Climate change: a summary for policy-makers

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Climate change: a summary for policymakers

- How rising atmospheric CO_2 causes global warming
- How global temperatures and sea level respond
- Quantifying human influence on climate and weather
- The fate of CO_2 and other anthropogenic emissions
- Global impact functions and the social cost of carbon
- Mitigation costs and pathways
- Policy options from carbon pricing to geo-engineering
- Capstone activity: design a robust climate policy

Summary of lecture 1: how rising CO_2 causes global warming

- Air temperature decreases with height at a constant *absolute* rate (c. 6.5° C/km) through the troposphere.
- The effective density of CO_2 absorber decreases with height at a constant *fractional* rate (c. 30%/km).
- Doubling CO_2 concentrations "thickens the fluffy blanket of greenhouse gases" by about 2km.
- In wavelengths partially absorbed by CO_2, this raises, and hence cools, the altitude from which IR escapes to space.
- Less energy out, same energy in: imbalance.

Summary of lecture 1: how rising CO_2 causes global warming

- Externally-driven imbalance between incoming and outgoing energy is known as "radiative forcing" :

$$F(t) = \frac{F_{2xCO_2}}{\log(2)} \log\left(\frac{C(t)}{C_{\text{pre-industrial}}}\right)$$

  - F_{2xCO2} = 3.7 Watts per square metre
    = 1.9 billion Gigawatts over the whole Earth
    = 1000x world primary energy consumption
- This energy has to go somewhere, so the surface and lower atmosphere have to warm up to restore balance.
- How much warming depends on other changes.

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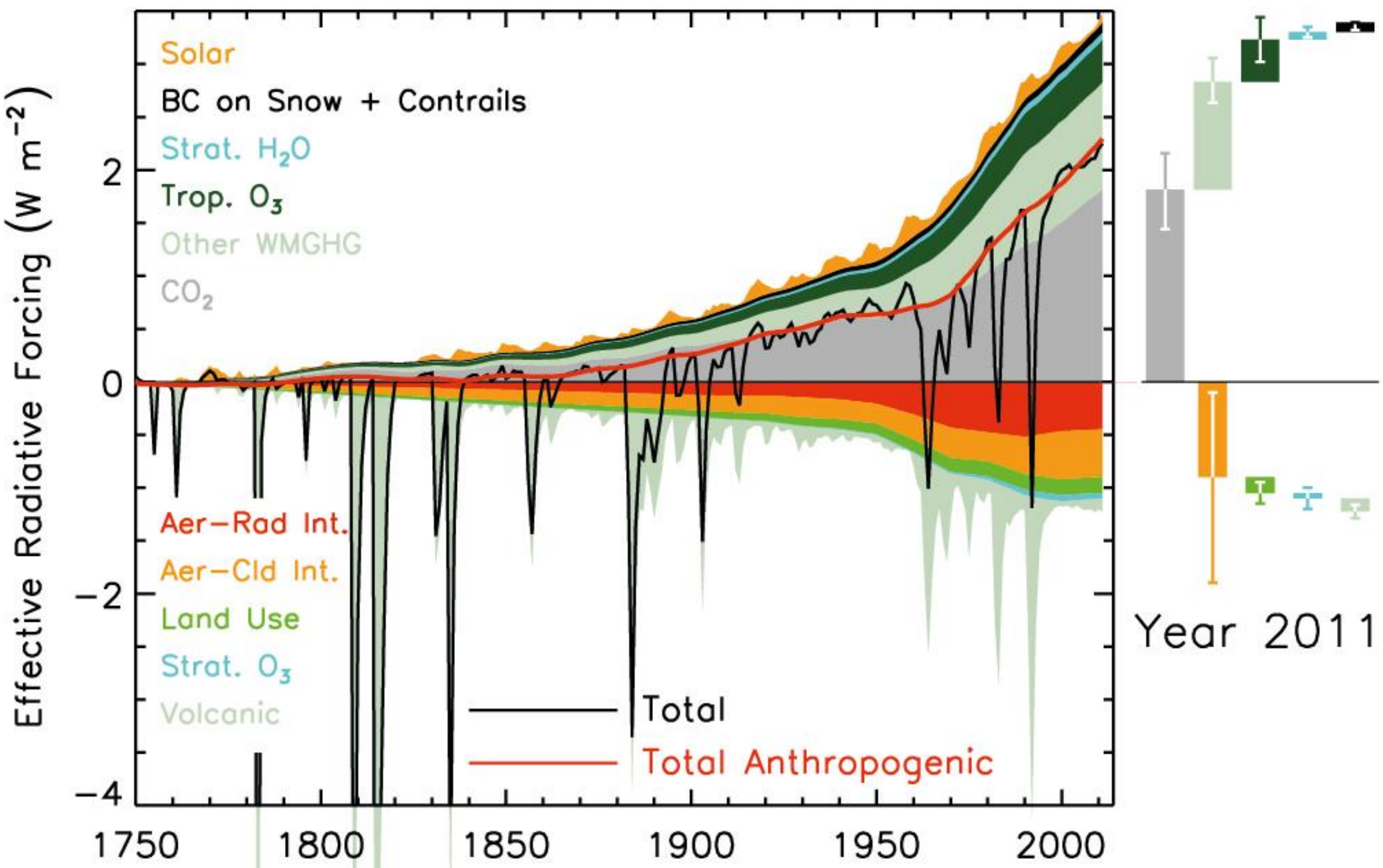
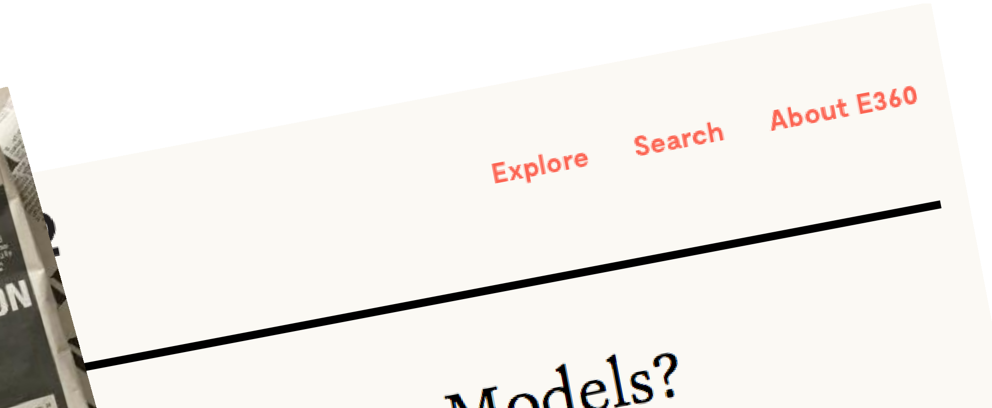
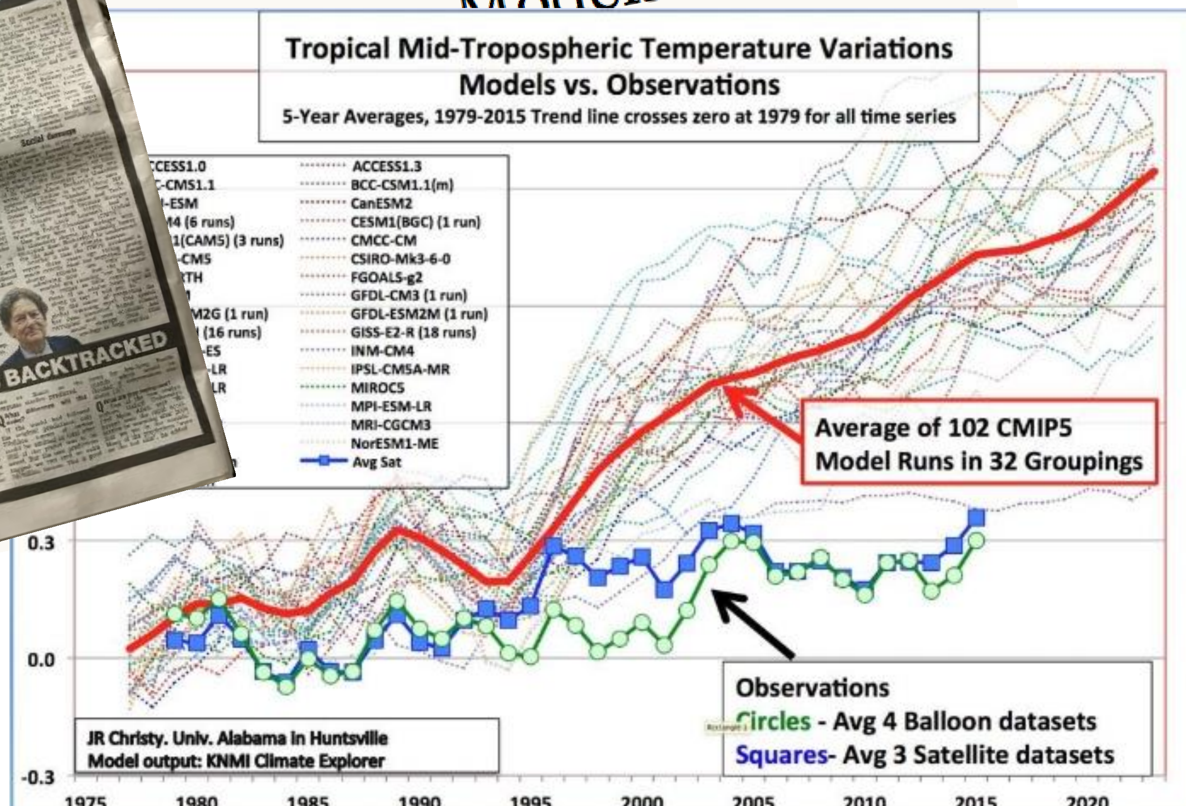
Drivers of change in the global energy budget:



To understand the response, we will need a climate model





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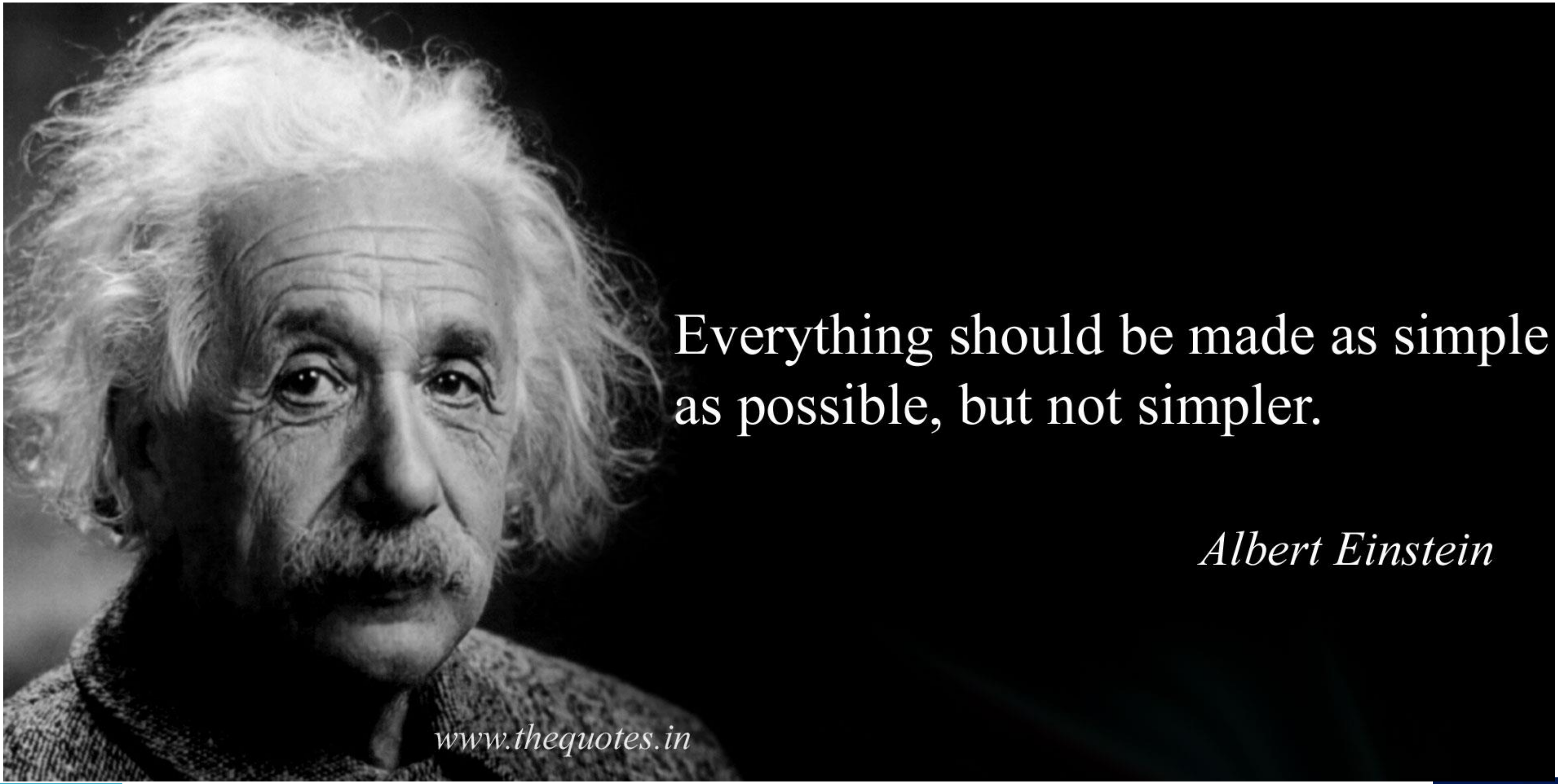
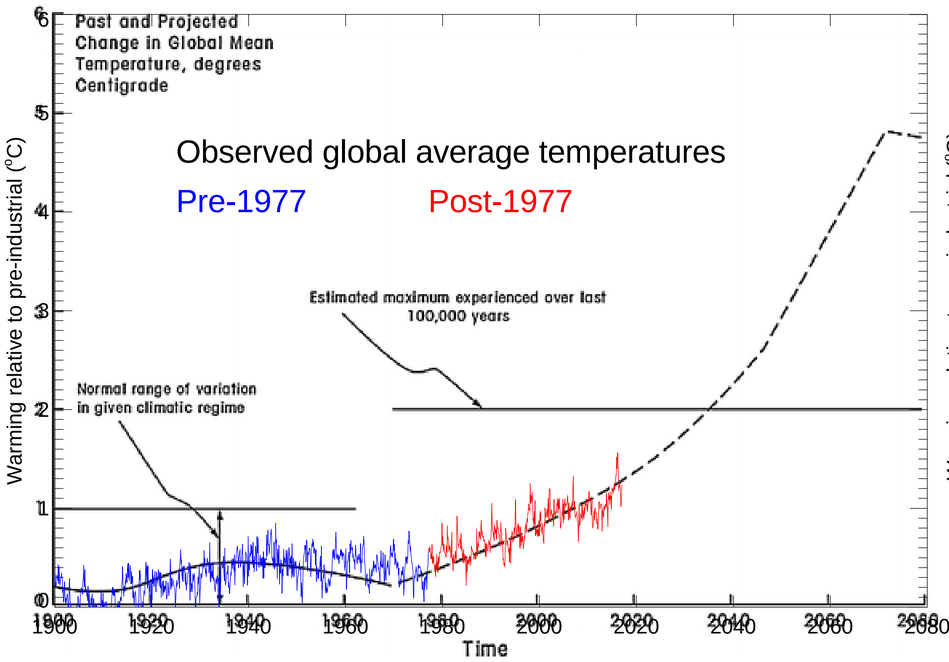
Our modelling philosophy



Evidence that you don't need a very complicated model to make a successful climate prediction



