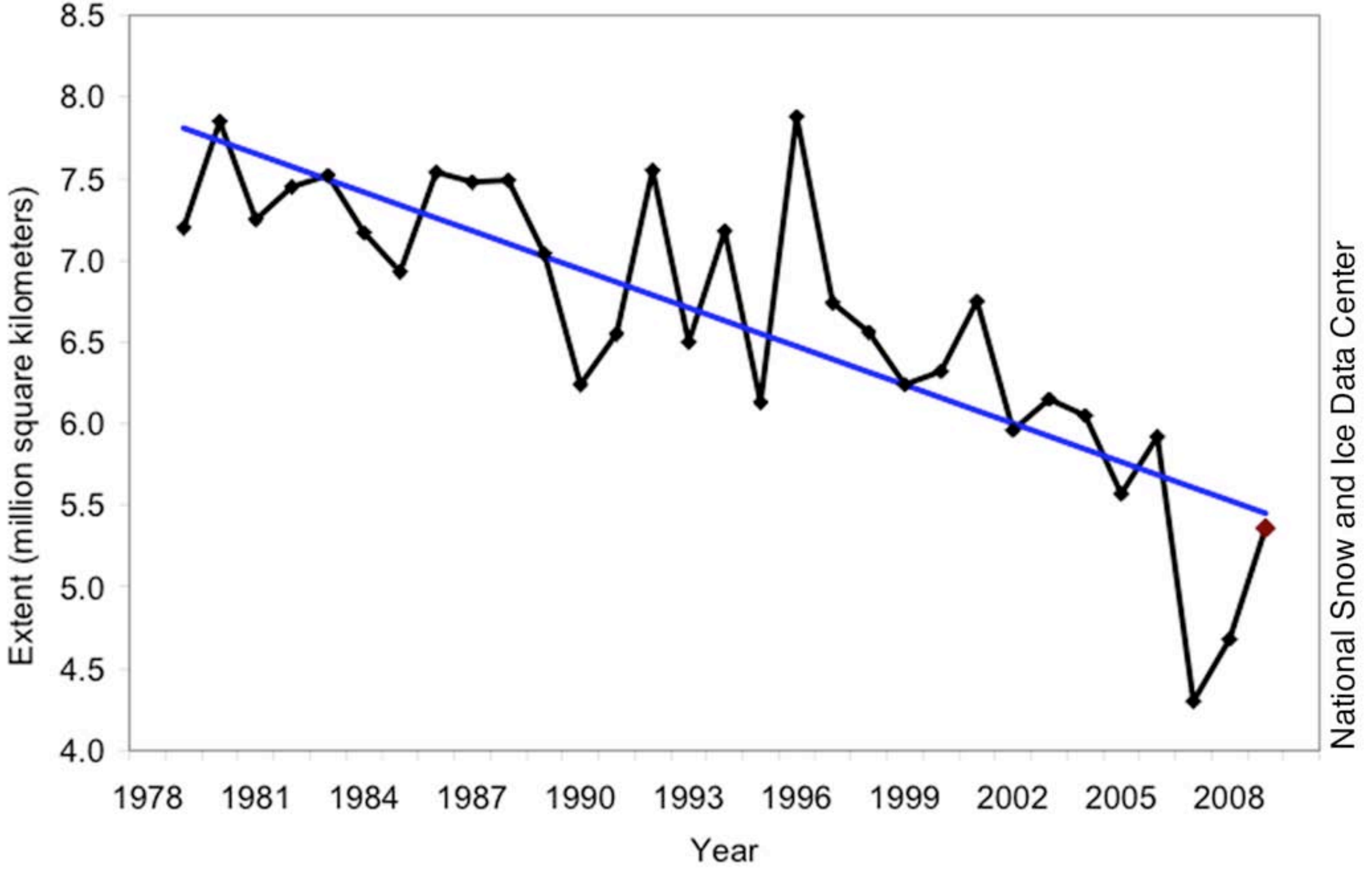
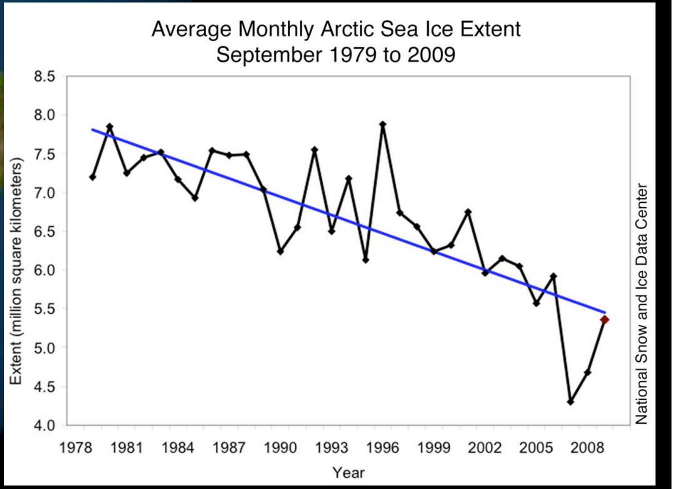


Average Monthly Arctic Sea Ice Extent
September 1979 to 2009



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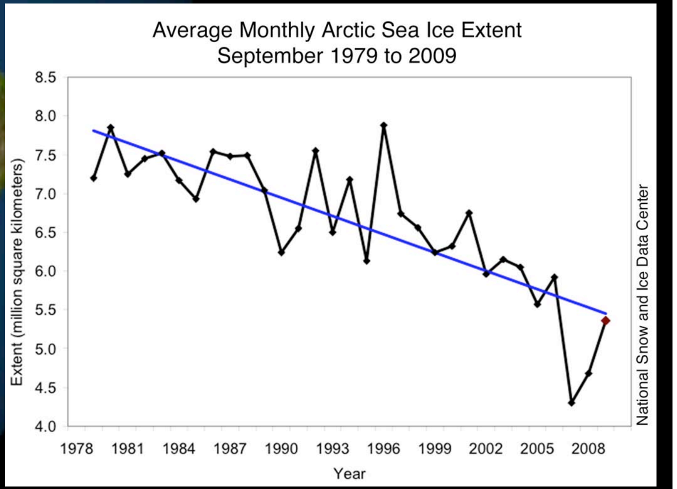

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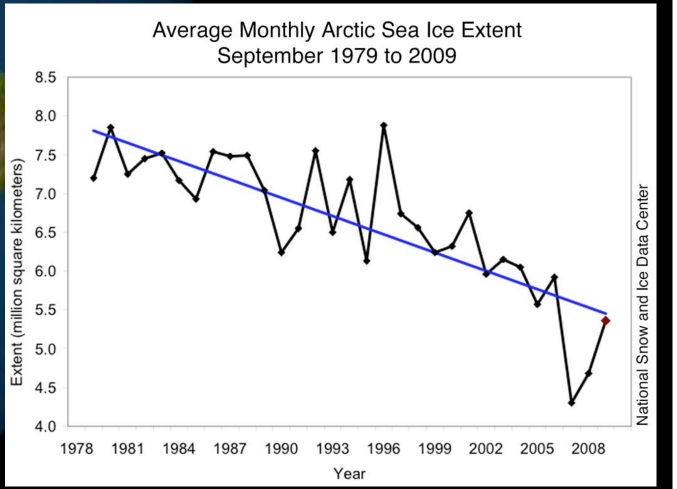

Sea ice field at time of annual minimum extent.

