Climate change forcing using simple physics

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Outline

- Motivation
  - -the debate about empirical evidence of climate change
  - -the debate about the realism of climate models
  - -is there a way out?
- The magnitude of the anthropogenic forcing of climate
  - -carbon dioxide forcing
  - -physically achievable equivalents
  - -equivalent changes in the planetary heat balance
- Stepping back
- Conclusions

Part 1. Motivation

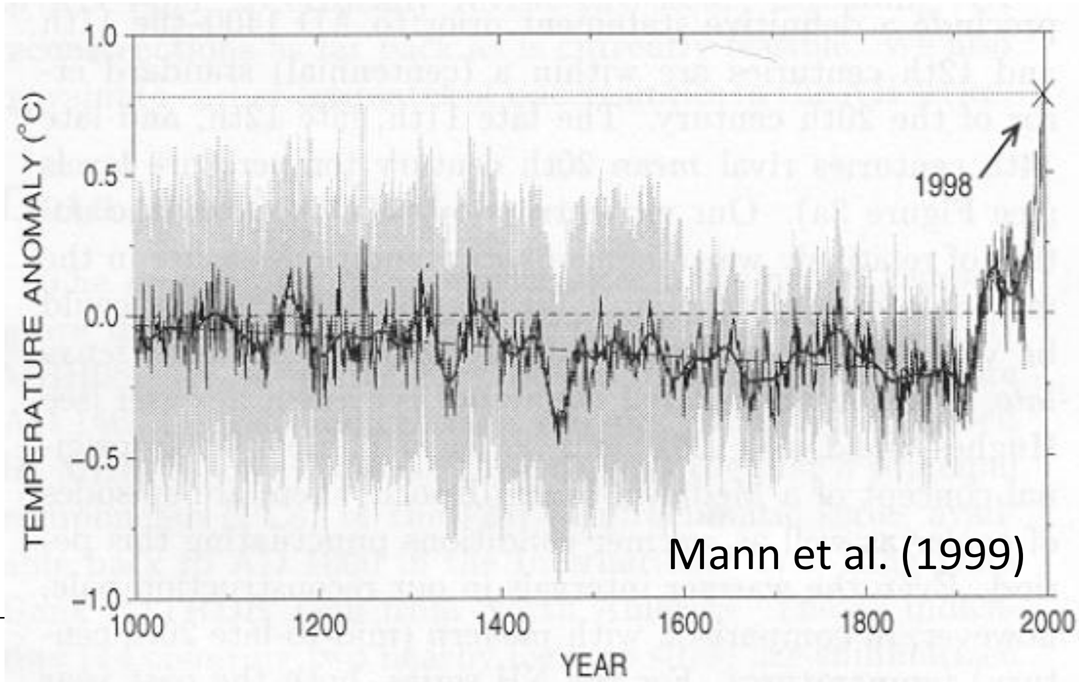
- Illustrate the debate about empirical evidence of climate change: ***the "Hockey stick" & statistics***

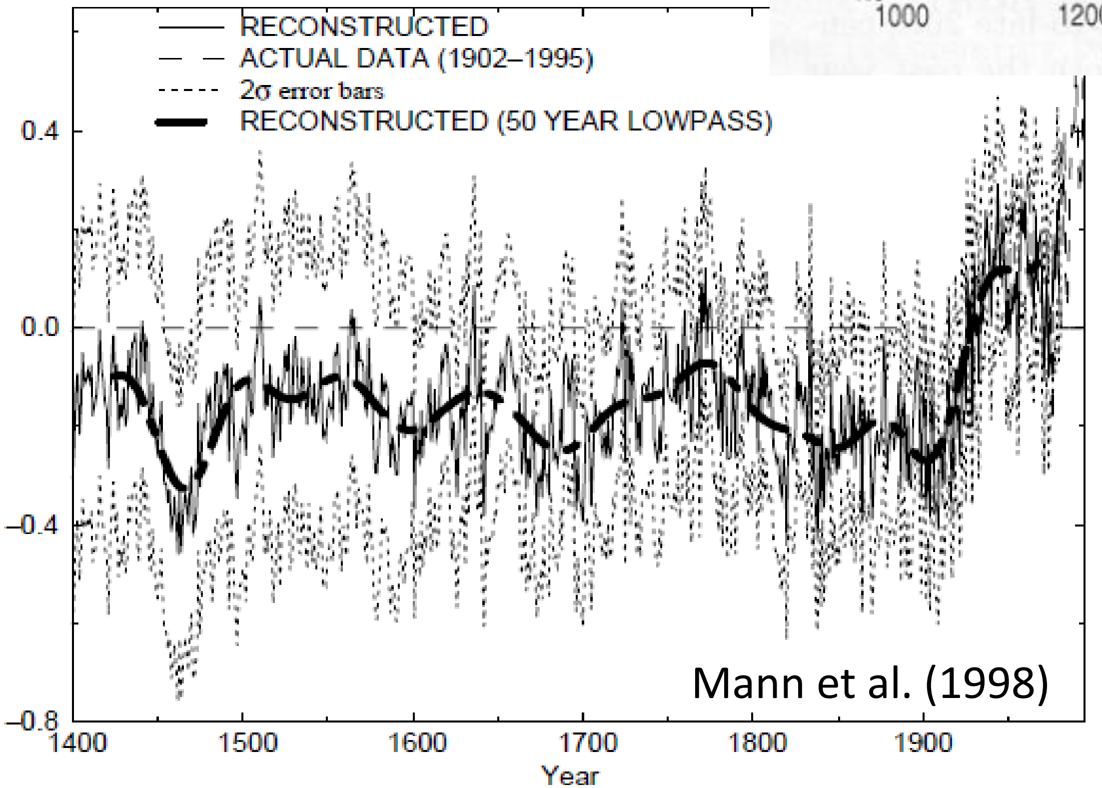
- Illustrate the debate about the accuracy of climate predictions: ***climate sensitivity & coupled climate models***

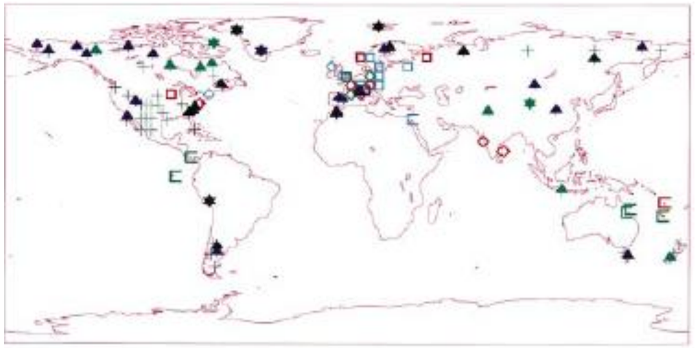
- Is there a way out of these two topics (especially for non experts!)...?

The "Hockey stick"

Northern Hemisphere surface temperature reconstruction



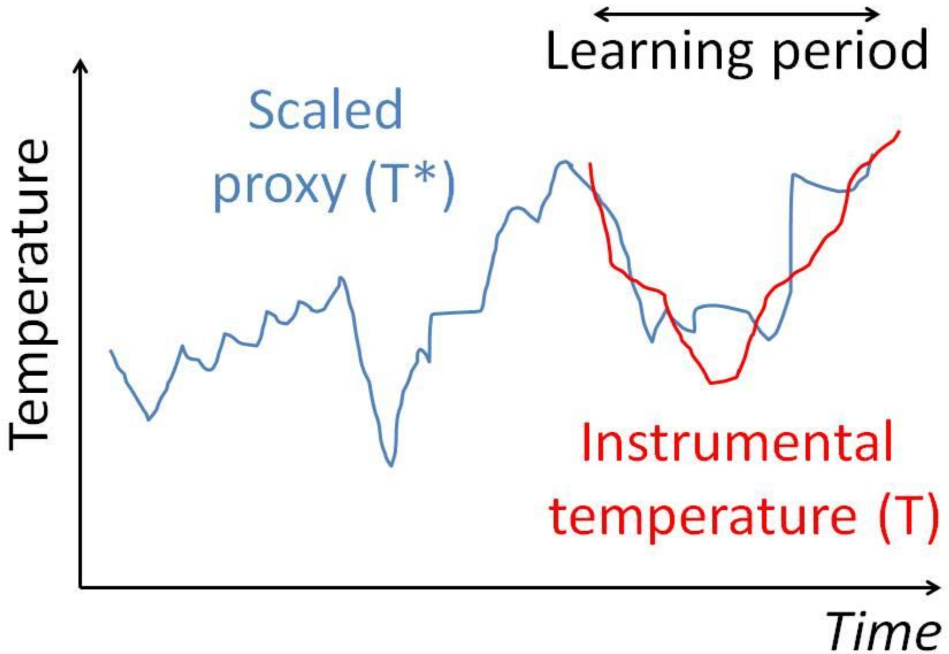




Location of tree rings, ice cores, corals proxy records + temperature and precipitation

Some criticisms of the "Hockey stick"

- Low dimensionality & stationnarity of surface temperature variability is assumed.
- Loss of variance (von Storch et al., 2004):



Correlation between proxy and instrumental records

$$\sigma_{T*}^2 = r^2 \sigma_T^2$$

$$< \sigma_T^2$$

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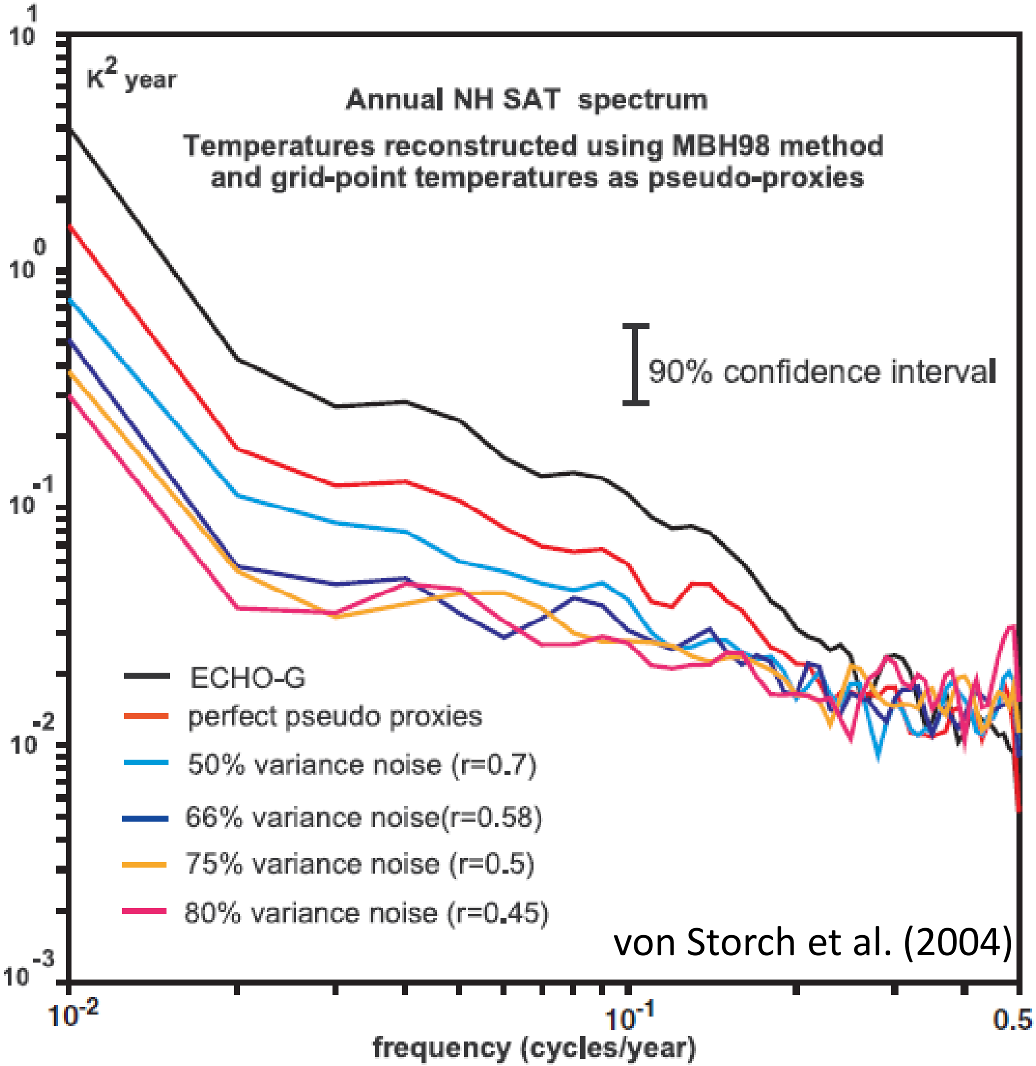