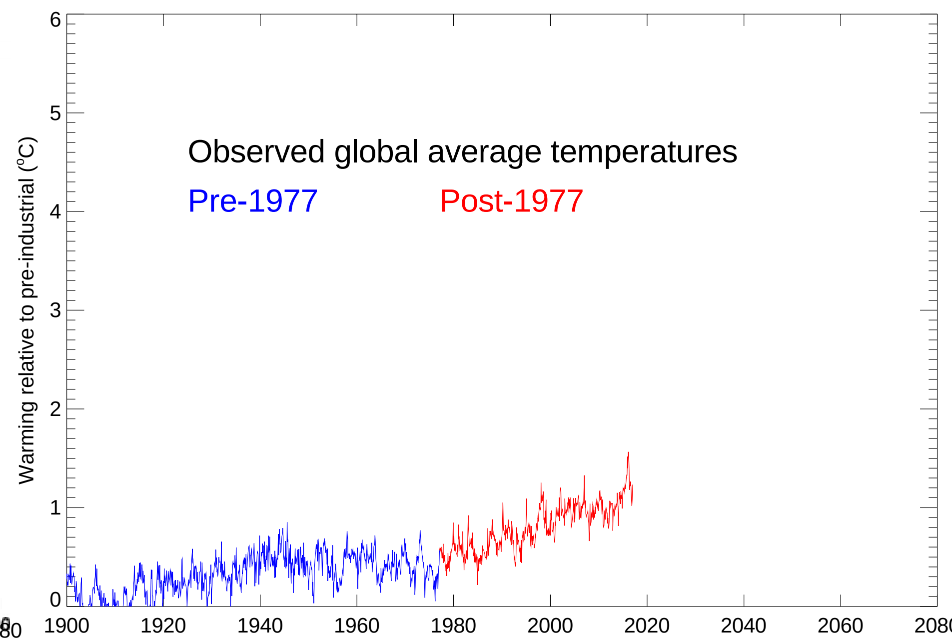


Figure 1 from William D. Nordhaus, "Strategies for Control of Carbon Dioxide", Cowles Discussion Paper 477, January 6, 1977

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Understanding what models are, and why you don't need to trust them

- A large burette:

$$A\frac{dh}{dt} = F - kh$$

- h is the water depth.
- A is the water cross-sectional area.
- F is the rate of water flowing in from the pump.
- k is the "openness" of the tap.
- Open L2_demos.xlsx & look at top sheet "Burette"
- Rearranging the equation (check cell C11):

$$dh = \frac{F - kh}{A}dt$$

Understanding what models are, and why you don't need to trust them

- Parameters in models correspond to quantities that are more or less easy to measure:
  - Cross-sectional area (easy to measure)
  - Flow (could be measured, but isn't)
  - "Openness of tap" (fuzzier concept, hard to measure, only really makes sense in the context of this simple model)
- But we can observe the behaviour of the system, and infer what values these parameters can take.
  - Group exercise: find values of *F* and *k* that reproduce the green diamonds (slightly noisy "observations" of water level)

A very simple model of the climate system

- The Earth's Climate:

$$C\frac{dT}{dt} = F_{\mathrm{ext}} - \ / \ T$$

- *T* is the global average surface temperature change.
- *C* is the "effective heat capacity".
- F_{ext} is imbalance between incoming and outgoing energy.
- *λ* is a constant "sensitivity parameter".

You’ve seen this model already

- A large burette:

$$A\frac{dh}{dt} = F - kh$$

- *h* is the water depth.
- *A* is the water cross-sectional area.
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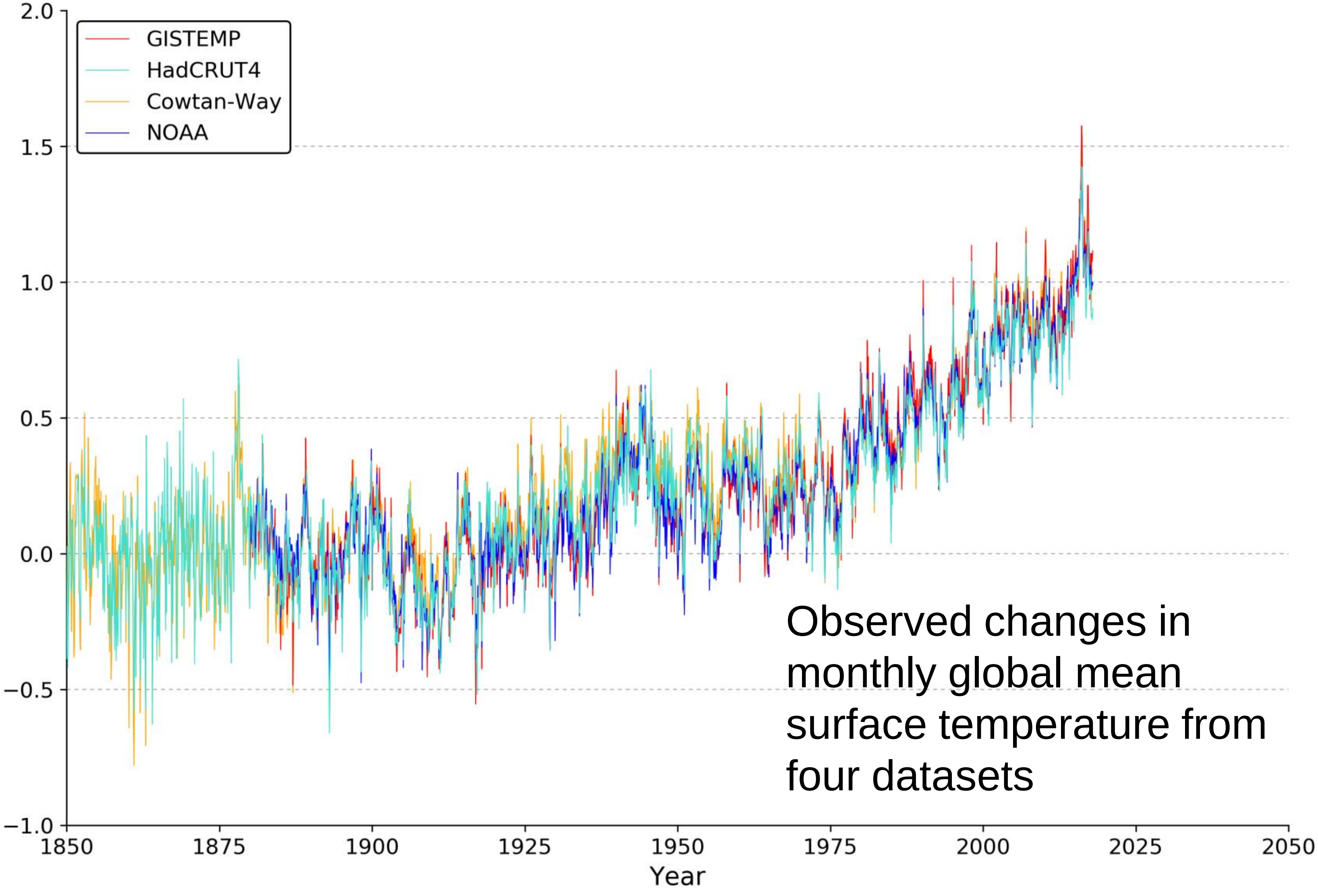
Some exercises with our very simple model