NASA

Climate Models & Climate Sensitivity: A Review

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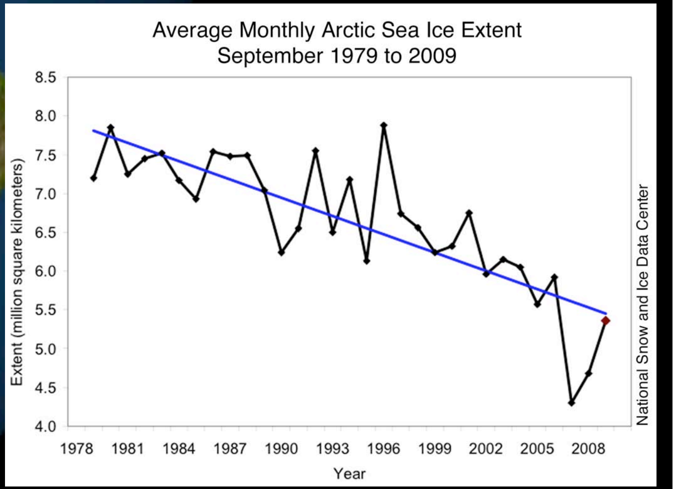
NASA

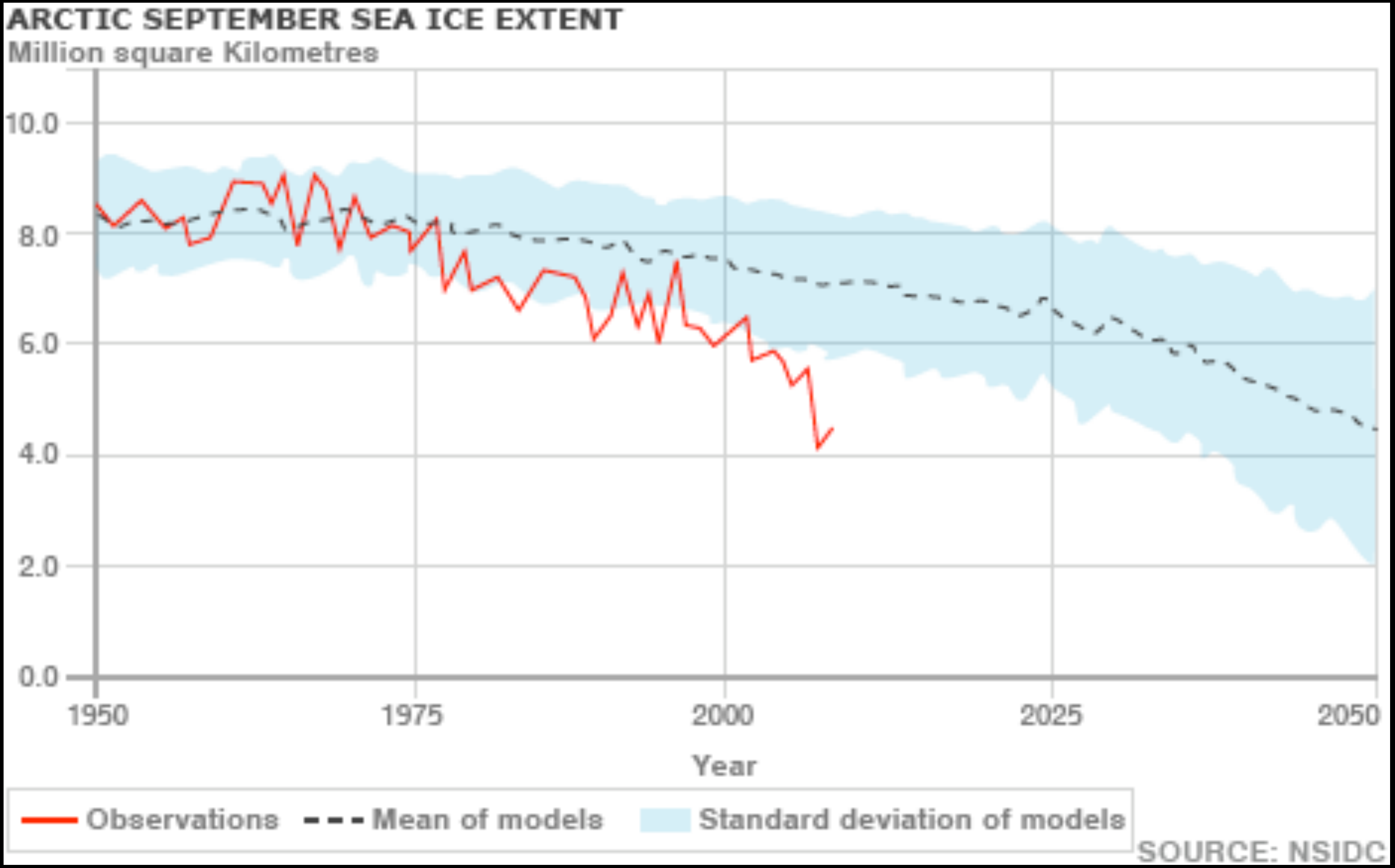


Average Monthly Arctic Sea Ice Extent
September 1979 to 2009

Paul Kushner

Department of Physics, University of Toronto

Climate Models & Climate Sensitivity: A Review



Stroeve et al. 2007, BBC

Paul Kushner

Department of Physics, University of Toronto

Outline

Introduction

- *Global warming and climate sensitivity.*

Intro Climate Theory

- *Simple models, variational techniques, feedbacks.*

Climate sensitivity in climate models.

- *Quantifying uncertainties.*

Case study: snow albedo feedback

- *Feedbacks and teleconnections*

Conclusion

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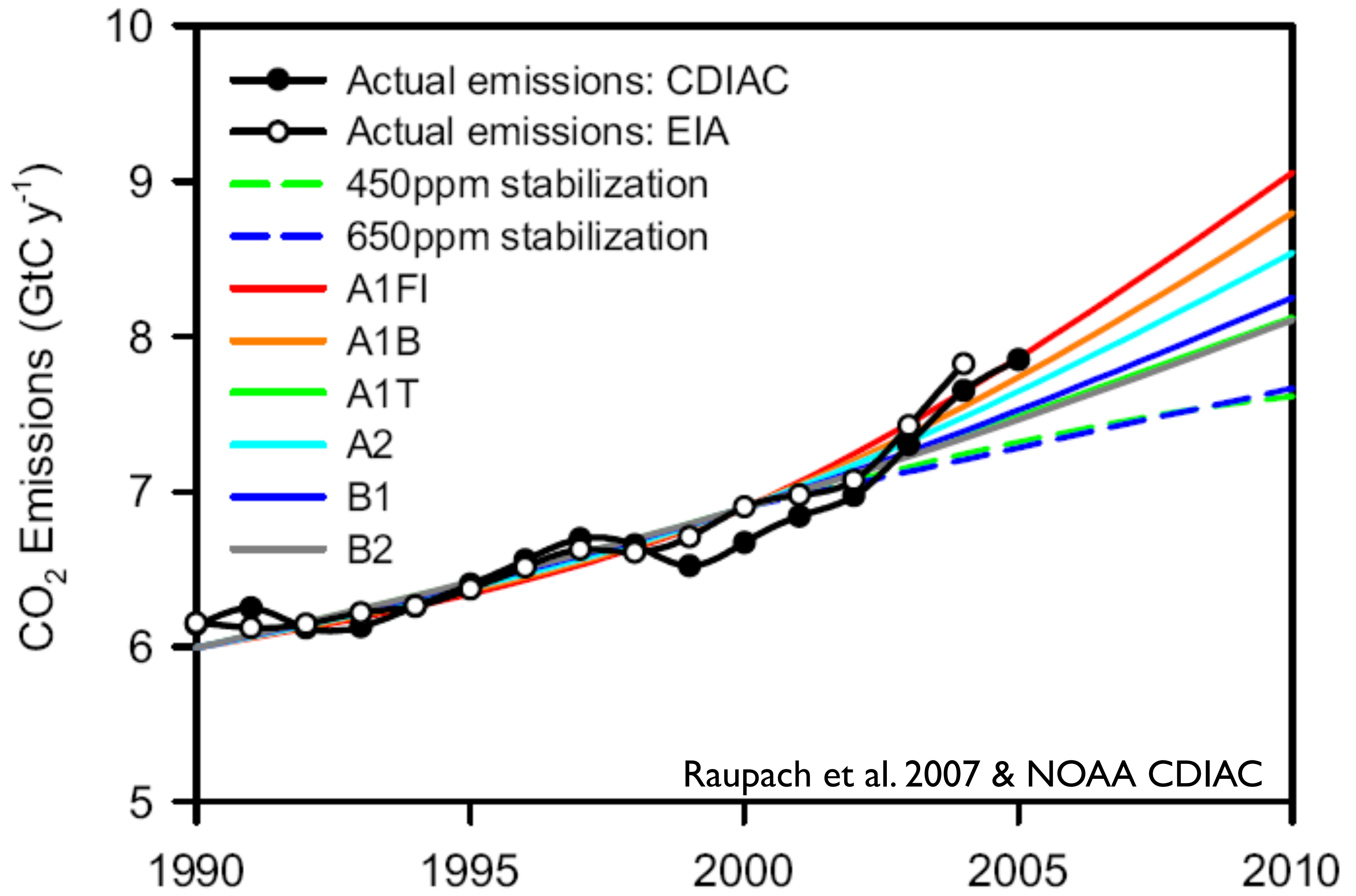
Review resources:
Held and Soden 2000
Bony et al. 2006
Soden et al. 2008

Review in prep.:
Kushner and Marston,
Rev. Mod. Phys.