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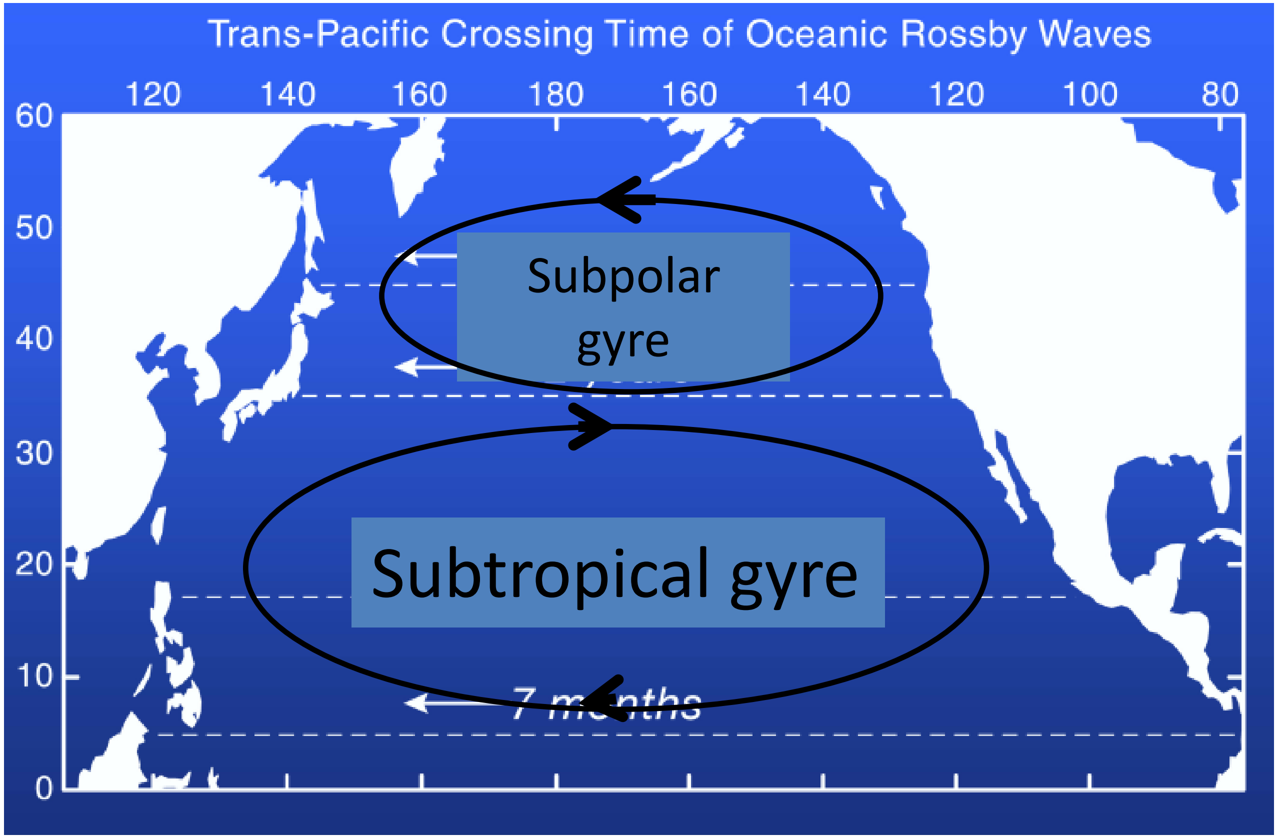
One out of many reasons for these long timescales: ocean dynamics

- The ocean adjusts to wind and buoyancy forcing through slowly propagating Rossby waves



Courtesy of Dudley Chelton

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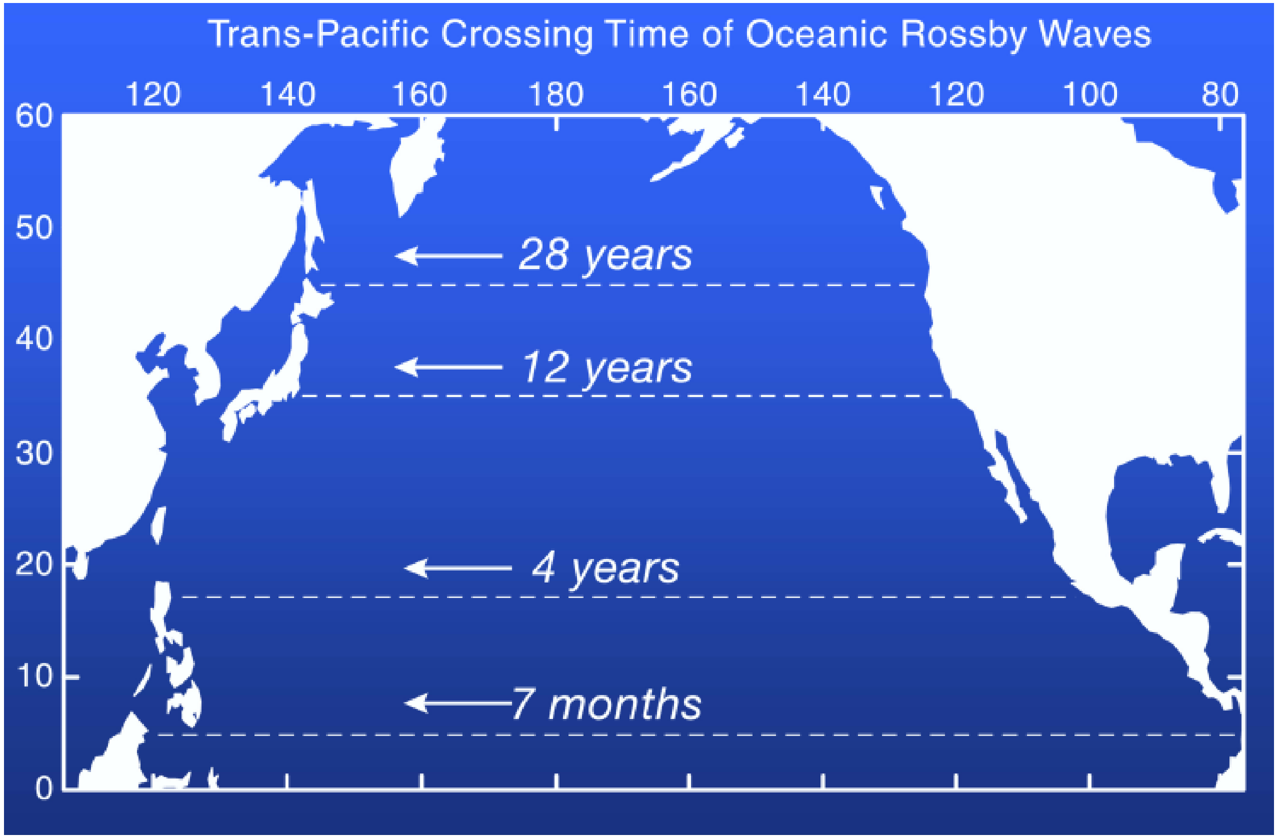

Courtesy of Dudley Chelton

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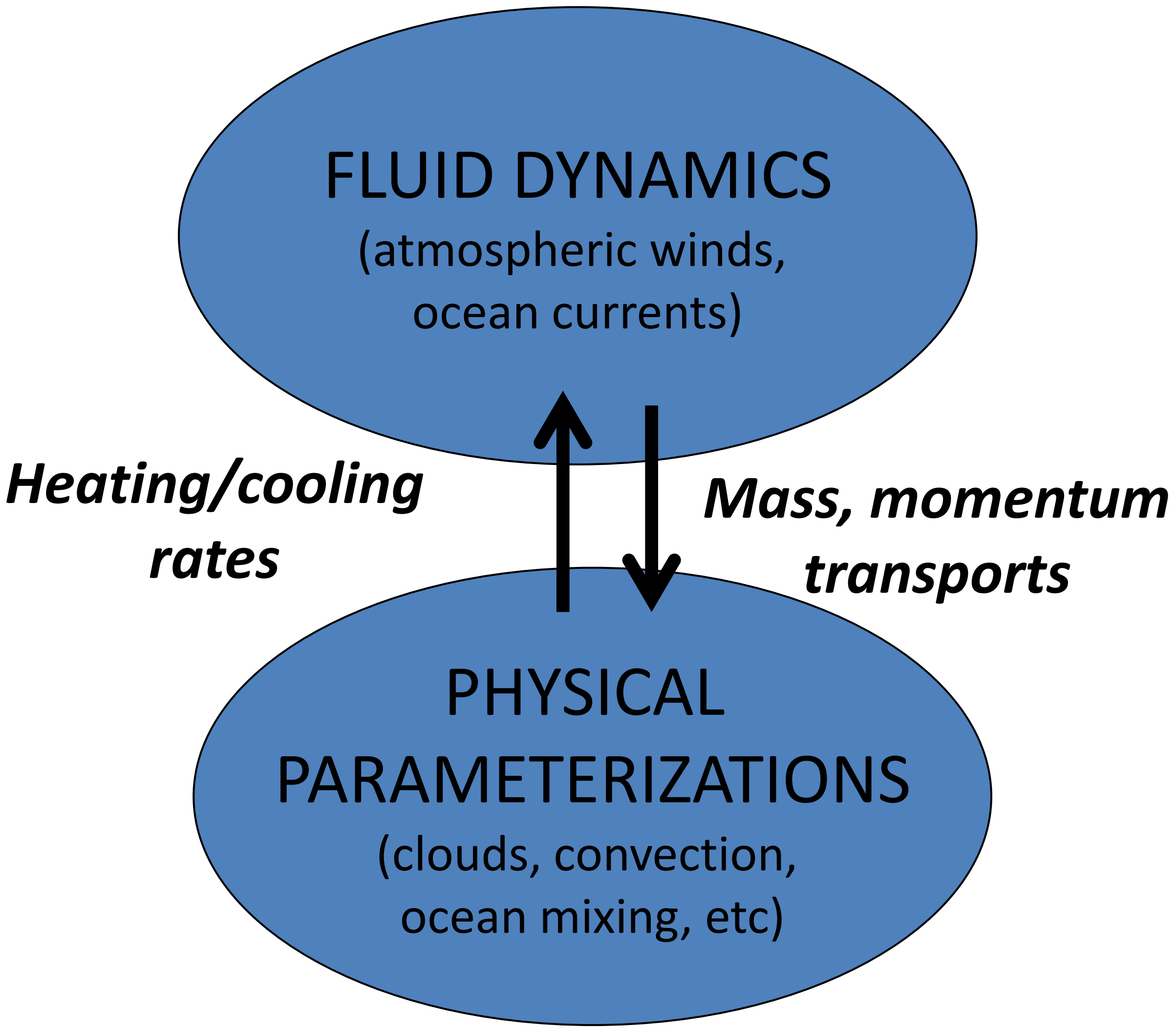
- Is there a way out of these two topics (especially for non experts!)...?

Climate models

- About 6X15X180X90≈1-2 million of prognostic variables for Oceans and Atmosphere.

- Climate models are very large systems of coupled, non linear, ordinary differential equations.



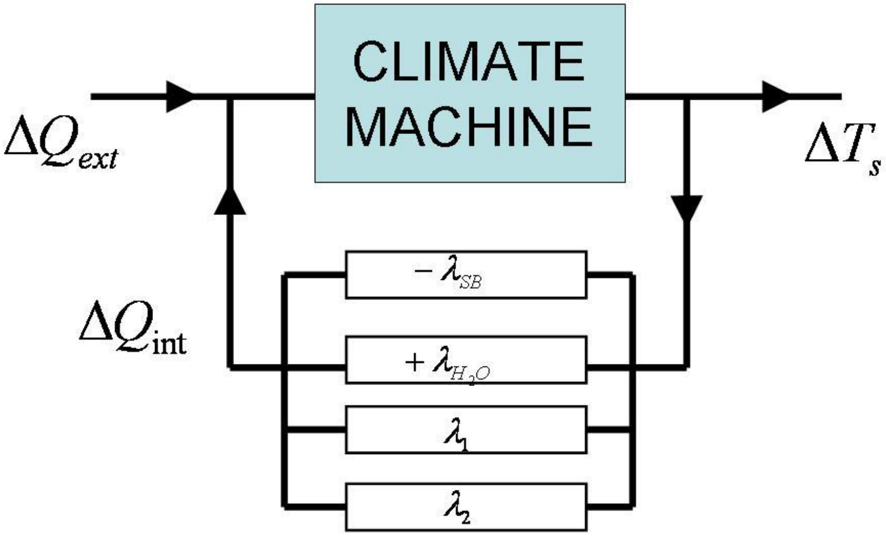
Climate sensitivity

- Defined as the equilibrium change in global surface temperature in response to a doubling of atmospheric CO2 concentrations
  (2K-4.5K in the latest IPCC report).

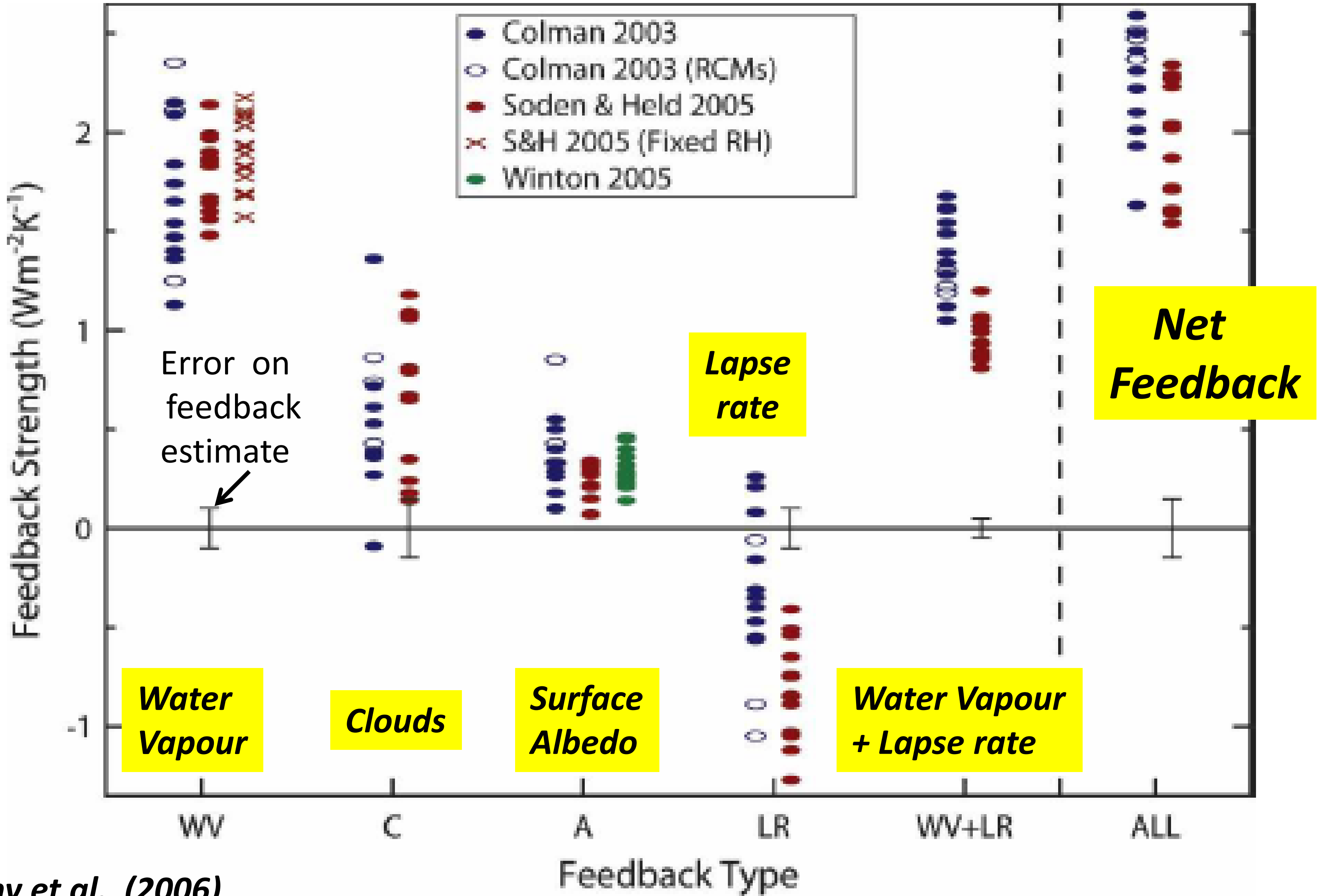
$$\Delta T_S = \frac{\Delta Q_{ext}}{\lambda_{SB}} \frac{1}{1 - \sum_i \lambda_i / \lambda_{SB}}$$

- Analyzed within a feedback framework

- “Charismatic” quantity
  (Global surface temperature is often chosen as a convenient metric for policy studies)



Climate feedbacks in models



Bony et al. (2006)

The bottom line...