- The Earth's Climate:

$$C\frac{dT}{dt} = F_{ext} - / T$$

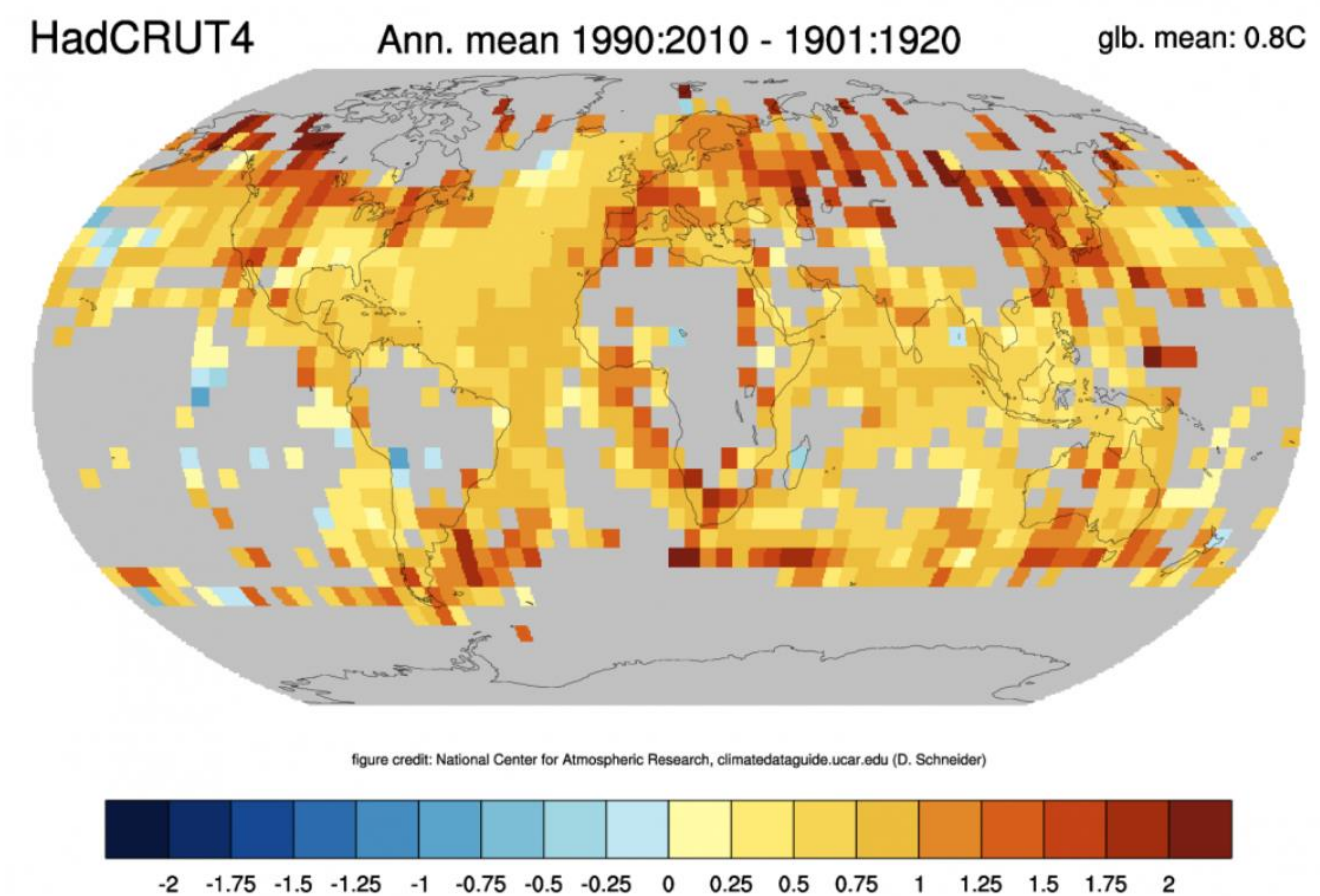
- *T* is the global average surface temperature change.
- *C* is the "effective heat capacity".
- F_{ext} is imbalance between incoming and outgoing energy.
- *λ* is a constant "sensitivity parameter".
- Open L2_demos.xlsx & look at second sheet "ClimateStep"
- Equations are the same, but units very different
- Try varying *λ* and *C*: what aspect of the response to this forcing profile does each one control?

What can we say about the real climate?

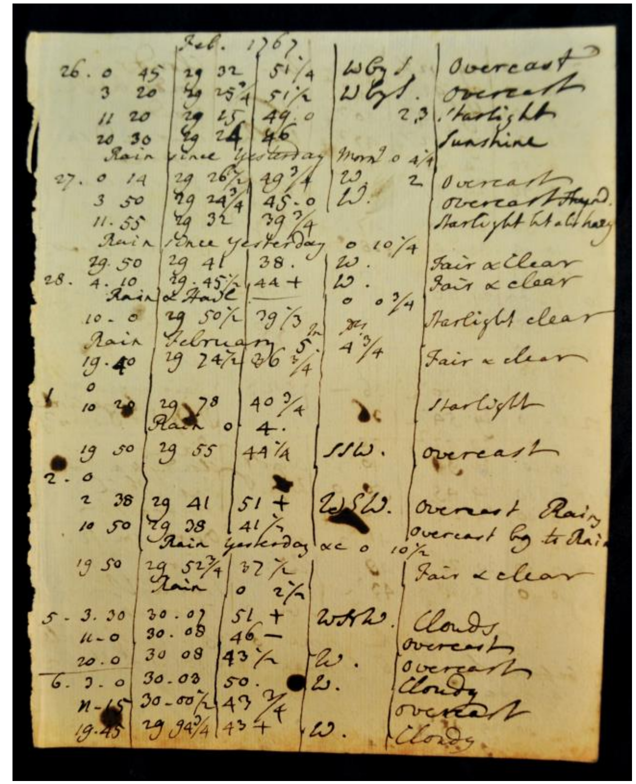


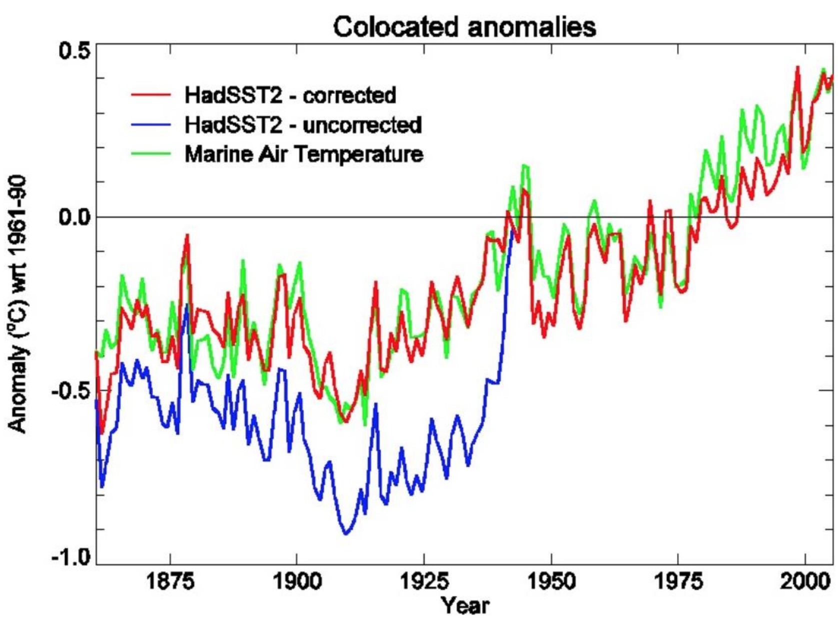
Observed changes in monthly global mean surface temperature from four datasets

Challenges in estimating 100-year global temperature change – observational coverage



Changing observing systems





Let’s see how we get on with our very simple model

- The Earth’s Climate:

$$C\frac{dT}{dt} = F_{\text{ext}} - / T$$

- *T* is the global average surface temperature change.
- *C* is the “effective heat capacity”.
- F_{ext} is imbalance between incoming and outgoing energy.
- *λ* is a constant “sensitivity parameter”.
- Open L2_demos.xlsx & look at third sheet “ClimateBasic”
- Equations as before, now with observed radiative forcing
- Group exercise: find combinations of *λ* and *C* that reproduce the observed warming

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What determines the effective heat capacity?