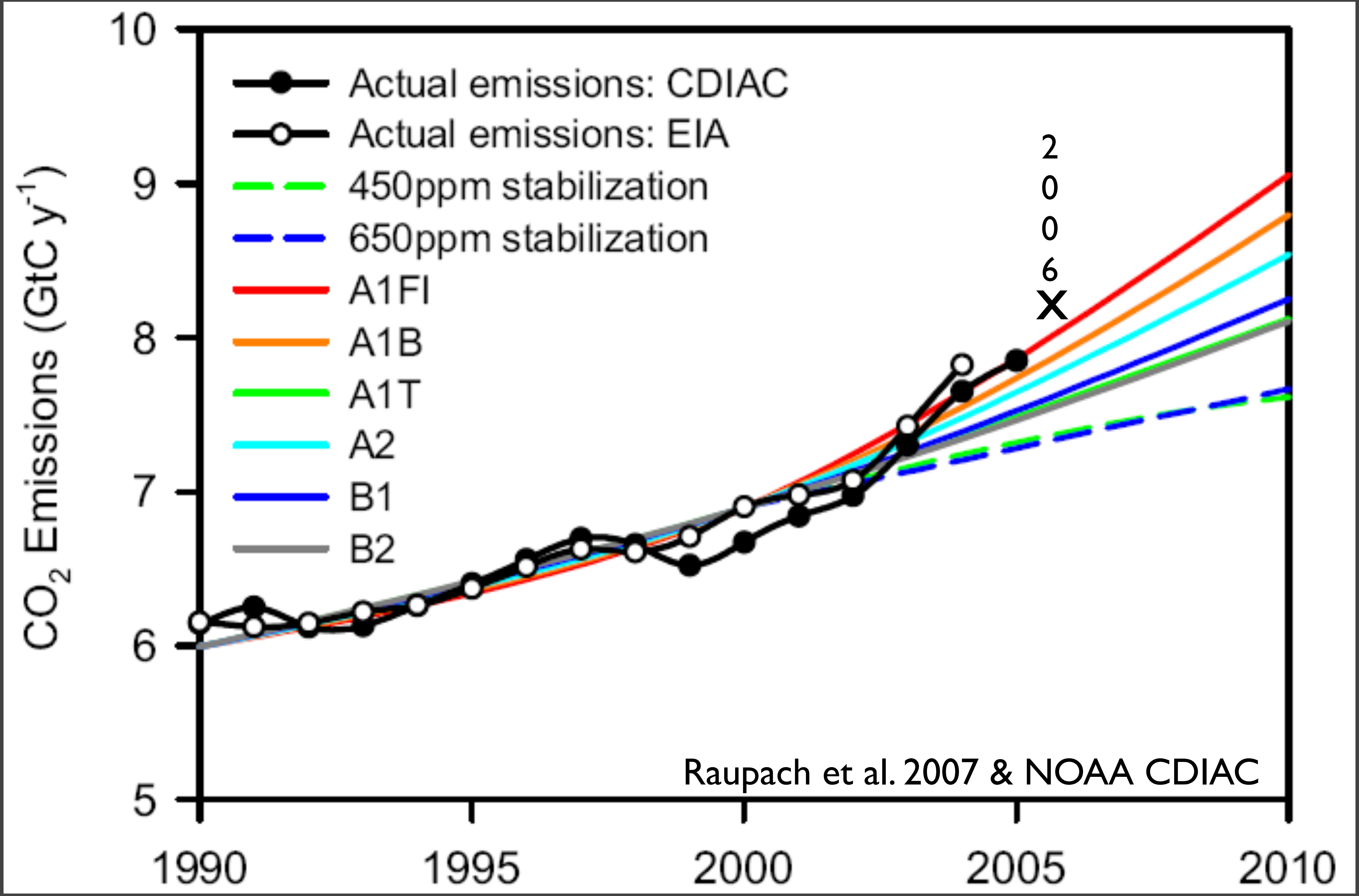
Introduction

Recent Carbon Dioxide Emissions



Raupach et al. 2007 & NOAA CDIAC

Recent Carbon Dioxide Emissions