- Climate models and instrumental / proxy records are fascinating tools to understand the Earth’s climate.

- These tools are however imperfect and, as a result, potentially subject to endless debates regarding the anthropogenic forcing of climate.

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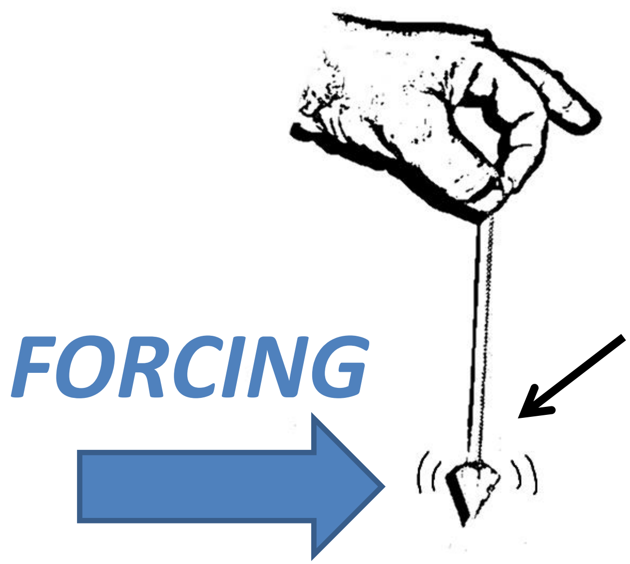
My personal take on this problem...

- For a non expert, it might be best to *focus on the magnitude of the anthropogenic forcing, rather than on the predicted response.*



The climate system
as an erratic pendulum

Part 2. The magnitude of the anthropogenic forcing of climate

- The “radiative forcing” of carbon dioxide

  (NB: CO2 is the only anthropogenic forcing considered here)

- Equivalent changes using simple physics

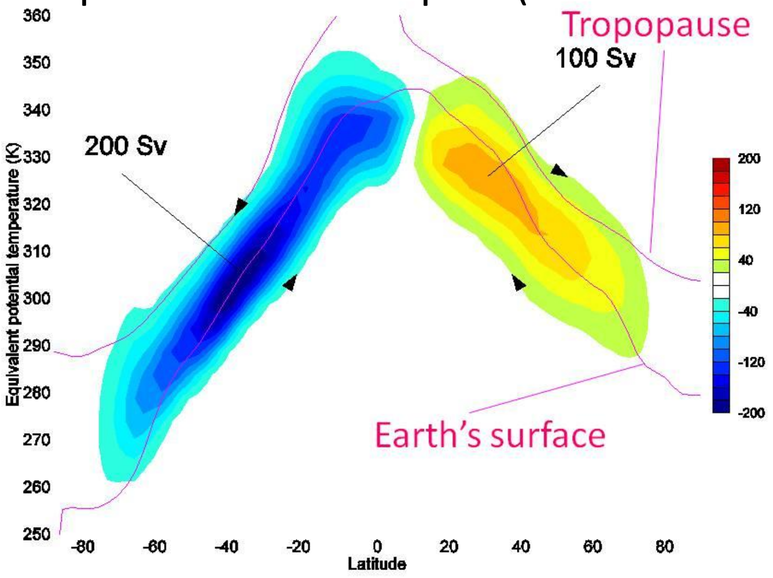
- Equivalent changes in planetary radiation

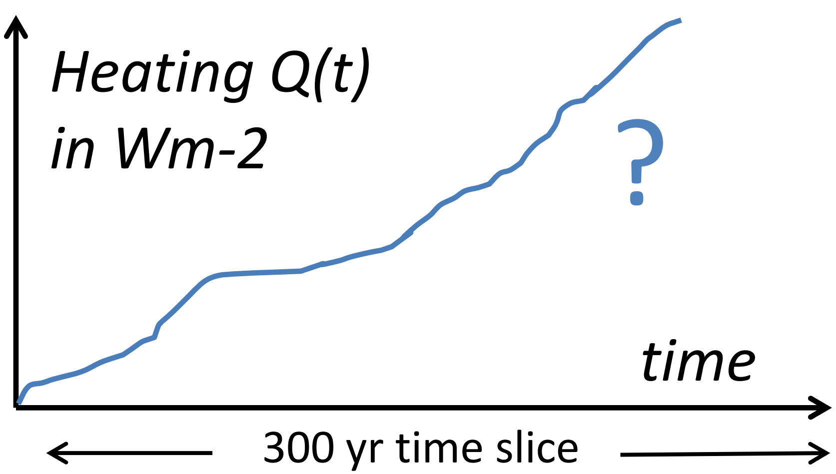
"Modelling" strategy

- Focus on a climate system below the tropopause (i.e., lower atmosphere, oceans, etc).
- Construct a simple time dependent formula for the heating of this system resulting from the emission of carbon dioxide.

t = 0 start of the industrial revolution

Atmospheric mass transport (JJA 1980-2000)





Instrumental records

Name	Code	Location	1981	1982	1983	1984	1985	1986	1987
South Pole	SPO	90°S	38.5	39.3	40.7	42.2	43.6	44.6	46.8
Halley Bay	HBA	76°S, 26°W			41.2	—	—	45.0	47.2
Palmer Station	PSA	65°S, 64°W		39.5	40.9	42.7	43.9	—	47.0
Cape Grim	CGO	41°S, 145°E				42.5	43.7	44.6	46.5
Amsterdam Island	AMS	38°S, 78°E		39.3	41.1	42.4	43.9	45.0	—
Samoa	SMO	14°S, 171°W	39.3	40.3	41.4	43.5	44.7	45.2	47.1
Ascension Island	ASC	8°S, 14°W	39.8	40.7	42.6	43.9	45.0	45.8	48.1
Seychelles	SEY	5°S, 55°E	40.2	40.5	41.1	44.1	45.2	46.1	—
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Shemya Island	SHM	53°N, 174°E						48.9	50.0
Cold Bay	CBA	55°N, 163°W	41.0	41.8	43.3	45.5	47.2	48.1	49.7
Station "M"	STM	66°N, 2°E	41.8	42.1	43.1	45.5	46.5	48.2	48.8
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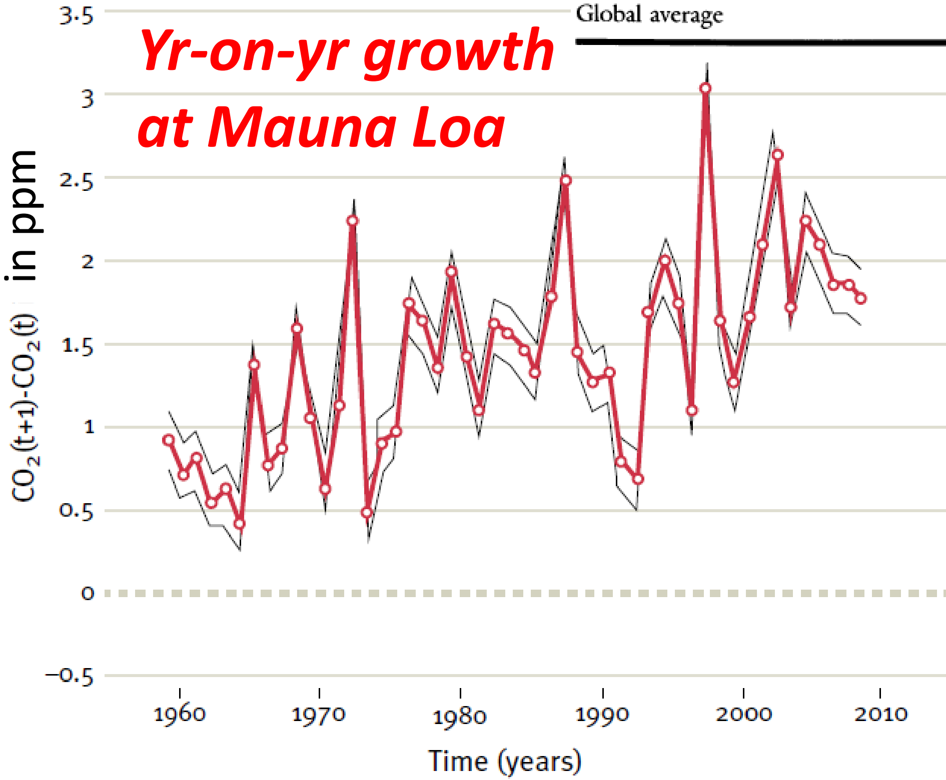
Alert	ALT	83°N, 62°W						48.0	49.5
Global average			40.00	40.65	42.03	43.91	45.27	46.26	48.10

Tans et al. (1990)



"Global" observations of atmospheric carbon dioxide concentrations (expressed as excursion above 300ppm)

$$N_{CO_2} / N_{air} = 300.10^{-6}$$

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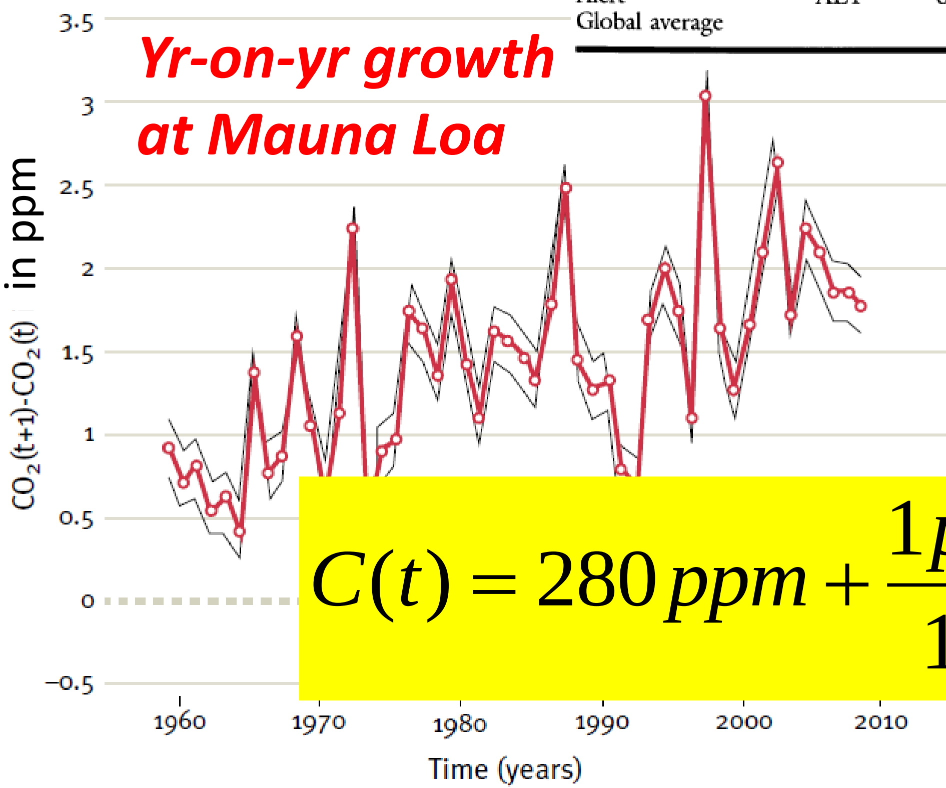

$$C(t) = 280\,ppm + \frac{1\,ppm}{1\,yr}\,t$$

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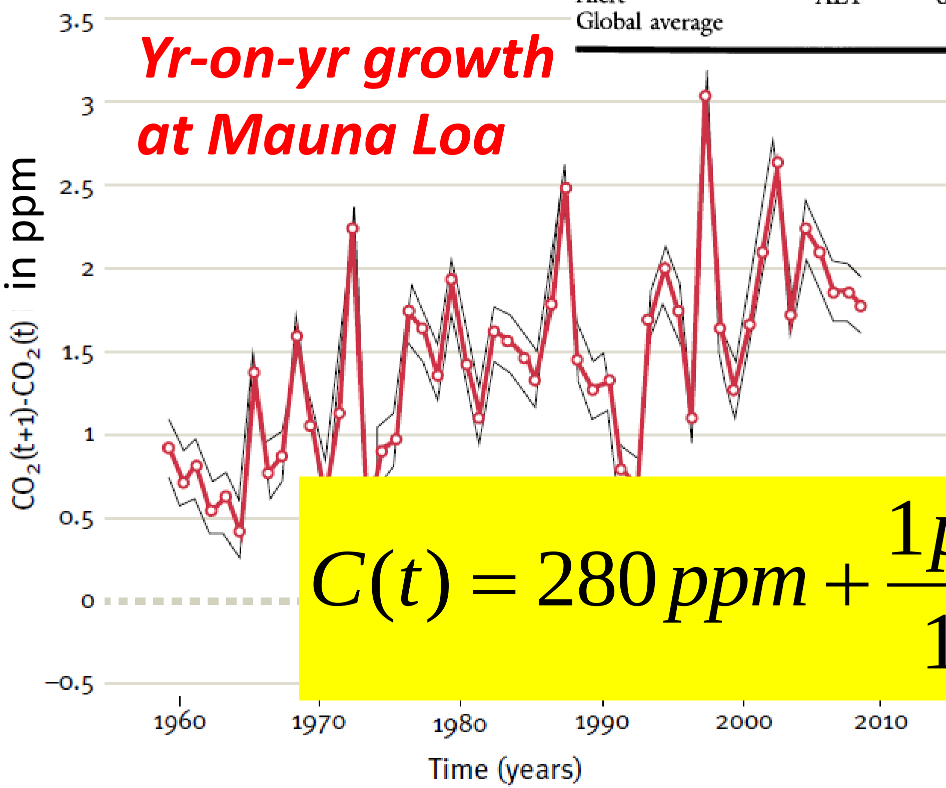
Global average									10



