Climate Change and Exoplanet Sciences

what can they learn from each other?

Peter Cox
Climate Change & Sustainable Futures
University of Exeter

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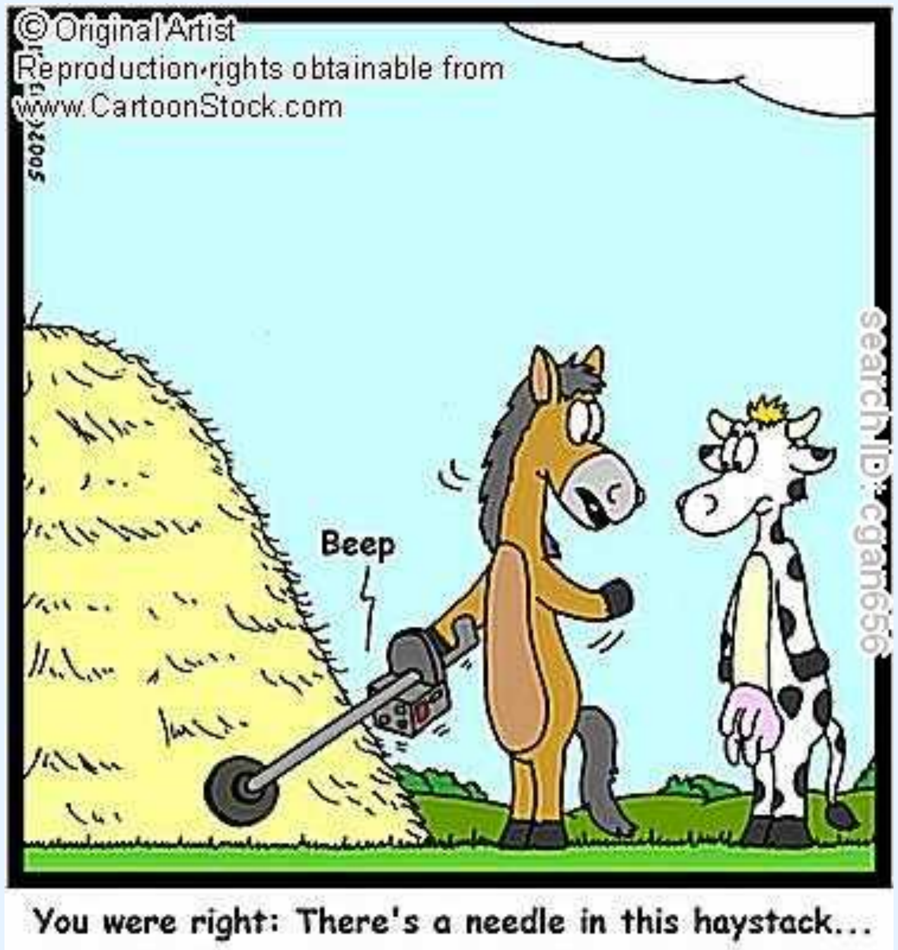
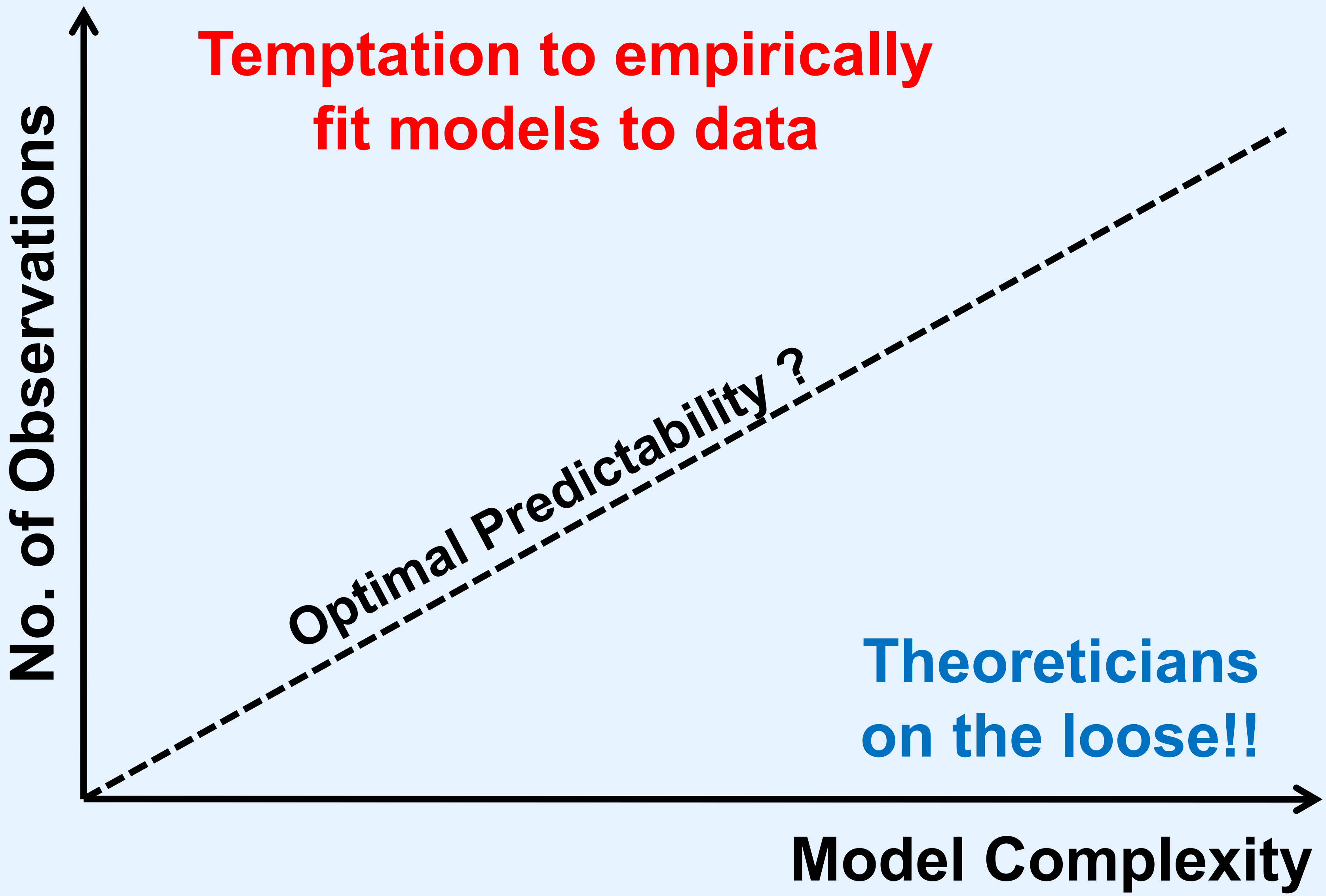


Flaming!

Exoplanets : Searching for a Needle in a Haystack...

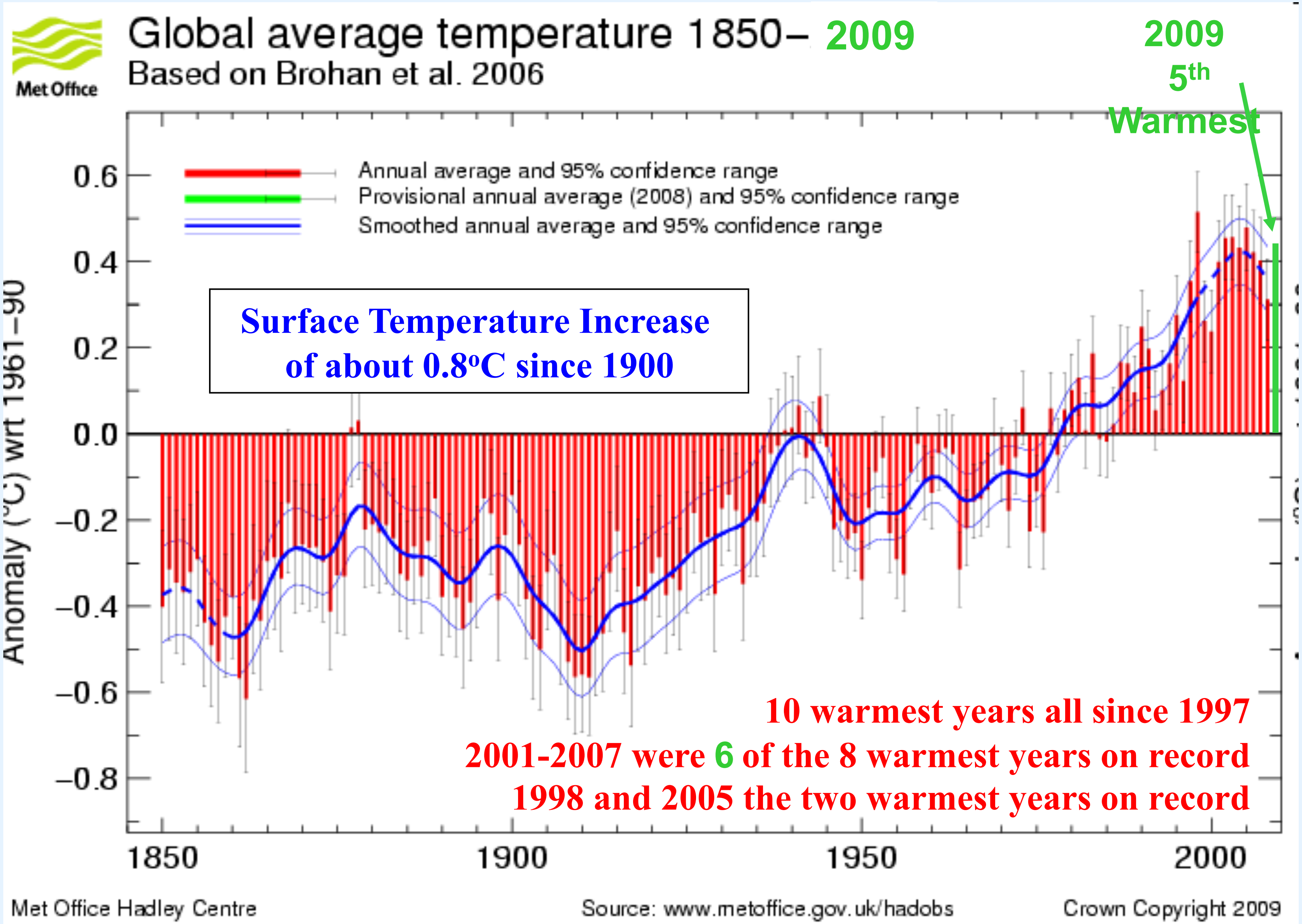
Climate Change : Can't see the Wood for the Trees

Optimizing Model Complexity for the Problem



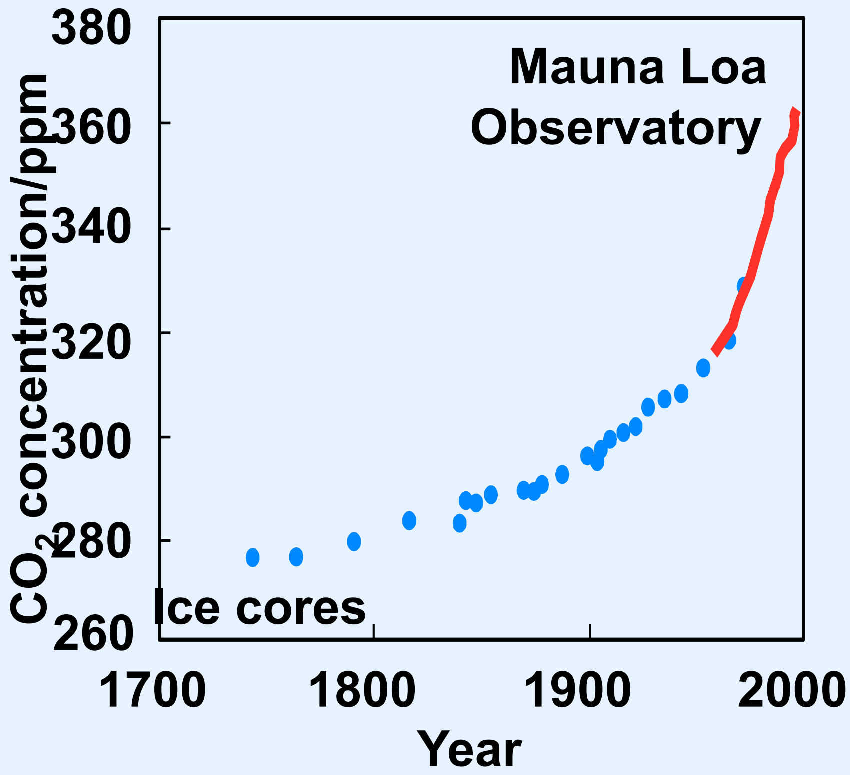
Recent Climate Change on Earth

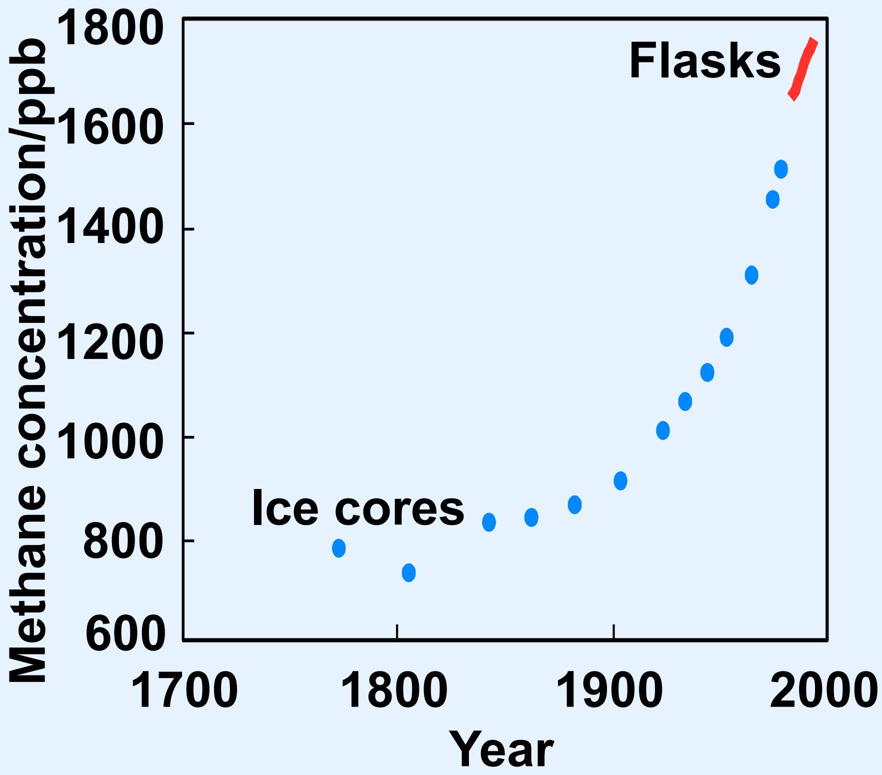
Evidence of Global Climate Warming



Greenhouse Gas Concentrations

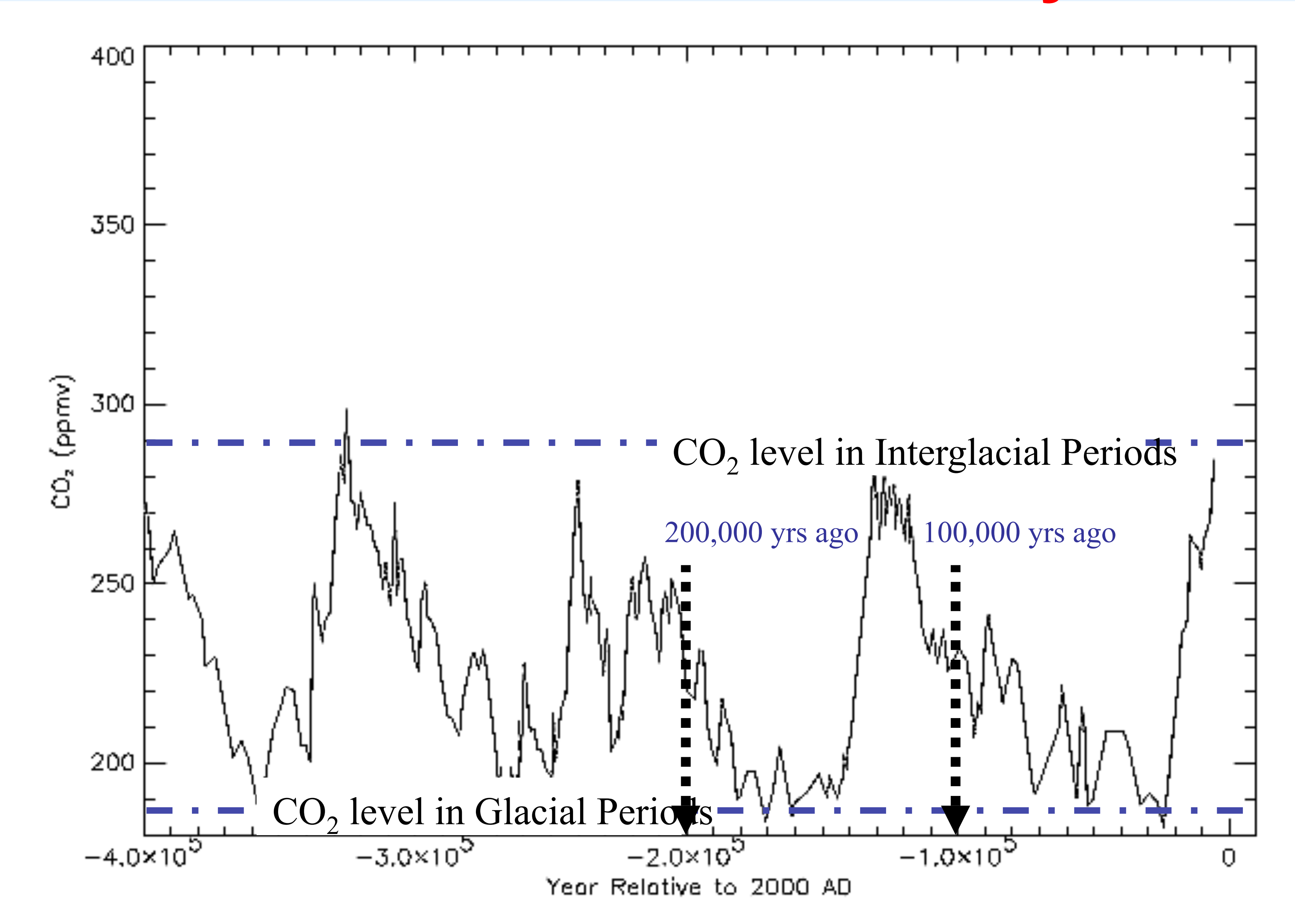
Carbon dioxide: 33% rise **Methane: 100% rise**