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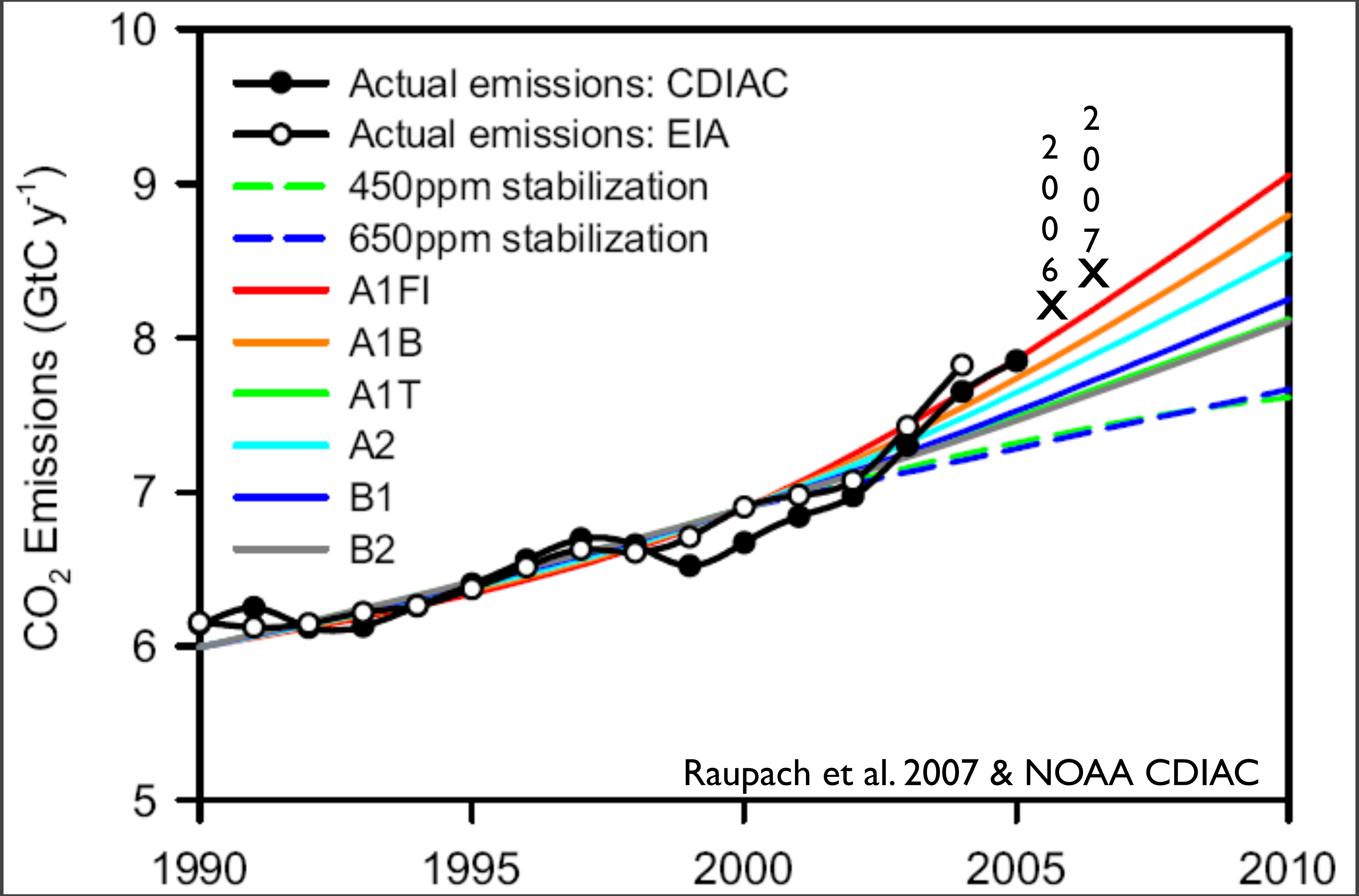
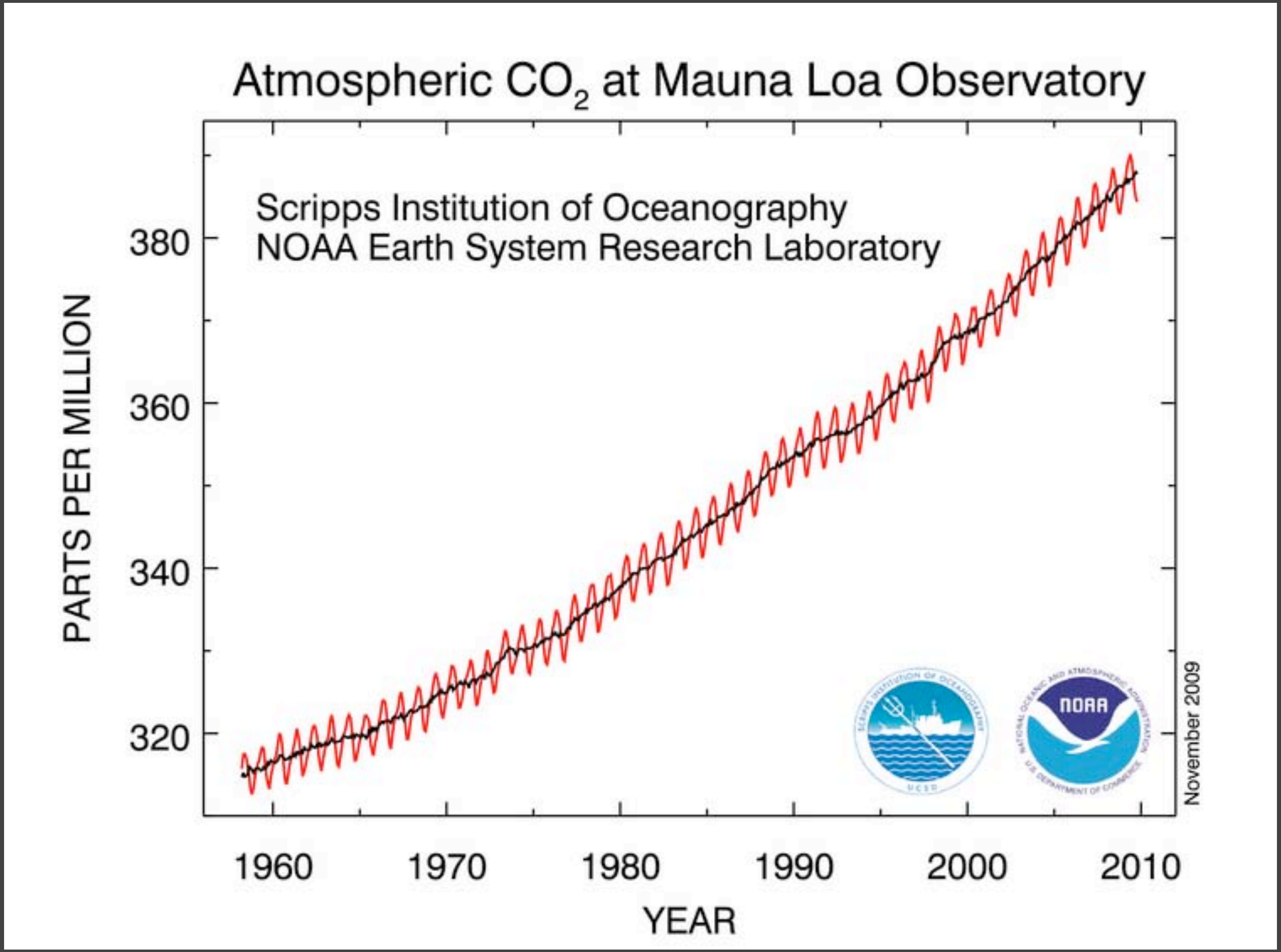
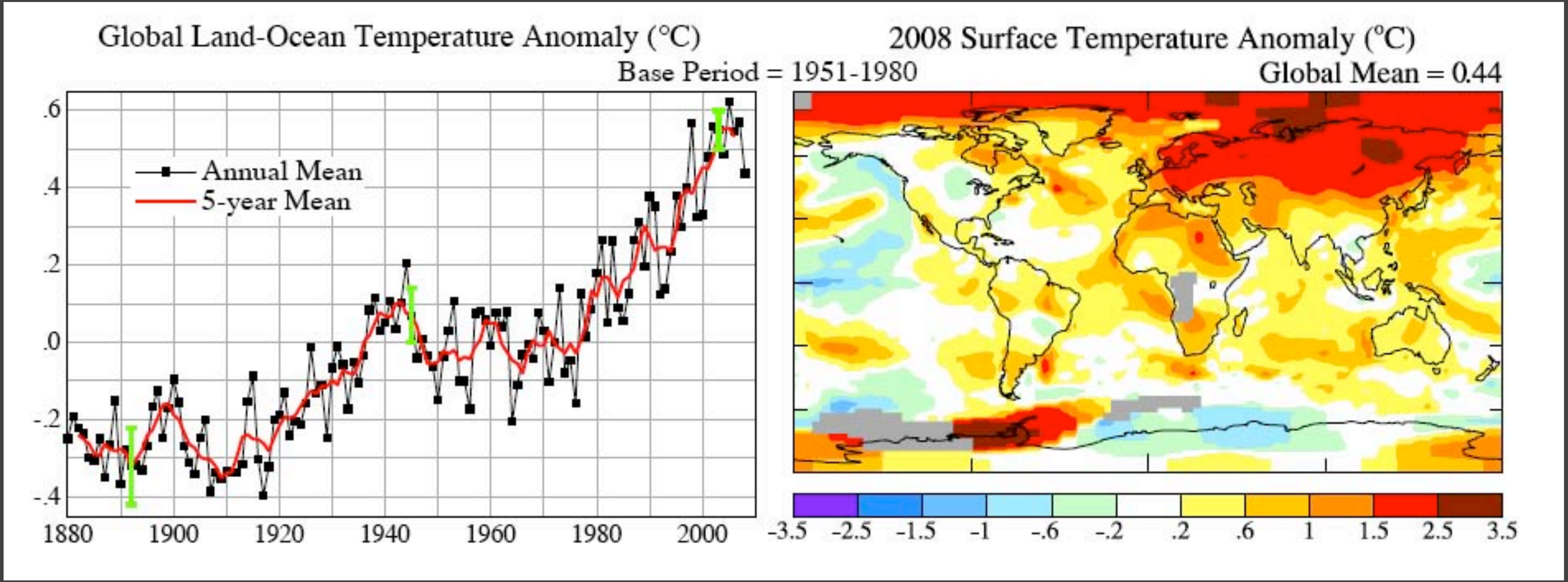