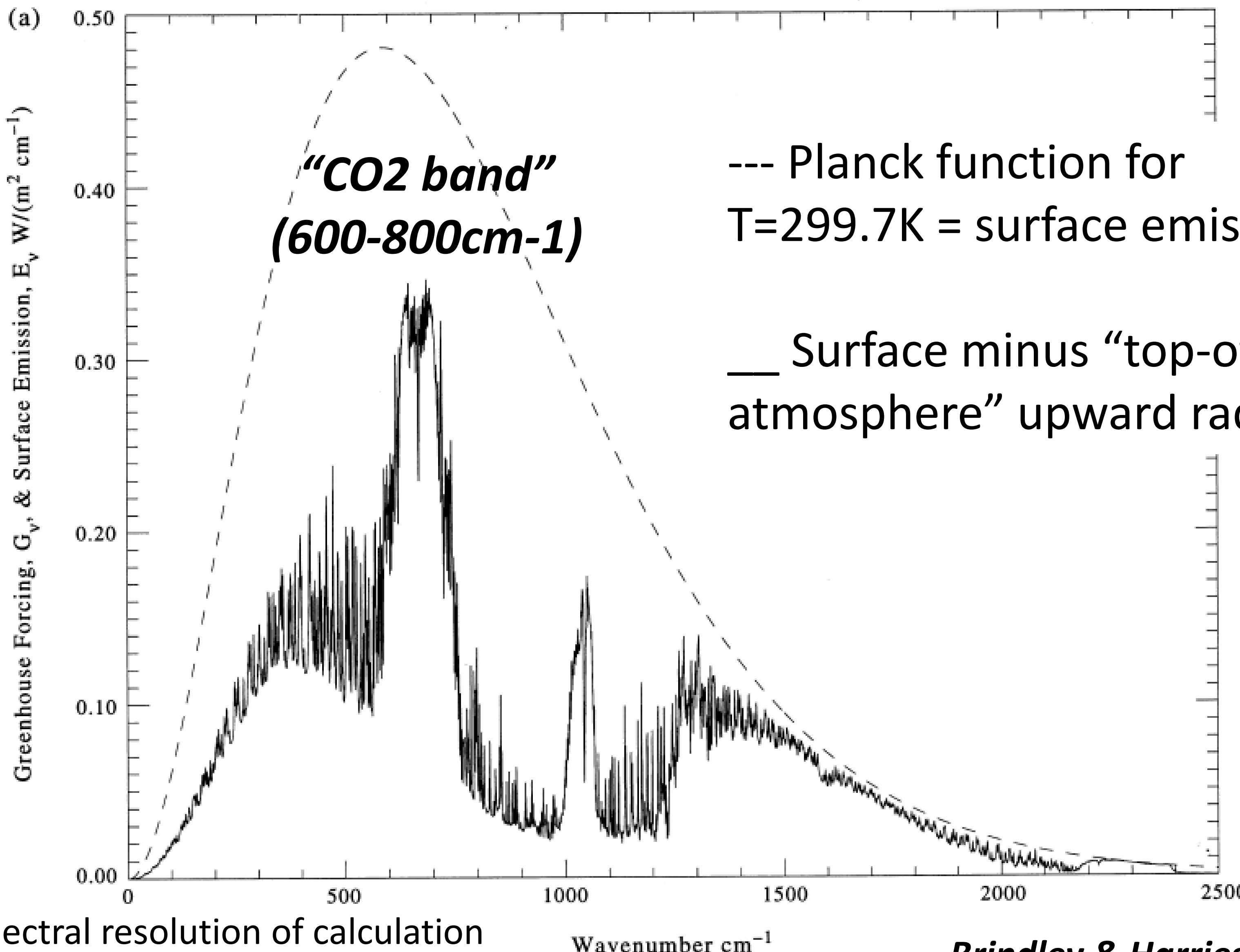
$$C(t) = 280\,ppm + \frac{1ppm}{1yr}t$$

Growth rate=1ppm/yr?

-likely smaller near t =0

-larger now: fossil fuel emission amount to about 6 Gt C/yr over the 1980-1999 period, i.e., 3ppm/yr (Sabine et al., 2004).

“Radiative forcing” of CO_2



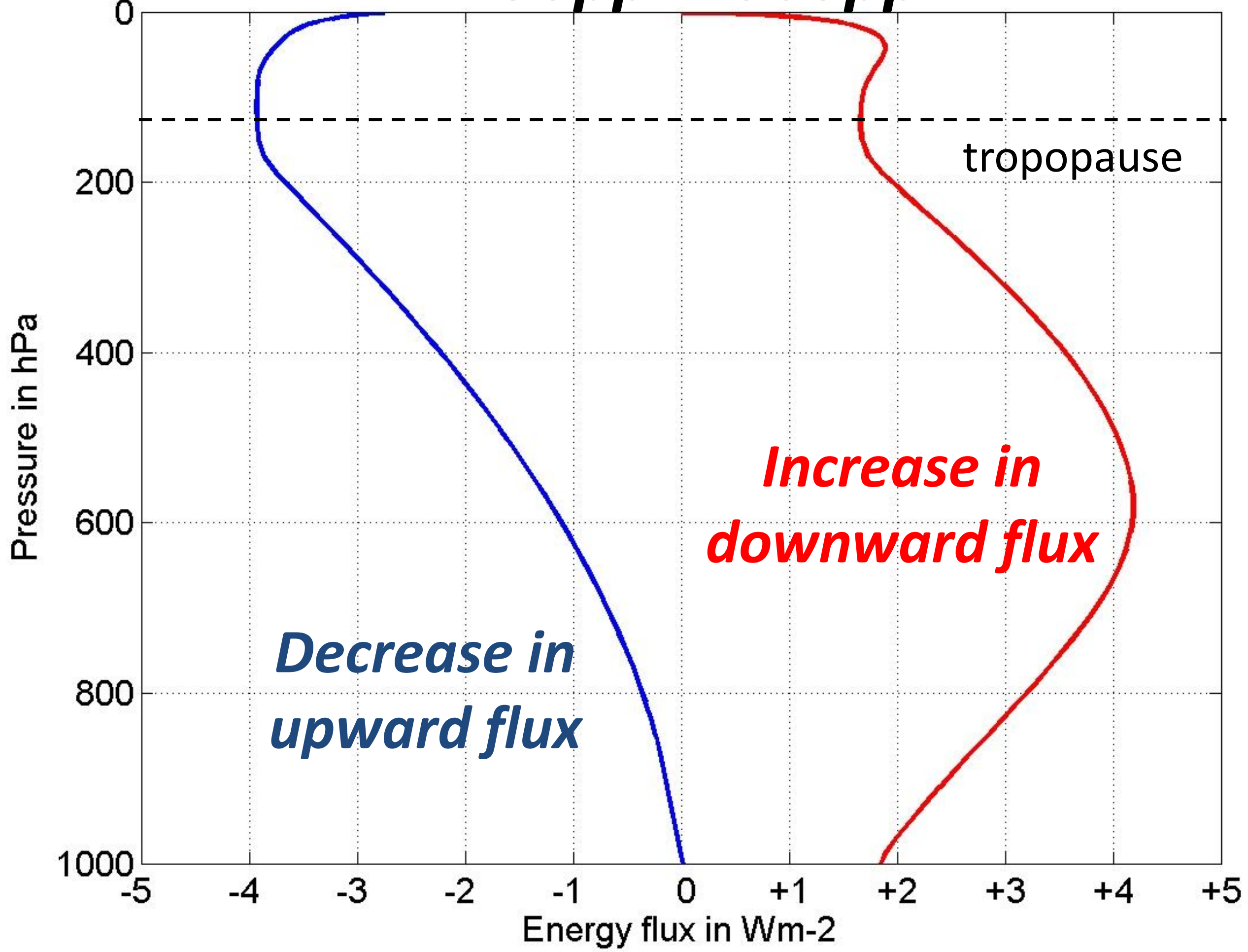
NB: spectral resolution of calculation
is >100 times larger than displayed.

Brindley & Harries (1998)

An example of anthropogenic heating calculation (courtesy of Zhong & Haigh)

- Summer conditions in midlatitudes
- Three atmospheric absorbers included (H2O, CO2, O3)

Change in infrared flux: 736ppm-368ppm



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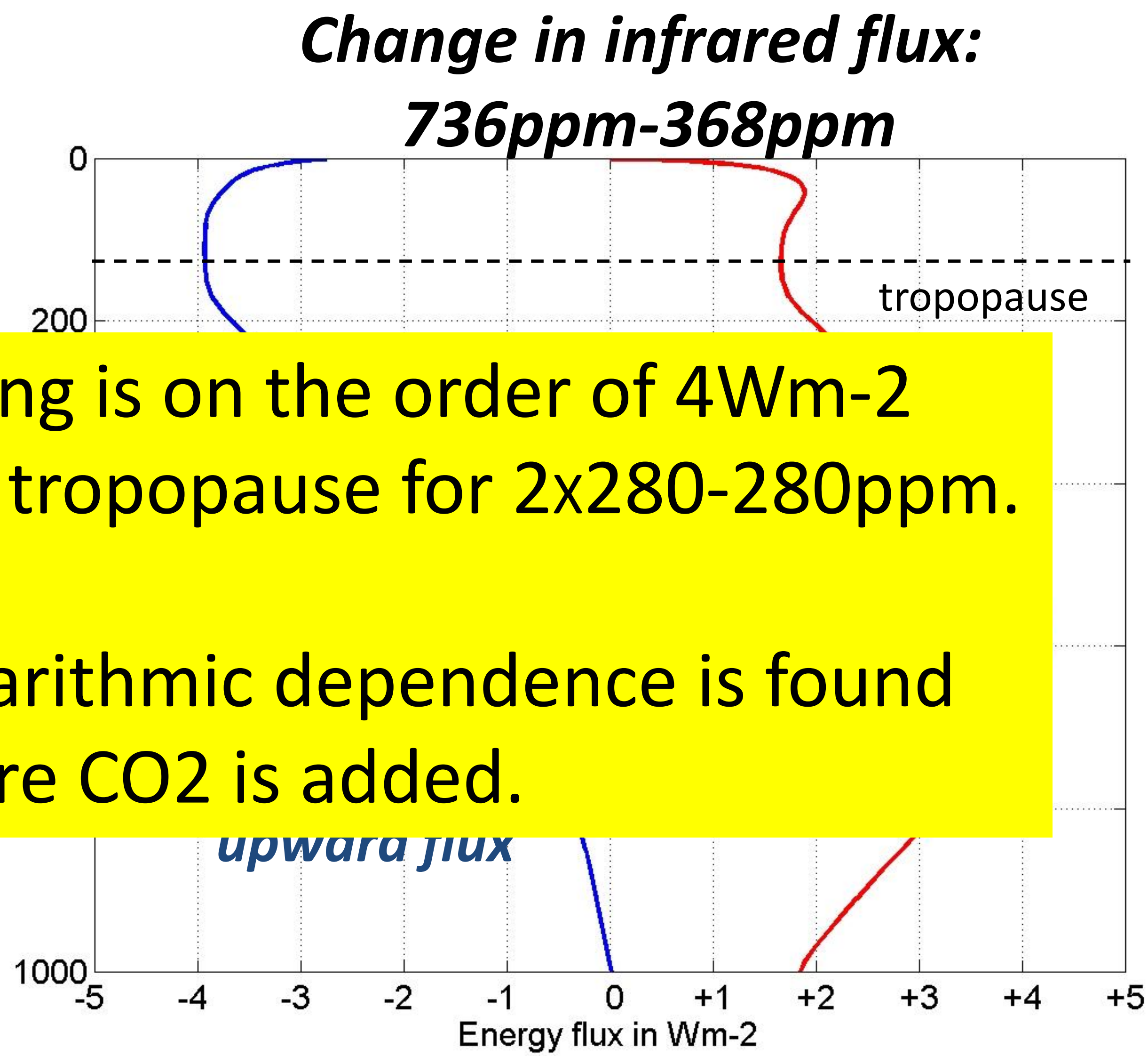


-Heating is on the order of 4Wm-2 at the tropopause for 2x280-280ppm.