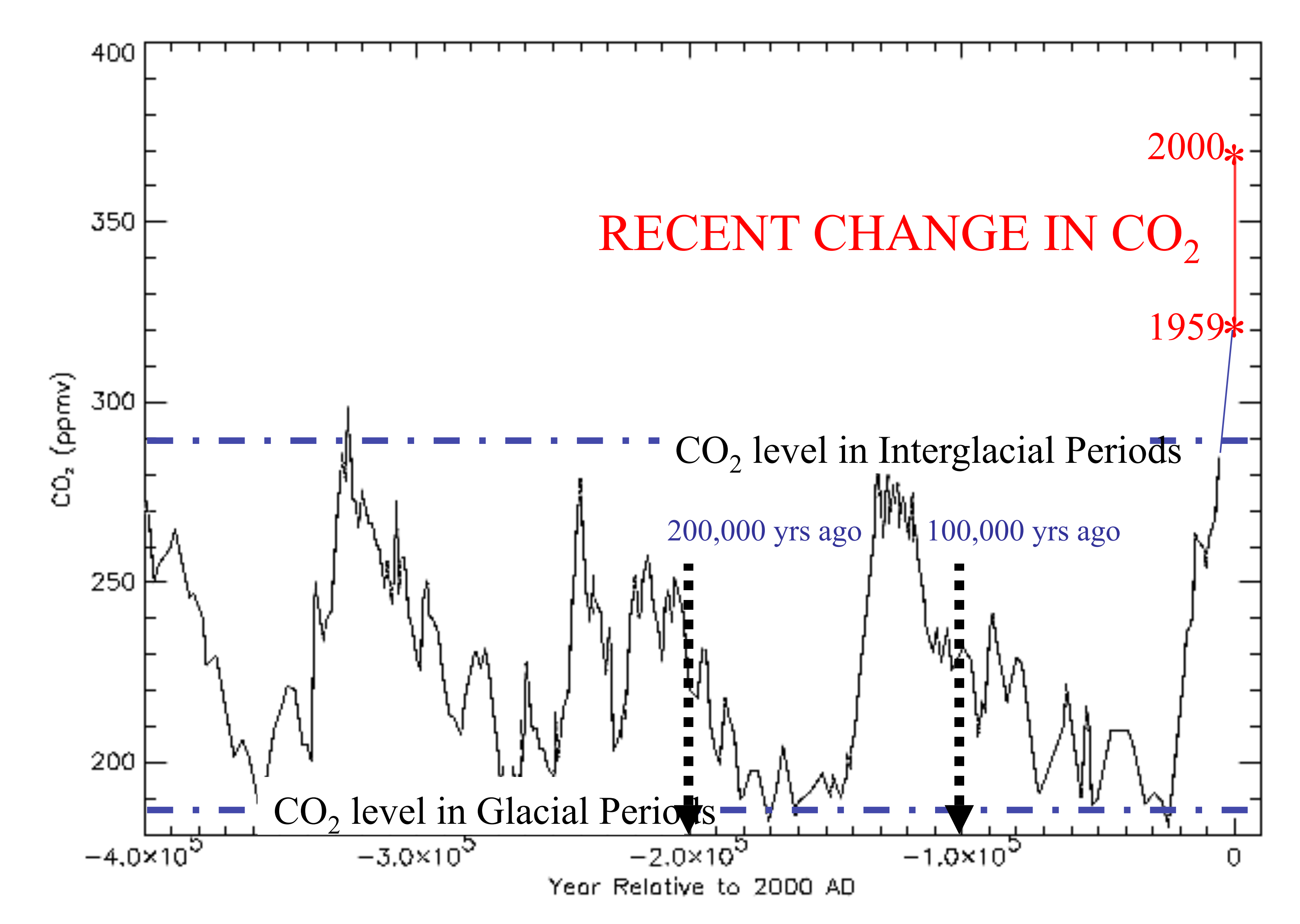


Source: IPCC

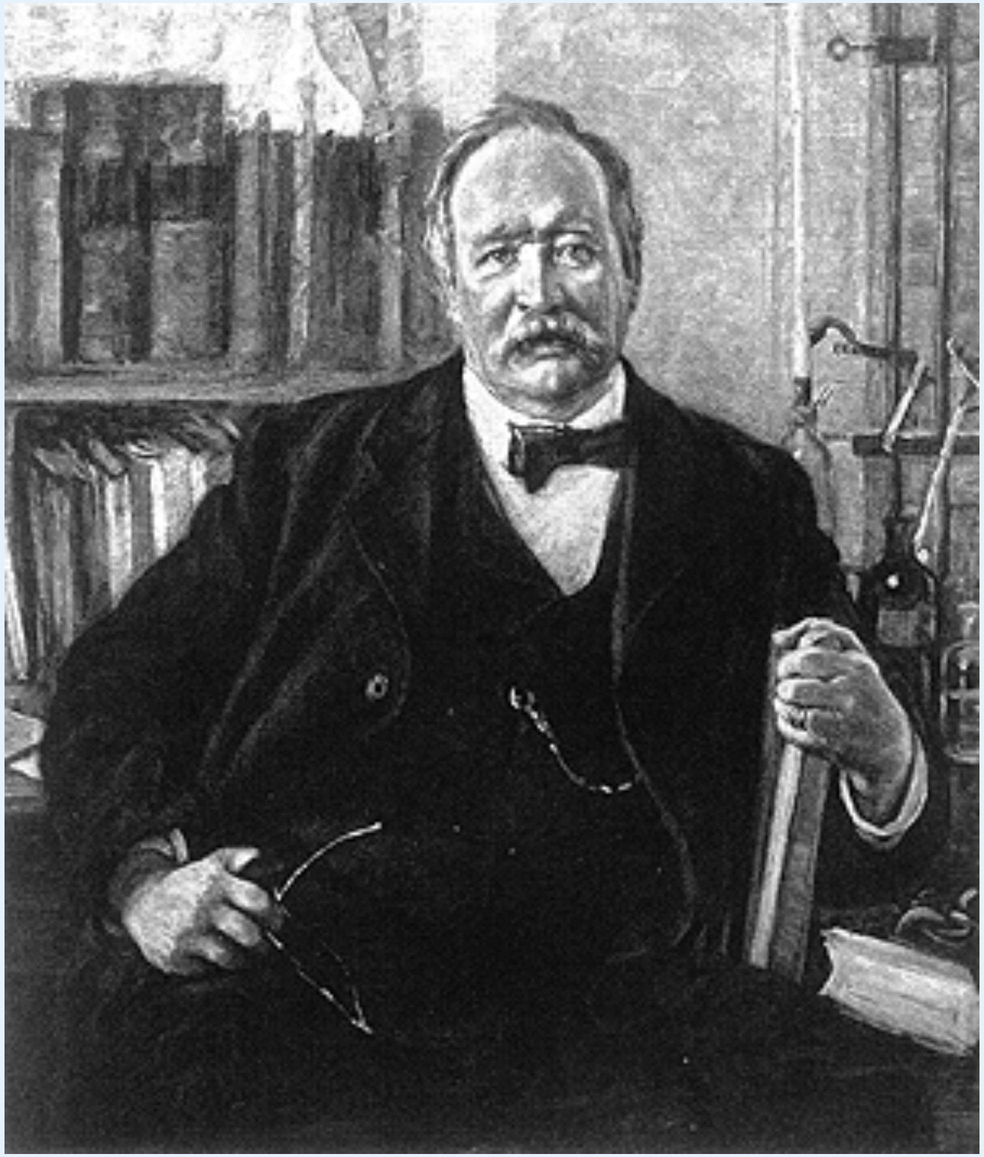
Recent CO_2 Increase in the Context of the last 400kyr



Recent CO_2 Increase in the Context of the last 400kyr



Svante Arrhenius (1859-1927)



- First to estimate the sensitivity of the Earth's climate to atmospheric carbon dioxide.
- Estimate of 5-7^{o}C for a doubling of CO_2 isn't too far from current estimates (1.5-4.5^{o}C)!

Arrhenius's 1896 Paper

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THE LONDON, EDINBURGH AND DUBLIN

PHILOSOPHICAL MAGAZINE AND JOURNAL OF SCIENCE

≡

[FIFTH SERIES APRIL 1896]

XXXI. ***On the Influence of Carbonic Acid in the Air upon the Temperature of the Ground.*** **By Prof. SVANTE ARRHENIUS*.**

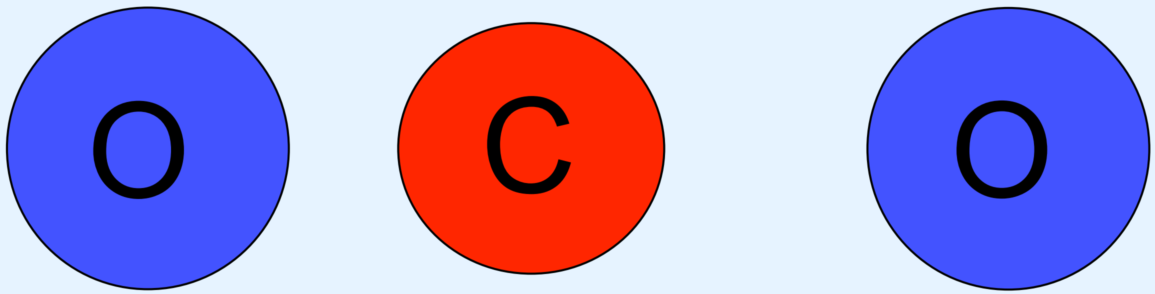
1. Introduction: Observations of Langley on Atmospherical Absorption.

A GREAT deal has been written on the influence of the absorption of the atmosphere upon the climate. Tyndall † in particular has pointed out the enormous importance of this question. To him it was chiefly the diurnal and annual variations of temperature that were lessened by this circumstance. Another side of the question, that has long attracted the attention of physicists, is this: Is the mean temperature of the ground in any way influenced by the presence of heat-absorbing gases in the atmosphere? Fourier ‡ maintained that the atmosphere acts like the glass in a hot house, because it lets through the light rays of the sun but retains the dark rays from the ground. This idea was elaborated by Pouillet §; and Langley was by some of his researches led to the view, that 'the temperature of the earth under direct sunshine, even though our atmosphere were present as now, would probably fall to – 200 °C., if that atmosphere did not possess the

*** Extract from a paper presented to the Royal Swedish Academy of Sciences, 11th December 1895. Communicated by the Author.**

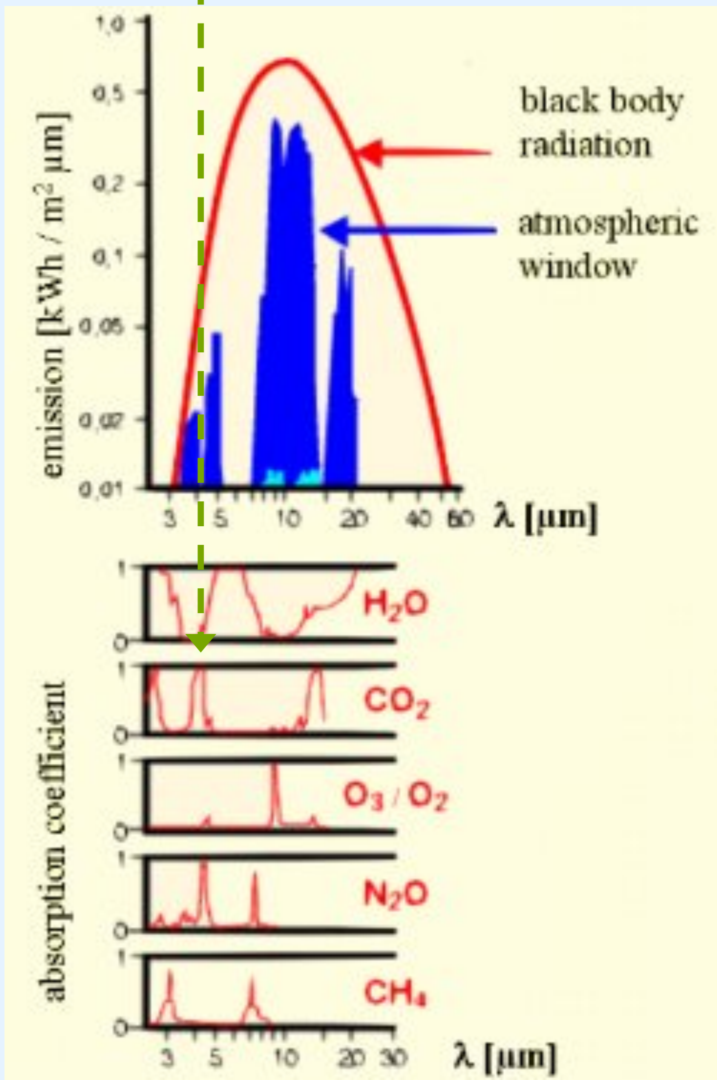
† "Heat a mode of motion," 2nd ed. p.405 (Lond.,1865).
‡ *Mem. de l'Ac. R. d. Sci. de l'Inst. de France,* t. vii. 1827.
§ *Compress rendus,* t. vii. p41 (1838).

CO_2 Greenhouse Effect at the Molecular Level

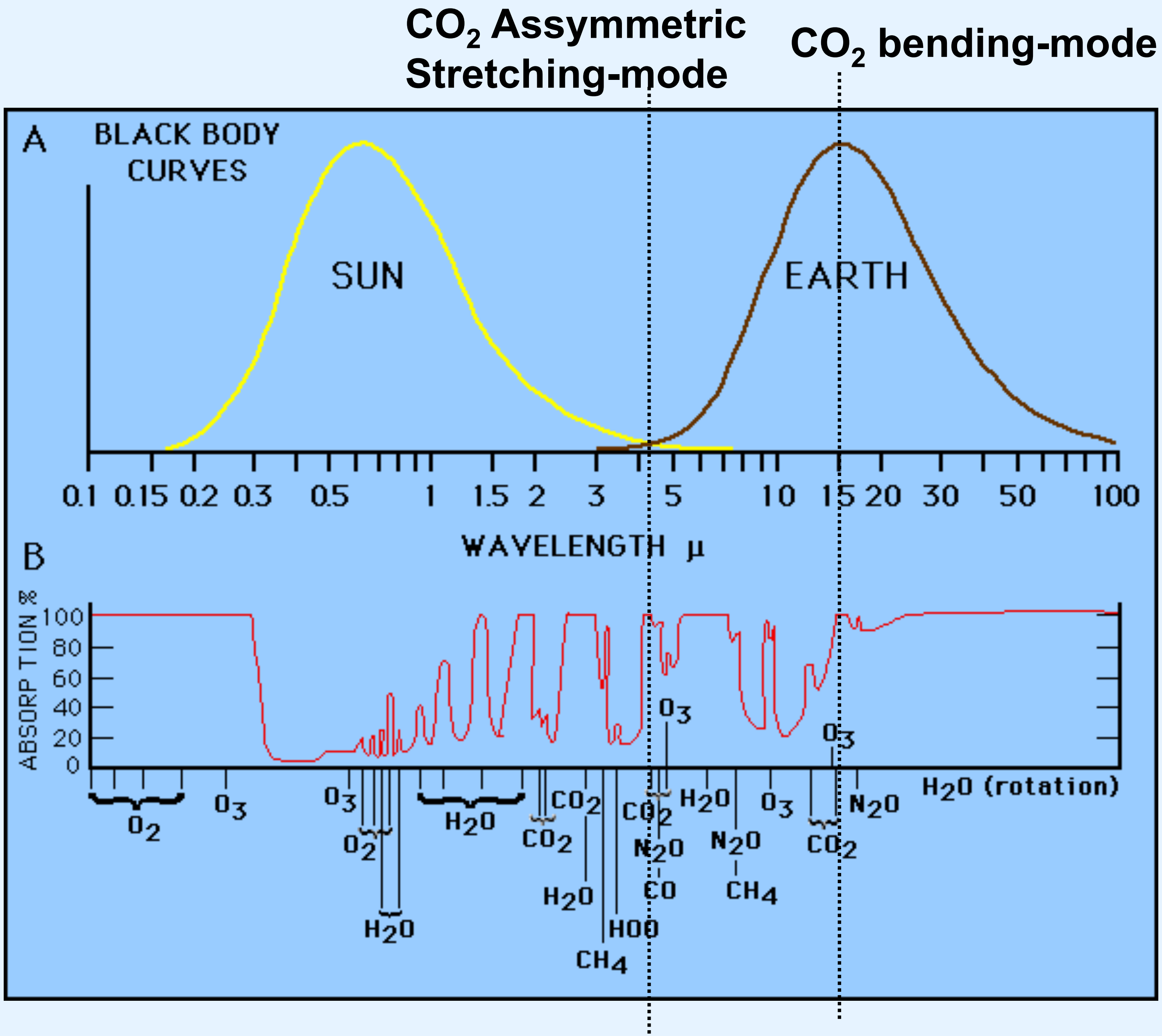


Assymmetric Stretching Mode

Absorption by CO_2 Assymmetric Stretching at 4.25 μm



Atmospheric Absorption



Future Climate Change on Earth :

Uncertainty in Predictions and Feedbacks

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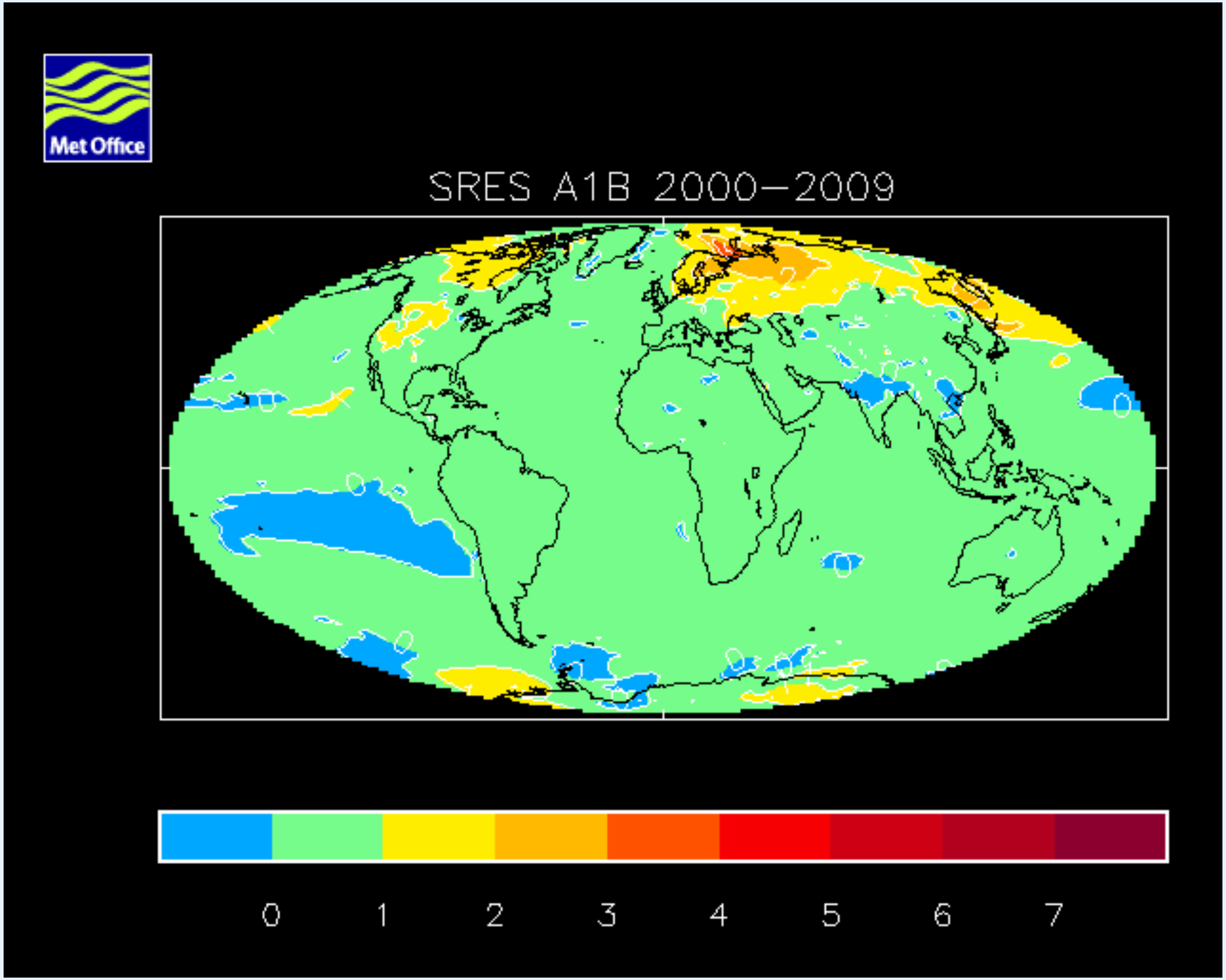
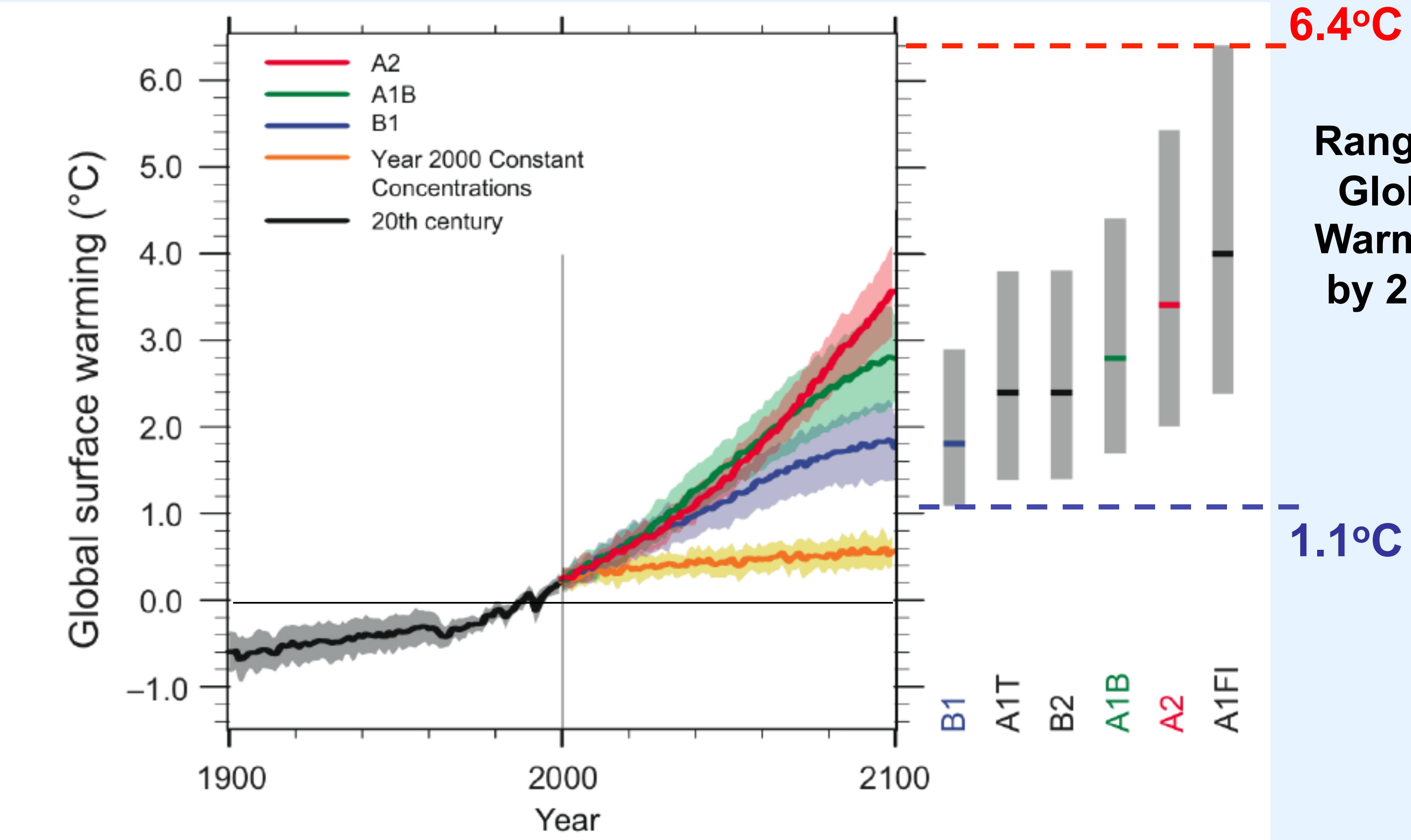
Predicted Pattern of Global Warming