Raupach et al. 2007 & NOAA CDIAC

Recent Carbon Dioxide Concentrations

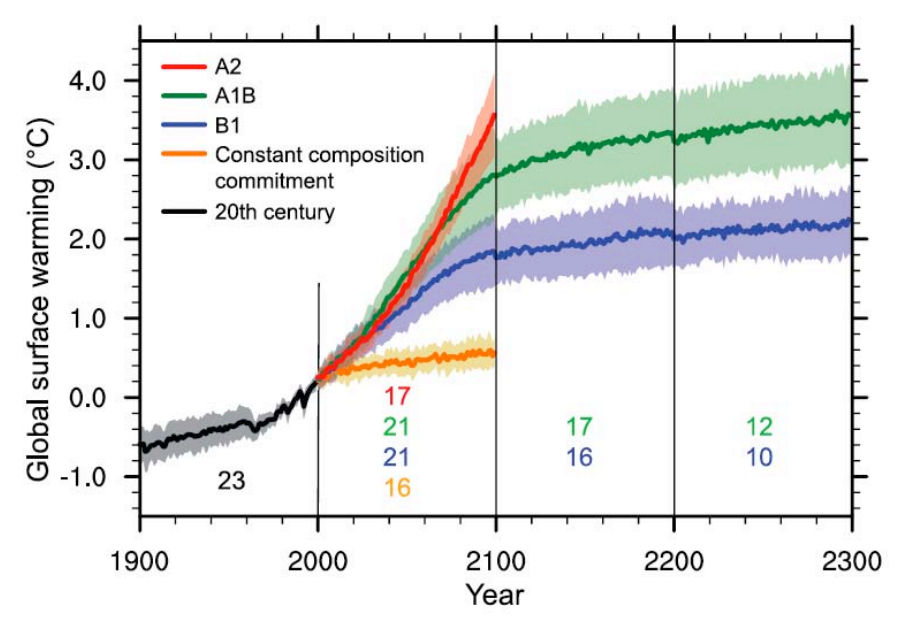


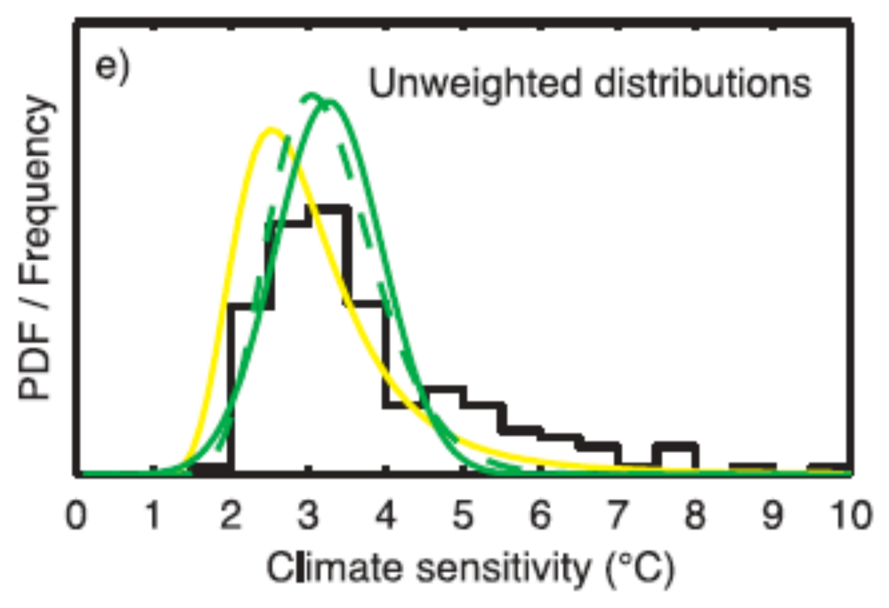
Observed Temperatures, Past and Present



(NASA GISS)

The Spread in Climate Change Predictions





IPCC 2007

Sources of spread:

Uncertainty in forcings (anthropogenic emissions).

Uncertainty in timing of response (oceans).

Uncertainty in climate sensitivity — equilibrium climate warming (atmosphere/cryosphere).

Climate Sensitivity Parameter

Change in Global Mean Surface Temperature . . .

$$\left(\frac{\partial T_s}{\partial \log_2 \mathrm{CO}_2}\right)_R$$

. . . Per Doubling of CO_2 Loading . . .

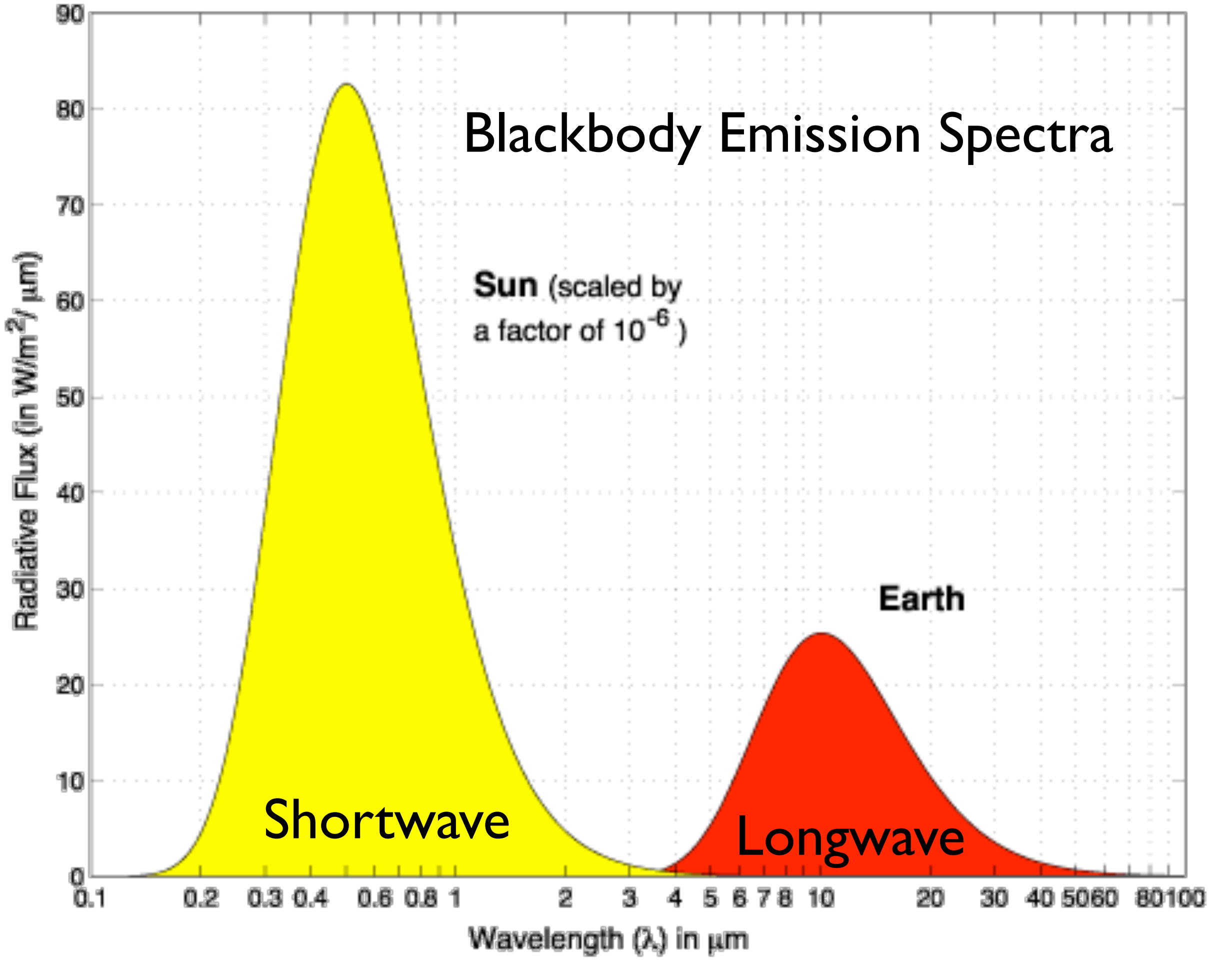
. . . For Fixed
Net Radiation
Absorbed.

