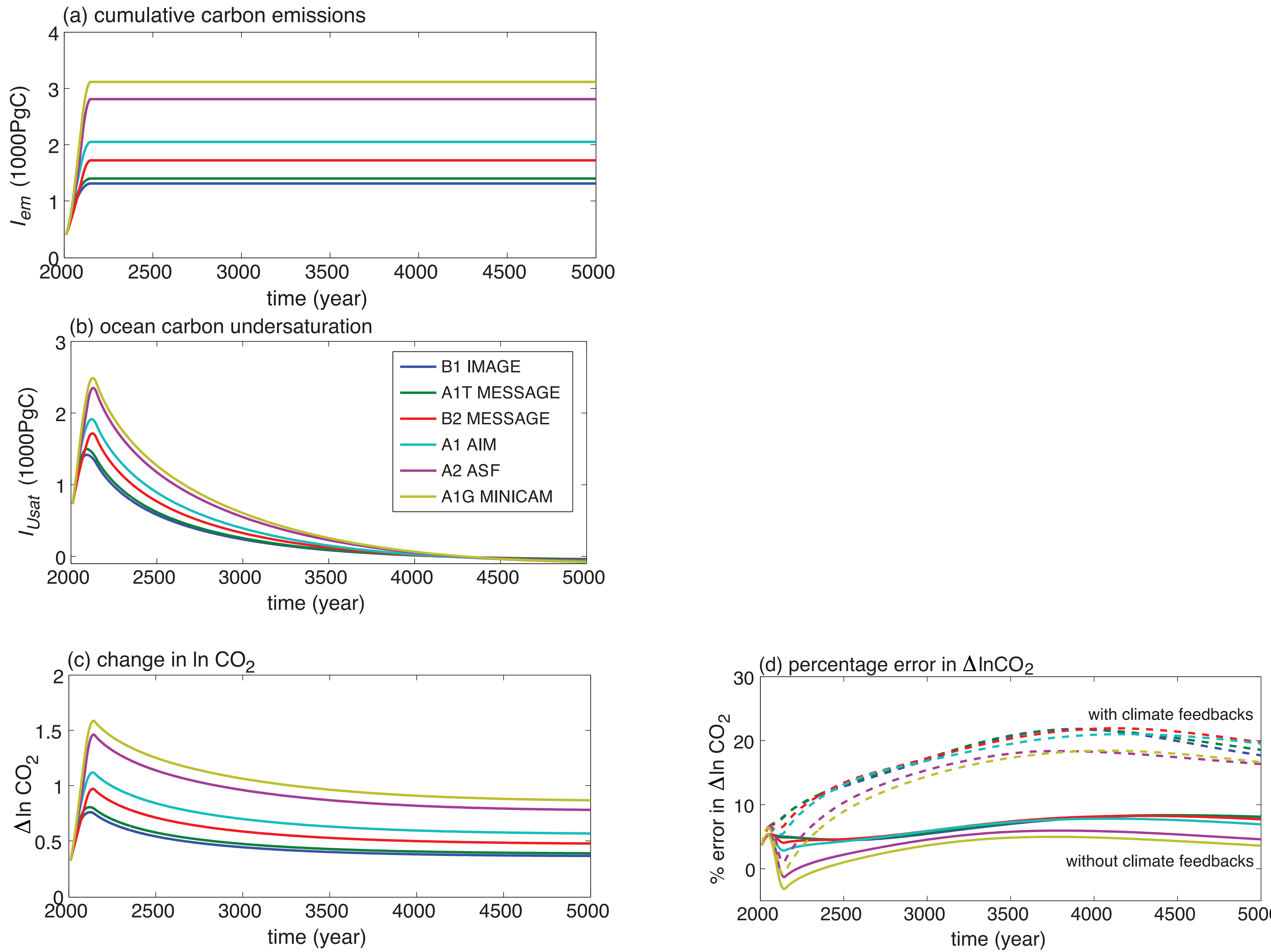


Our tests of an atmosphere-ocean only (GENIE) model



(Goodwin et al. 2015, Nature Geoscience)

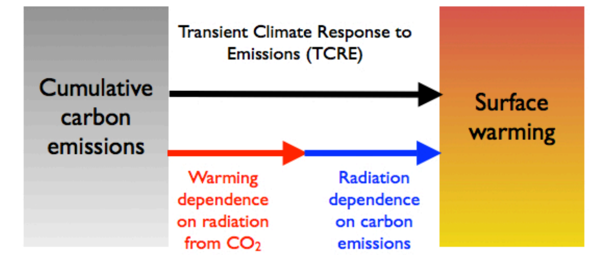
Our tests of an atmosphere-ocean only (GENIE) model