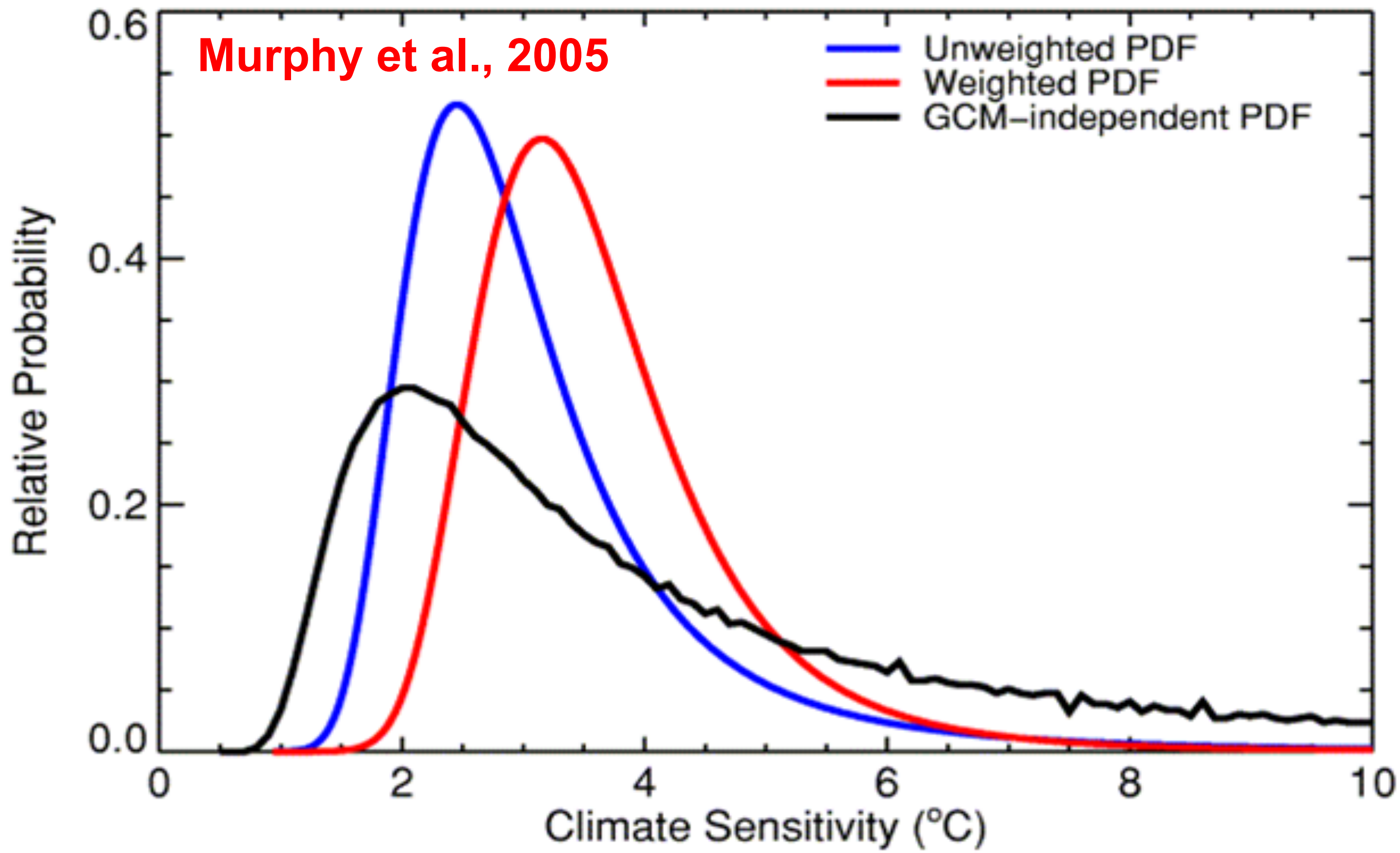
Uncertainty in Future Climate Change



Range of Global Warming by 2100

Intergovernmental Panel on Climate Change (IPCC), 2007

Climate Sensitivity to Doubling CO_2 remains uncertain….



Due to uncertainties in climate feedbacks….

Simple Linear Conceptual Model

Global warming, **ΔT** (K), due to radiative forcing, **ΔQ** (W m^{-2}) :

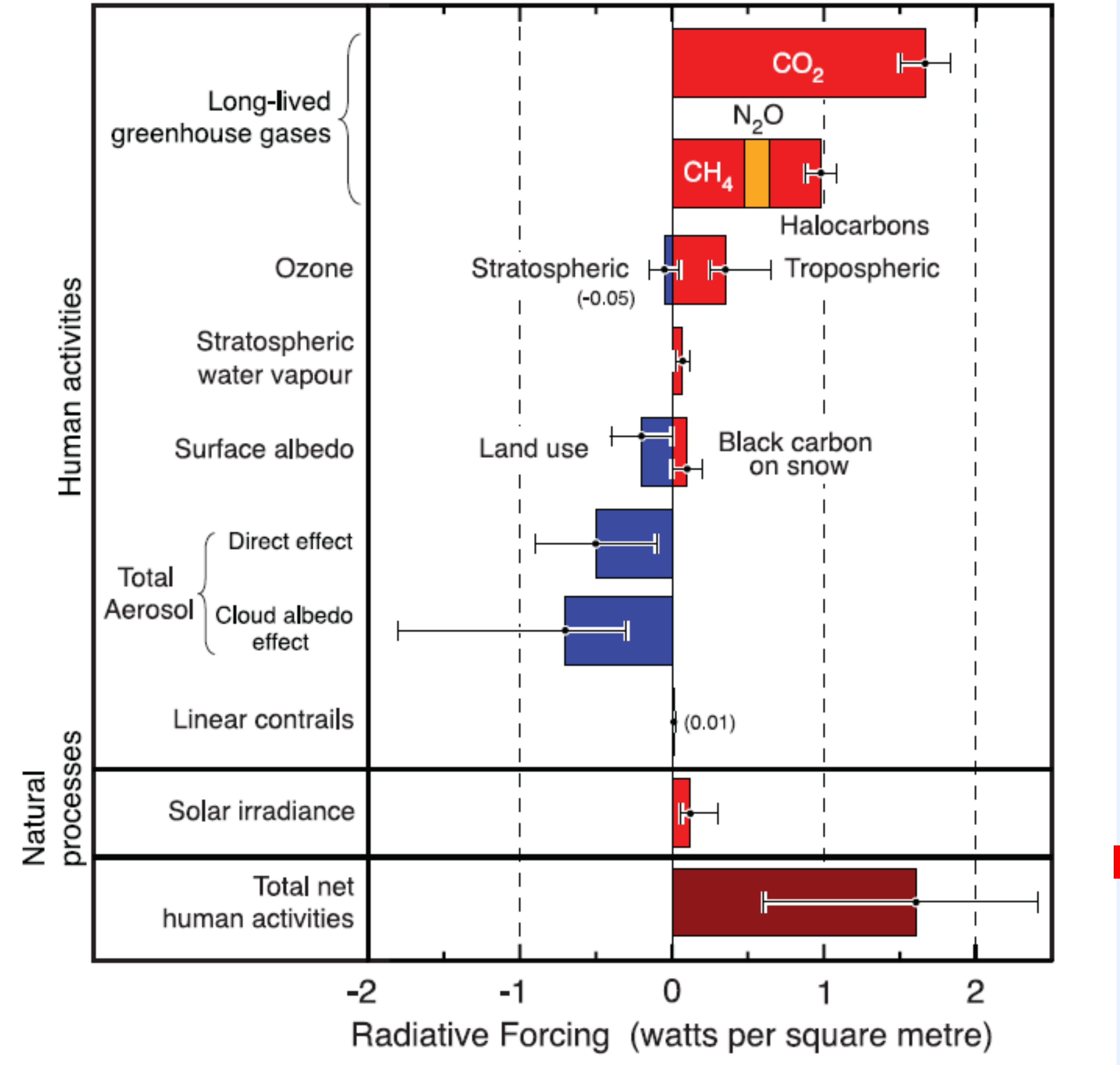
$$C.\ d\Delta T/dt + \lambda.\ \Delta T = \Delta Q$$

Climate Feedback Factor (W m^{-2} K^{-1})

where **ΔQ** depends on the changing concentrations of greenhouse gases and aerosols (particulates), as well as natural factors such as solar variability etc.

where λ depends on climate feedbacks

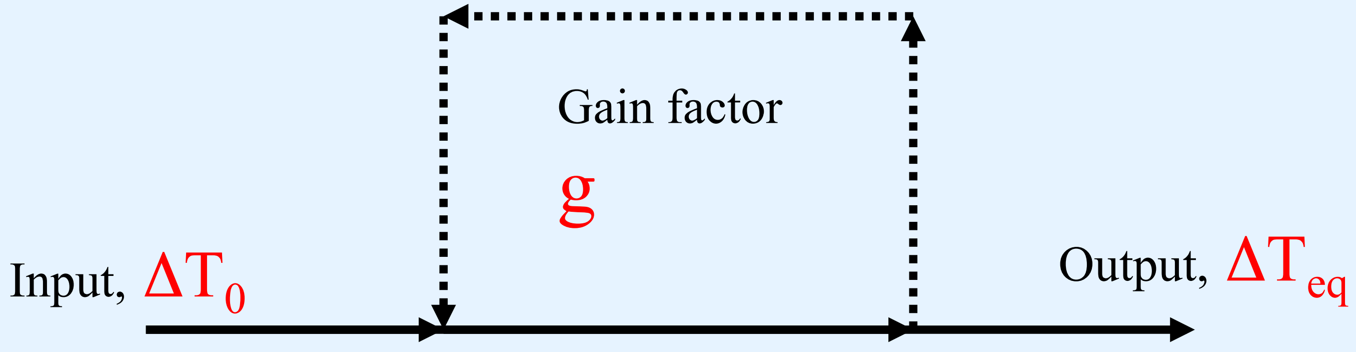
Radiative Forcing of Climate 1750-2005



Human Factors Dominate

IPCC 2007

Feedbacks and gain factors, positive and runaway feedbacks



Consider *long-term response* to an initial perturbation, ΔT_0:

$$\Delta T_{eq} = \Delta T_0 \{1 + g + g^2 + \ldots..\}$$

$$= \Delta T_0 / \{1 - g\} \;\; ; \;\; \text{for } |g| < 1$$

- Positive feedback for $g > 0$
- Negative feedback for $g < 0$
- "Runaway" feedback/ linear instability for $g > 1$

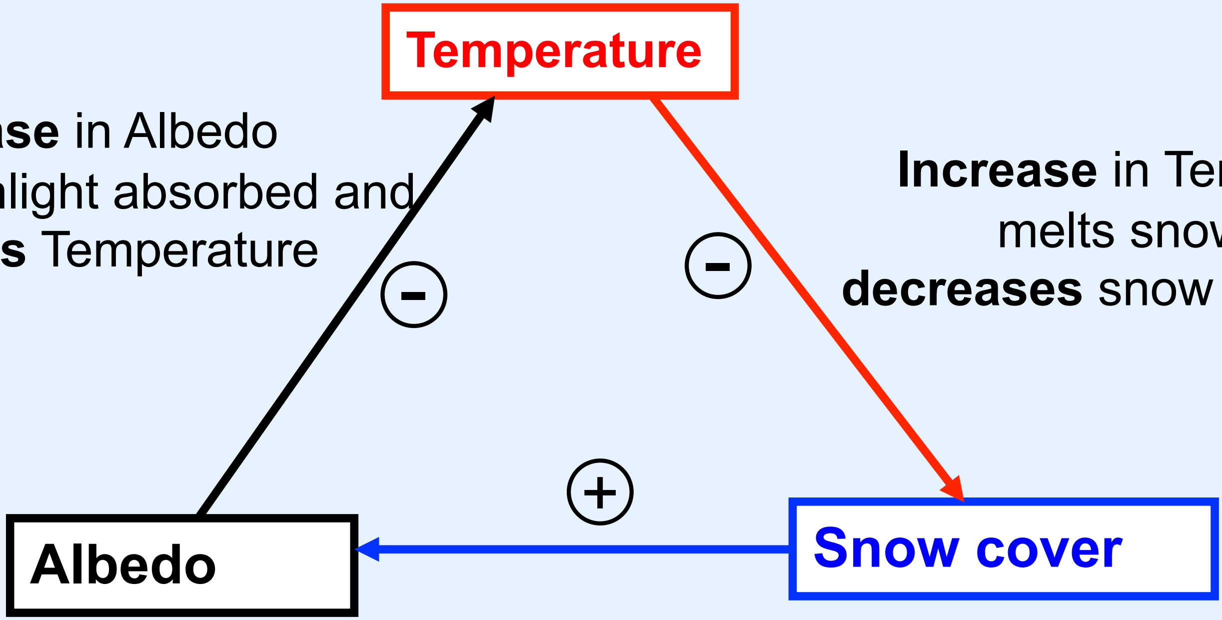
Examples of Climate Feedbacks on Earth

- **Water vapour feedback**
- **Snow/sea-ice albedo feedback**
- **Cloud feedbacks**
- Ocean circulation changes
- Atmospheric circulation changes
- Carbon cycle feedbacks
- Lapse-rate feedback

Snow-Albedo Feedback

Decrease in Albedo
increases sunlight absorbed and
Increases Temperature

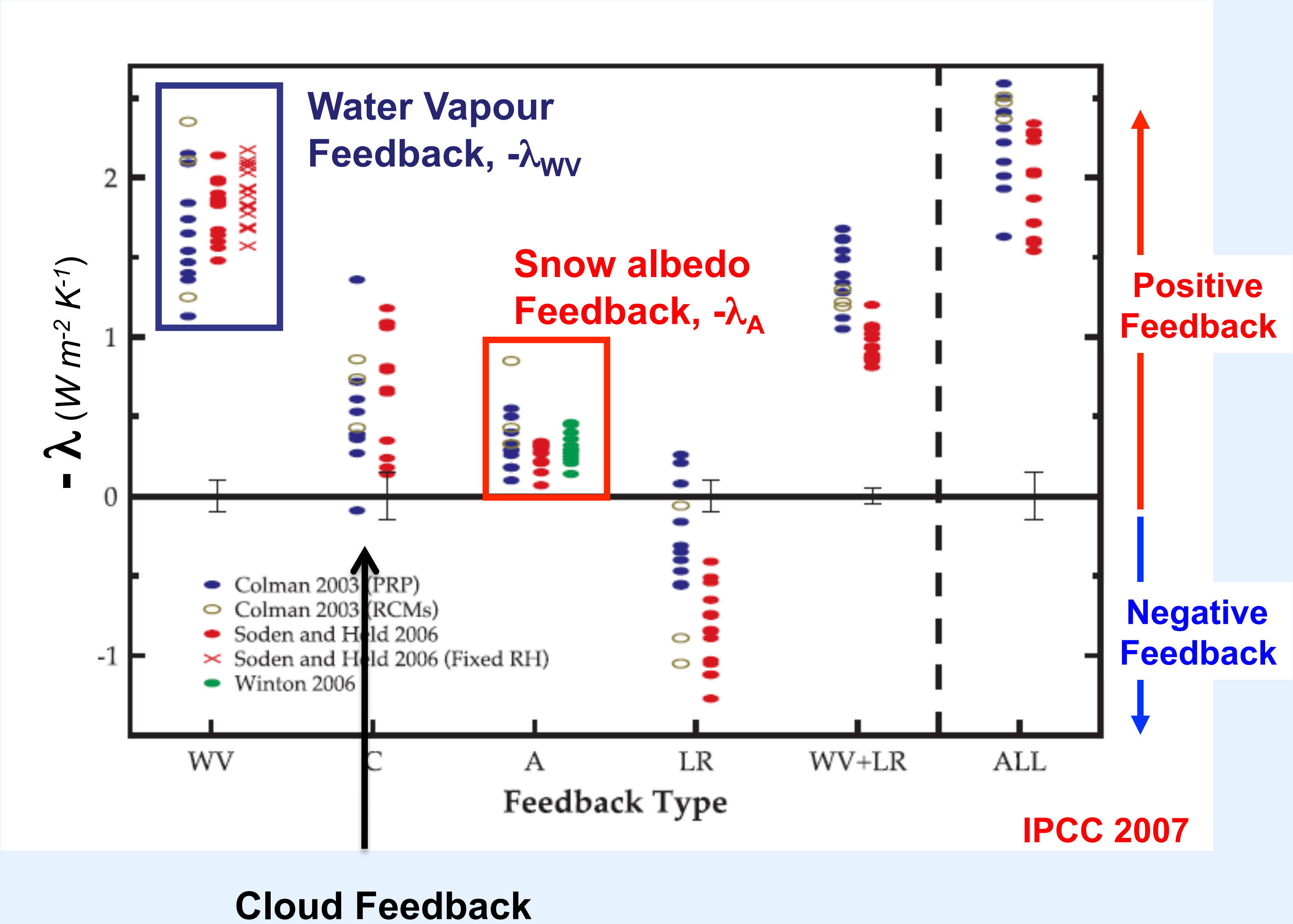
Increase in Temperature
melts snow and
decreases snow cover extent



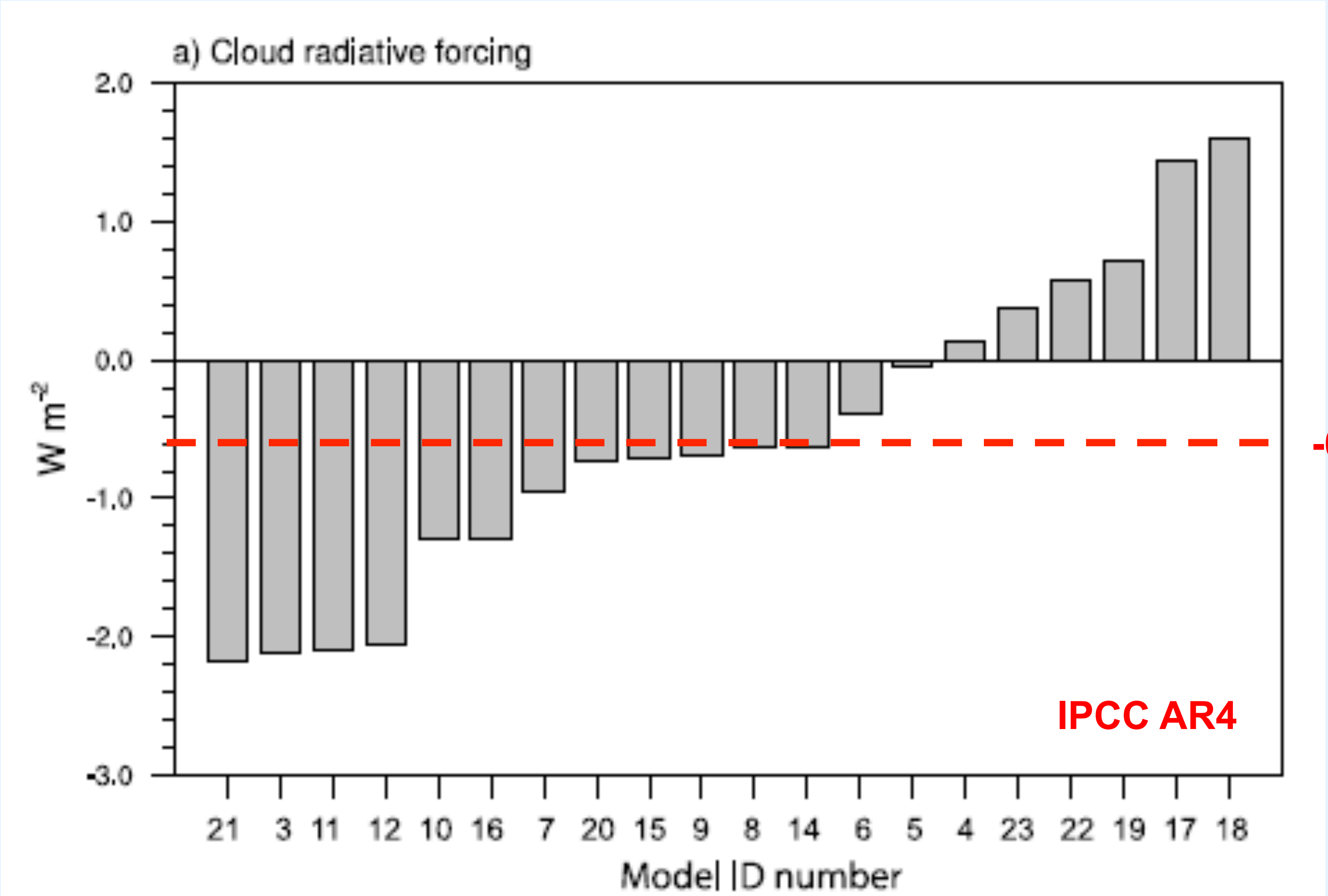
Decrease in snow cover extent
decreases the brightness (“albedo”)
of the surface