- Most energy shows up in the oceans – but if the oceans warmed uniformly:

$$C = \text{Heat capacity per unit Earth surface area}$$

$$= \text{Density}´\ \text{Specific heat capacity}´\ \text{Depth}´\ \text{Ocean area fraction}$$

$$= 1000\,\text{kg m}^{-3}´\ 4000\,\text{J kg}^{-1}\,{}^{o}\text{C}^{-1}´\ 4000\,\text{m}´\ 0.7$$

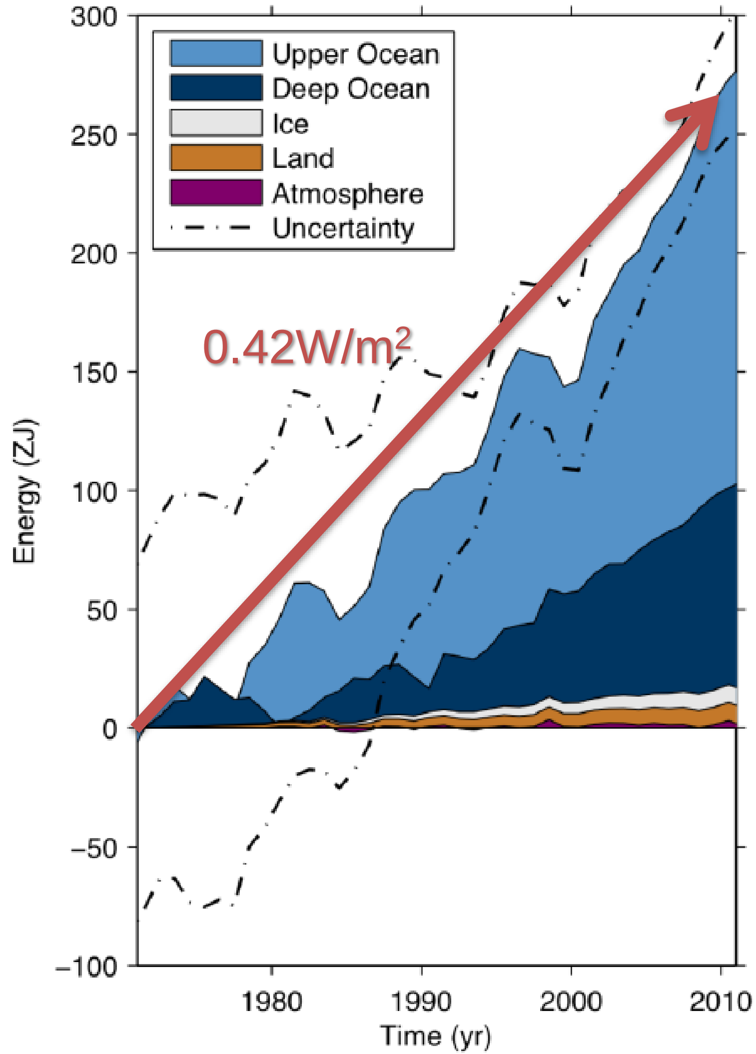
$$= 355\ \text{W-yr} / \text{m}^{2} / {}^{o}\text{C}^{-1}$$

Units:

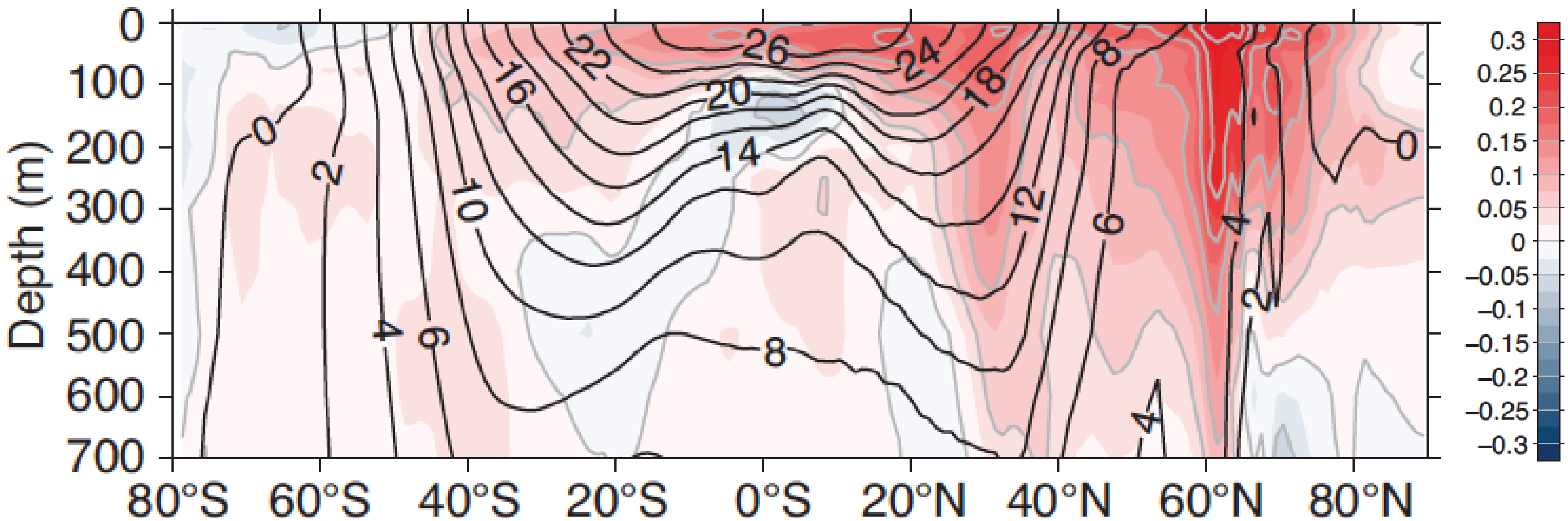
$$1\ \text{W-yr} / \text{m}^{2} = 16.1\ \text{ZettaJoules}\ (10^{21}\ \text{Joules})$$

Most heat accumulates in the upper ocean. Why?