-A logarithmic dependence is found as more CO2 is added.

Simple analytical formula for the anthropogenic forcing

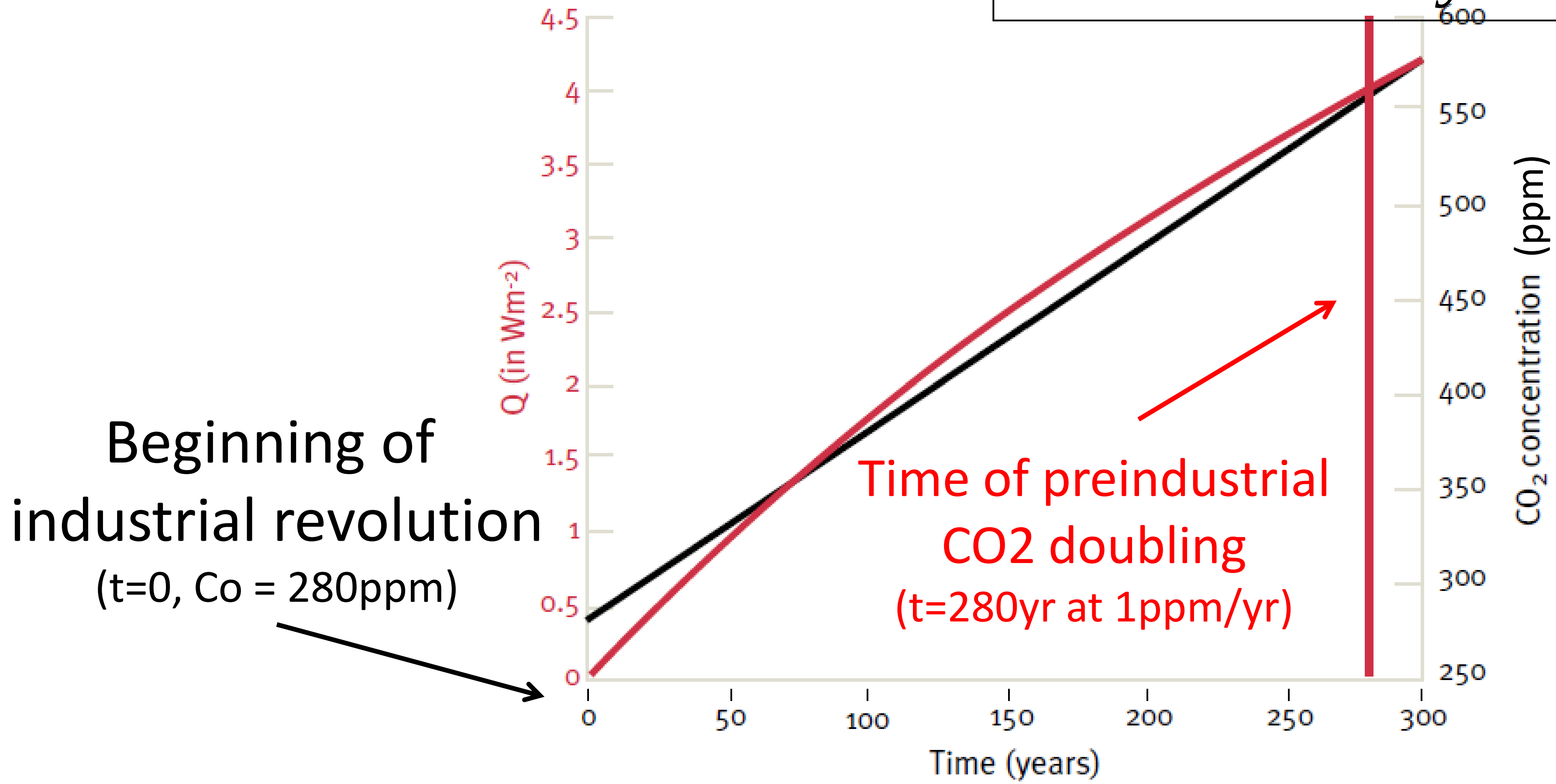
(in Wm-2)

$$Q(t) = 4\log_2 C(t)/C_o$$

with

$$C(t) = 280 + \frac{1ppm}{1yr}t$$

(in ppm)



Part 2. The magnitude of the anthropogenic forcing of climate

- The “radiative forcing” of carbon dioxide

  (NB: CO2 is the only anthropogenic forcing considered here)

- Equivalent changes using simple physics

- Equivalent changes in planetary radiation

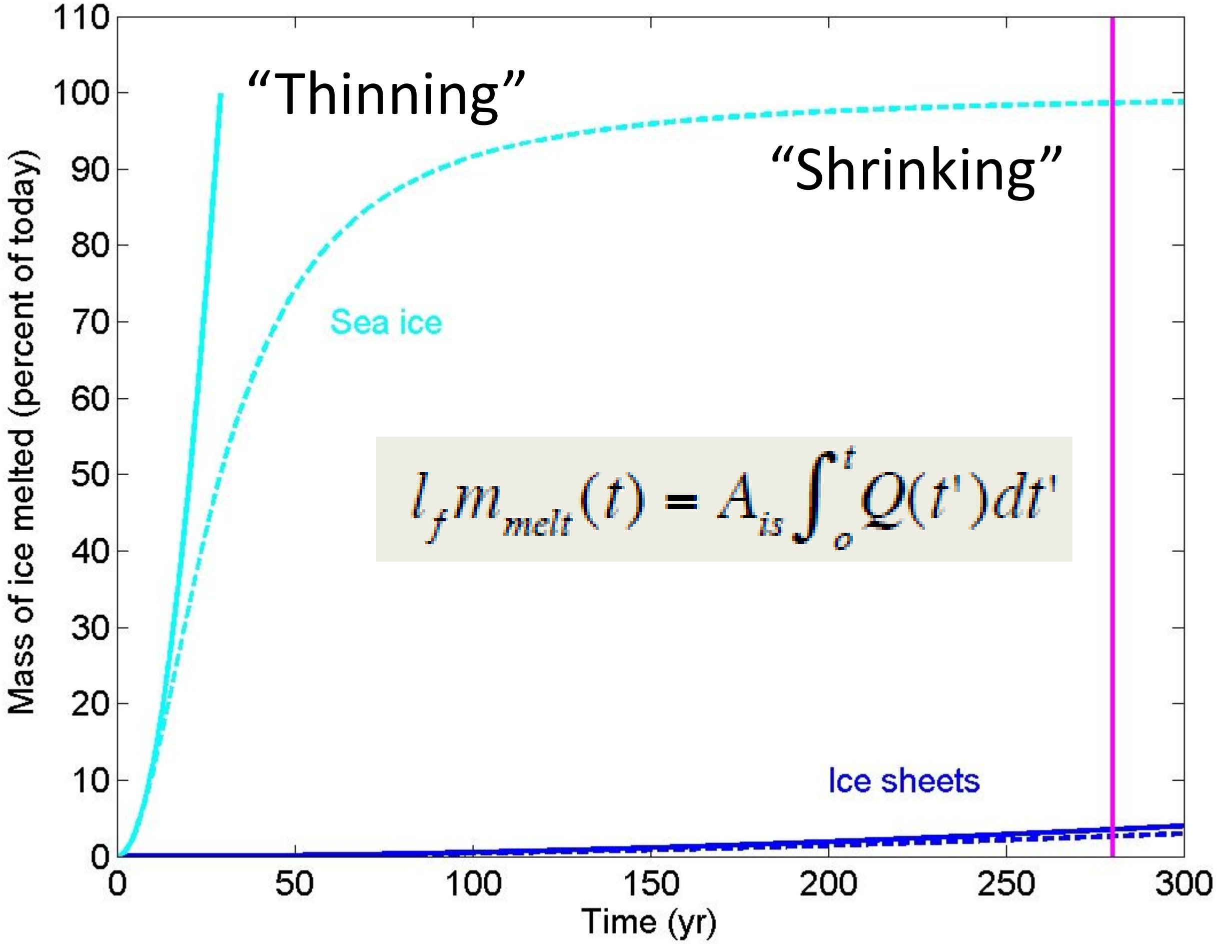
Q ≈ a few Wm-2… So what…?

- Does not tell much to the average person on the street.
- Does not tell much to a climate scientist (?)

Space & Atmospheric Physics group at Imperial College

A first example of physically achievable equivalent to Q(t): ice melting

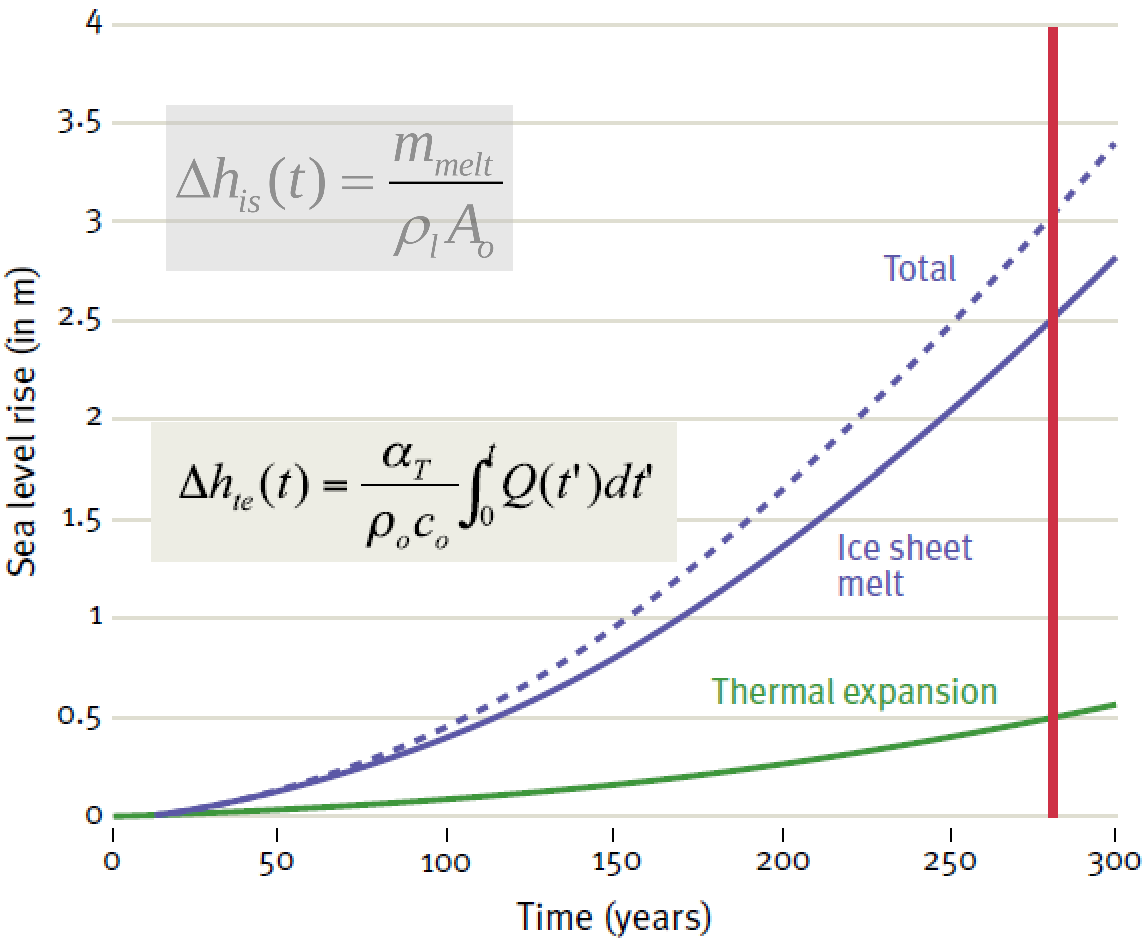
- Ice is a good infrared absorber... So how much ice can be melted as a function of time given Q(t)?



$$l_f m_{melt}(t) = A_{is} \int_o^t Q(t')dt'$$

Second example: sea level rise

- Mass added to the ocean by melting of ice sheet.
- Increase in the volume of the ocean by thermal expansion



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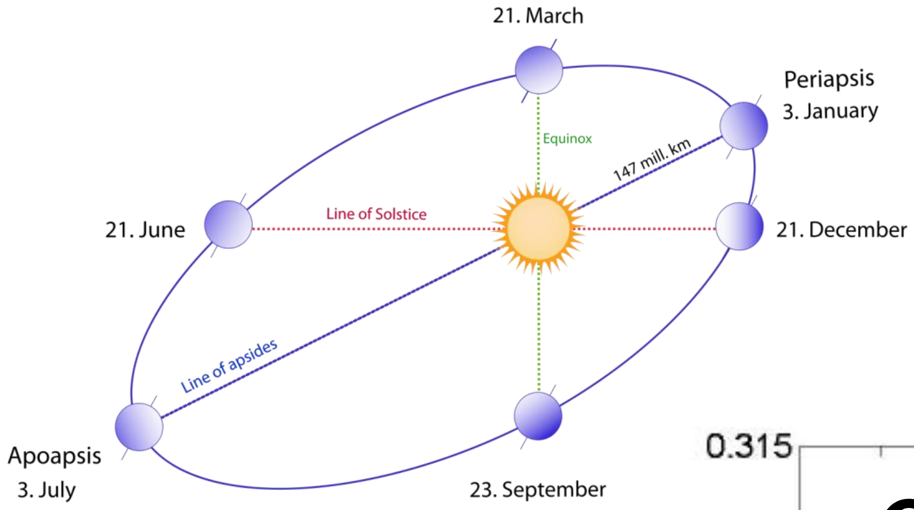
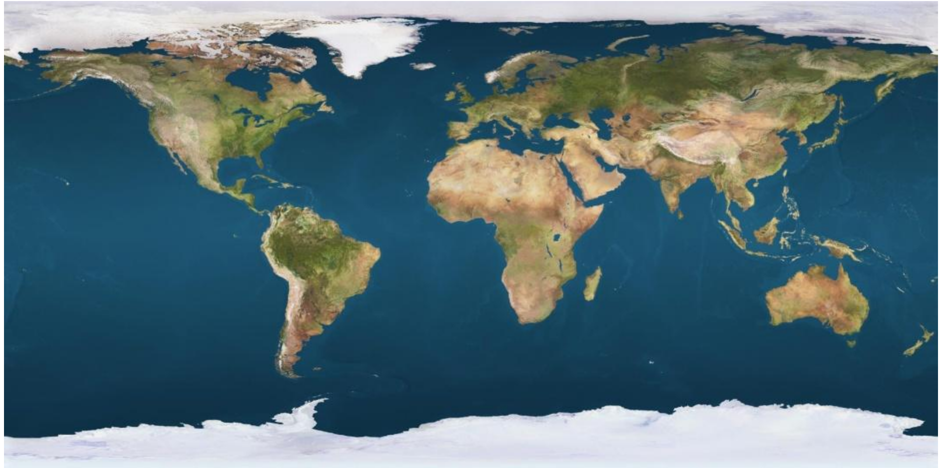
Planetary heat balance