Overall sign of feedback loop is positive

Diagnosis of GCM Feedbacks



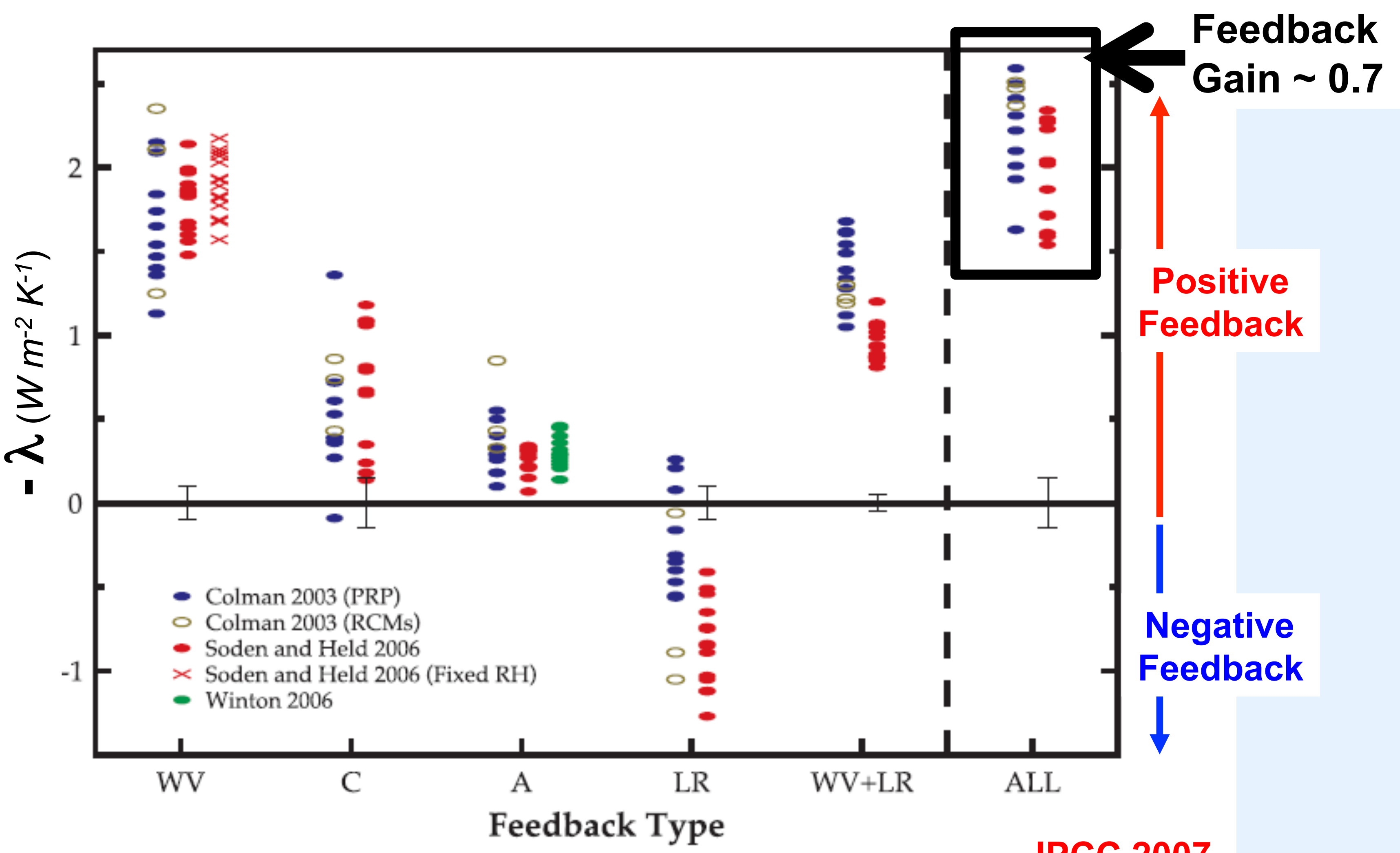
Uncertainties in Cloud Radiative Forcing



-0.6 W m^{-2}

"Cloud Feedbacks (particularly from low clouds) remain the largest source of uncertainty" **in climate projections.**

Diagnosis of GCM Feedbacks



IPCC 2007

Viewing the Earth as an Exoplanet :

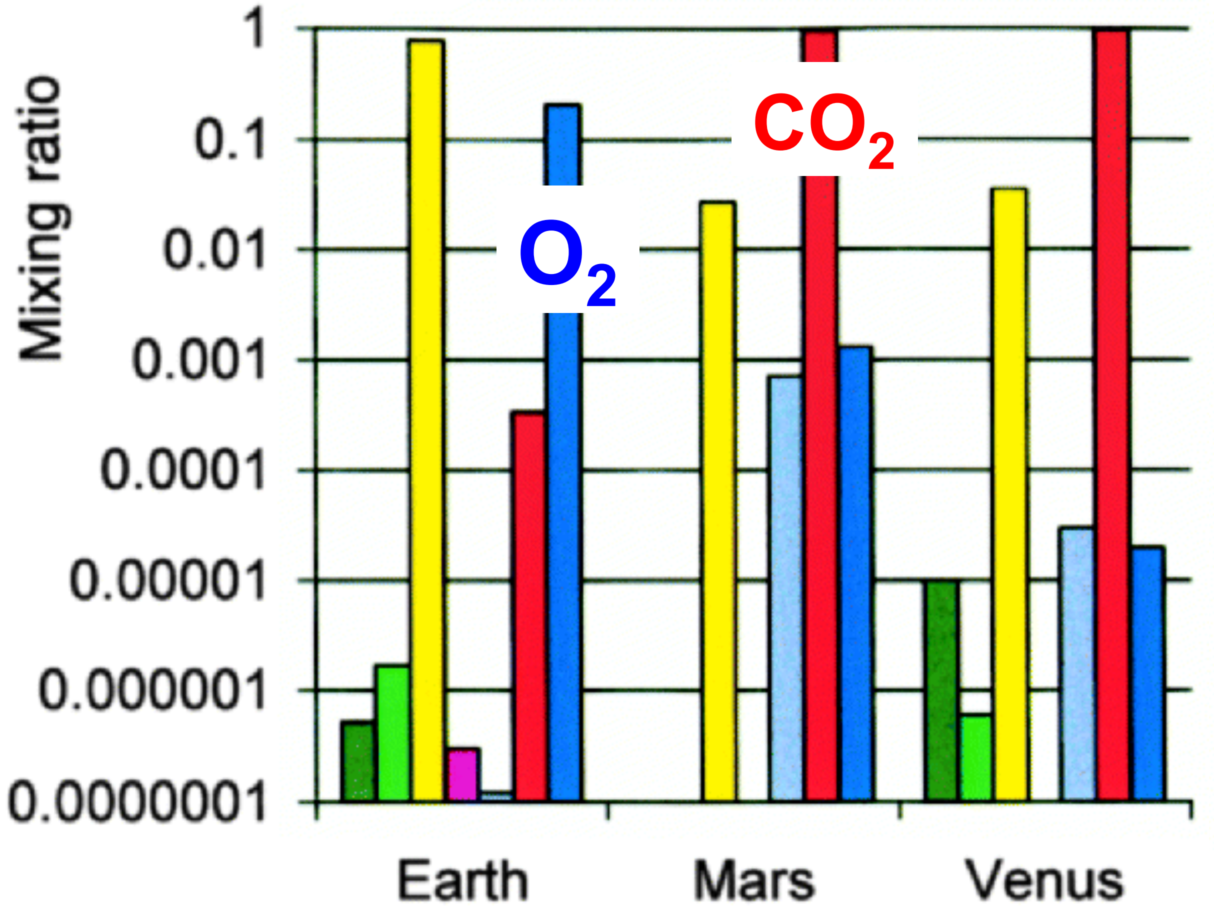
Would it be possible to detect Human Influence?

James Lovelock

- Author of the original Gaia hypothesis “that supposed the Earth to be kept at a state favourable for life by the living organisms”.
- Based partly on the observation that Earth’s atmosphere has been kept far from equilibrium by life.

Life keeps the Atmosphere from Chemical Equilibrium on Earth

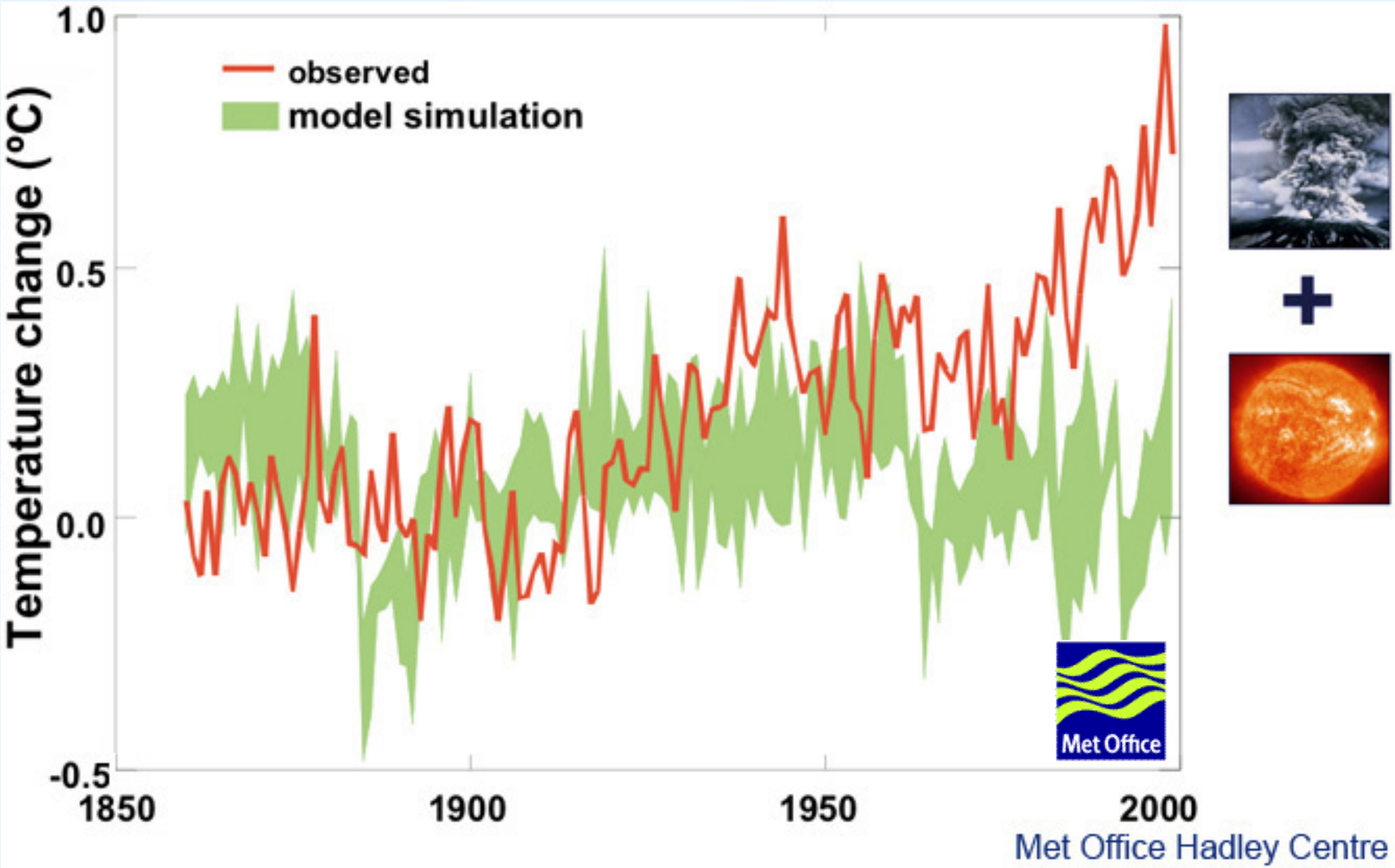
...but does it have to on other planets ?



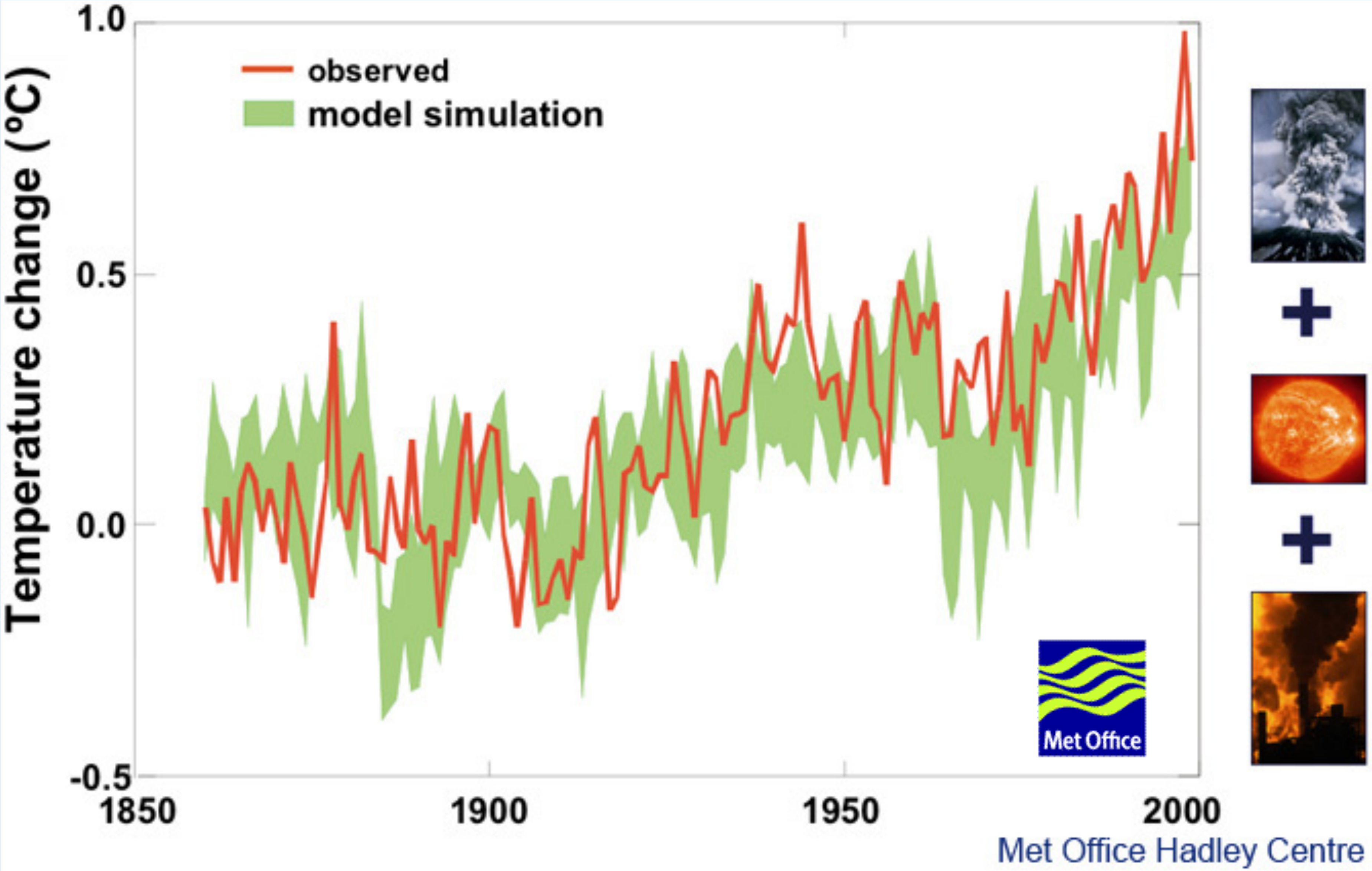
Earth's atmosphere has ~100 times more oxygen, and ~1000 times less carbon dioxide than if it was in a chemical equilibrium state without life.

Lenton, 1998

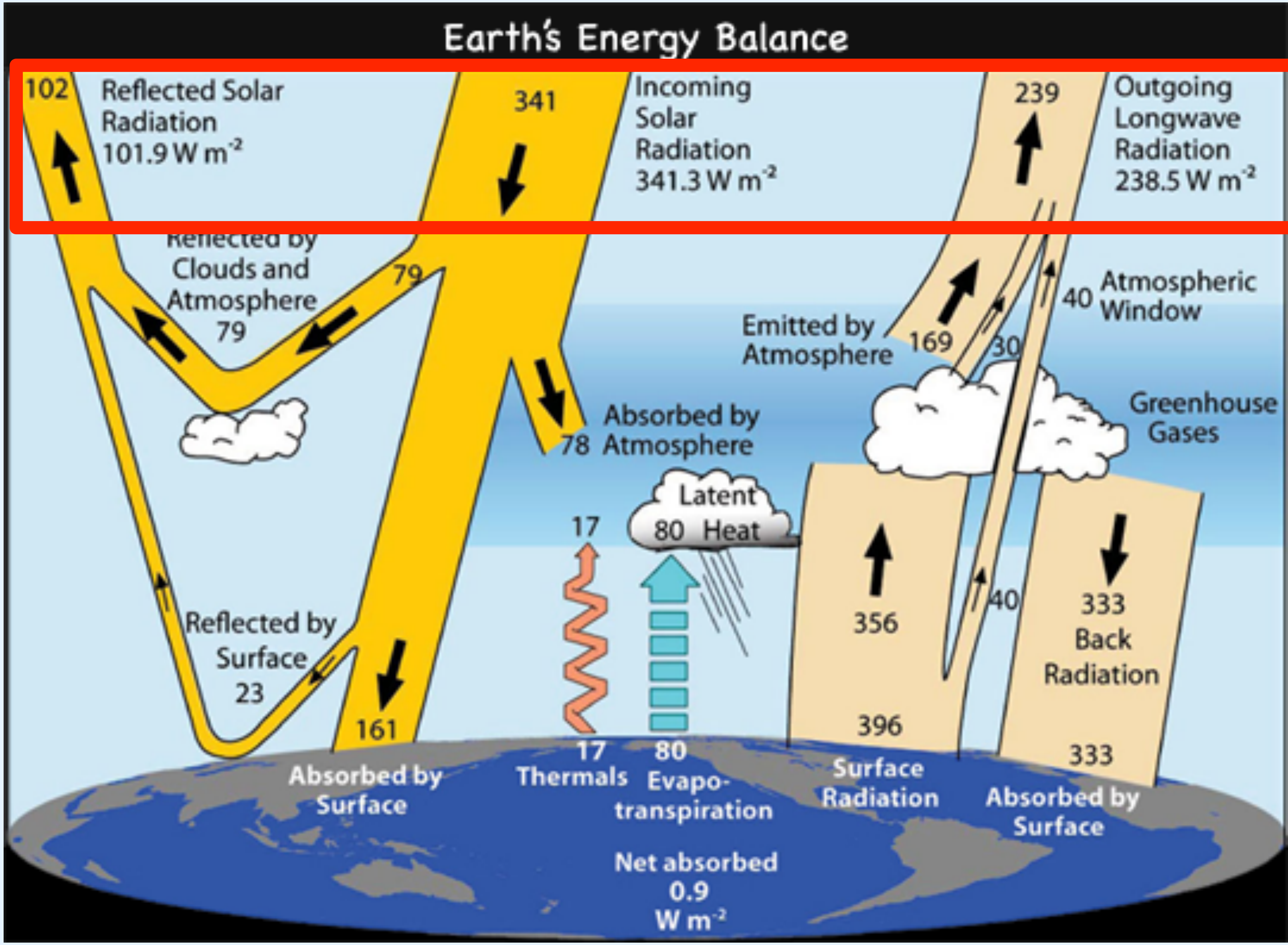
Natural factors cannot explain recent warming