- Increase in ocean heat content since 1970

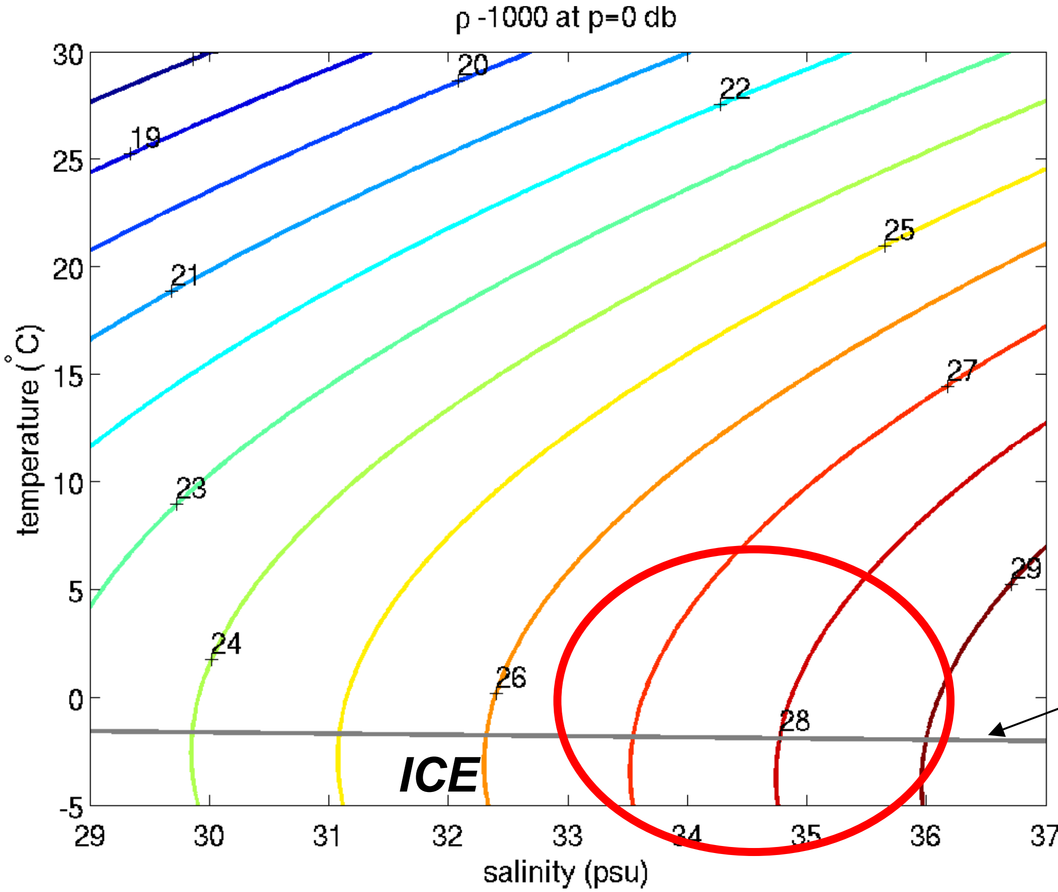


Where the oceans are warming up



Oceanic temperature trend 1971-2010 in ° C/decade

Density of sea-water controlled by salinity at low temperatures



Density anomaly

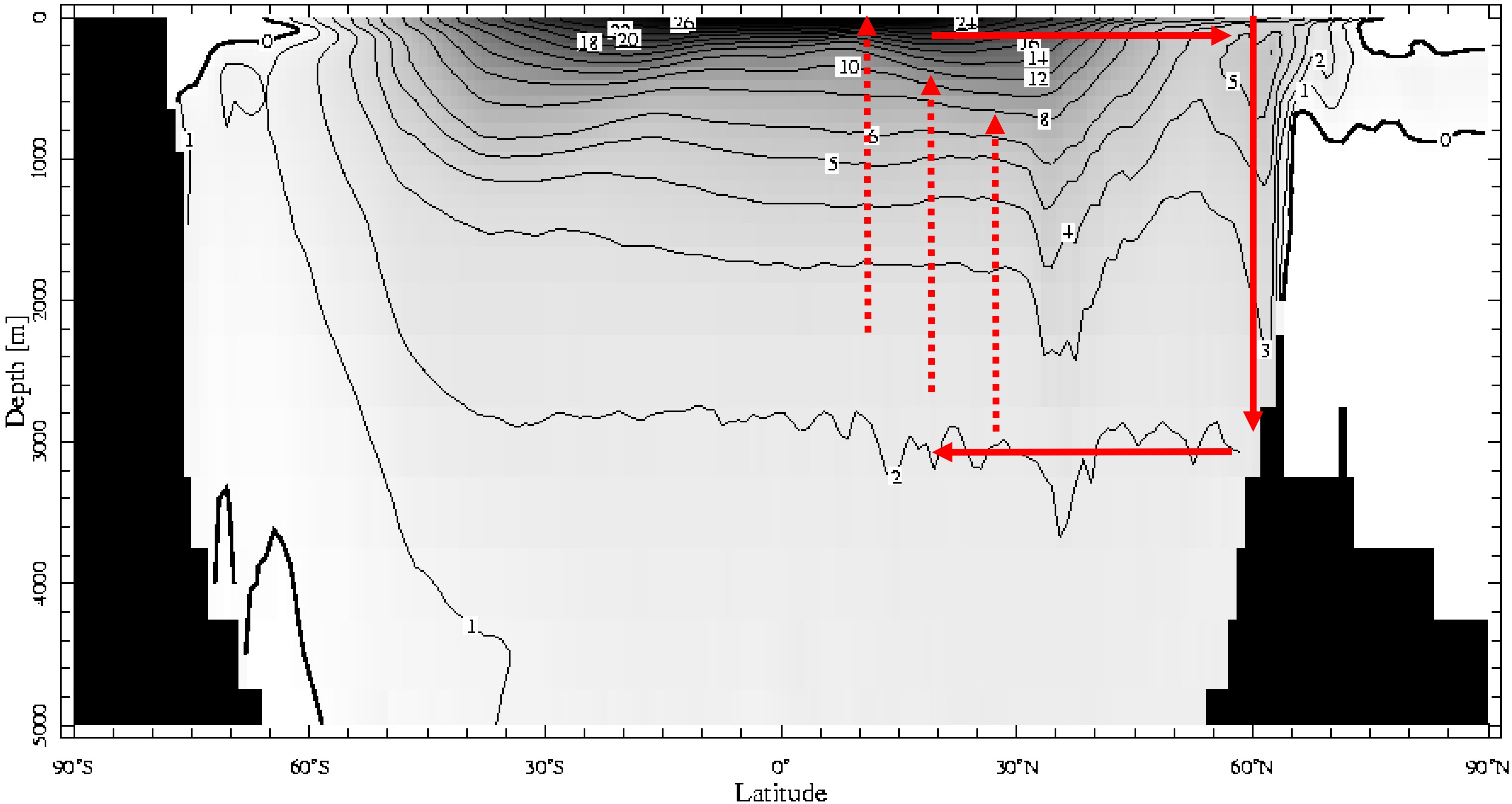
$$\sigma = \rho - \rho_{ref}$$

$$\rho_{ref} = 1000 \text{ kg m}^{-3}$$

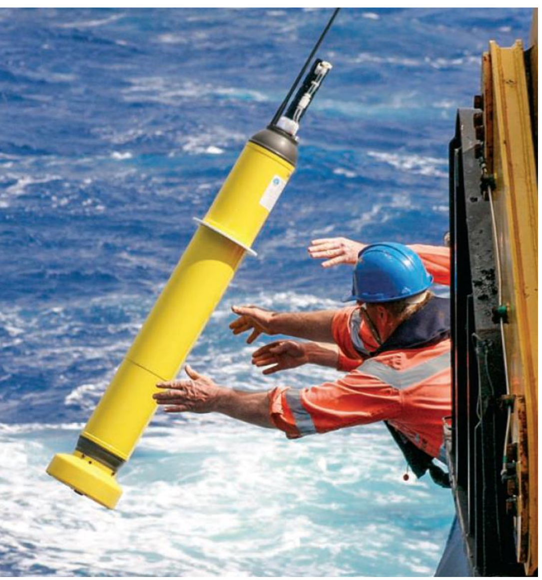
Freezing point of water

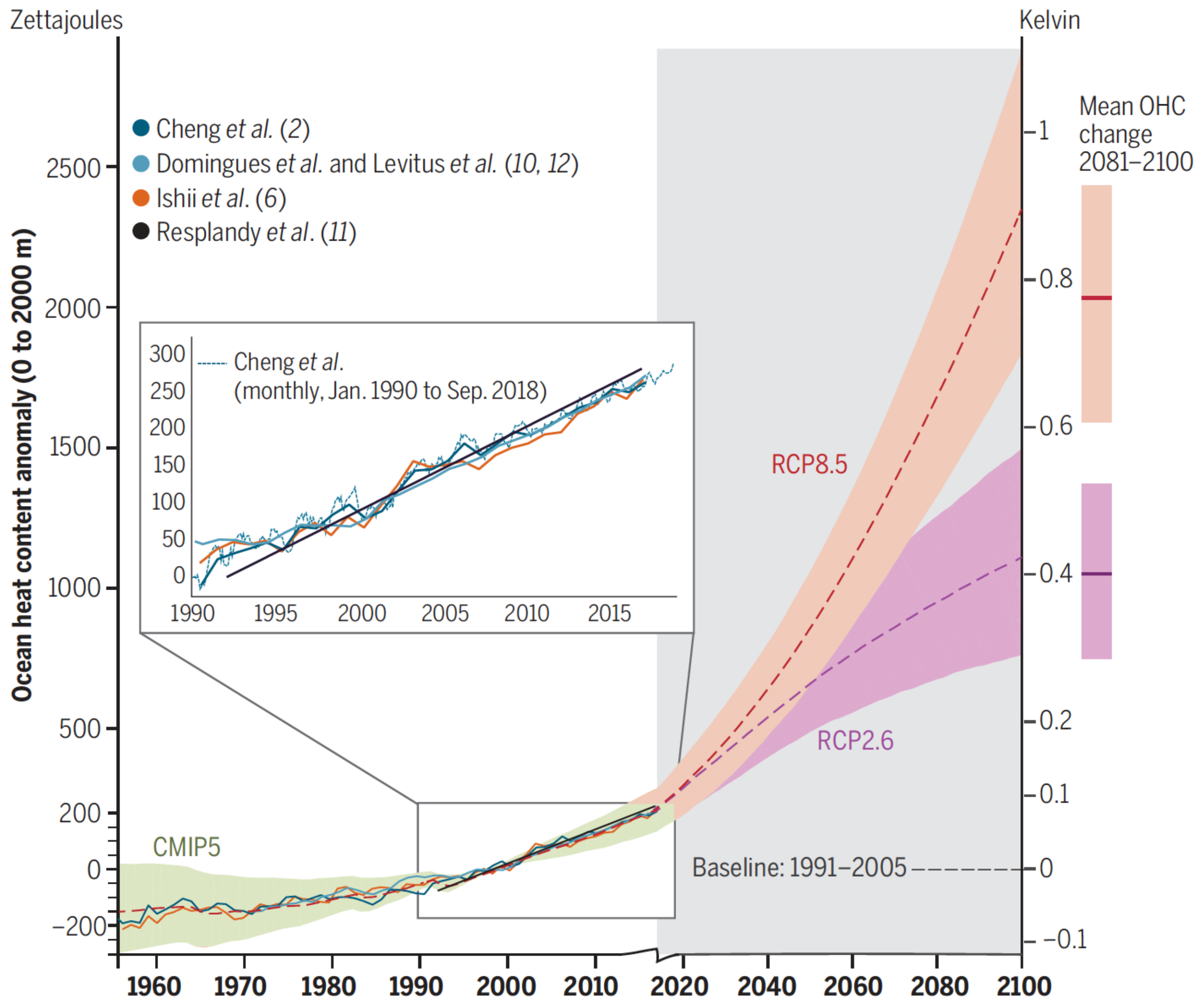
$$\rho = \rho(S, T, p)$$

Water is cold enough to "escape to depth" only at high-latitudes, carrying warming with it



Updating heat content estimates





Cheng et al, *Science*, 2019

Including the deep ocean in our simple model

- Simple mixed-layer energy balance model with a deep ocean:

$$C_s \frac{dT_s}{dt} = F_{\text{ext}} - \lambda T_s - \gamma (T_s - T_d)$$