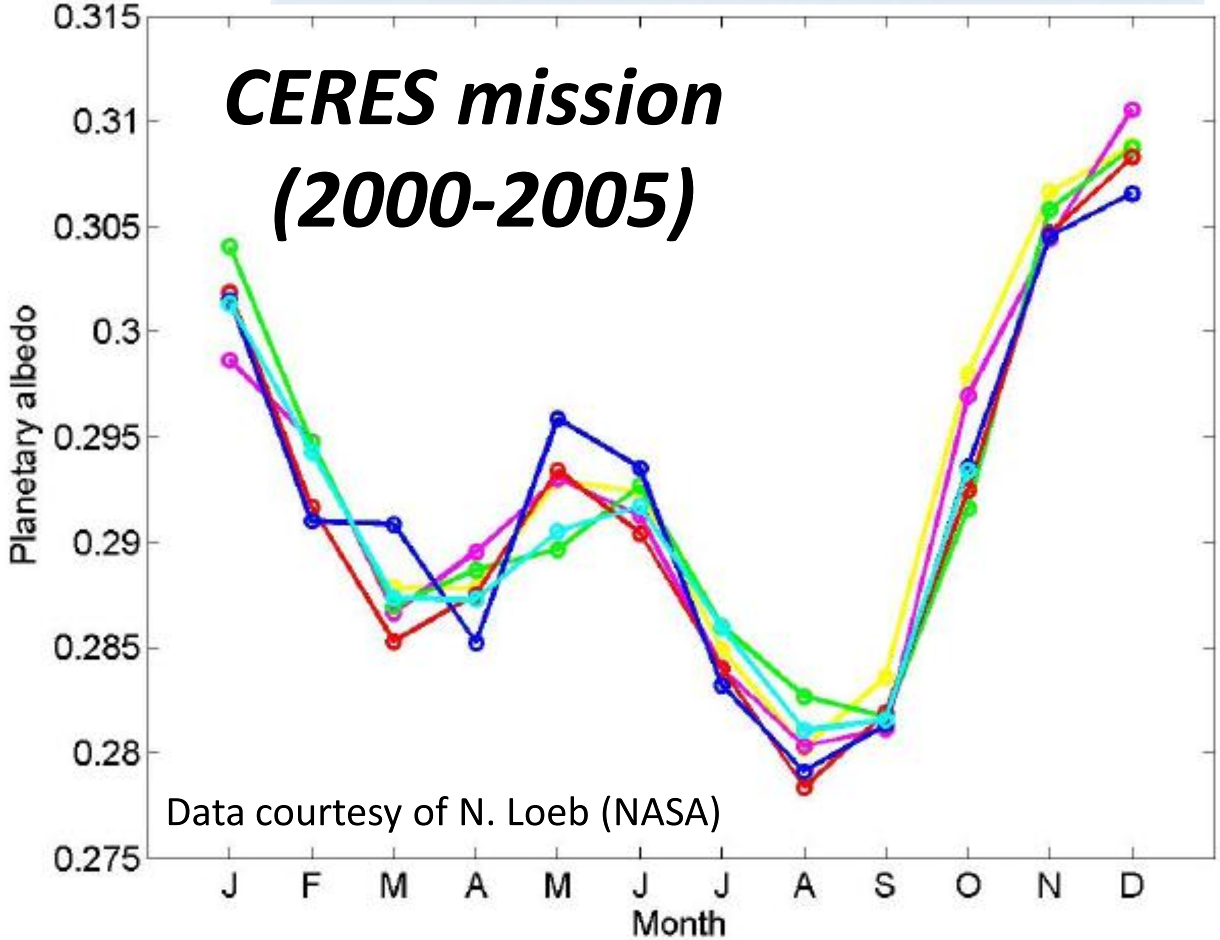
- The Earth absorbs short wavelength radiation from the Sun and reflects a fraction α_P (the planetary albedo)

- The Earth emits infrared radiation to Space

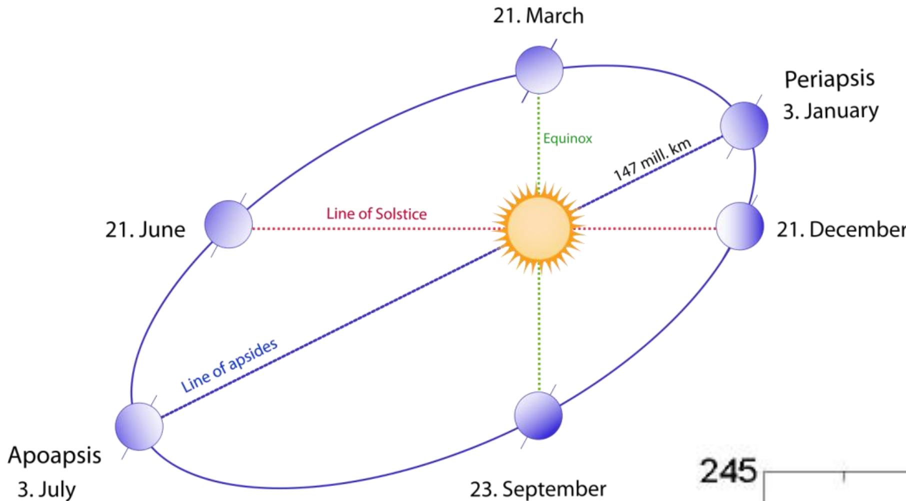


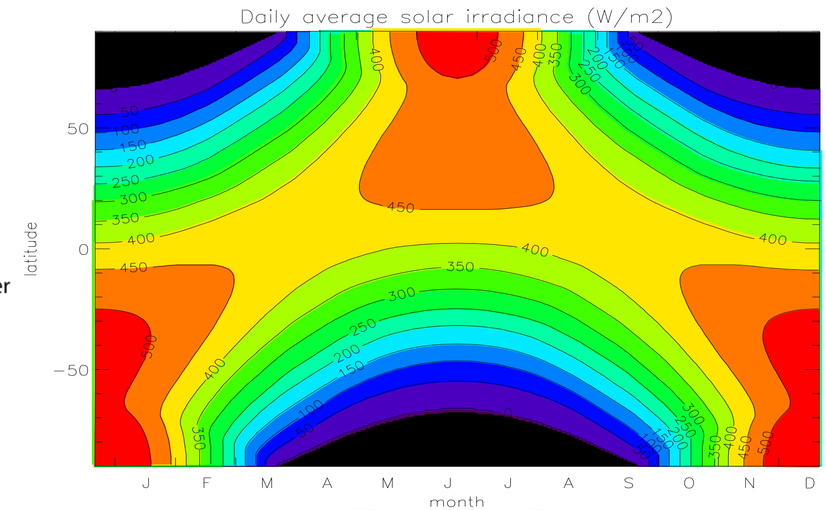


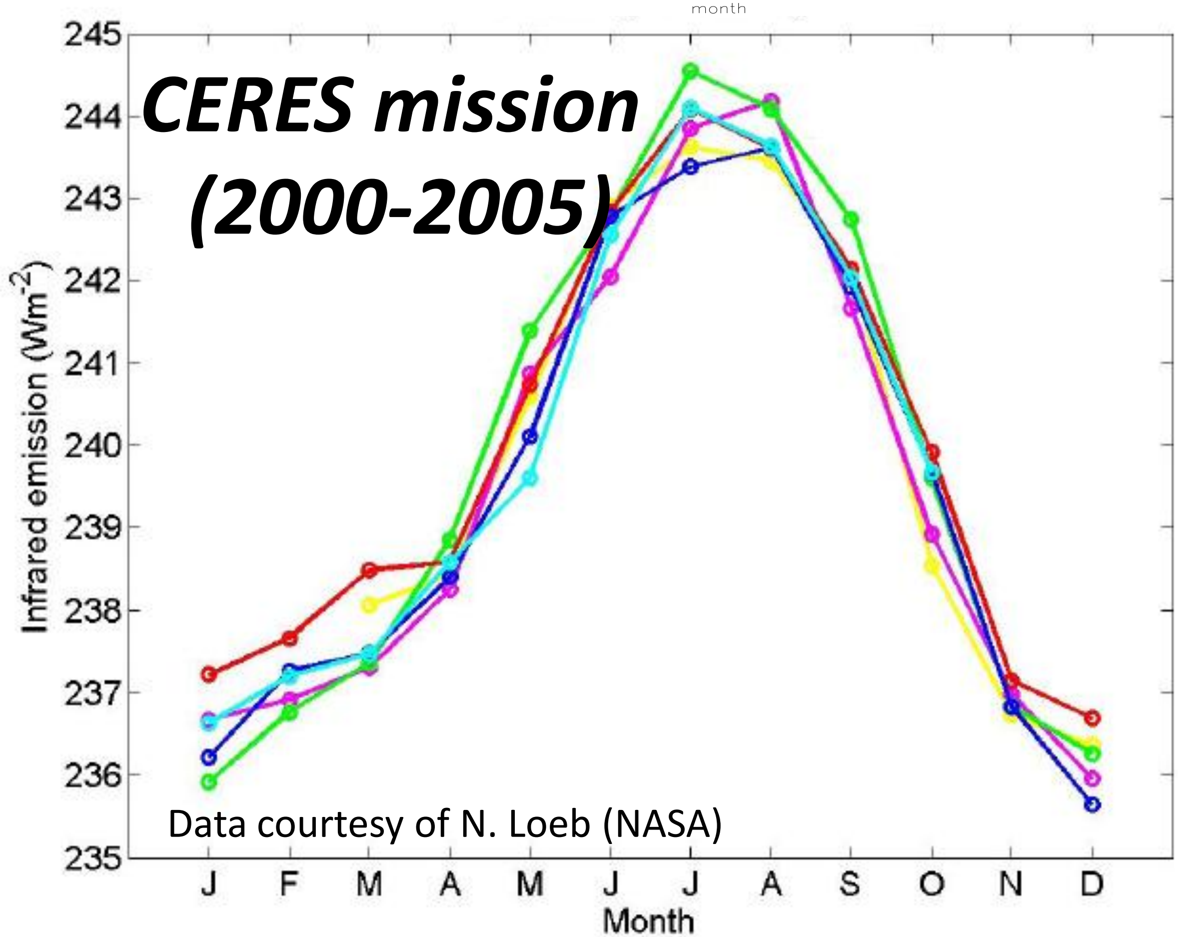
Planetary albedo



Planetary infrared emission

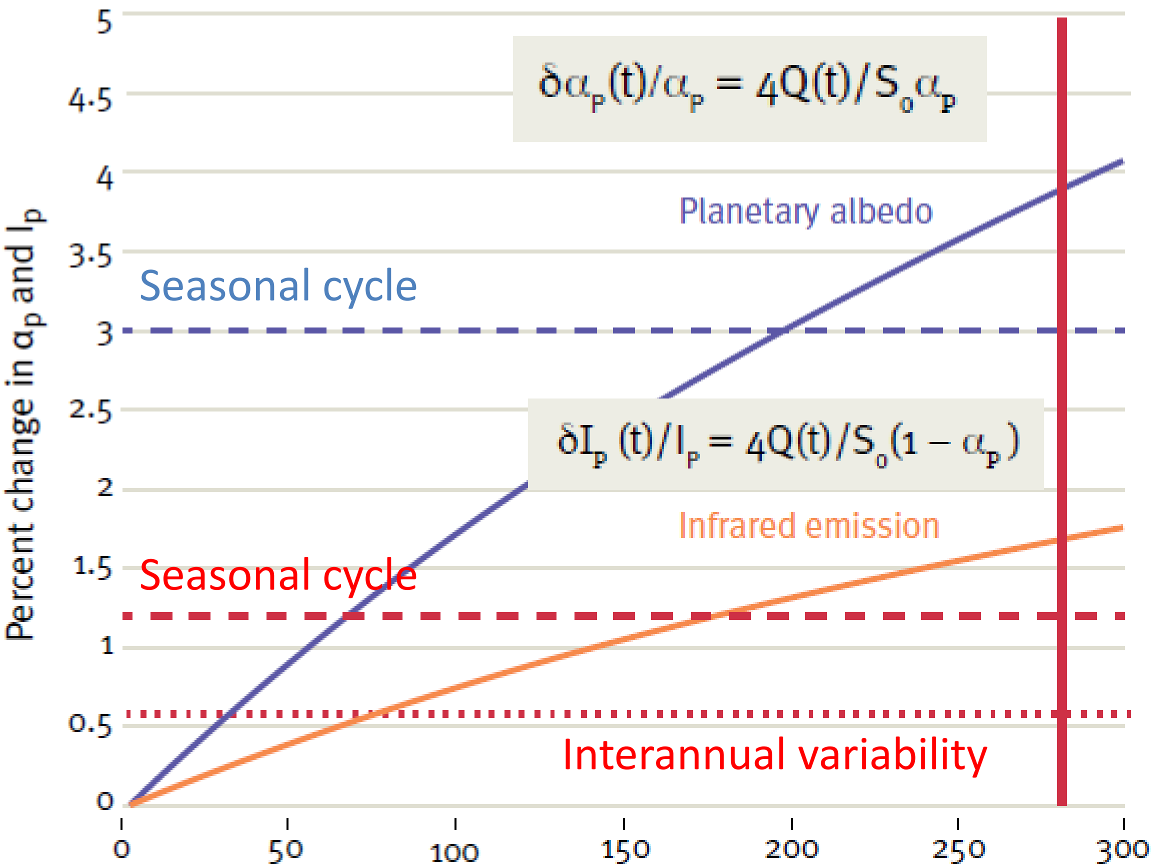






Relative change in planetary emission of the same magnitude as Q(t)