Recent warming can be simulated when man-made factors are included

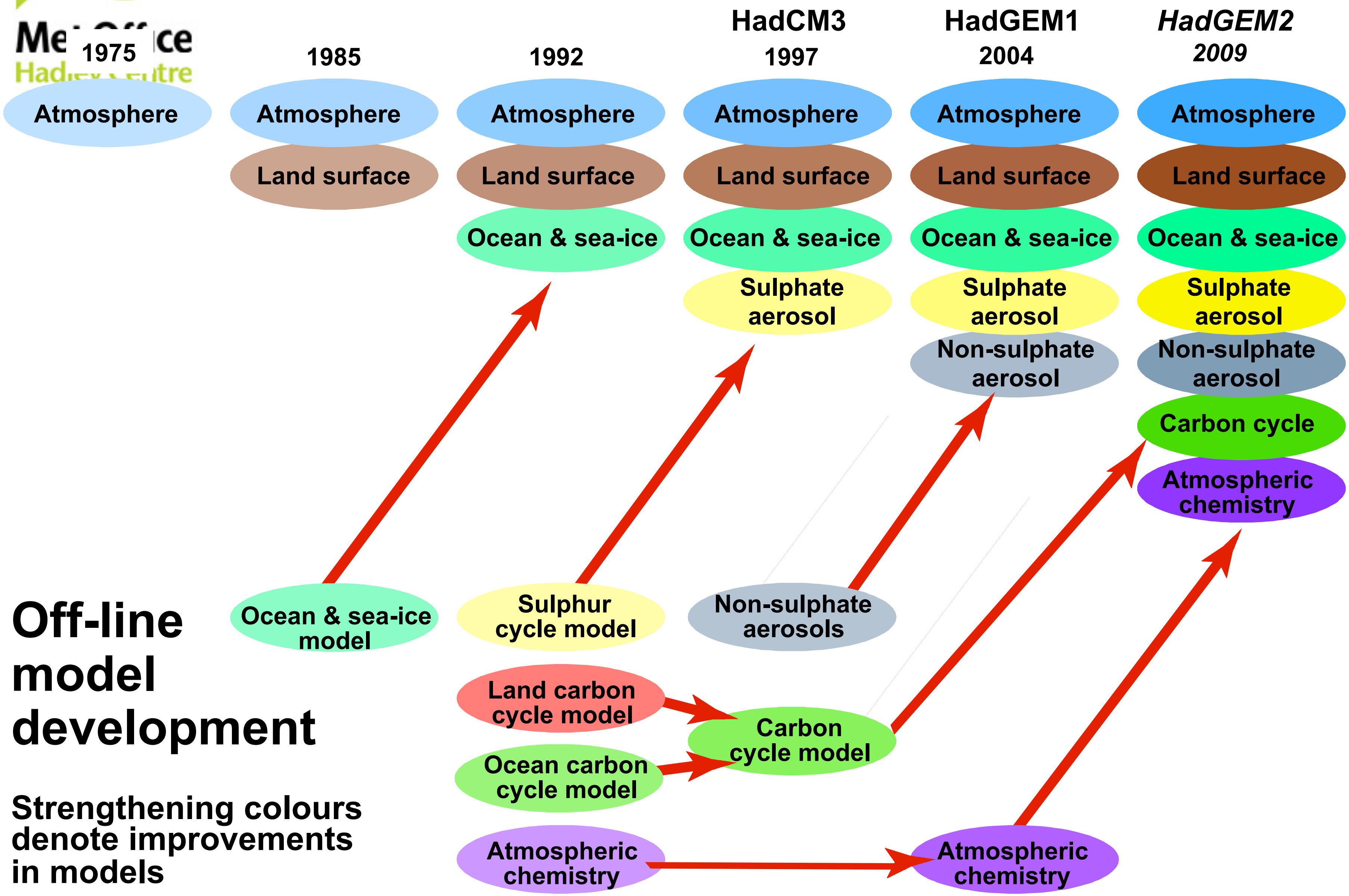


Atmospheric Energy Balance on Earth



TOA Fluxes

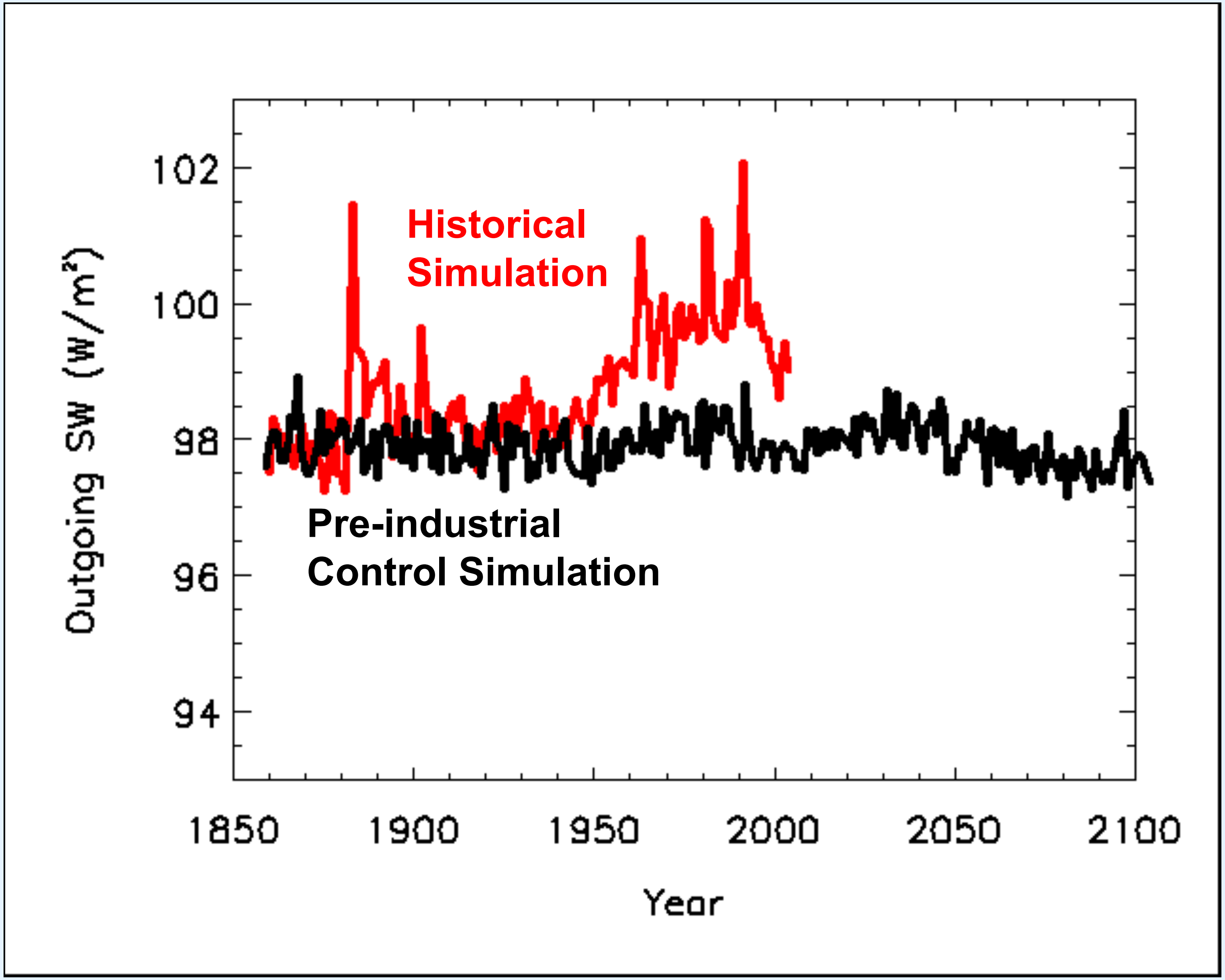
Development of the Hadley Centre models



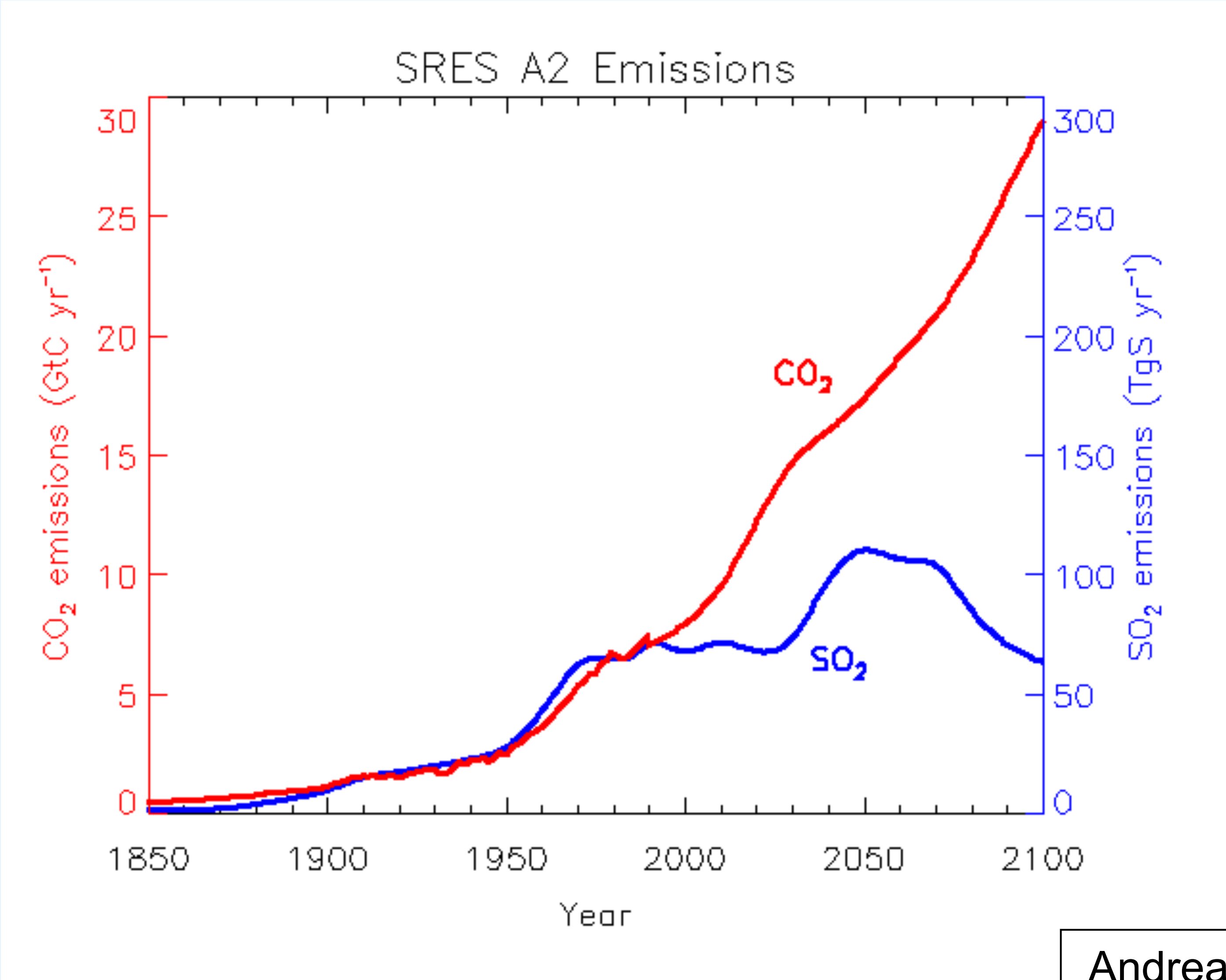
Off-line model development

Strengthening colours denote improvements in models

HadGEM2-ES Simulation: Reflected SW at TOA

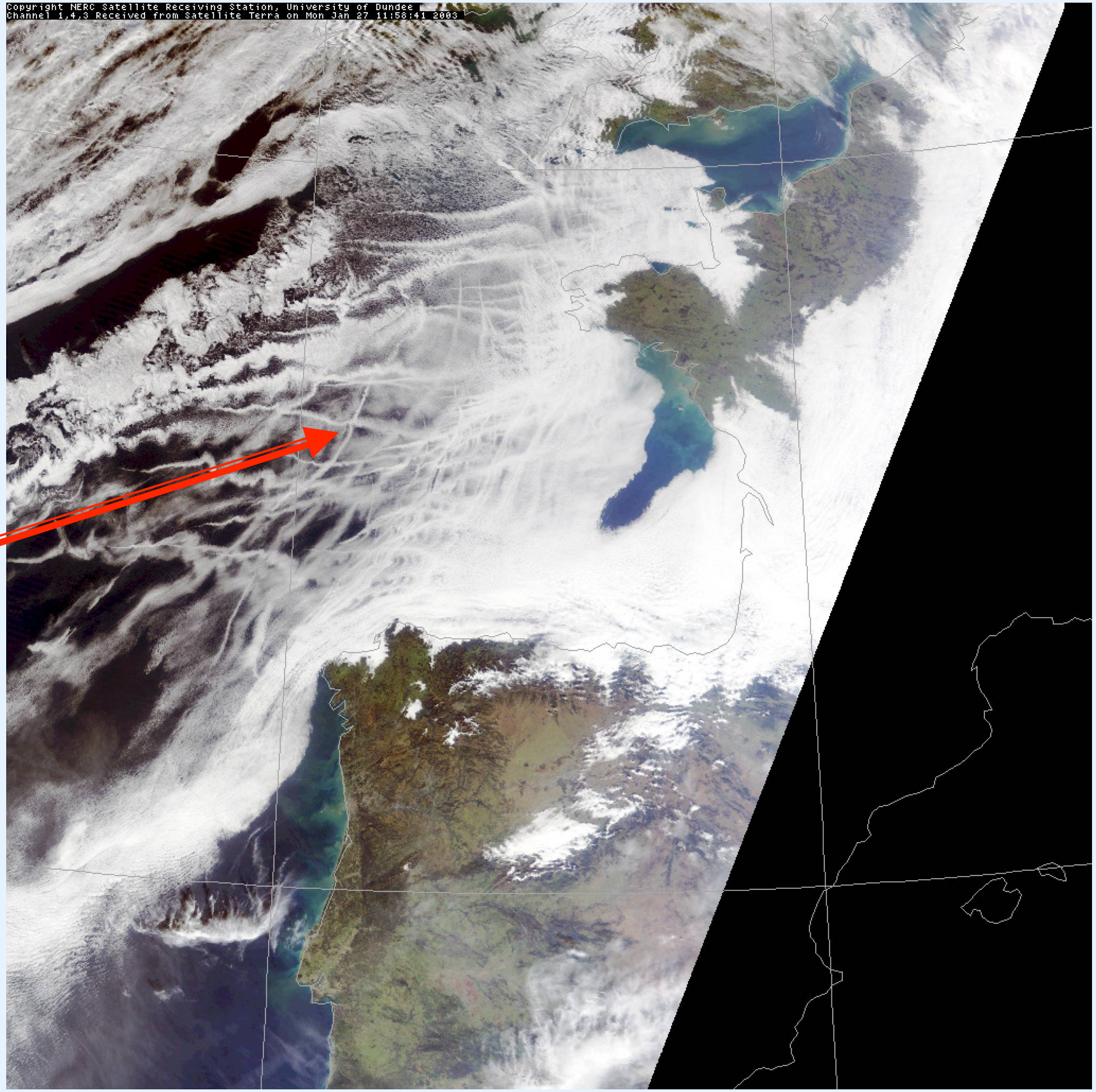


Aerosol and Greenhouse Gases have increased together until now, but are now decoupling….