$$C_d \frac{dT_d}{dt} = \gamma (T_s - T_d)$$

- C_s is effective heat capacity of surface and mixed layer.
- C_d is effective heat capacity of deep ocean ($C_d >> C_s$).
- T_s is average surface temperature change
- T_d is average deep ocean temperature change
- Flux of heat into deep ocean given by a constant mixing rate γ.

Back to burette analogy

- Two coupled burettes, X-sectional areas a_1 & a_2, $a_2 >> a_1$

$$a_1 \frac{dh_1}{dt} = F - k_1 h_1 - k_2 (h_1 - h_2)$$

$$a_2 \frac{dh_2}{dt} = k_2 (h_1 - h_2)$$

- F is incoming flow
- h_1 & h_2 are depth of water in each burette
- k_1 & k_2 represent transmissivity ("openness") of taps

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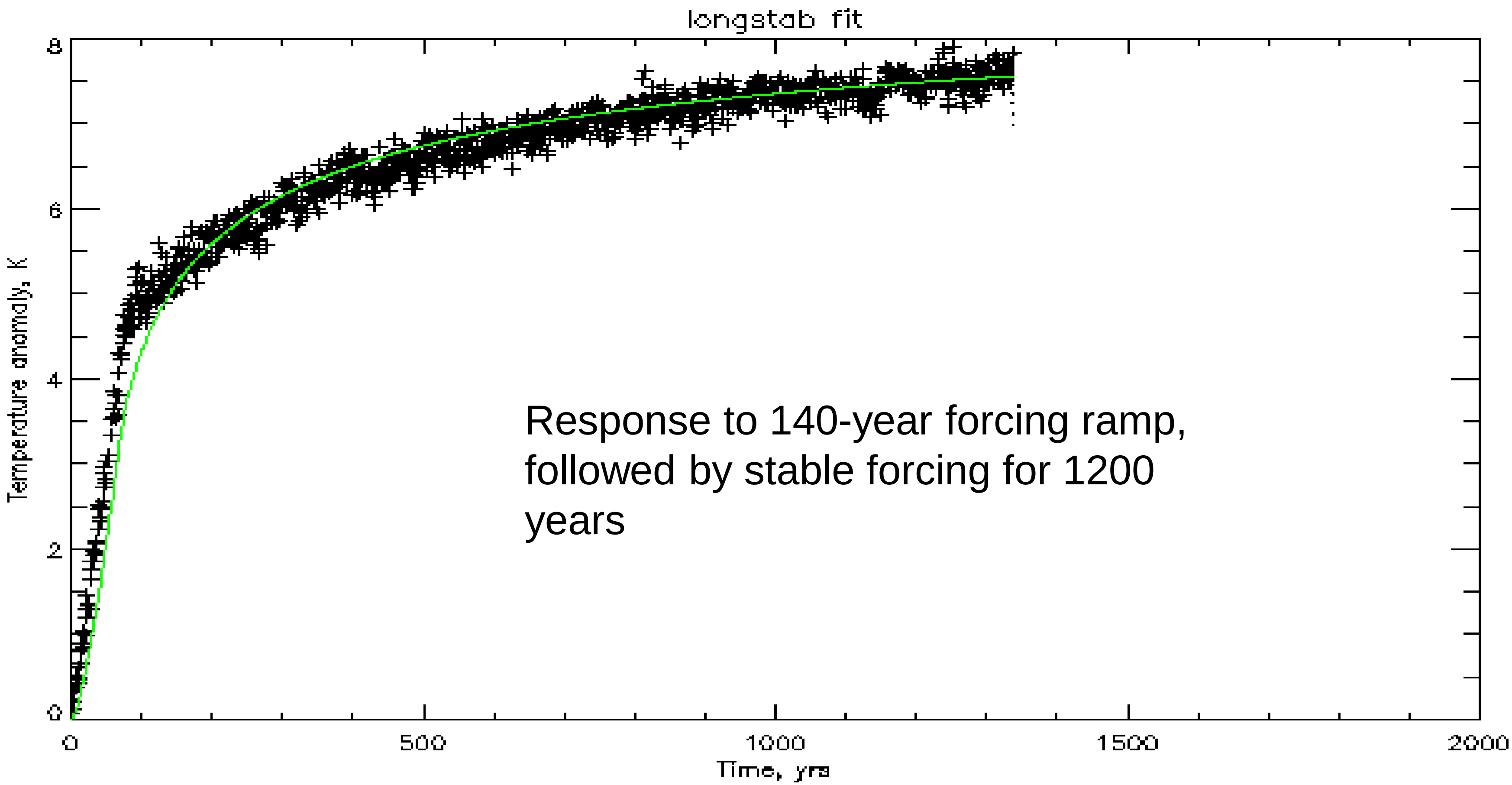
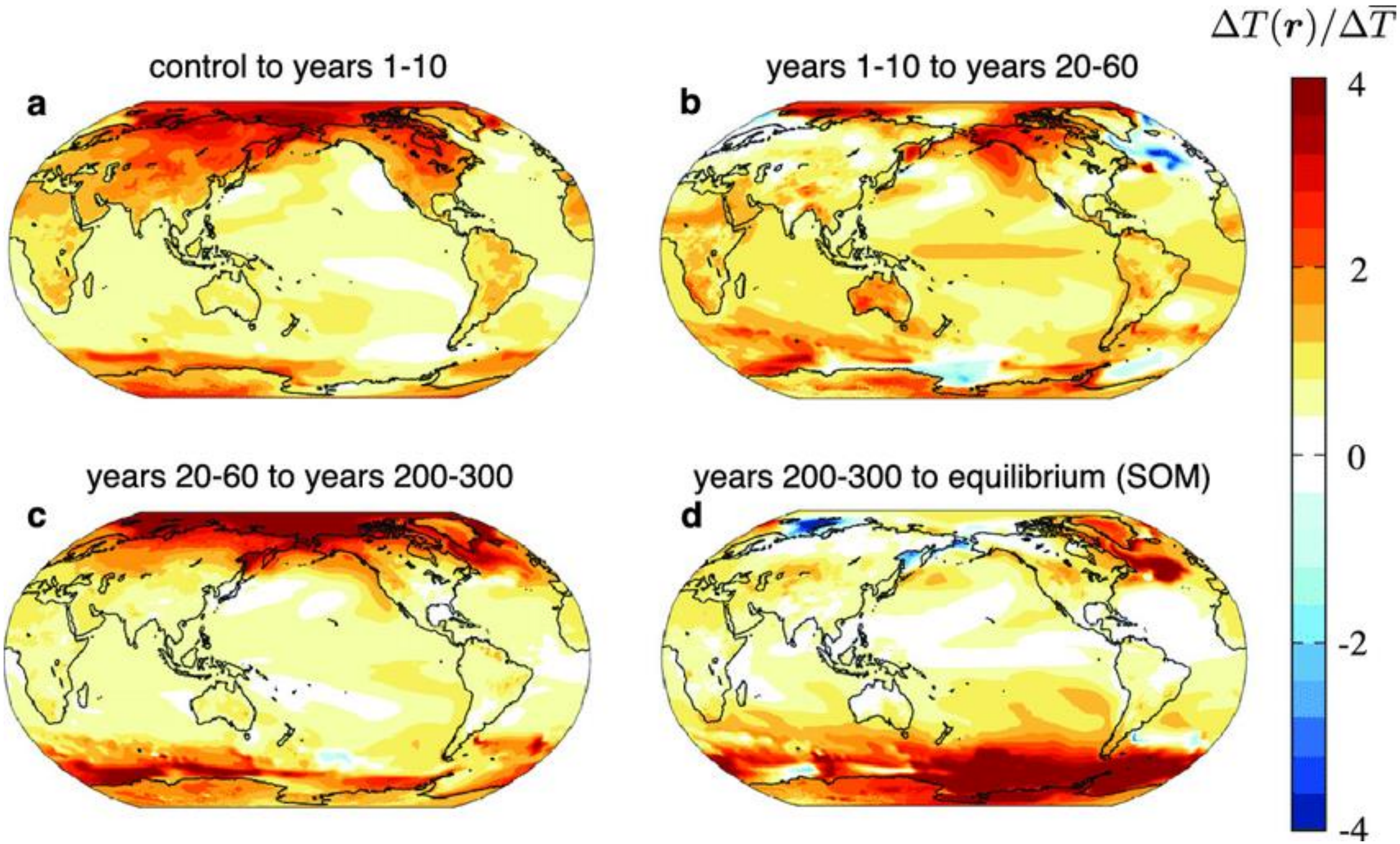
This explains a rapid initial adjustment, and then centennial-timescale adjustment to equilibrium