At equilibrium, $R = 0$.

Intro Climate Theory

Held and Soden, Bony et al.

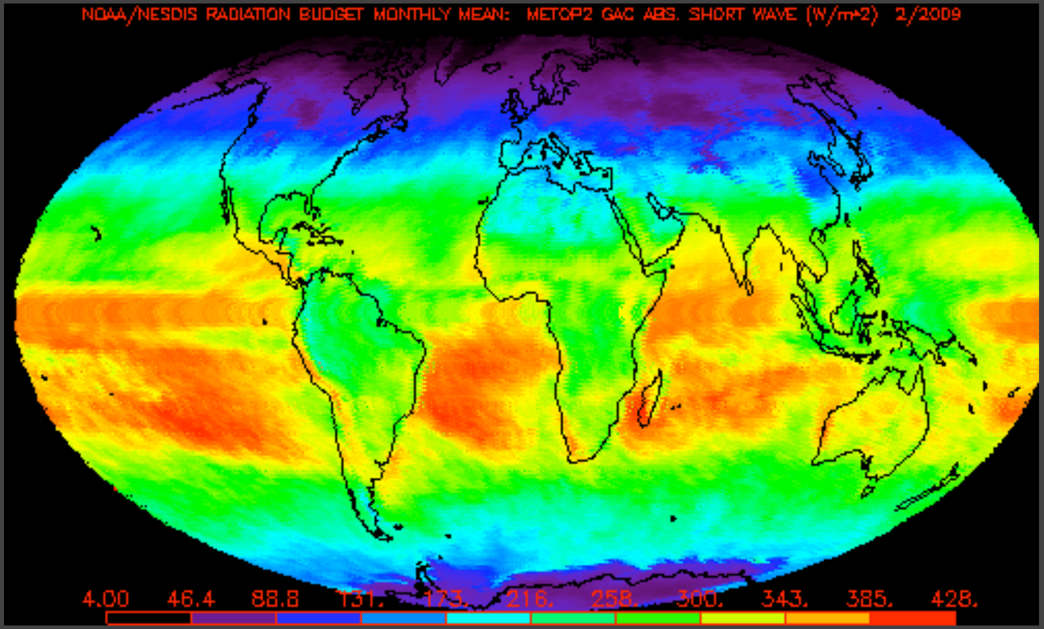
Blackbody Emission Spectra



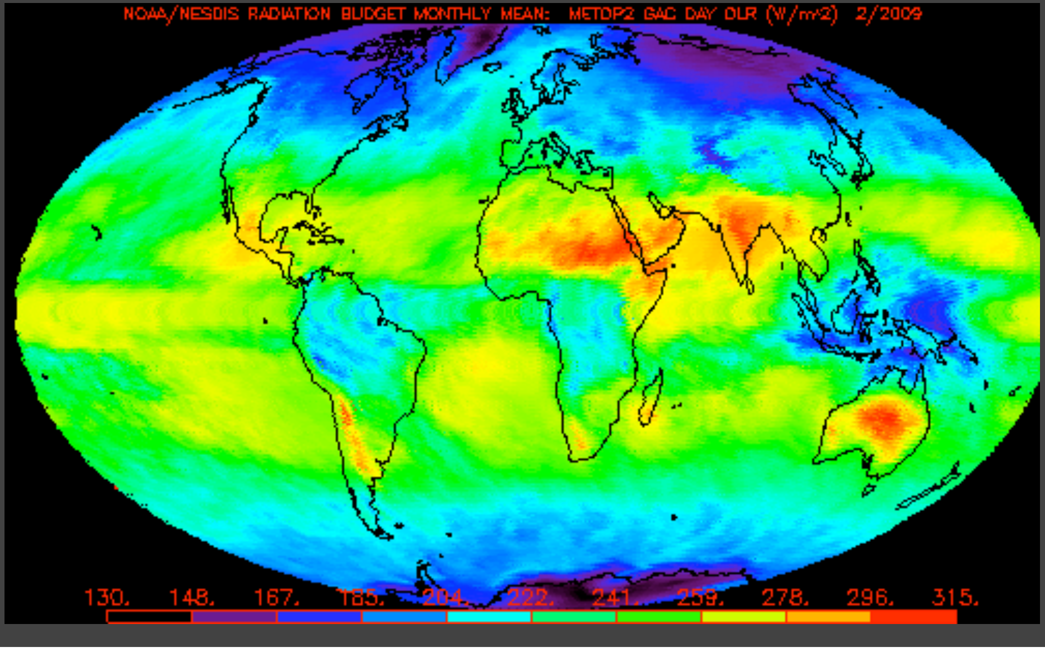
Yochanan Kushnir

Earth’s Radiation, February 2009

Shortwave Absorbed



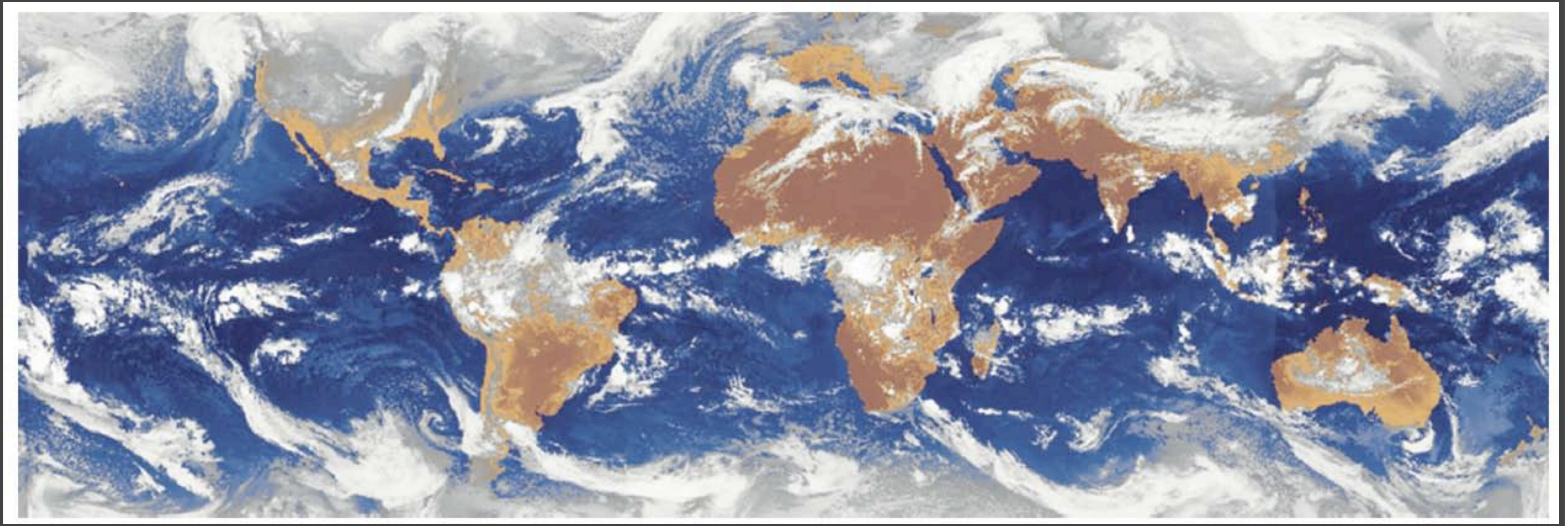
Longwave Emitted



(NOAA)