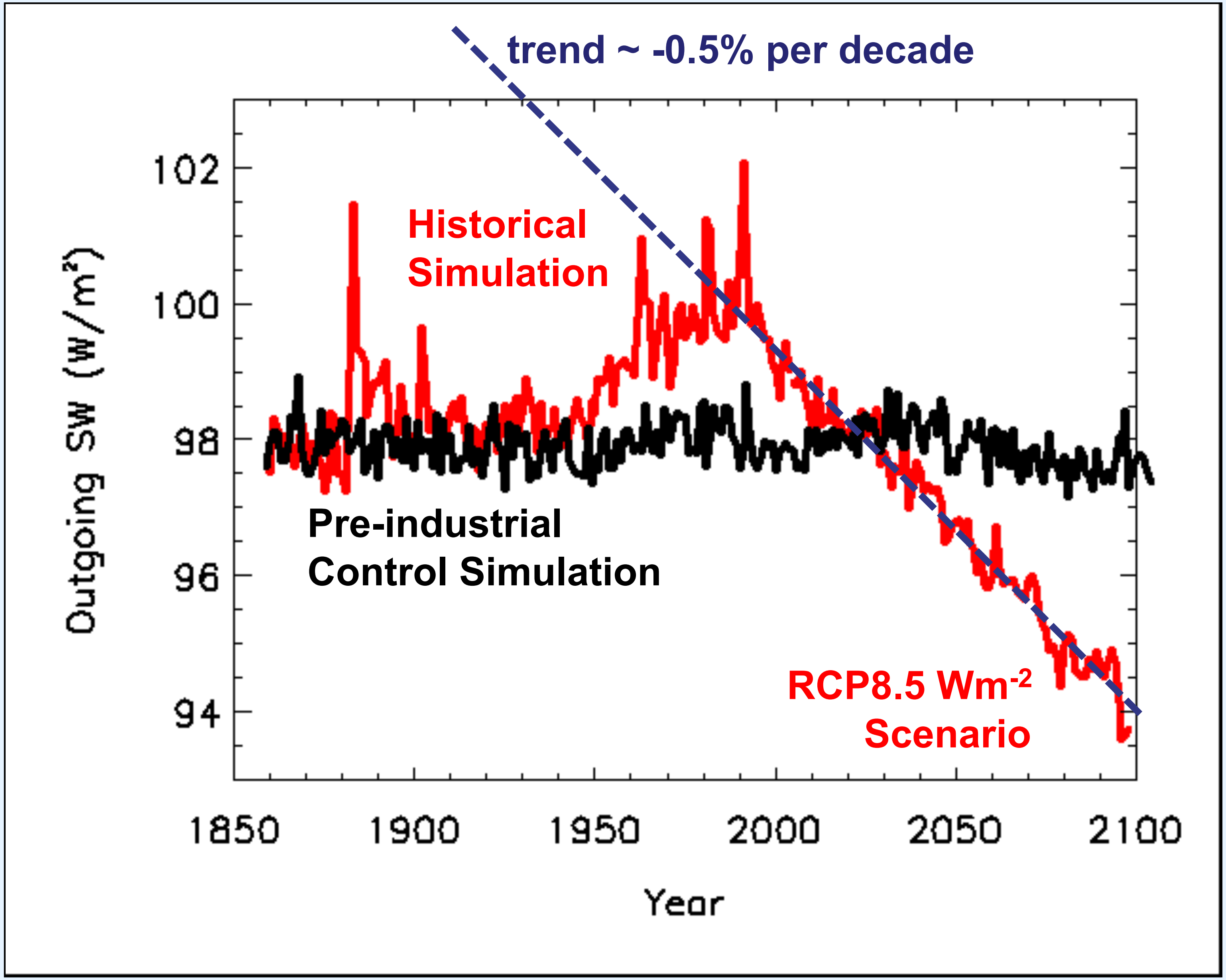
Andreae et al., 2005

Aerosol Pollution has had a large impact on climate

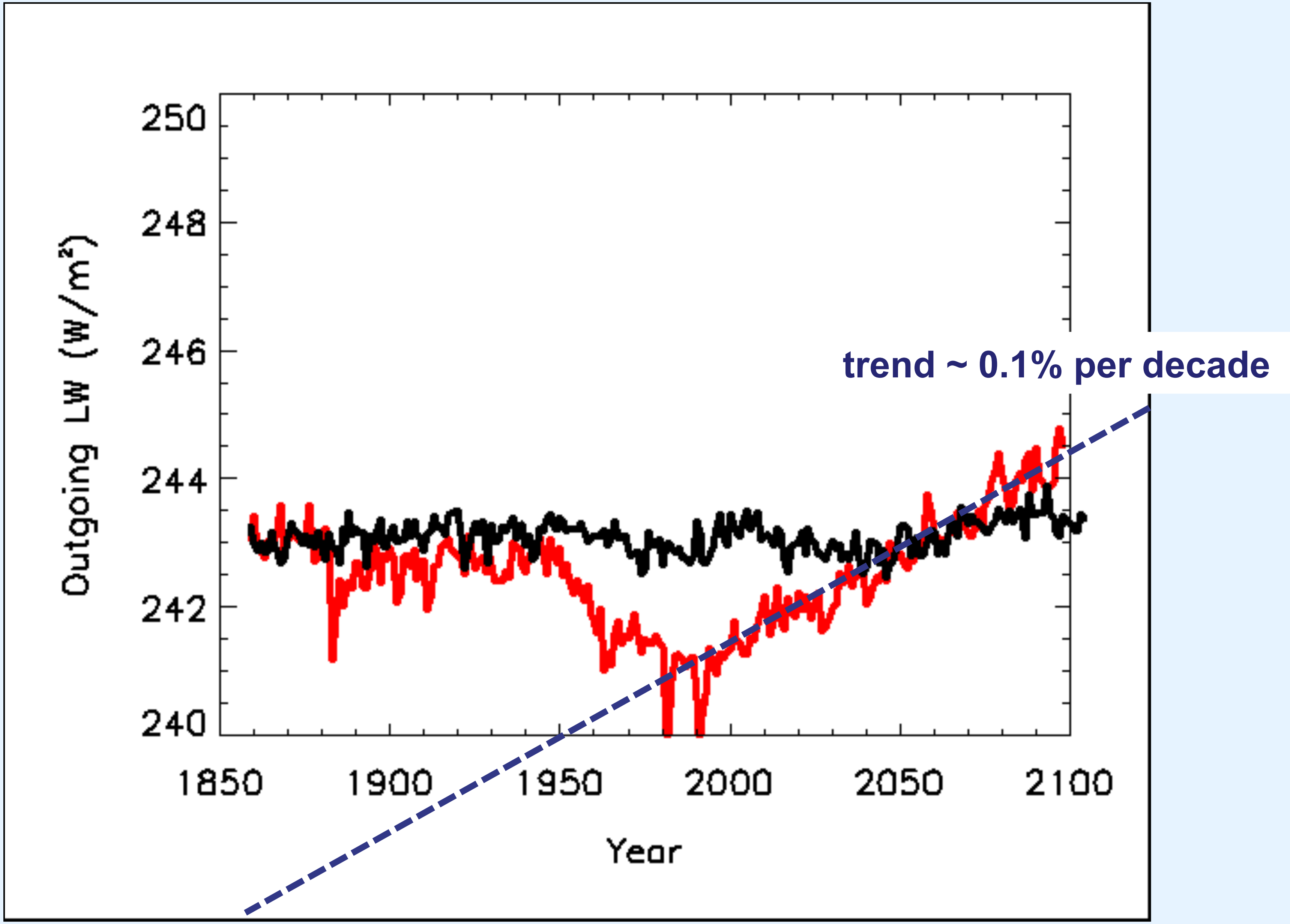


Pollution from ships giving brighter clouds

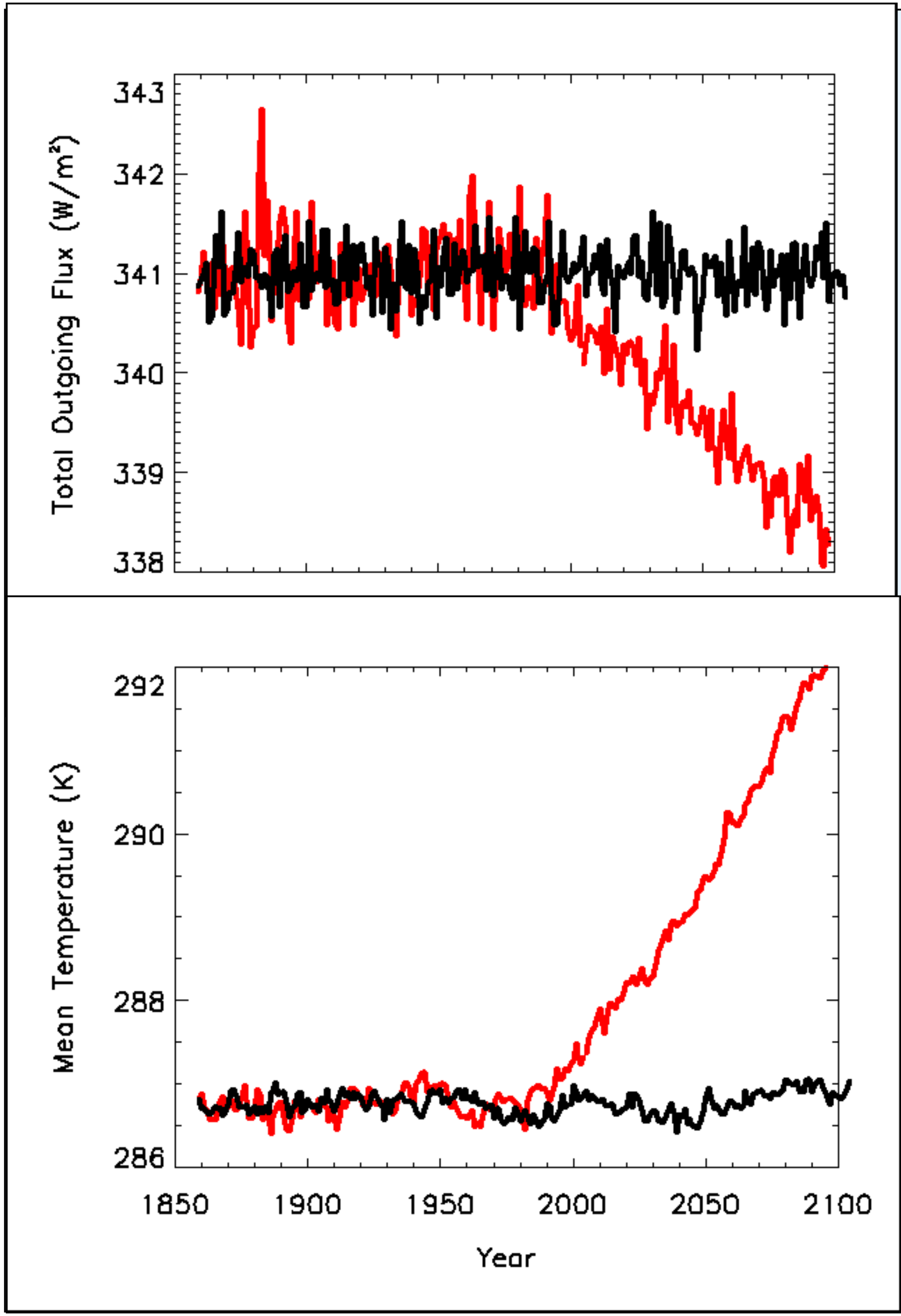
HadGEM2-ES Simulation: Reflected SW at TOA



HadGEM2-ES Simulation: Outgoing LW at TOA



HadGEM2-ES Simulation

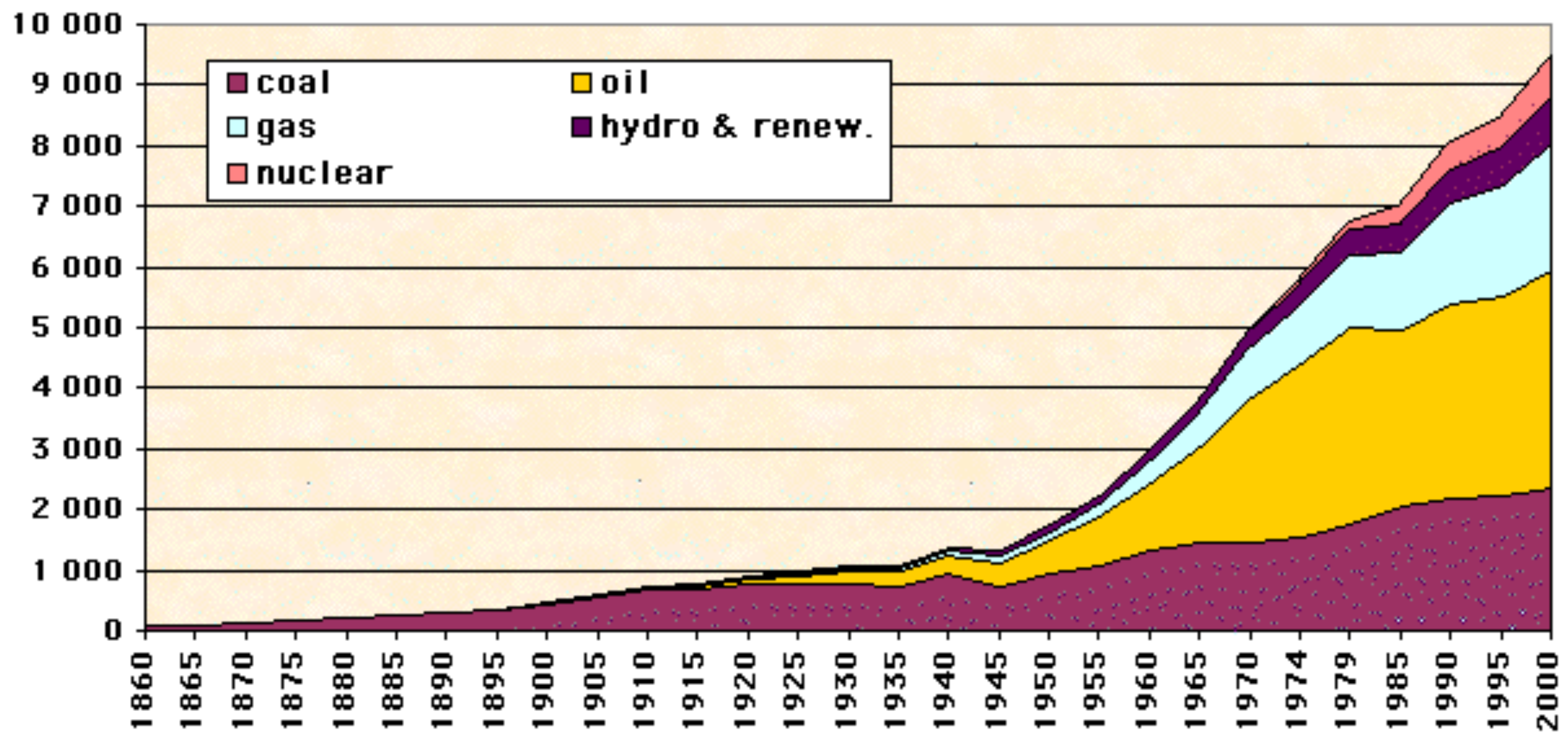


Outgoing LW + Outgoing SW

$$C.\ d\Delta T/dt = \Delta Q - \lambda.\ \Delta T$$

Surface Air Temperature

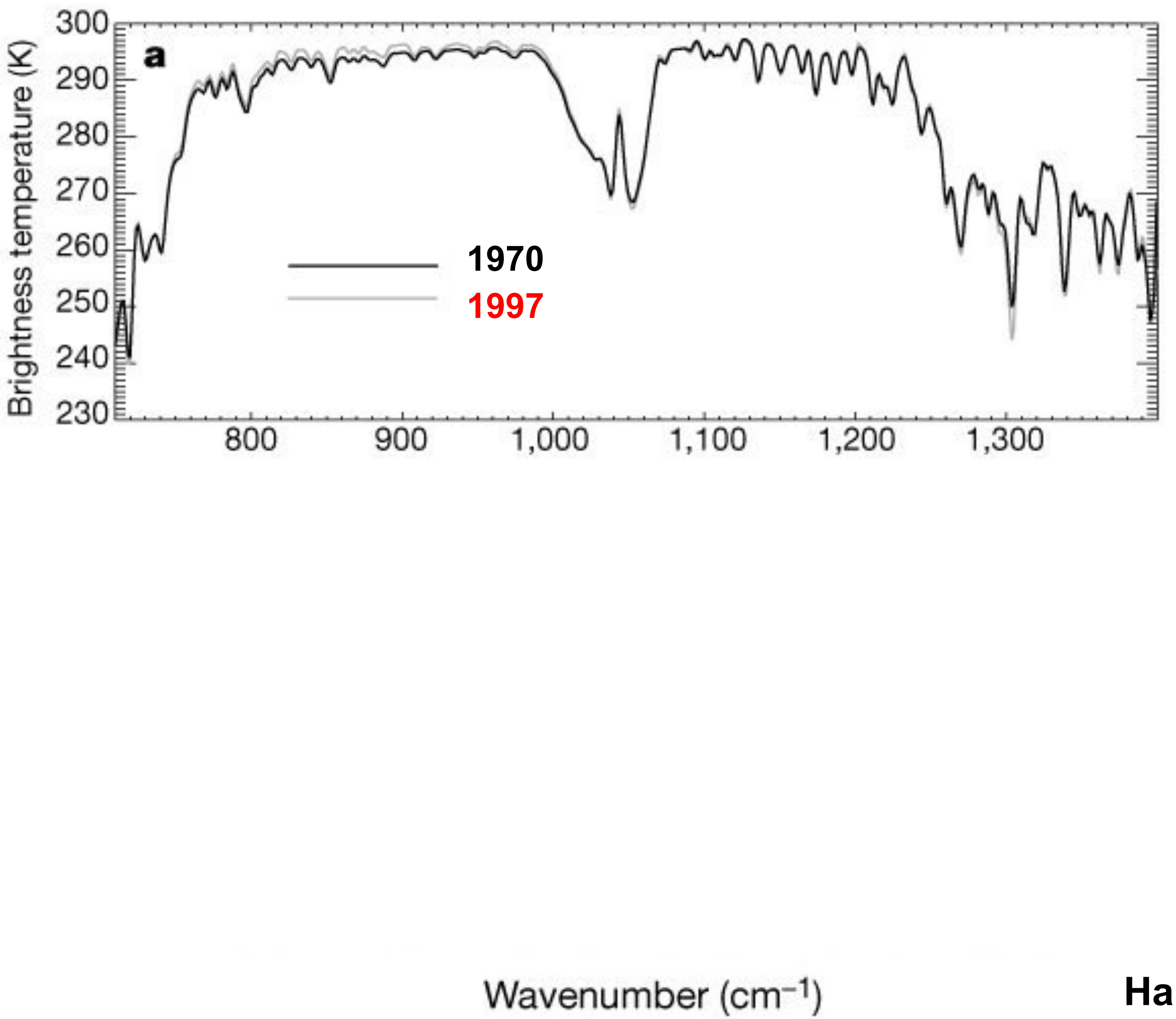
World Energy Consumption



About 15 TW of total power consumed globally implies about 0.1 Wm^{-2} of waste heat (assuming an efficiency of 30%)

- so we will become even less visible as we become more sustainable !

Observed Change in Outgoing LW Spectra



Harries et al., 2001

Unifying Principles to Simplify Models of Climate Systems

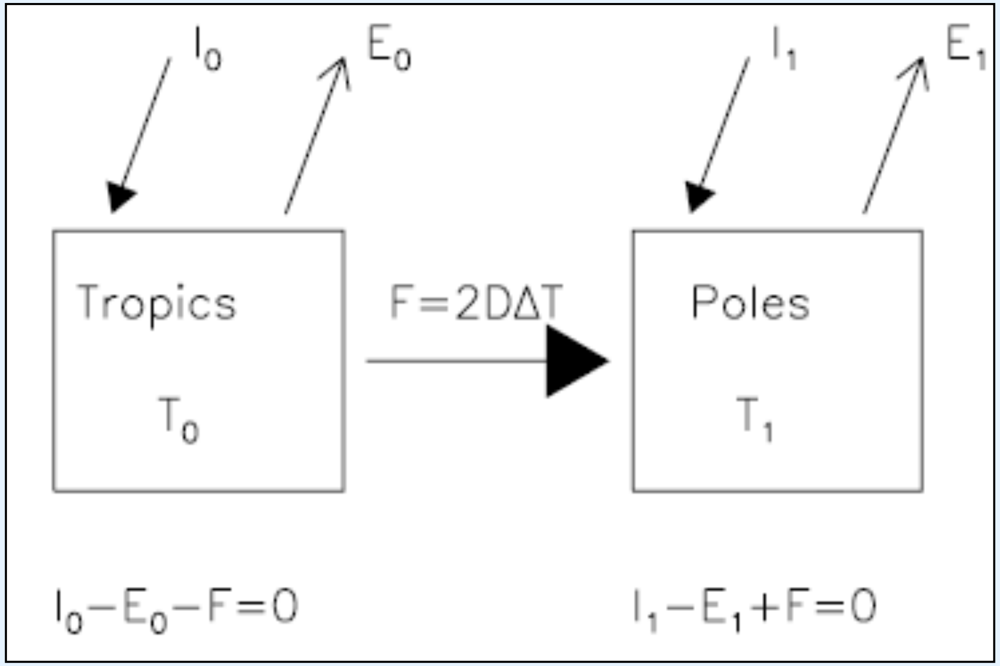
Maximum Entropy Production : Application to the Climate System

- 1960s : Ed Lorenz suggests that the climate system maximises "work". (E. Lorenz, 1960)

- 1970s : Garth Paltridge develops successful climate model based on the assumption that heat transports maximise the rate of entropy production. (Paltridge 1975; 1978)

- 2003 : Ralph Lorenz et al. show that MEP is consistent with the observed equator-to-pole temperature contrasts on Titan and Mars (as well as Earth). (R. Lorenz et al., 2003).

Entropy Production by Zonal Heat Transport



Lorenz et al., 2003

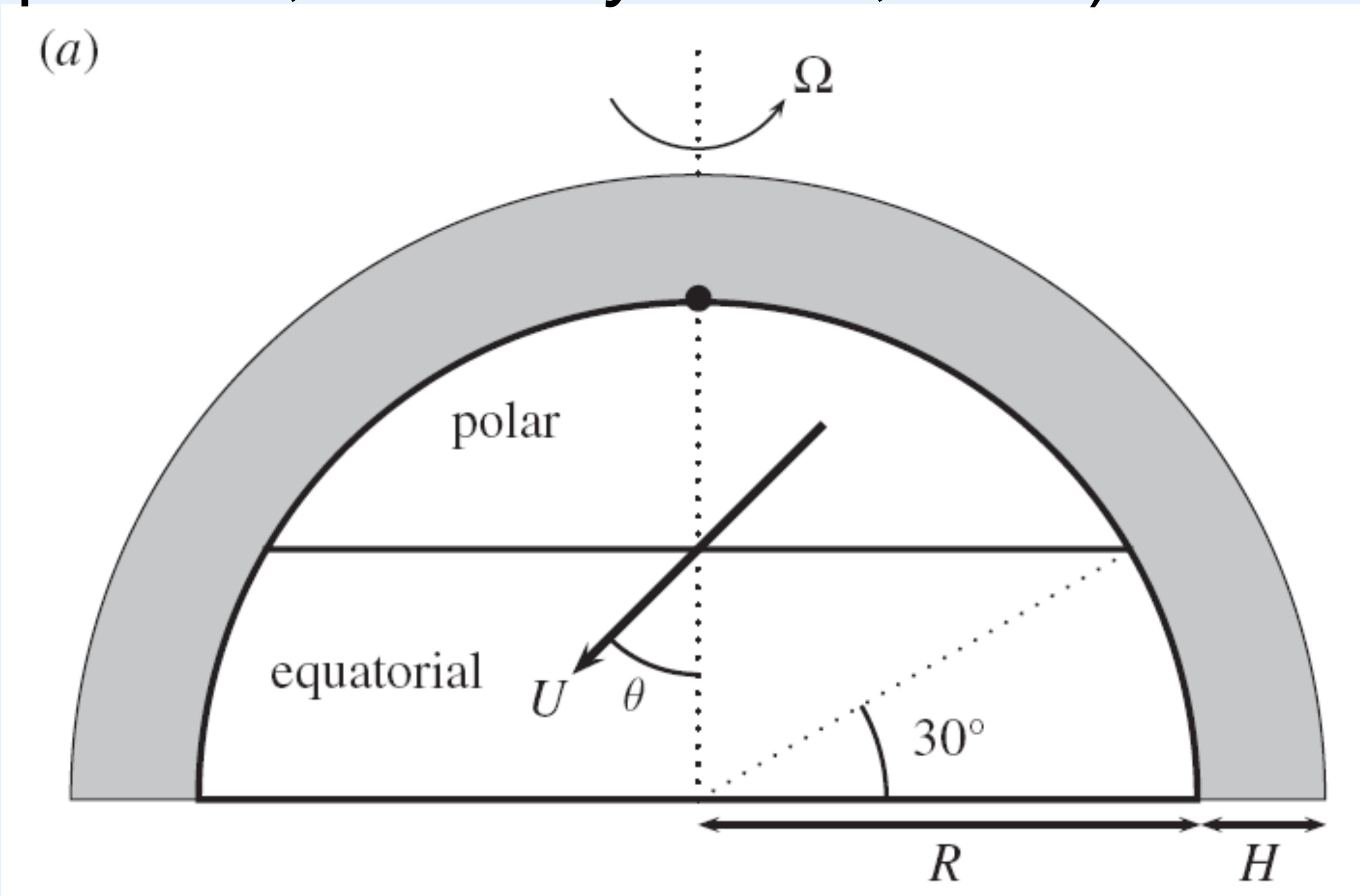
Equator-Pole heat flux $F = 2D\,(T_0 - T_1)$

D chosen to maximise the rate of Entropy Production

Entropy Production Rate $= F\,\{\,1 / T_1 - 1 / T_0\,\}$

2-box MEP model including dynamics

(Jupp + Cox, *Proc Roy Soc B*, 2010)