But the pattern of warming changes as climate equilibrates, reducing energy lost to space per ° C



Armour et al, 2013

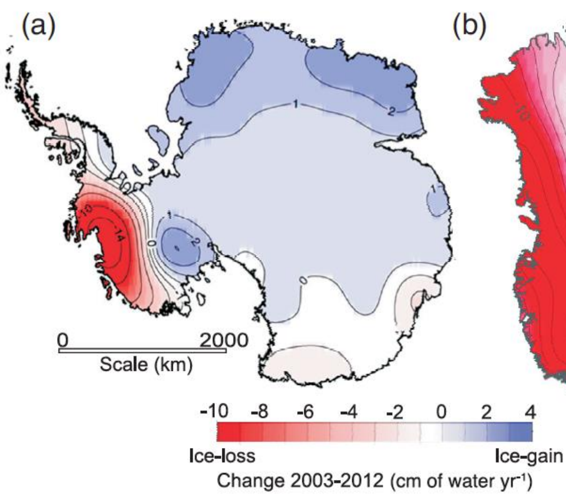
Allowing for changing feedbacks as the climate system adjusts to equilibrium

$$C_s \frac{dT_s}{dt} = F_{\text{ext}} - \lambda T_s - \gamma (T_s - T_d) - \lambda' (T_s - T_d)$$

$$C_d \frac{dT_d}{dt} = \gamma (T_s - T_d)$$

- $\lambda' (T_s - T_d)$ represents additional radiation to space due to disequilibrium.
- Open L2_demos.xlsx & look at third sheet "ClimatePro"
- Take-home exercise: explore what combinations of parameters are consistent with observed warming and rate of heat uptake (0.3-0.5 W/m^2 over 1971-2010)

Multiple drivers of sea level change



- Ocean thermal expansion.
- Groundwater extraction.
- Worldwide retreat of mountain glaciers.
- Mass loss of Greenland and Antarctic peripheral icecaps.

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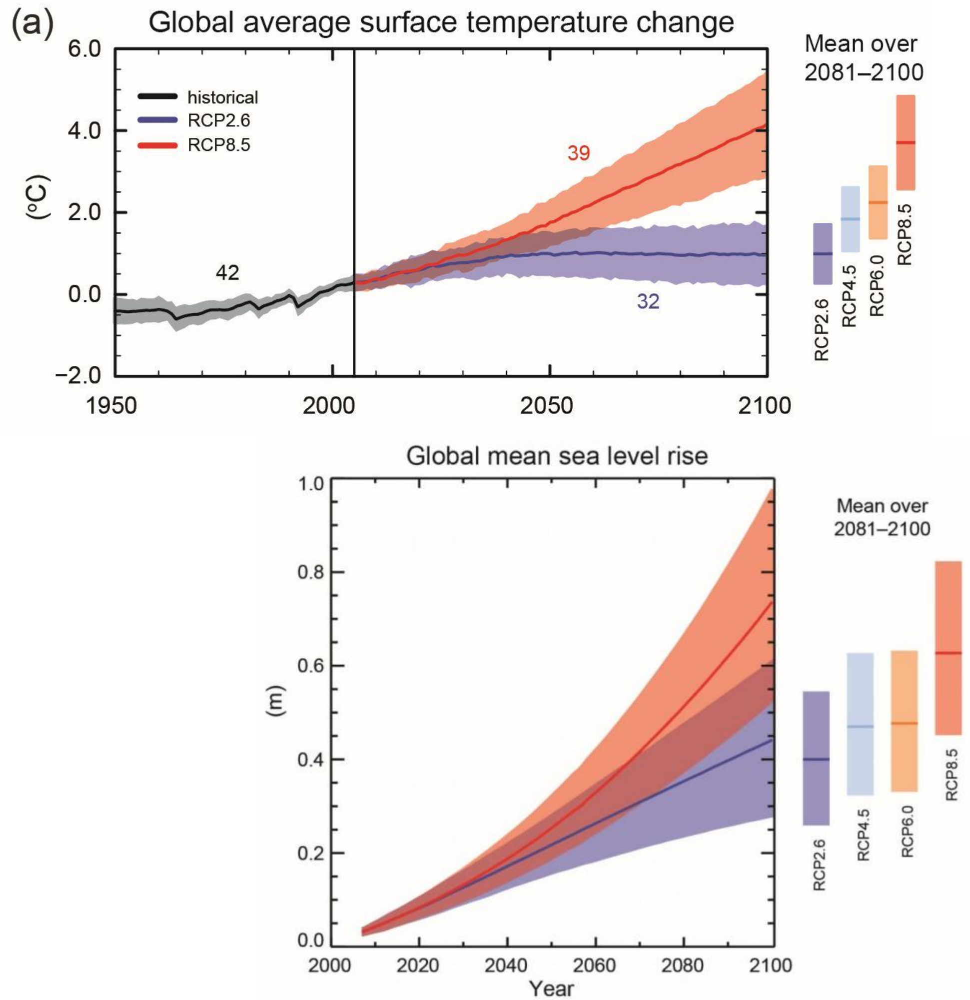
Halting surface warming slows sea-level rise but doesn't stop it



Conclusions from simple global climate models

- No such thing as a "observational" estimate of an unobservable quantity: all estimates involve a combination of observations and modelling.
- At least two response-timescales are needed to reproduce changes in global mean surface temperature in more complex models.
- Changing feedbacks with state means higher equilibrium warming than predicted by recent energy budget.
- Stable temperatures = constant rate of sea level rise
  - (on century timescale)

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