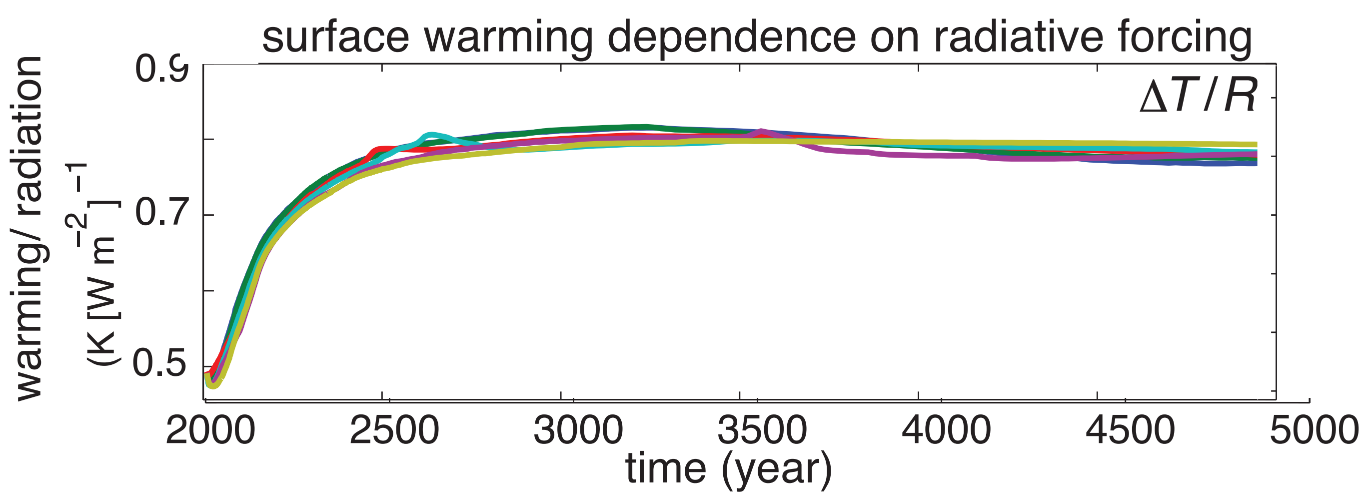
(Goodwin et al. 2015, Nature Geoscience)

3. Climate response on multi-decadal timescales

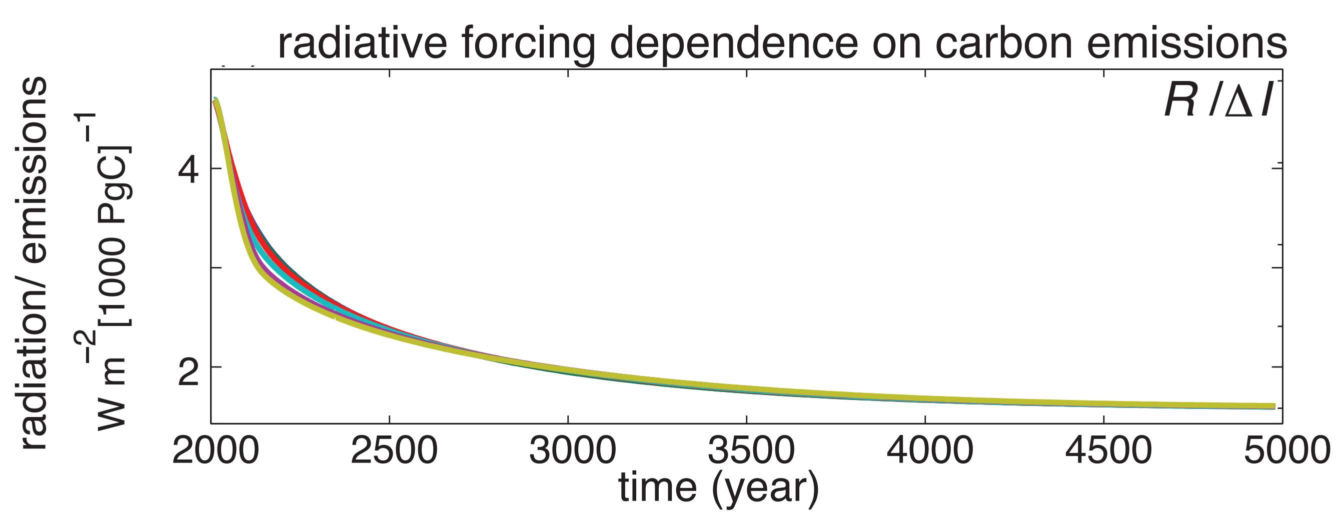
$$\Delta T(t) = \frac{1}{\lambda}\left(1 - N^*(t)\right) \frac{a}{I_B}\left(1 + I^*_{Usat}(t)\right) \Delta I_{em}(t)$$