Solve for flow *U*, θ with surface drag C_D as free parameter

Maximum Entropy Production : Application to the Climate System

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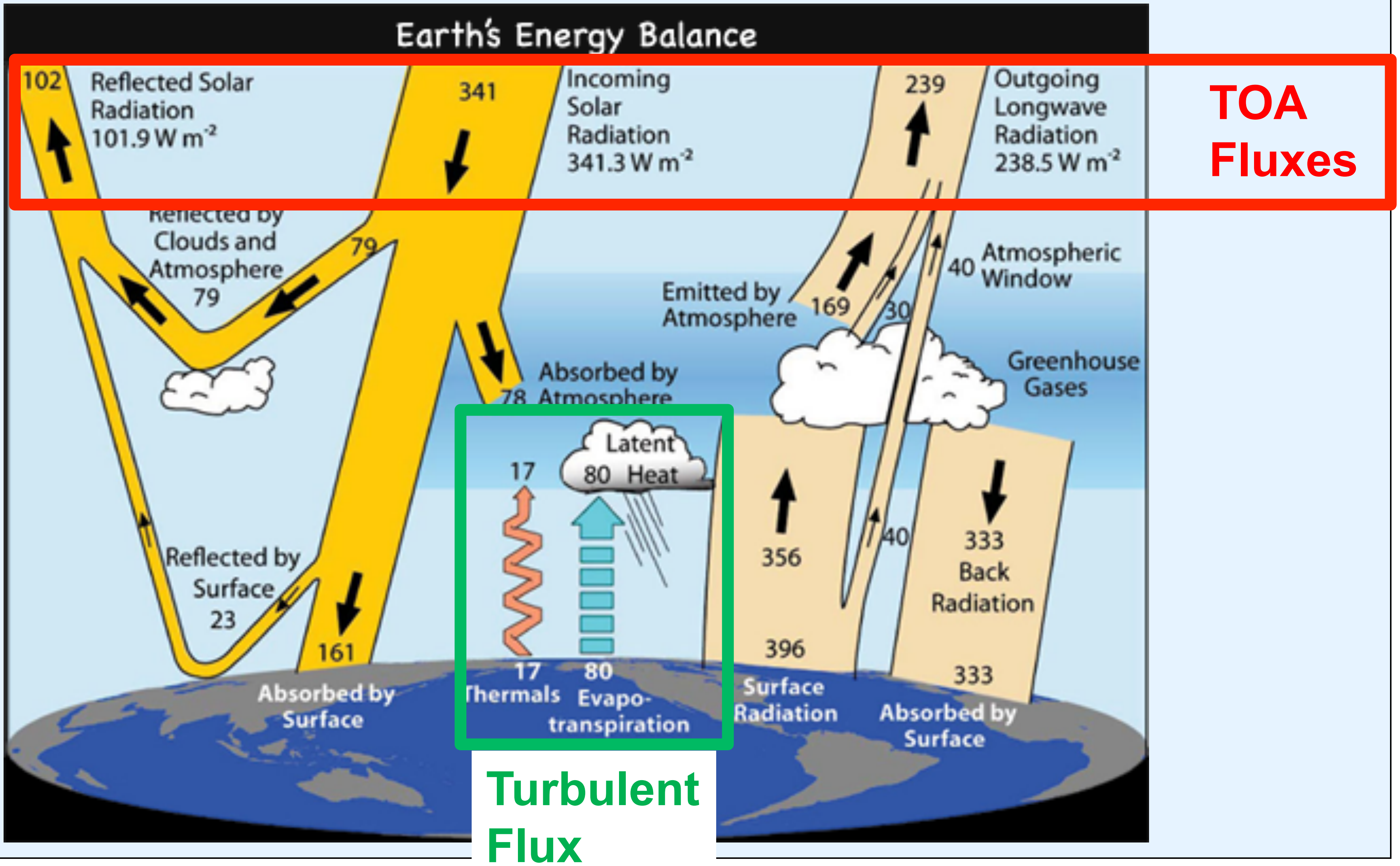
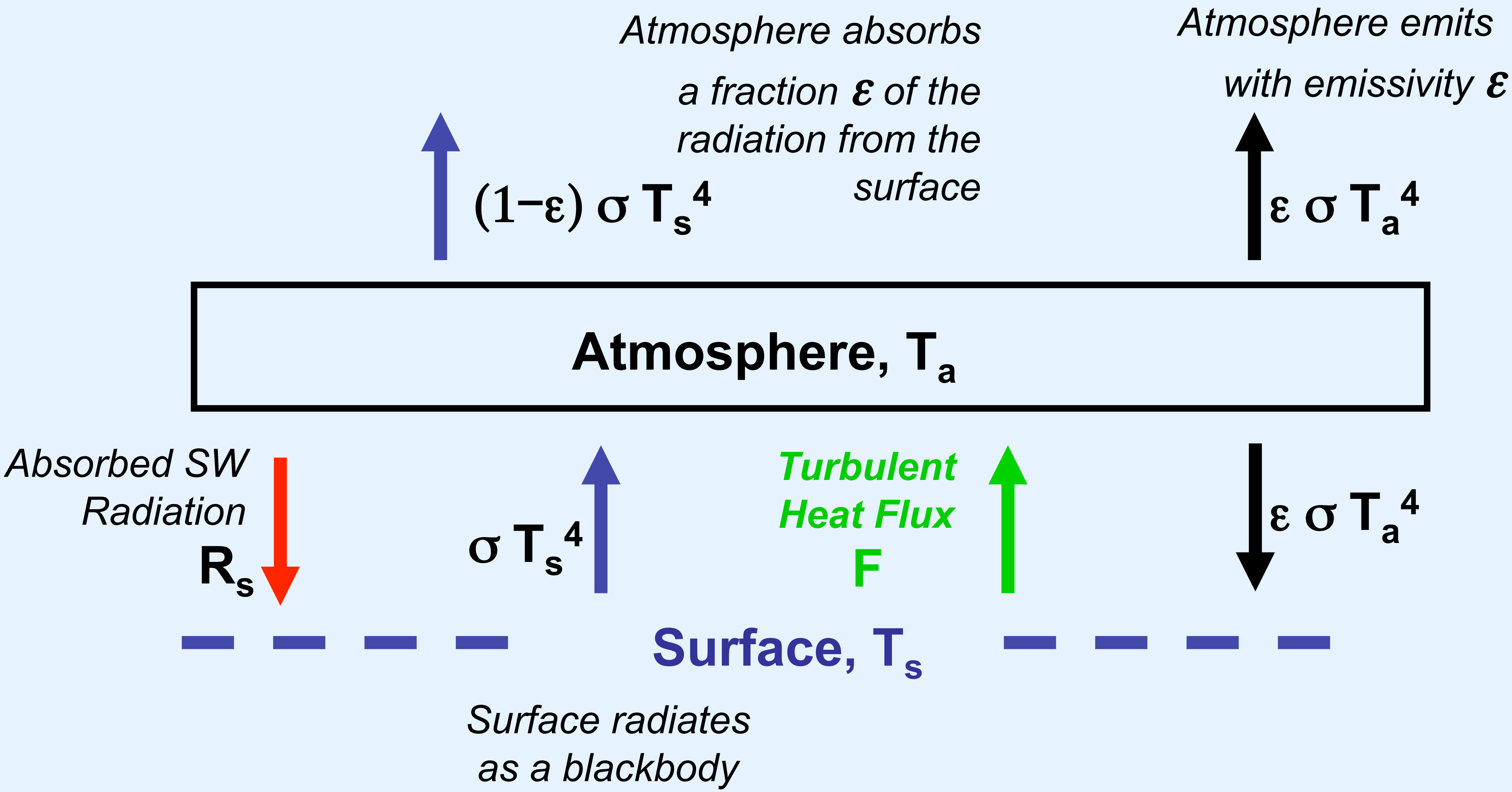
- 2003 : Ralph Lorenz et al. show that MEP is consistent with the observed equator-to-pole temperature contrasts on Titan and Mars (as well as Earth). (R. Lorenz et al., 2003).
- 2003: Roddy Dewar derives the MEP principle from Information Theory, in a manner similar to the information approach to the second law of thermodynamics. (Dewar, 2003, 2005).

"Dangerously Seductive" ...but sometimes it's nice to be seduced...

Atmospheric Energy Balance on Earth



Leaky Greenhouse Model
+ Turbulent Flux by MEP



Equations of the "Model"

Top-of-the-atmosphere energy balance:

$$R_s = (1-\varepsilon)\,\sigma\, T_s^4 + \varepsilon\,\sigma\, T_a^4$$

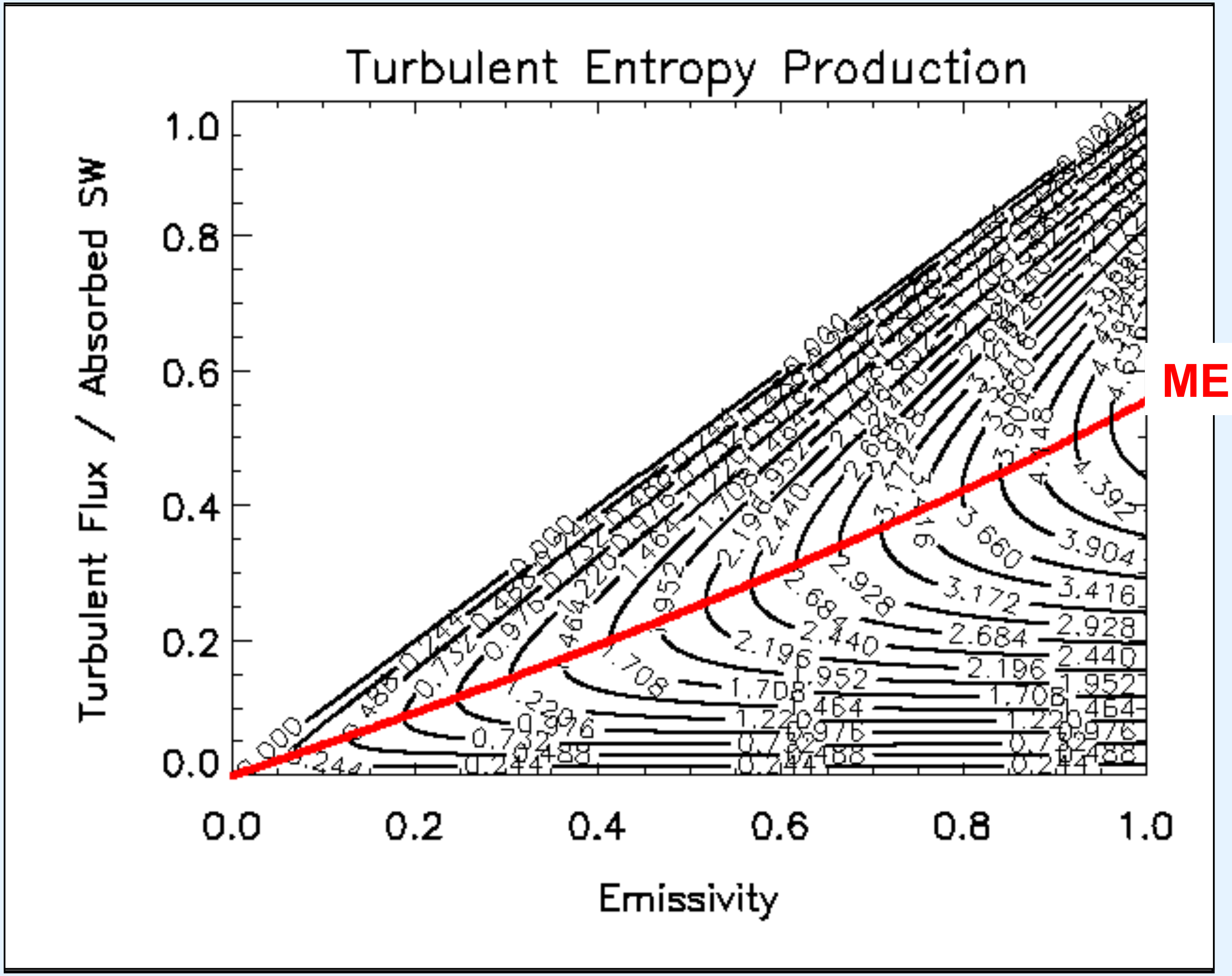
Surface energy balance:

$$R_s + \varepsilon\,\sigma\, T_a^4 = \sigma\, T_s^4 + F$$

Assume **F** *maximises the rate of entropy production:*

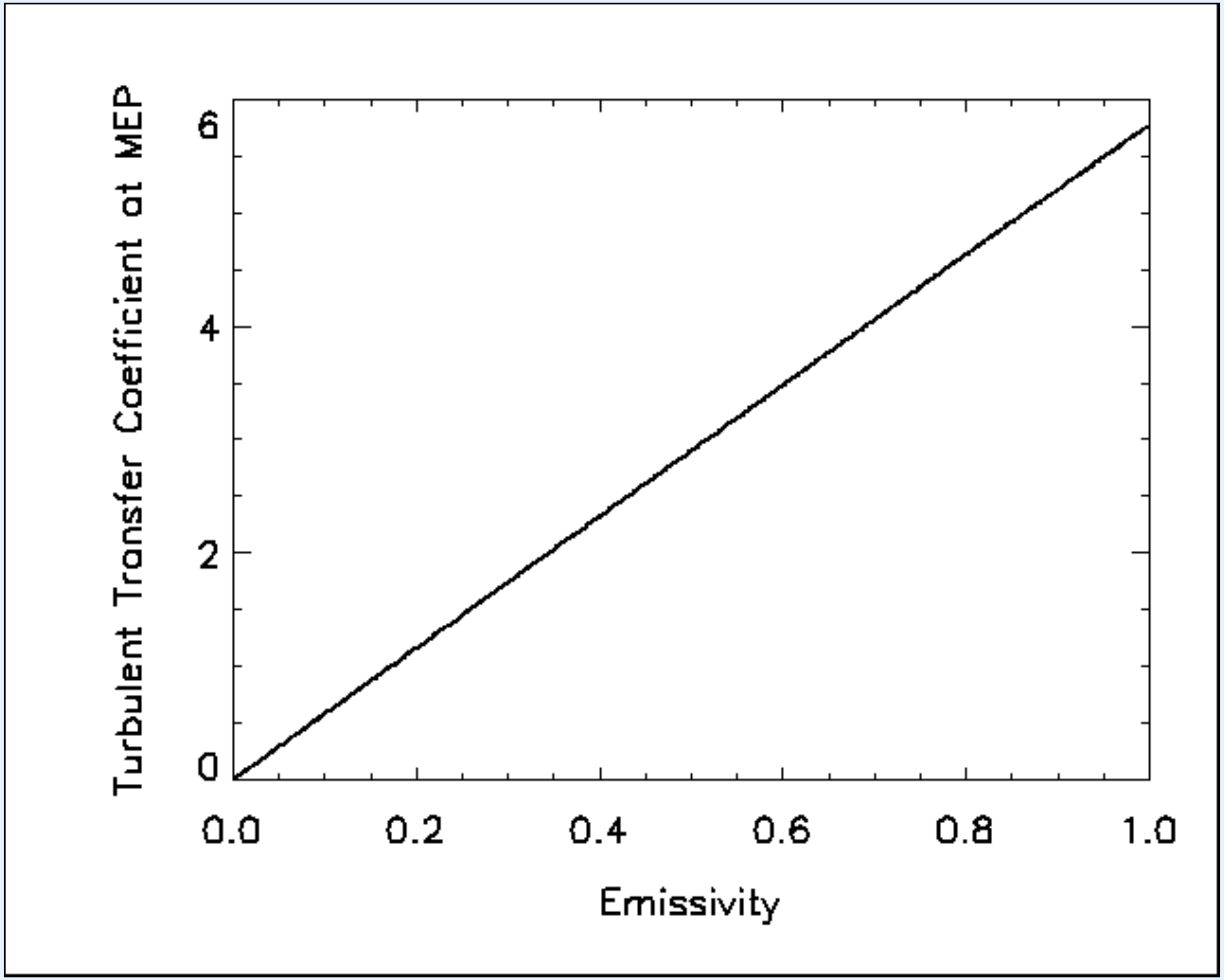
$$dS/dt = F\,\{1/T_a - 1/T_s\}$$

Entropy Production vs Turbulent Flux and Emissivity

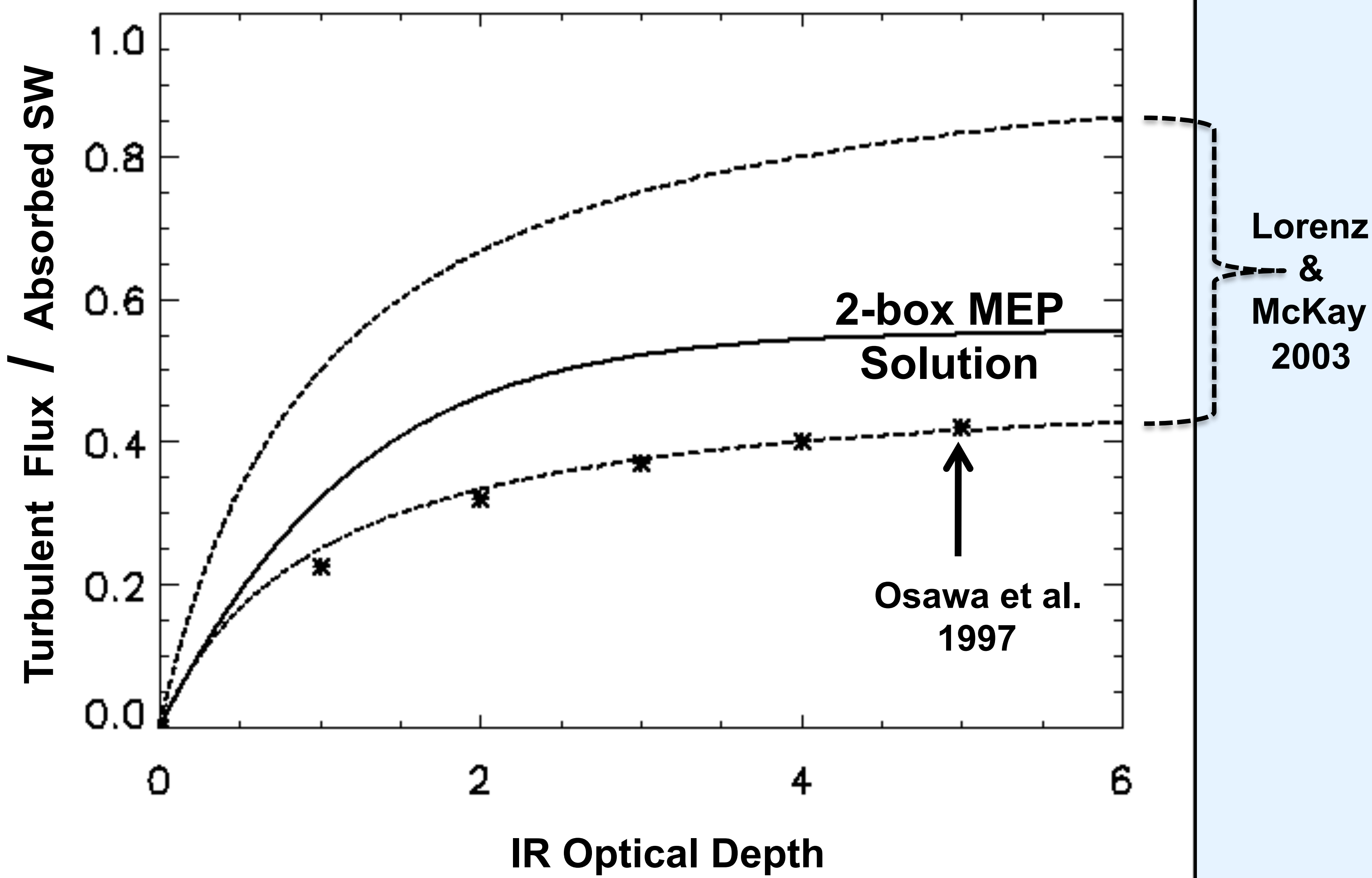


MEP Condition

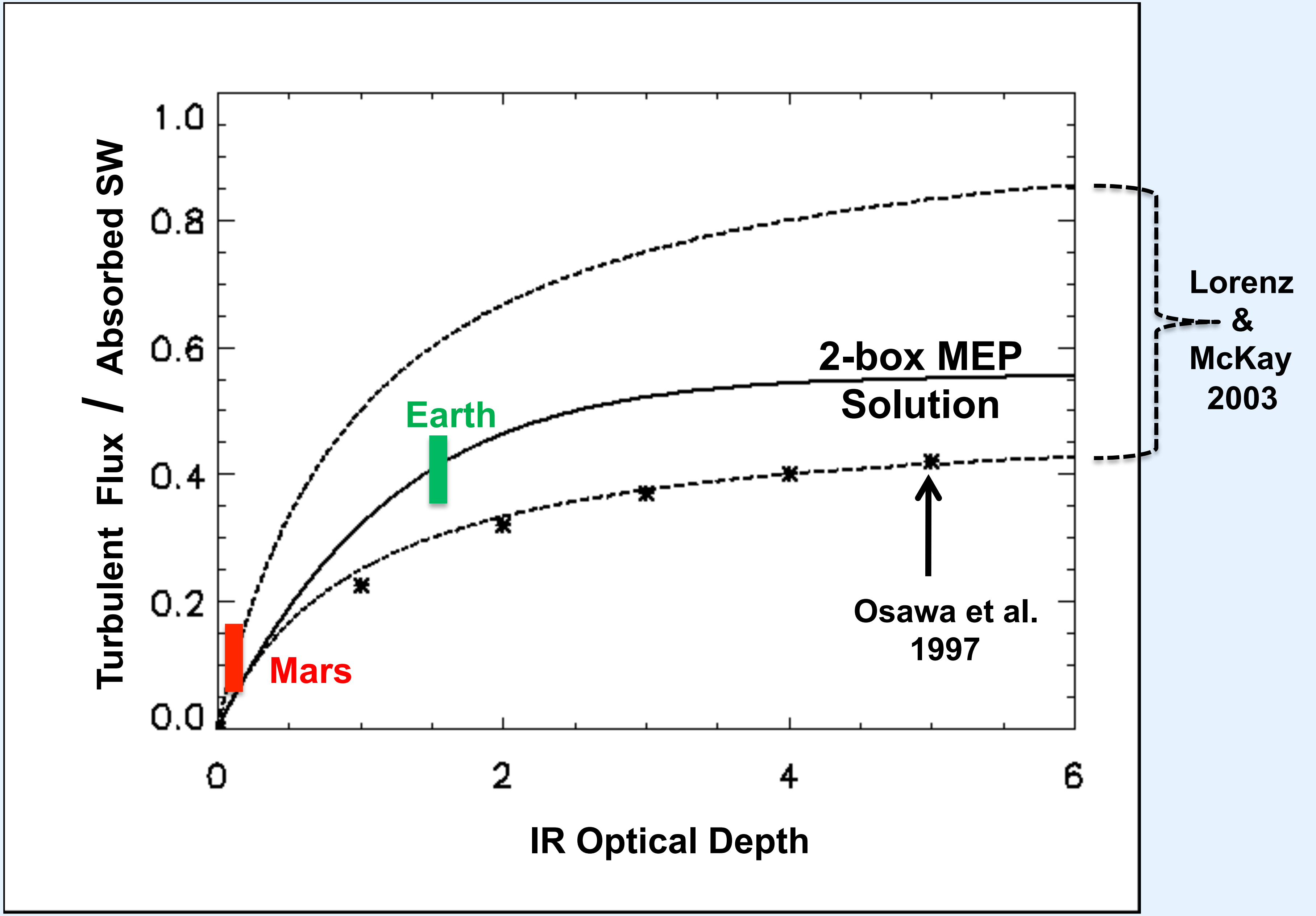
Turbulent Transfer Coefficient at MEP versus Emissivity