http://www.osdpd.noaa.gov/PSB/EPS/RB/RB.html

Emitted Longwave Radiation



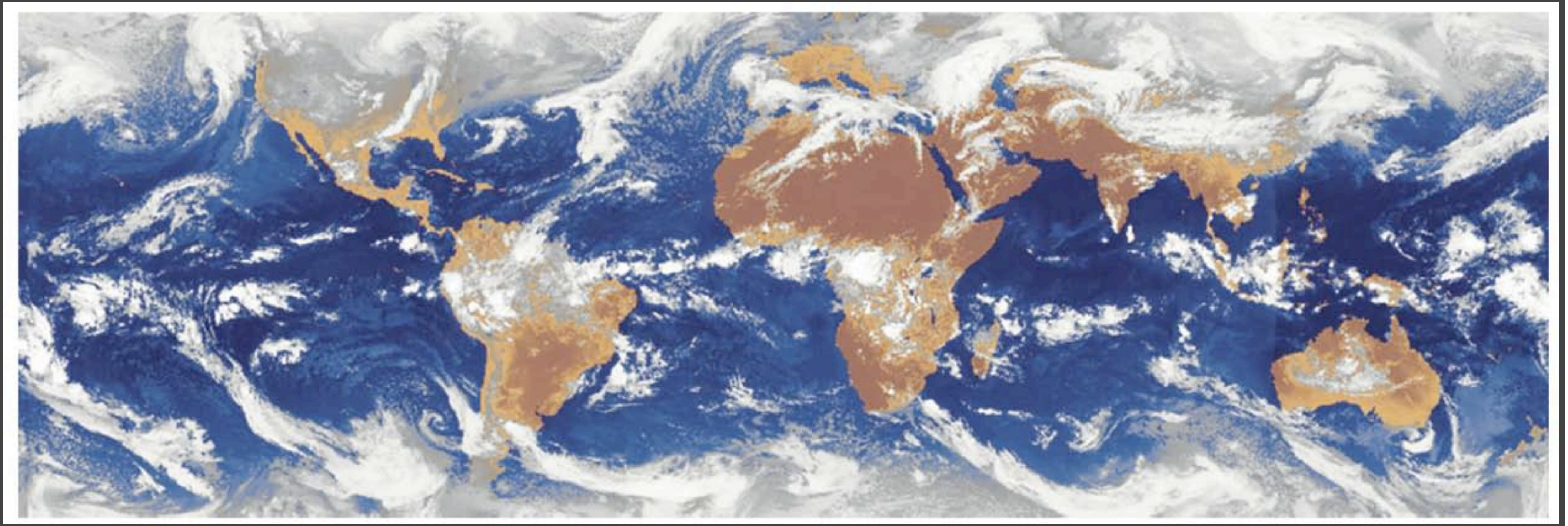
Bony et al. 2006

Infrared light $h\nu \sim 0.3$ eV ~ 7×10^{-29} LHC

Infrared flux ~ 240 W/m^2 ~ 0.3 $\propto$LHC/(m^2 s)

Total infrared radiance ~ 10^{11}MW ~ 200 MLHC/s

Emitted Longwave Radiation



Bony et al. 2006

LHC Beam Energy
~ 700 MJ

Infrared light $h\nu \sim 0.3$ eV ~ 7 x 10^{-29} LHC

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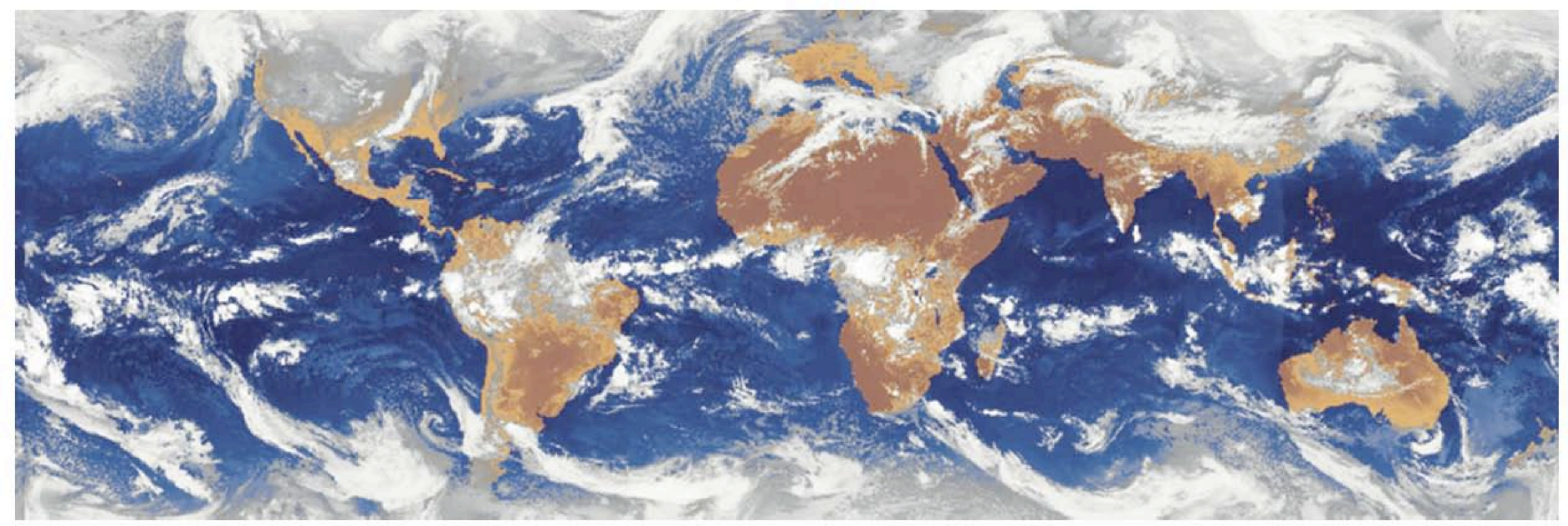

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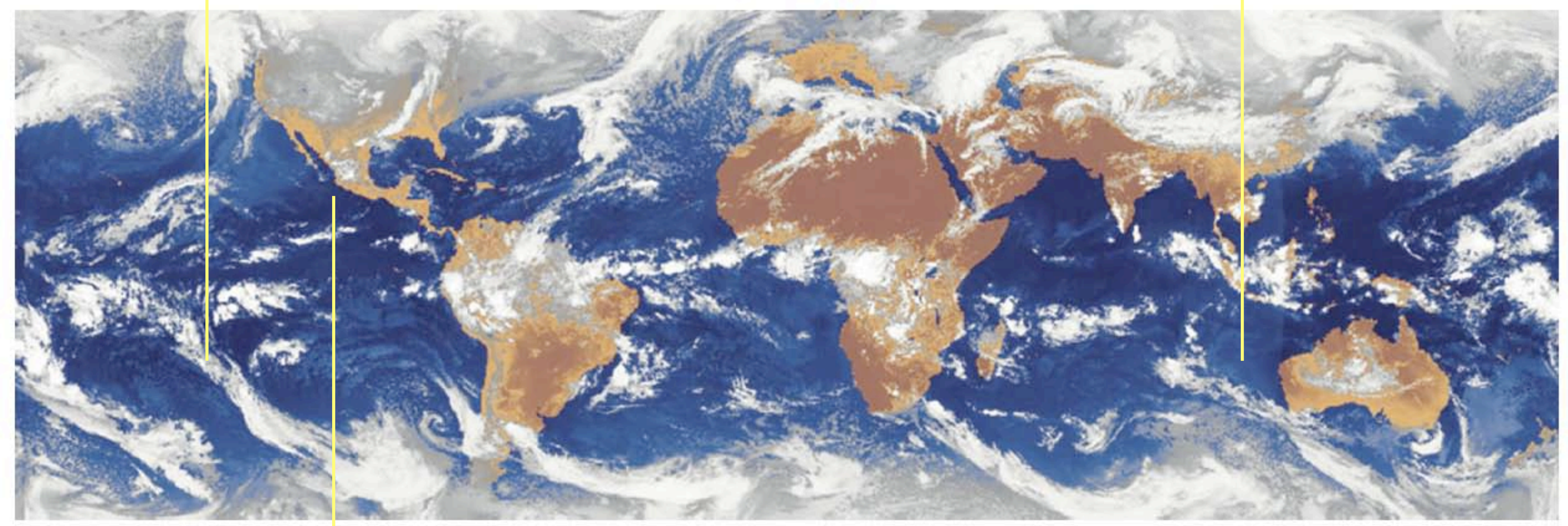
Emitted Longwave Radiation