surface warming *increases* in time due to weakening ocean heat uptake



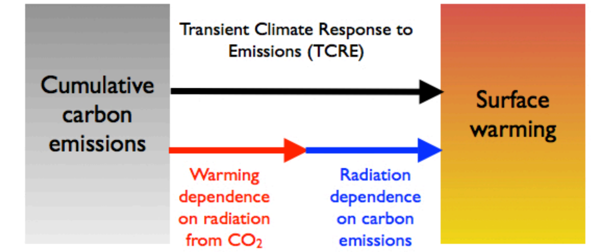
radiative forcing *decreases* in time due to ocean carbon uptake



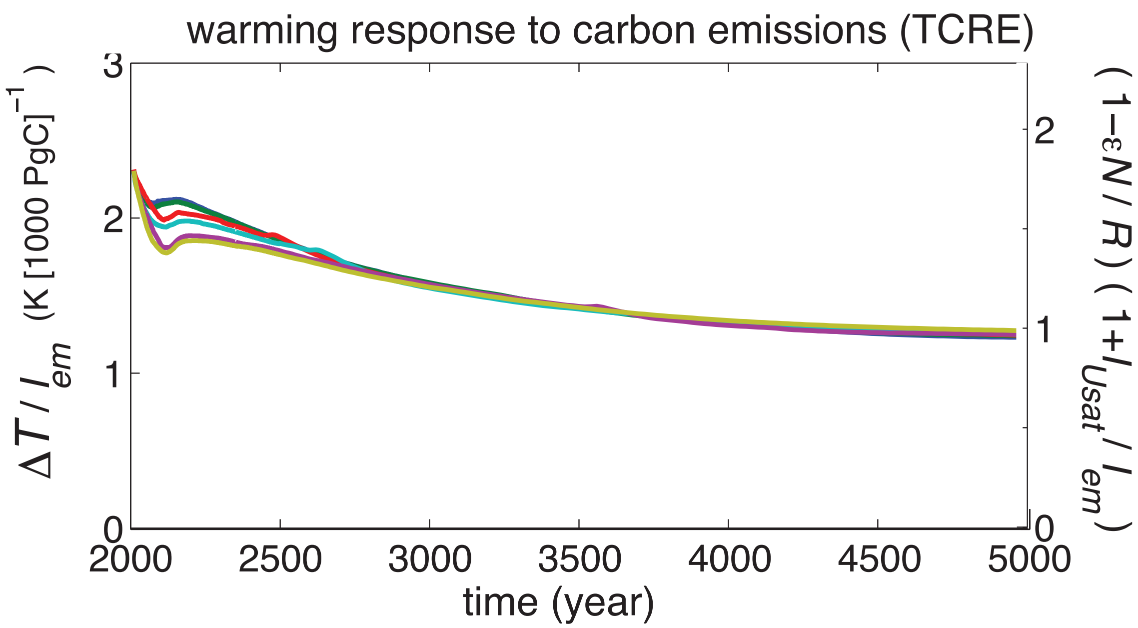
(Goodwin et al. 2015, Nature Geoscience)