Simple Models for Turbulent Flux



Simple Models for Turbulent Flux



Climate Tipping Points

United Nations Framework Convention on Climate Change (UNFCCC)

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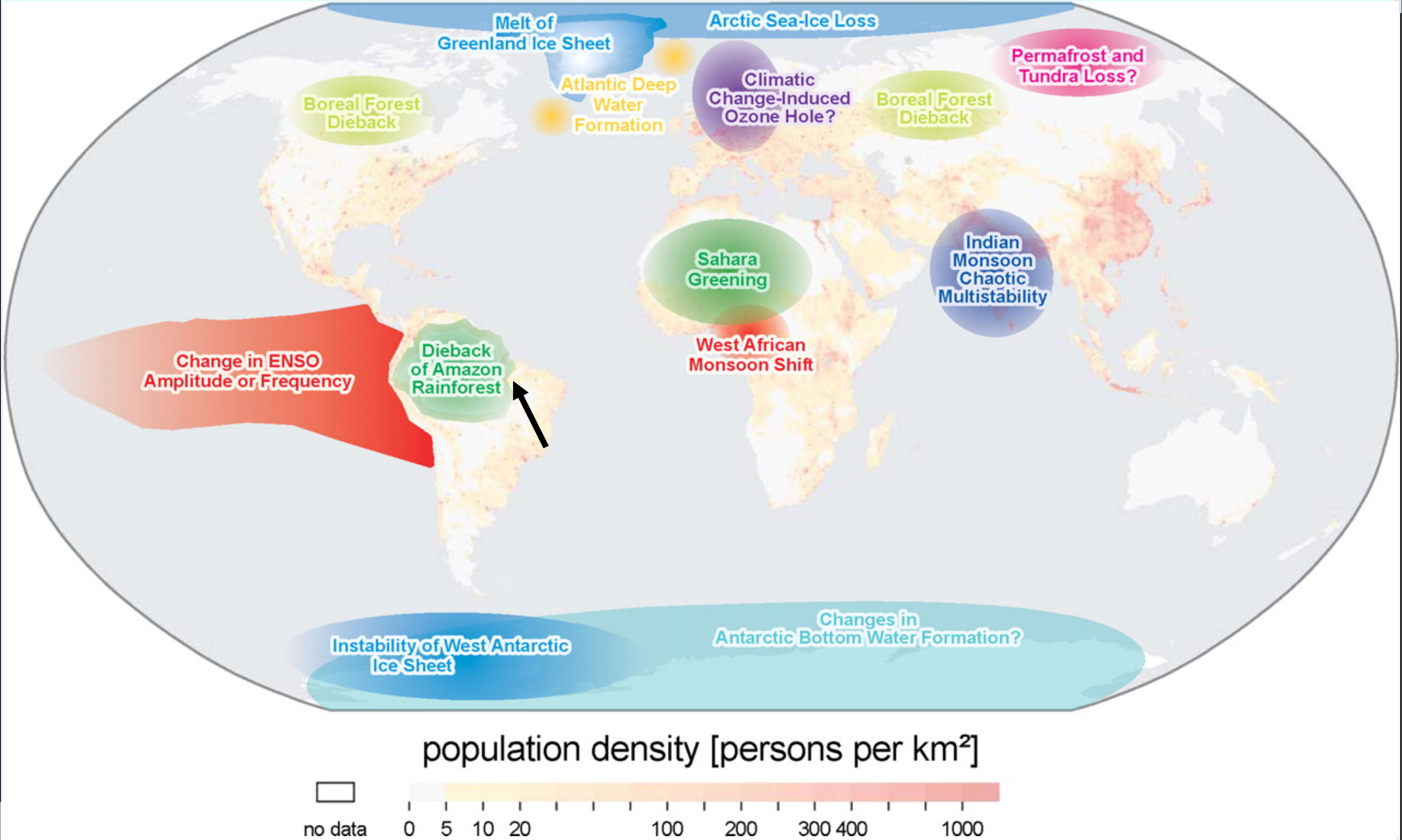
"The ultimate objective [is]….

stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system…"

Introduces the notion of "Dangerous" Climate Change…

….but how can this be defined ?

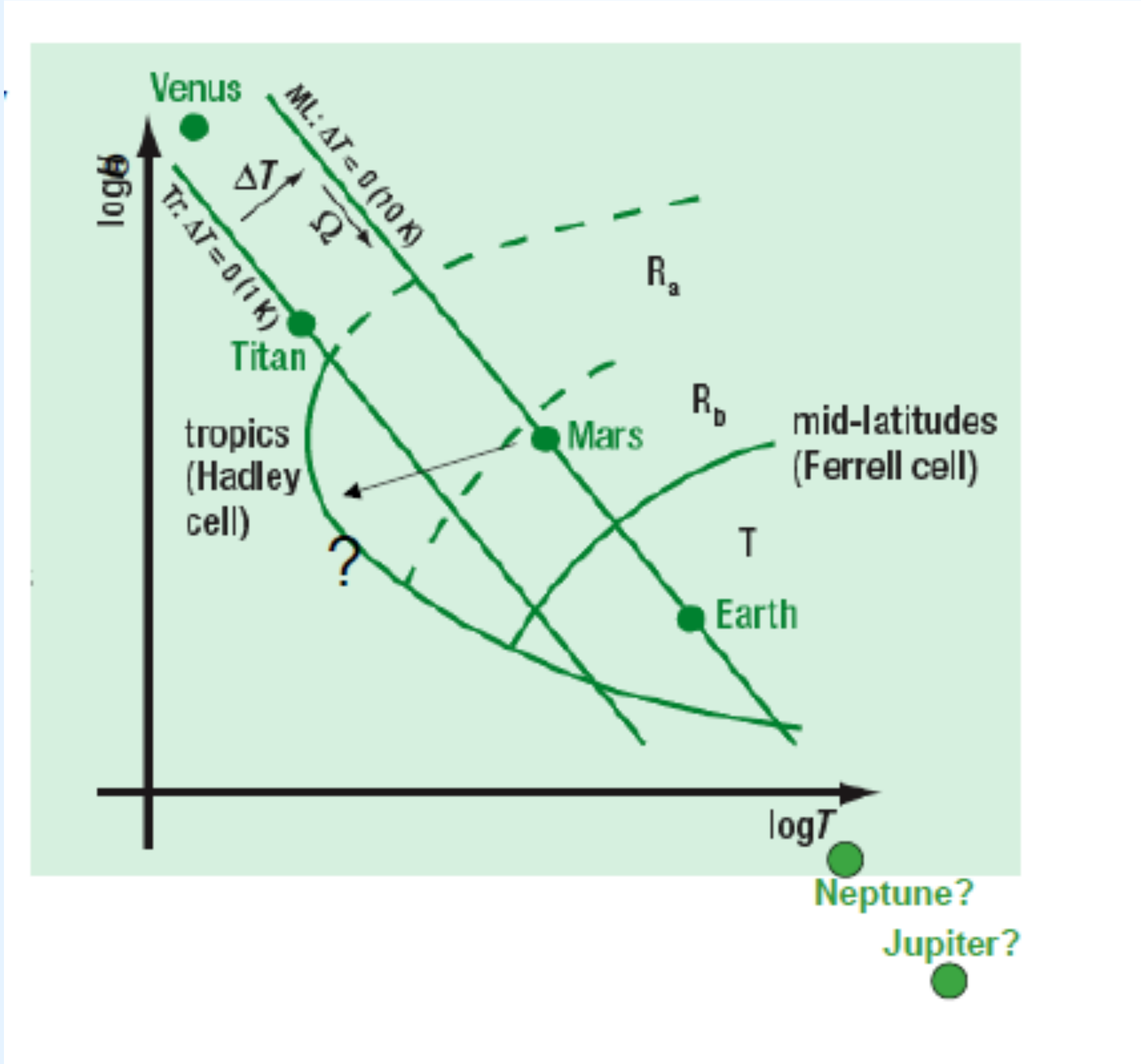
Tipping Points (Lenton et al., 2008)



Lenton T. M. et.al. PNAS 2008;105:1786-1793

PNAS

Planetary Circulation Regimes and Climate Tipping Points



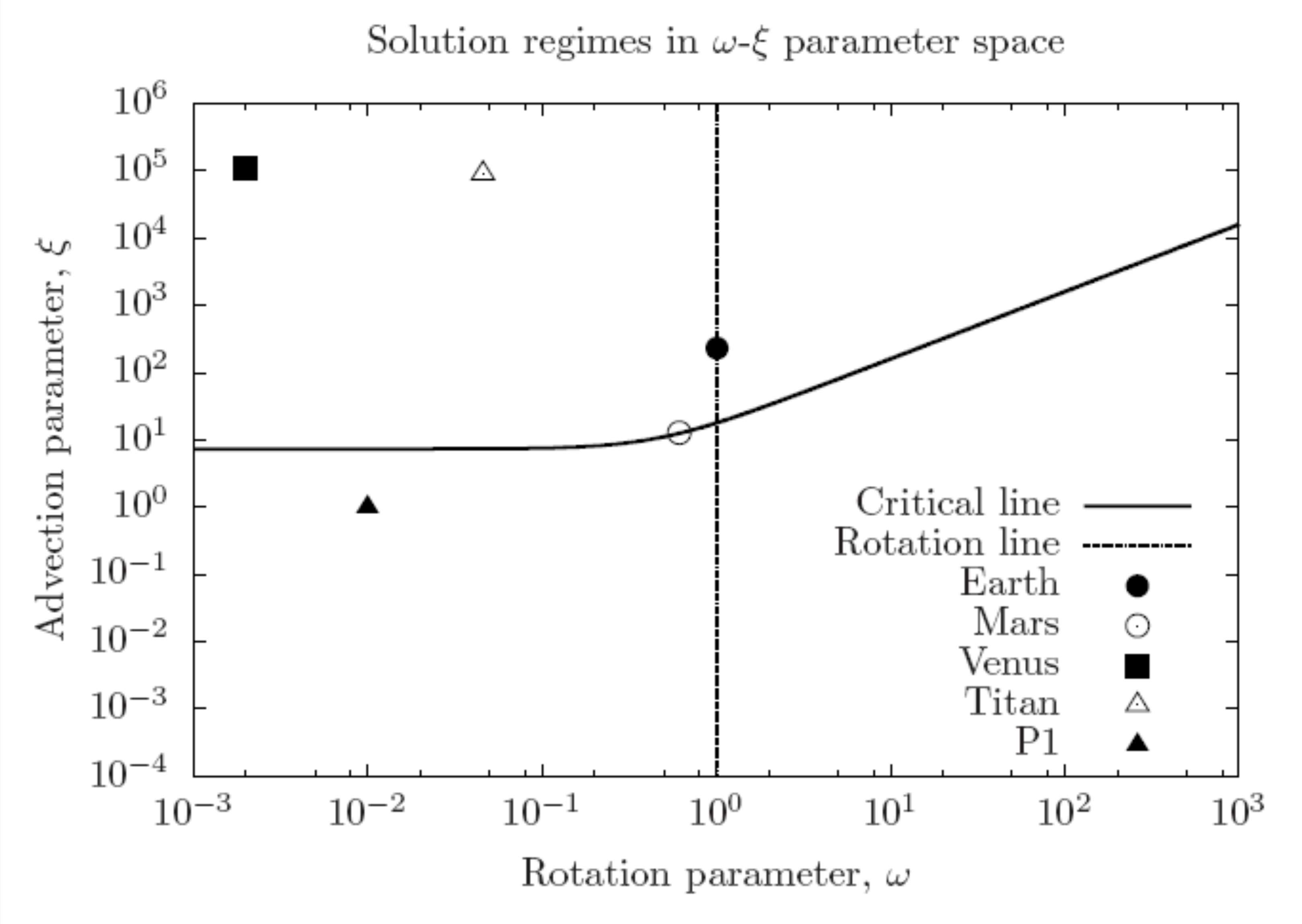
Peter Read,
***this conf*.**

What can they learn from each other?

- Climate/Planetary Atmosphere Models are now converging, so modelling techniques can be shared.
- Climate Scientists can provide insights into the uncertainties in models.
- Planetary Scientists can provide insights into the diversity of planetary “climates”, which may help us to understand the possible future (and past) development of Earth’s climate, and identify “tipping points”.
- Together we need to develop more robust representations of climate processes. Developments in MEP principles may help in this respect.

Together we can have fun searching for Needles in the Haystack !

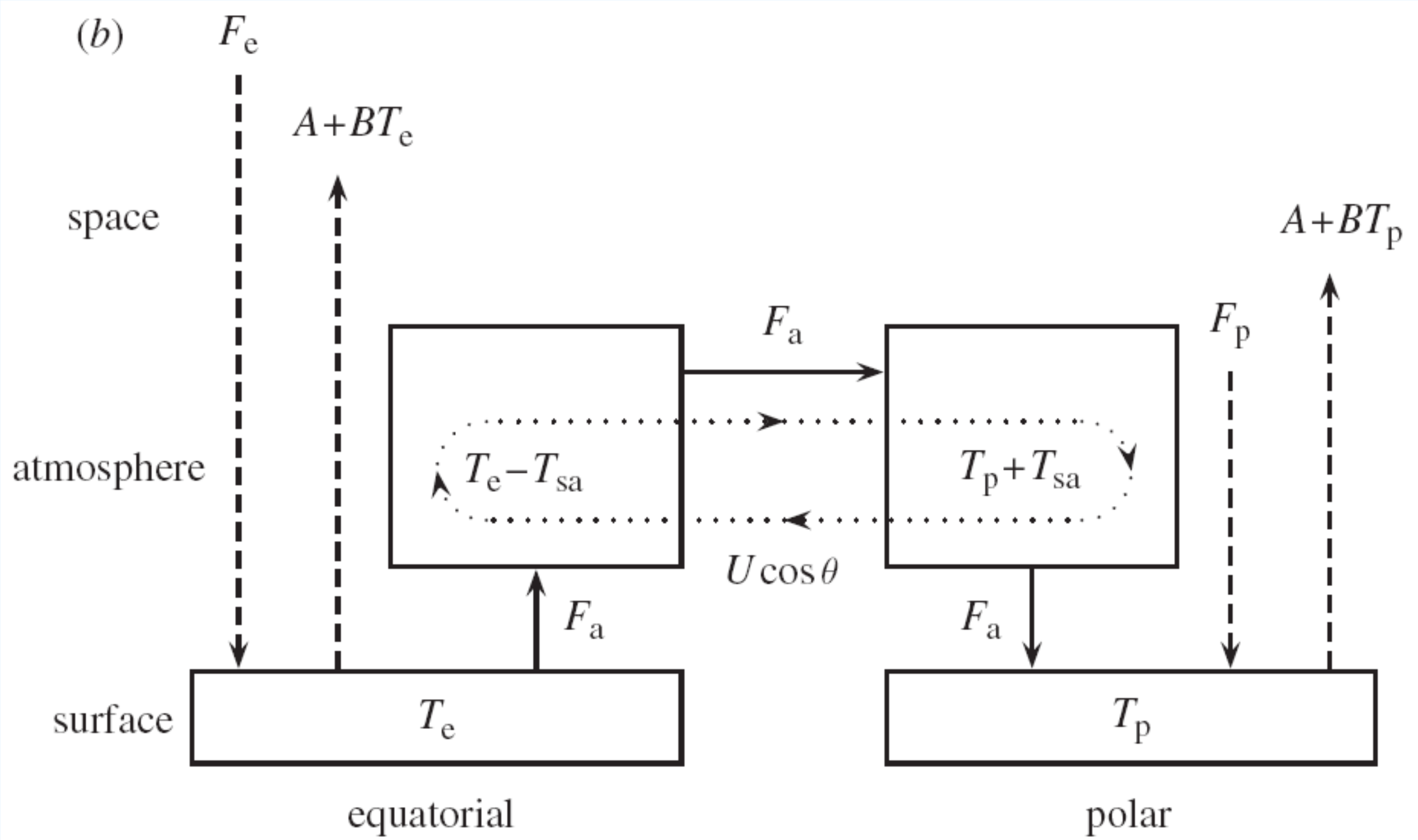
Planets in Advection vs Rotation Space



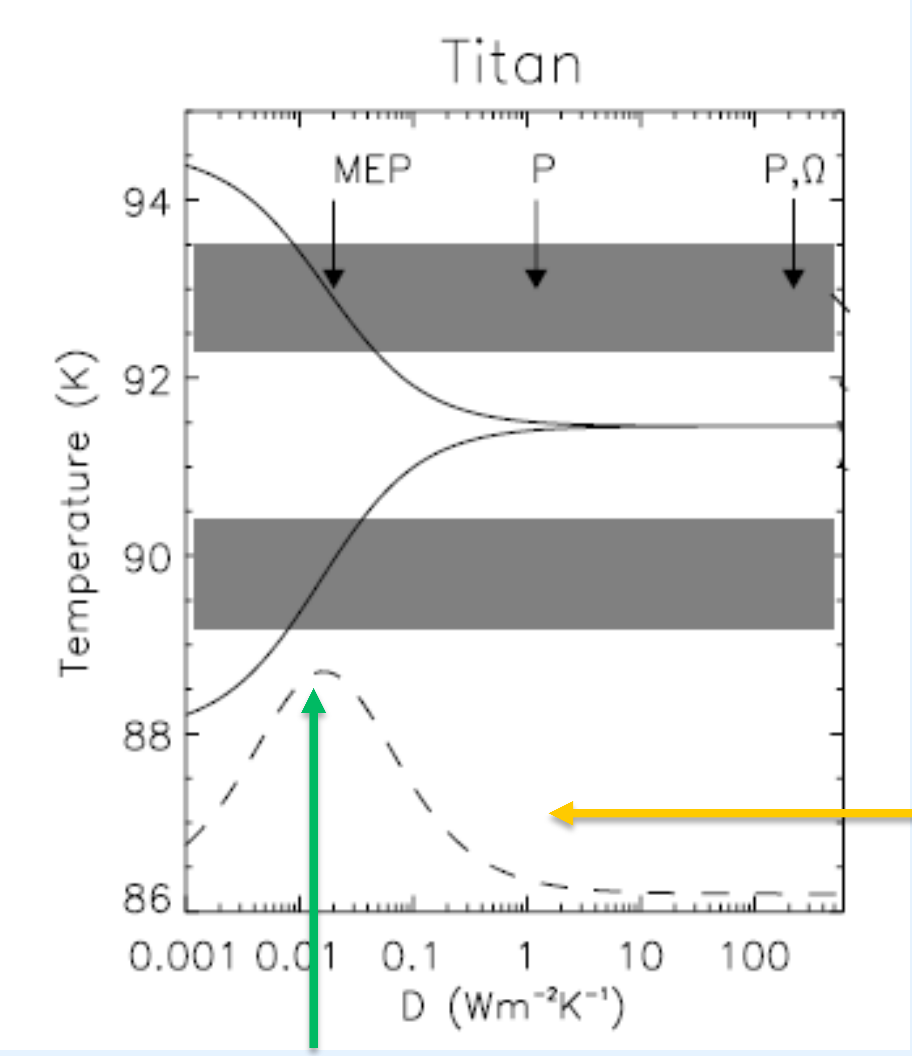
Dynamics affect MEP state

Rotation matters

Energy balance (schematic)



Application of MEP Principle to Titan



Observed Equatorial Temperature

Modelled Polar and Equatorial Temperatures

Observed Polar Temperature

Entropy Production Rate due to equator-pole heat transport

Maximum Entropy Production (MEP) fits observations

Lorenz et al., 2003