- Equivalent change in planetary albedo α_P
- Equivalent change in infrared emission I_P



Summary of Part 2

- The excess infrared energy due to anthropogenic CO2 emissions is “large” in the sense that it is energetically equivalent to:

*a disappearance of the sea ice in a few decades

*a sea level rise of a few meters in a few hundred years

*Planetary albedo and infrared emission changes of the same order as seasonal changes in these quantities

Part 3. Stepping back

Imperfect climate tools (observations, models)

Large anthropogenic heating (Q)

Part 3. Stepping back

Imperfect climate tools (observations, models)

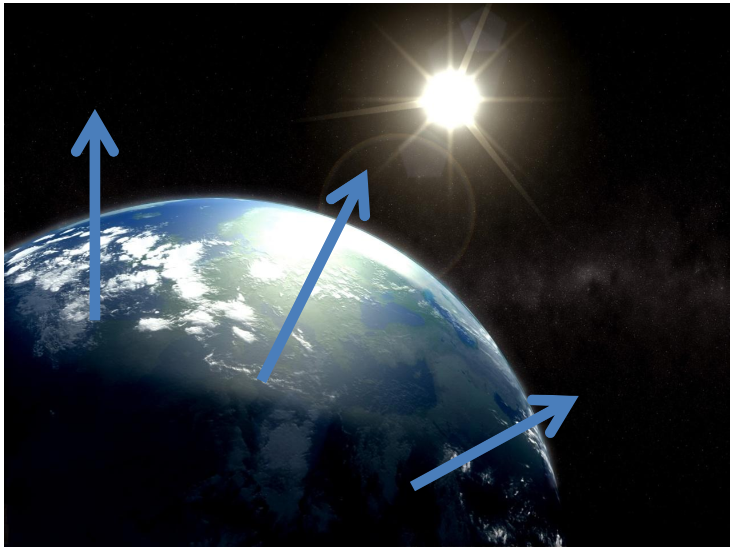
Large anthropogenic heating (Q)

Where is the heat going?

Where is the heat going?

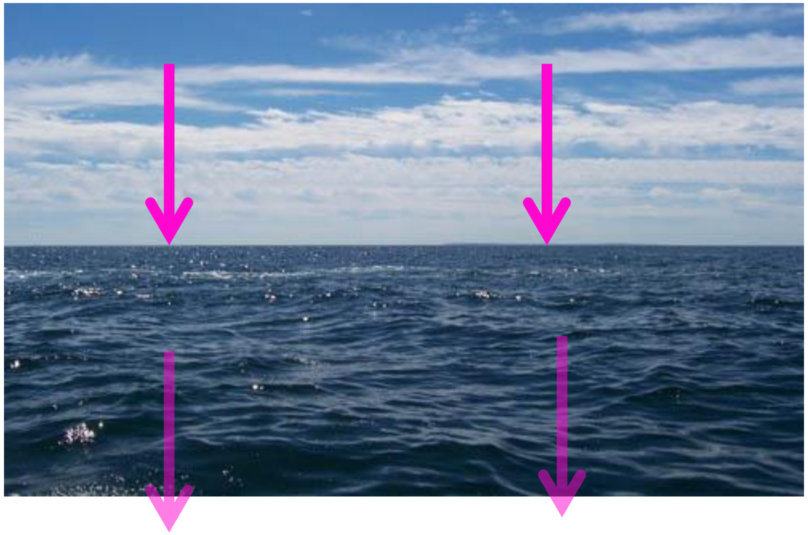
- Surface warms (Ts’), more radiation is emitted to Space: Q ≈ λTs’

Net climate feedback



- Anthropogenic heating is absorbed by the deep ocean: Q ≈ μT’s

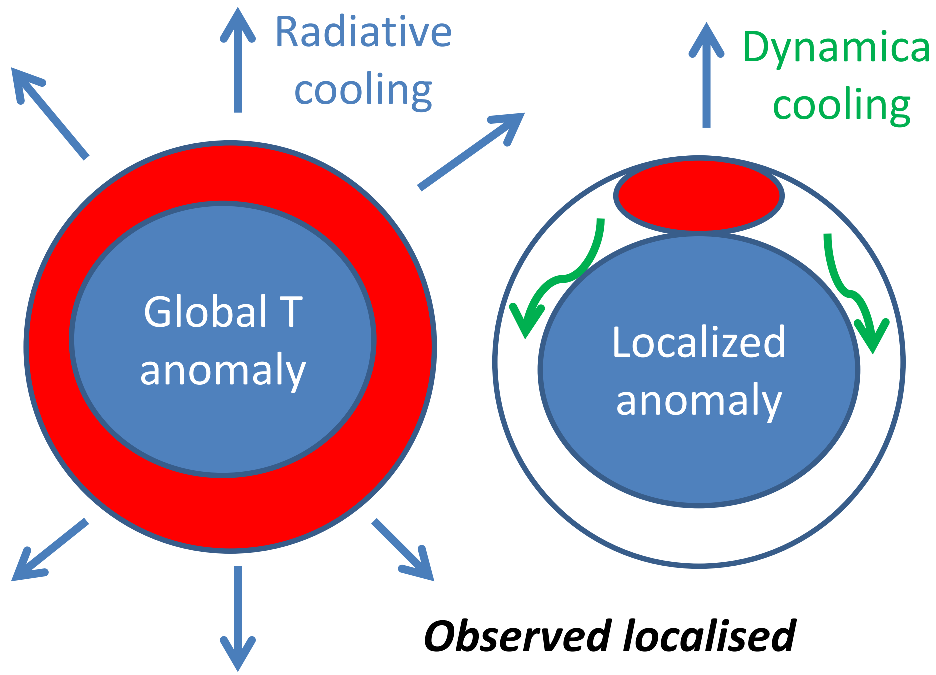
Vertical ocean heat flux sensitivity



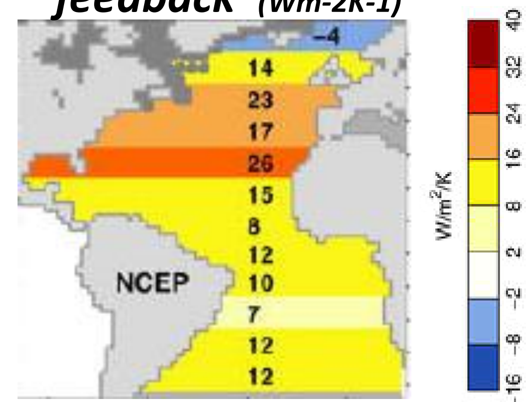
Order of magnitude for λ (net climate feedback)

- Cannot exceed the feedback associated with localised, as opposed to global, surface temperature anomaly.

- This implies λ ≈ a few W m-2 K-1



***Observed localised feedback** (Wm-2K-1)*



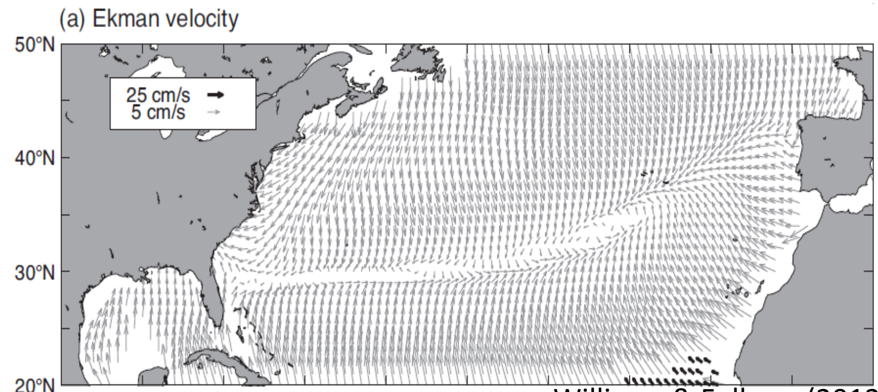
Frankignoul et al. (2004)

Order of magnitude for μ

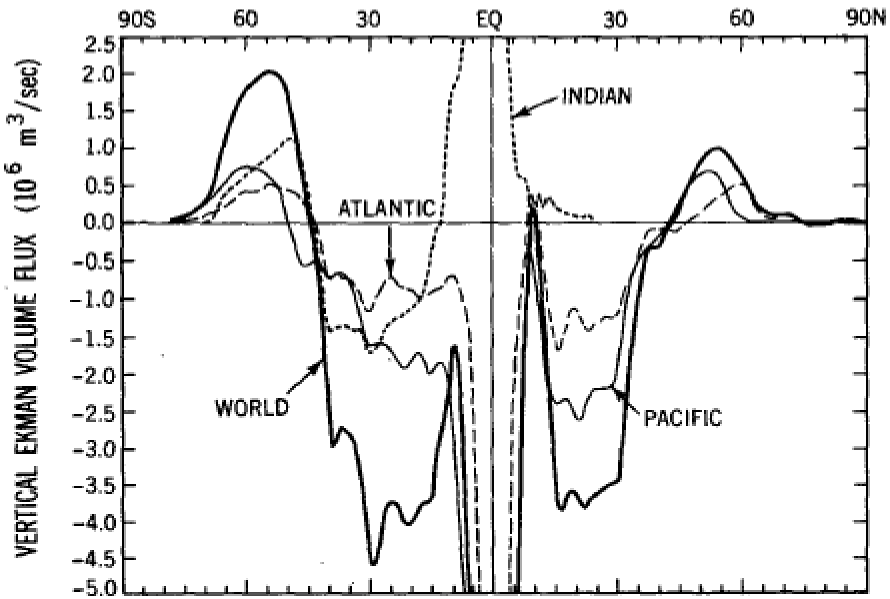
(vertical ocean heat flux sensitivity)

- Focus on only one mechanism: the global downward ocean heat transport driven by the winds.

- This leads to:



Williams & Follows (2012)



Levitus (1988)

$$\mu = \rho_o c_p w_{Ek} \approx 10^3 \times 4.10^3 \times \frac{30m}{yr} = 4Wm^{-2}K^{-1}$$

Where is the heat going?

- $\mu \approx \lambda$ implies that the heating caused by increased carbon dioxide concentrations cannot be simply opposed by an increased planetary emission of infrared radiation. The heat must also significantly be stored in the deep ocean.
- This points to sea level rise as an inevitable consequence of the accumulation of carbon dioxide in the atmosphere.