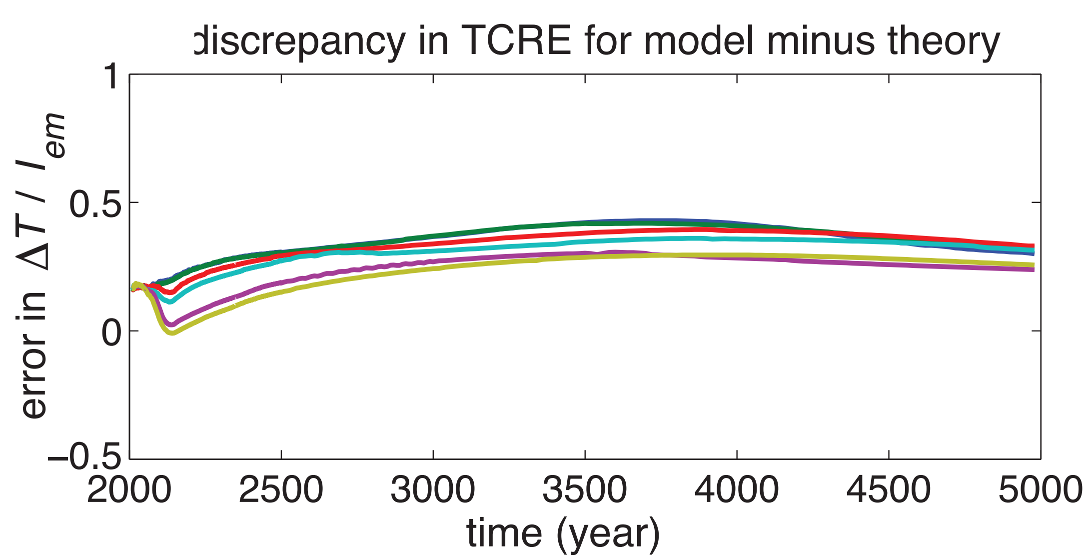
3. Climate response on multi-decadal timescales

$$\Delta T(t) = \frac{1}{\lambda}\left(1 - N^*(t)\right) \frac{a}{I_B}\left(1 + I^*_{Usat}(t)\right) \Delta I_{em}(t)$$



The TCRE changes by factor 2 over 5000 years in the GENIE model





(Goodwin et al. 2015, Nature Geoscience)

Quantifying the Transient Climate Response to Emissions

$$\Delta T = \frac{1}{\lambda}(1 - N^*)\frac{a}{I_B}(1 + I^*_{Usat} - \Delta I^*_{ter})\Delta I_{em}$$

ΔI_{ter} change in terrestrial sink since preindustrial

$$\Delta I^*_{ter} = \Delta I_{ter} / \Delta I_{em}$$

at 2011, cumulative emissions	ΔI_{em}	545 +/- 85 PgC		
atmospheric C increase		240 +/- 10 PgC		
ocean C increase		155 +/- 30 PgC		
terrestrial C increase	ΔI_{ter}	150 +/- 90 PgC	ΔI^*_{ter}	0.28 +/-0.2
ocean carbon undersaturation	I_{Usat}	797 +/- 30 PgC	I^*_{Usat}	1.5 +/-0.4

$\Delta T/\Delta I_{em} \sim$ 1.5 +/- 0.7 K per 1000 PgC for atmosphere-ocean only

1.1+/- 0.5 K per 1000 PgC for atmosphere-ocean-terrestrial system

For 2100, based on synthesis of coupled CIMP4 terrestrial coupled models (Friedlingstein et al., 2006)

normalised change in terrestrial sink for 2100 ΔI^*_{ter} 0.27 to 0.14

implied terrestrial change from 2011 to 2100 in $\Delta T/\Delta I_{em}$ is 10% to -21%

