How warming relates to cumulative carbon emissions after many centuries or many decades

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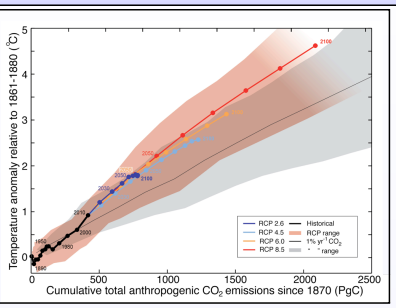
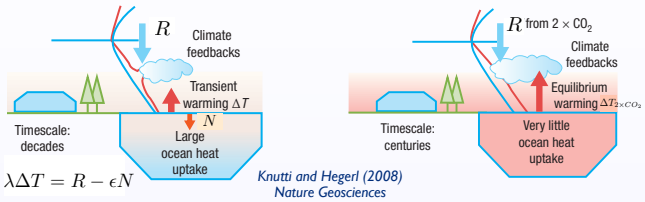
1. The problem

Climate models reveal warming is linked to cumulative carbon emissions.

Derive underlying theoretical relationship for an atmosphere and ocean after
(a) many centuries
(b) many decades



2. Different climate responses



$$\lambda \Delta T = R - \epsilon N$$

Knutti and Hegerl (2008) Nature Geosciences

Over many decades, ocean takes up heat & carbon modifying warming & forcing.

Over many centuries after emissions cease, an air-sea equilibrium is approached.

3. Long-term response

Many centuries after emissions cease, ocean heat & carbon uptake ceases.

A simple climate relationship emerges by combining climate sensitivity and carbon relation accounting for ocean chemistry (Goodwin et al, 2007; Williams et al., 2012).

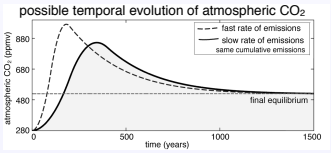
surface warming linked via to climate sensitivity

$$\Delta T(t) = \underbrace{\Delta T_{2\times CO_2}}_{\text{climate sensitivity}} \frac{\ln(CO_2(t)/CO_2(t_o))}{\ln 2}$$

typically 2 to 4.5 K, mean of 3 K

$$\underbrace{\Delta T(t_{equilib})}_{\text{surface temperature change}} = \left(\frac{\Delta T_{2\times CO_2}}{I_B \ln 2}\right) \underbrace{I_{em}}_{\text{cumulative carbon emission}}$$

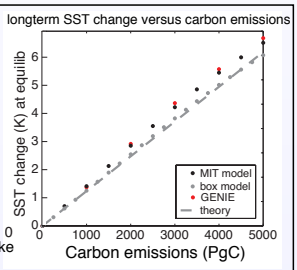
Our theory: global warming is ~1.5 K for every 1000 PgC (range of 0.8-1.9 K for every 1000 PgC)



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

exponential relationship due to +ve feedback: atmospheric CO_2 *rises, increase* ocean acidity, less CO_3, more ocean CO_2, *inhibits* ocean CO_2 uptake

I_B is 3500 PgC, nearly conserved for emissions up to 4000 PgC



cf Earth system models find 1 to 2.1 K for every 1000 PgC (Matthews et al., 2009)

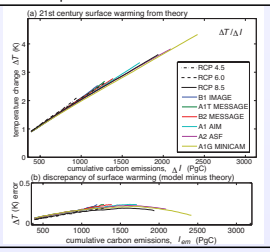
4. Short-term response

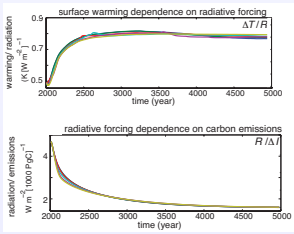
Over several decades, ocean heat and carbon uptake modify both surface warming & radiative forcing.

A modified climate relationship emerges including dependences on ocean heat uptake & ocean carbon undersaturation (Goodwin et al., 2014).

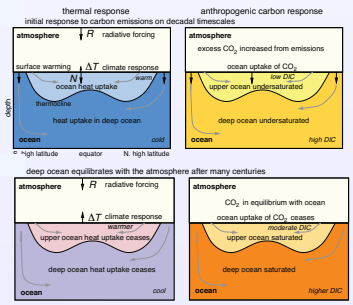
$$\Delta T(t) = \left(\frac{\Delta T_{2\times CO_2}}{I_B \ln 2}\right)(1 - \epsilon \underbrace{N^*(t)}_{\text{normalised ocean heat uptake}})(1 + \underbrace{I^*_{Usat}(t)}_{\text{normalised ocean carbon undersaturation}}) I_{em}(t)$$

See near linear response when diagnose theory in GENIE Earth System model for an atmosphere & ocean





See opposing dependencies for surface warming & radiative forcing with time



Ventilation leads to similar heat & carbon evolution

5. Summary

Our theory for an atmosphere & ocean reveals a near *linear* dependence of warming on carbon emissions.
Linear transient response is due to opposing effects of ocean uptake of heat & carbon.
Longterm response due to climate sensitivity & ocean chemistry feedback.

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Further reading: Goodwin, P., R.G. Williams, M.J. Follows & S. Dutkiewicz, 2007. *GBC*, 21, GB1014.
Goodwin, P., R.G. Williams & A. Ridgwell, 2014. Nature Geoscience, doi:10.1038/ngeo2304.
William, R.G., P. Goodwin, A. Ridgwell & P.L. Woodworth, 2012. Geophysical Research Letters, 39, L19715.