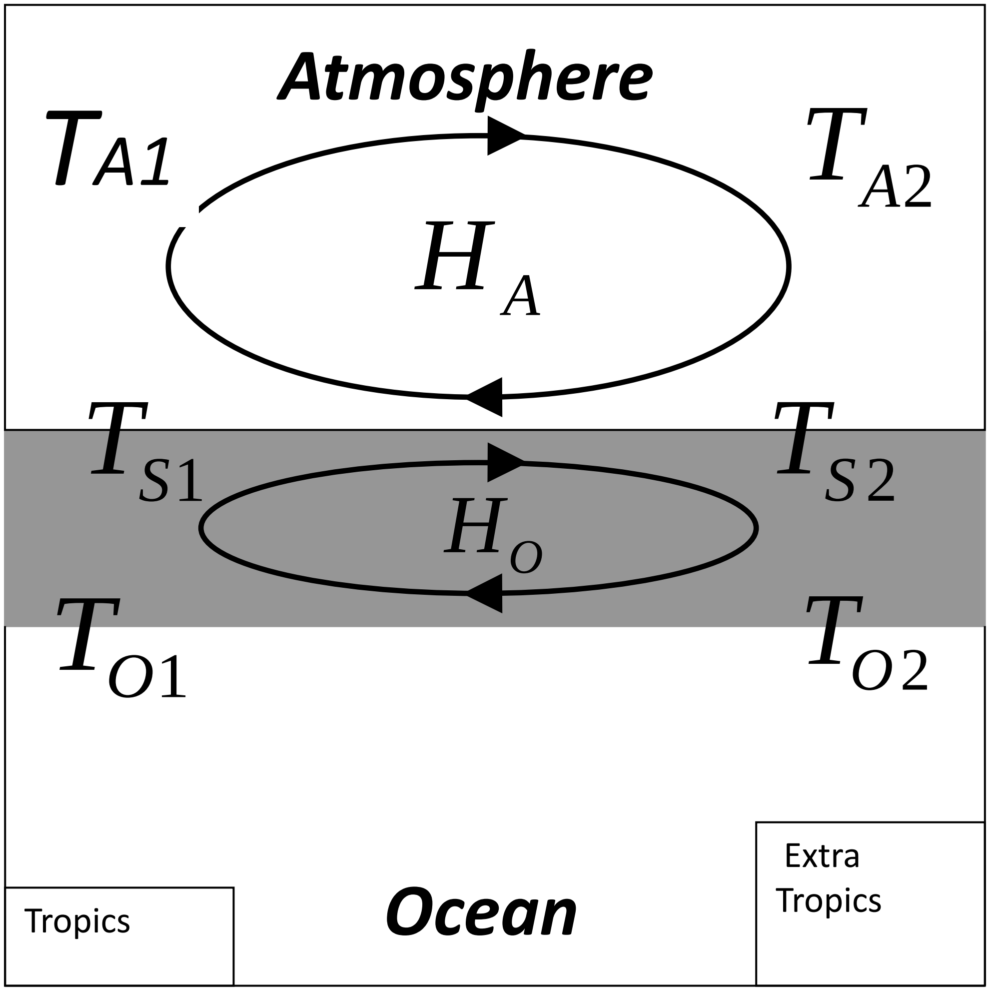
Conclusions

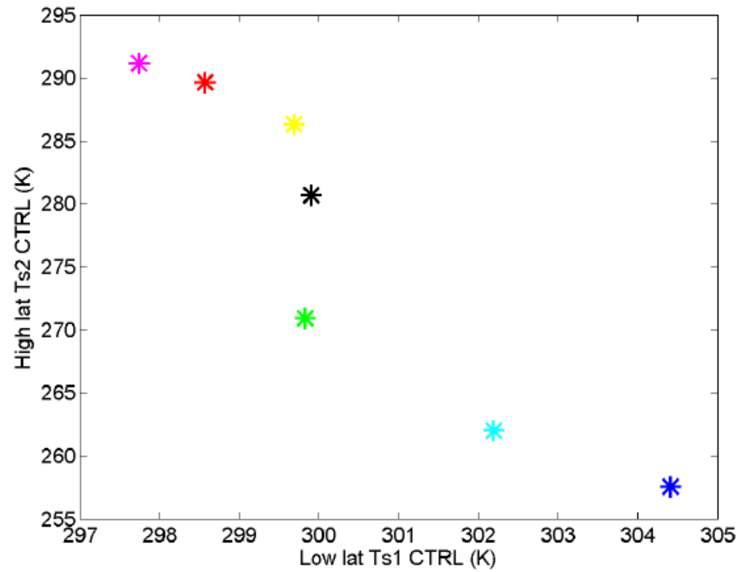
- One does not need to rely on observations or climate models to understand that the anthropogenic forcing of climate is large.

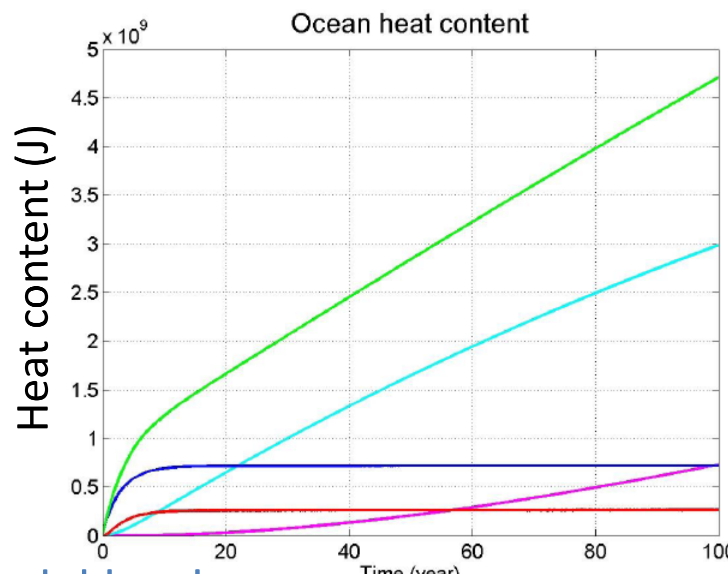
- It is fascinating that one can put illuminating numbers on such a complex topic by simply considering the size of the forcing. This approach may help non experts like engineers, school teachers, etc, to tackle the Climate change debate.

- If interested further feel free to use the "climate model" developed at Imperial College (*EP*cm).

The Environmental Physics Climate Model

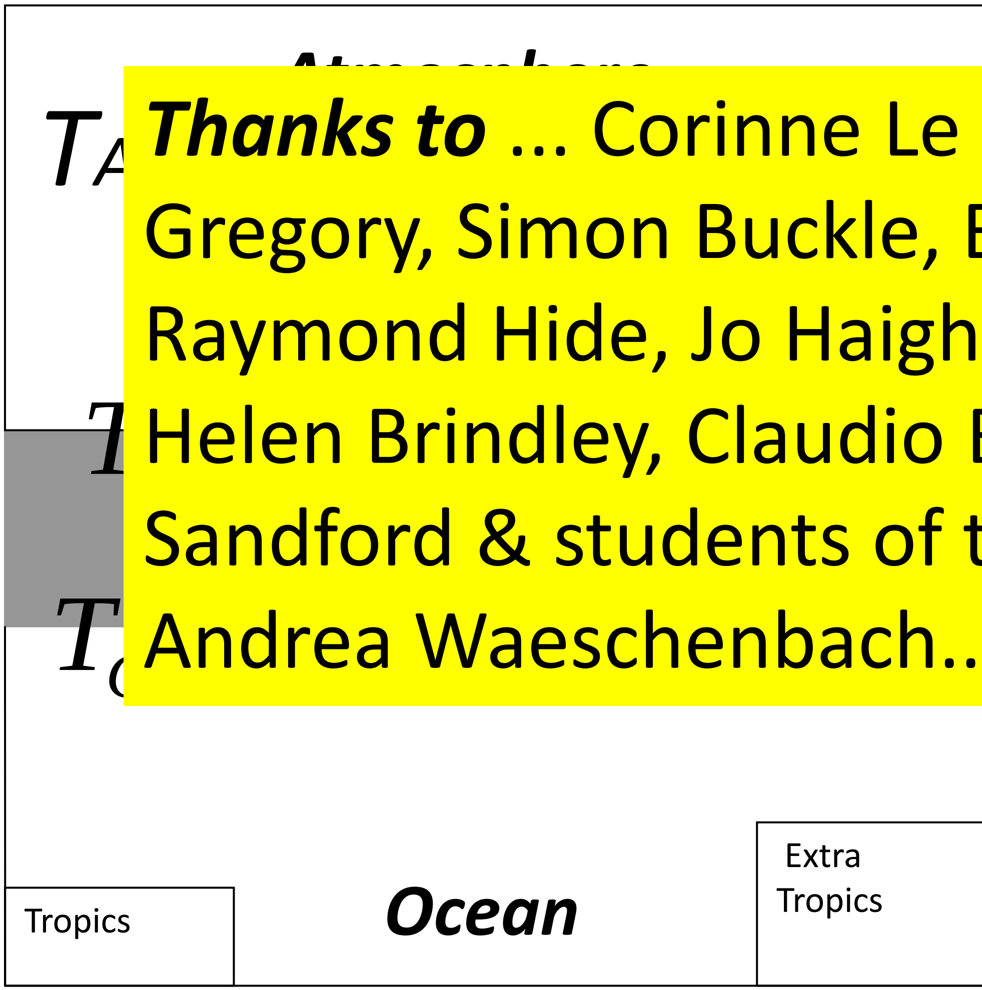


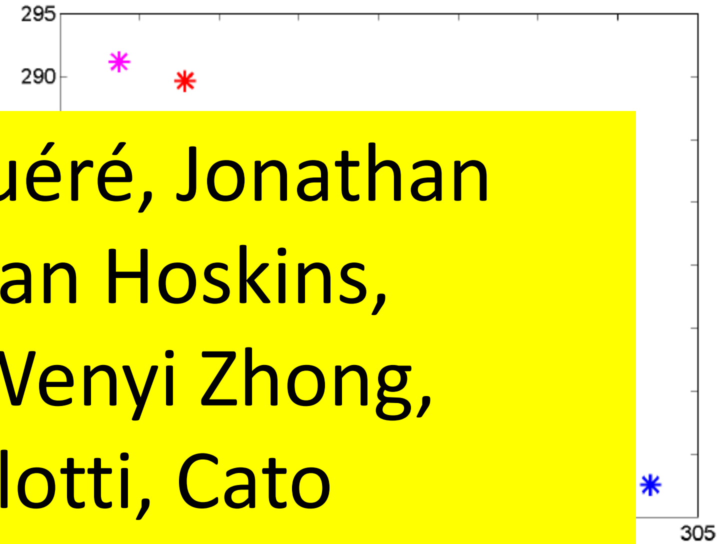




http://www.sp.ph.ic.ac.uk/~aczaja/EP_ClimateModel.html

The Environmental Physics Climate Model





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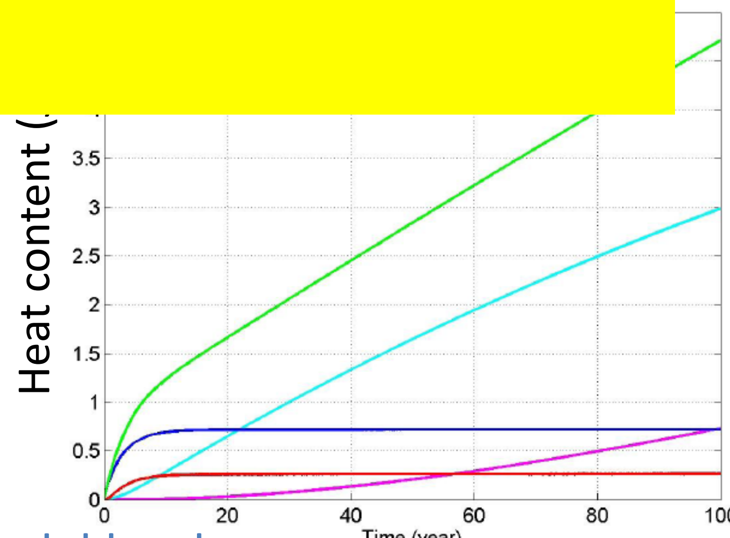

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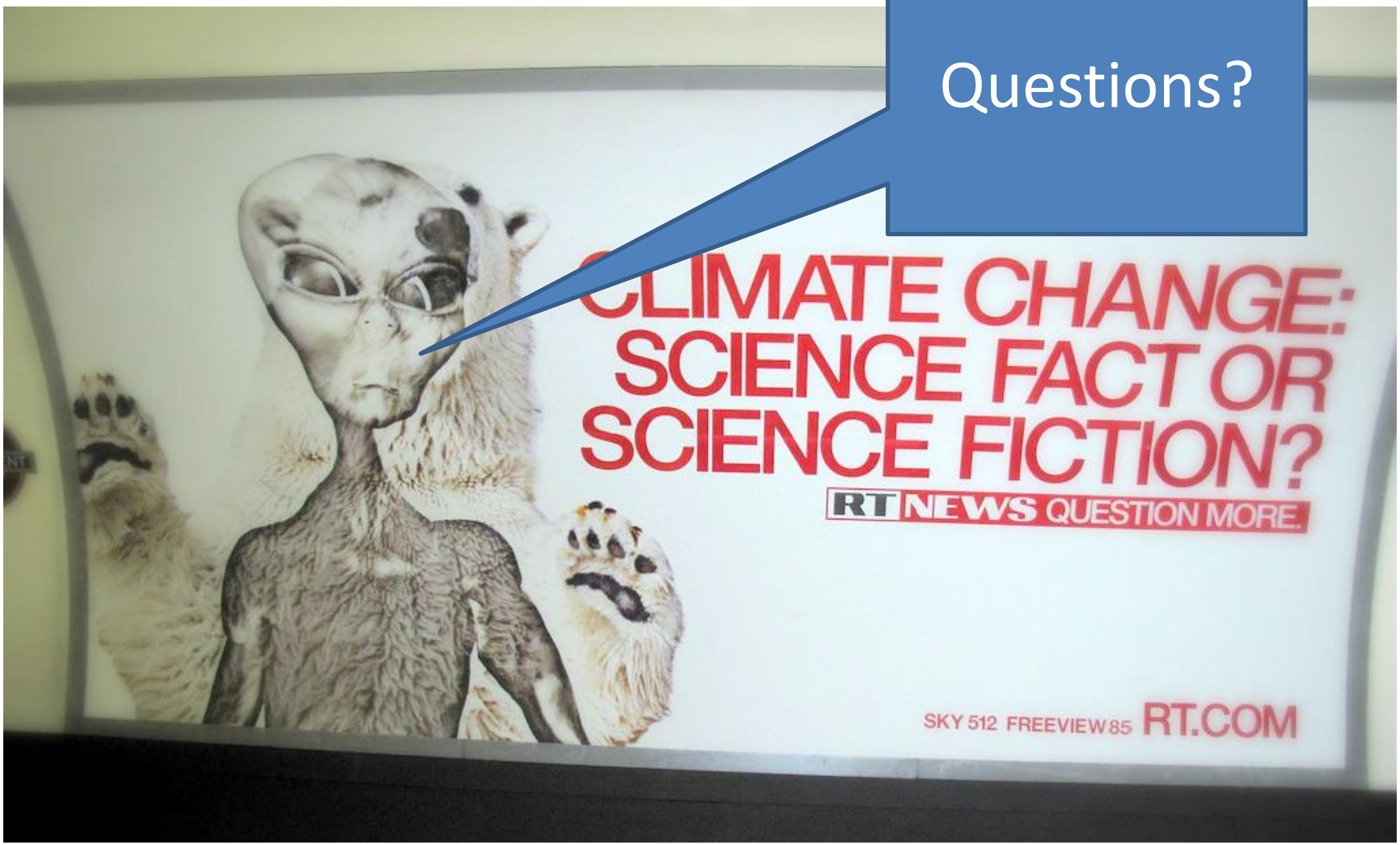
Questions?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