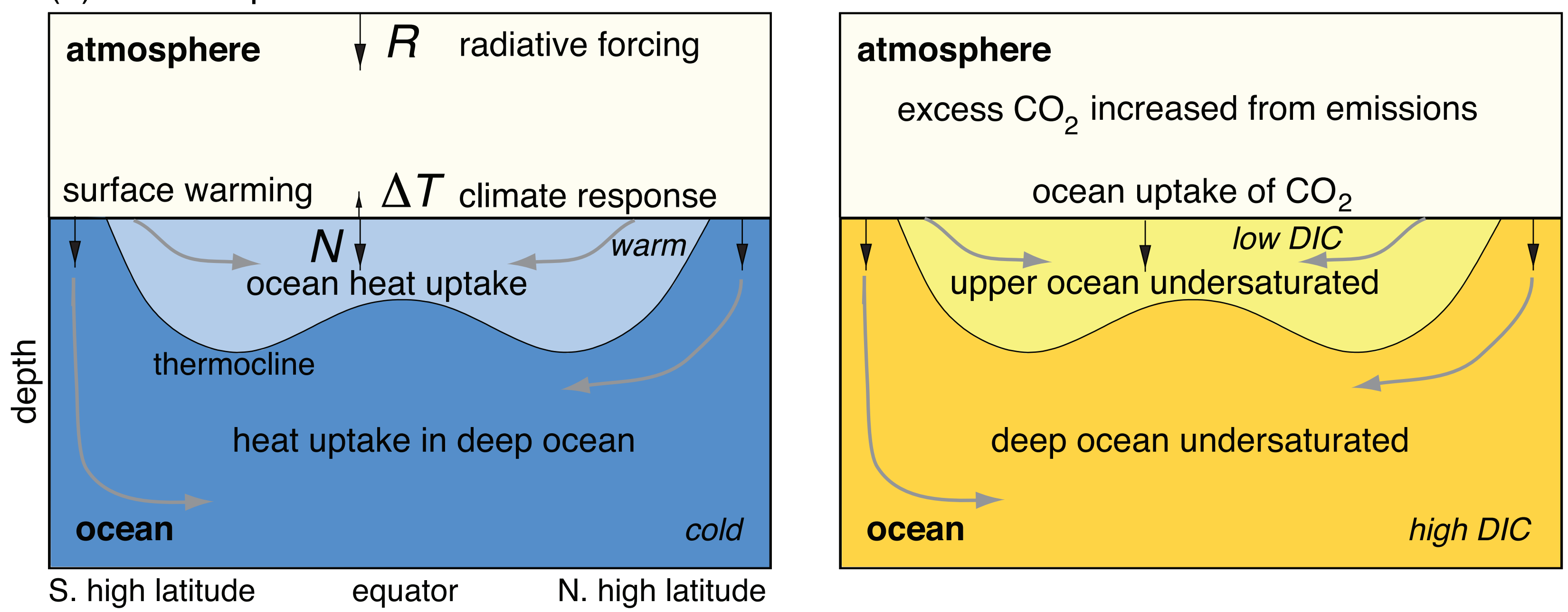
(Goodwin et al. 2015, Nature Geoscience)

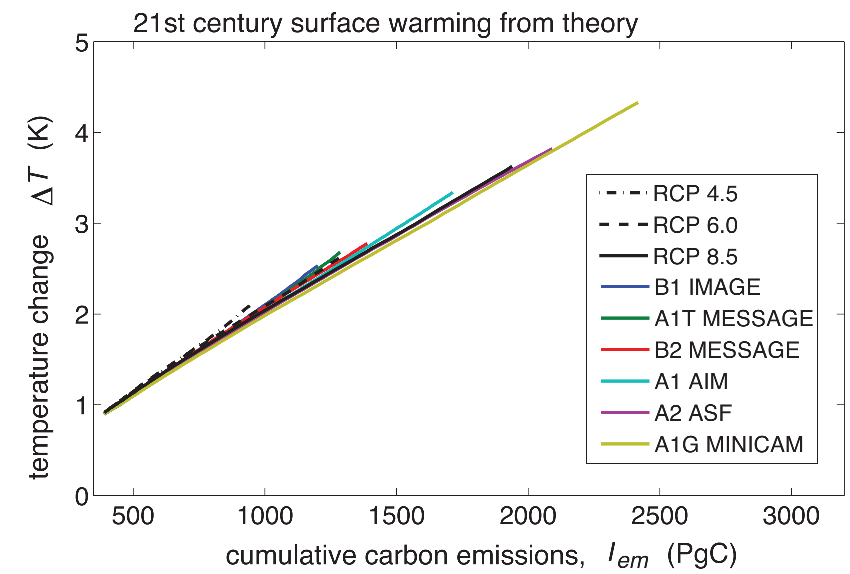
Conclusions

$$\Delta T = \frac{1}{\lambda}(1 - N^*)\,\frac{a}{I_B}\left(1 + I^*_{Usat} - \Delta I^*_{ter}\right)\Delta I_{em}$$

thermal response　　　　anthropogenic carbon response

(a) initial response to carbon emissions on decadal timescales





Goodwin, Williams & Ridgwell (2015)

- The ocean heat uptake & carbon undersaturation partly compensate, helps determine how carbon emissions translate into global warming

  modified by terrestrial drawdown, other greenhouse gases, aerosols ....

- Ventilation in the Southern Ocean is likely to play a particularly important role.

- Multidecadal variability in this relationship likely to be mainly from the heat flux