High Clouds (8-12 km)

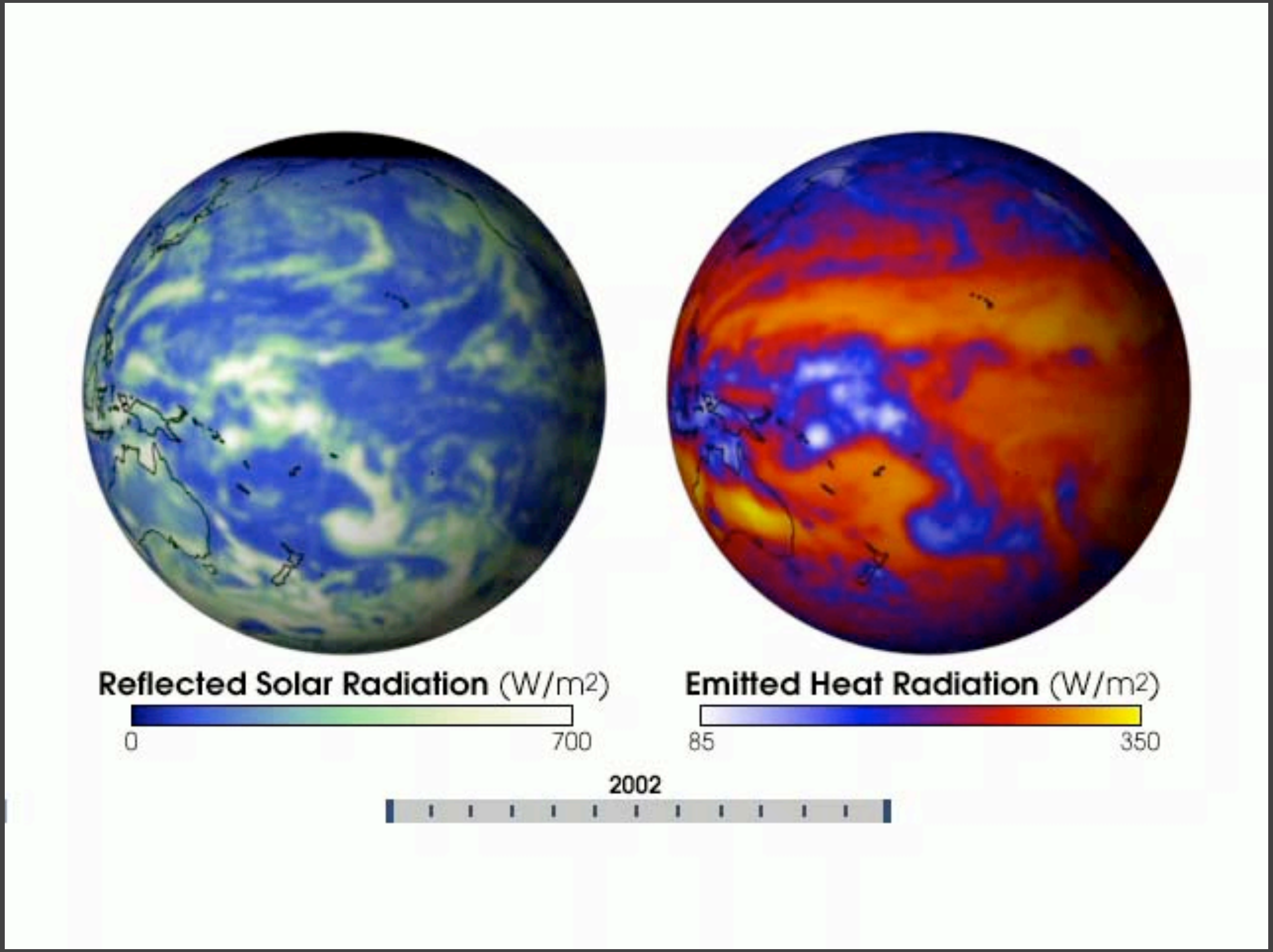
Low Clouds (0-3 km)



Bony et al. 2006

Clear sky

http://www.nasa.gov/mov/113809main_ceres_15fps_320.mov



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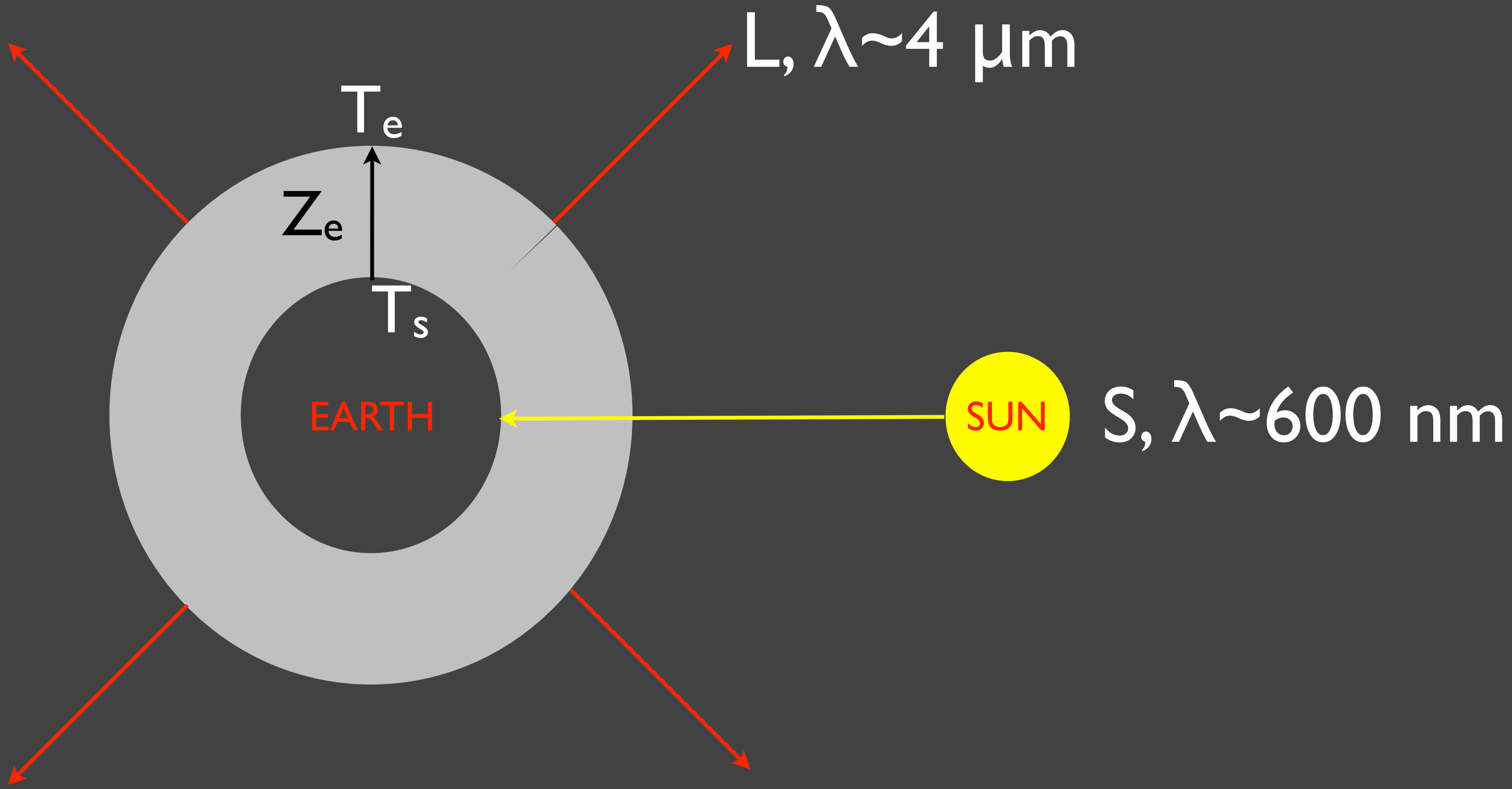
0-D Radiative Model for Temperature



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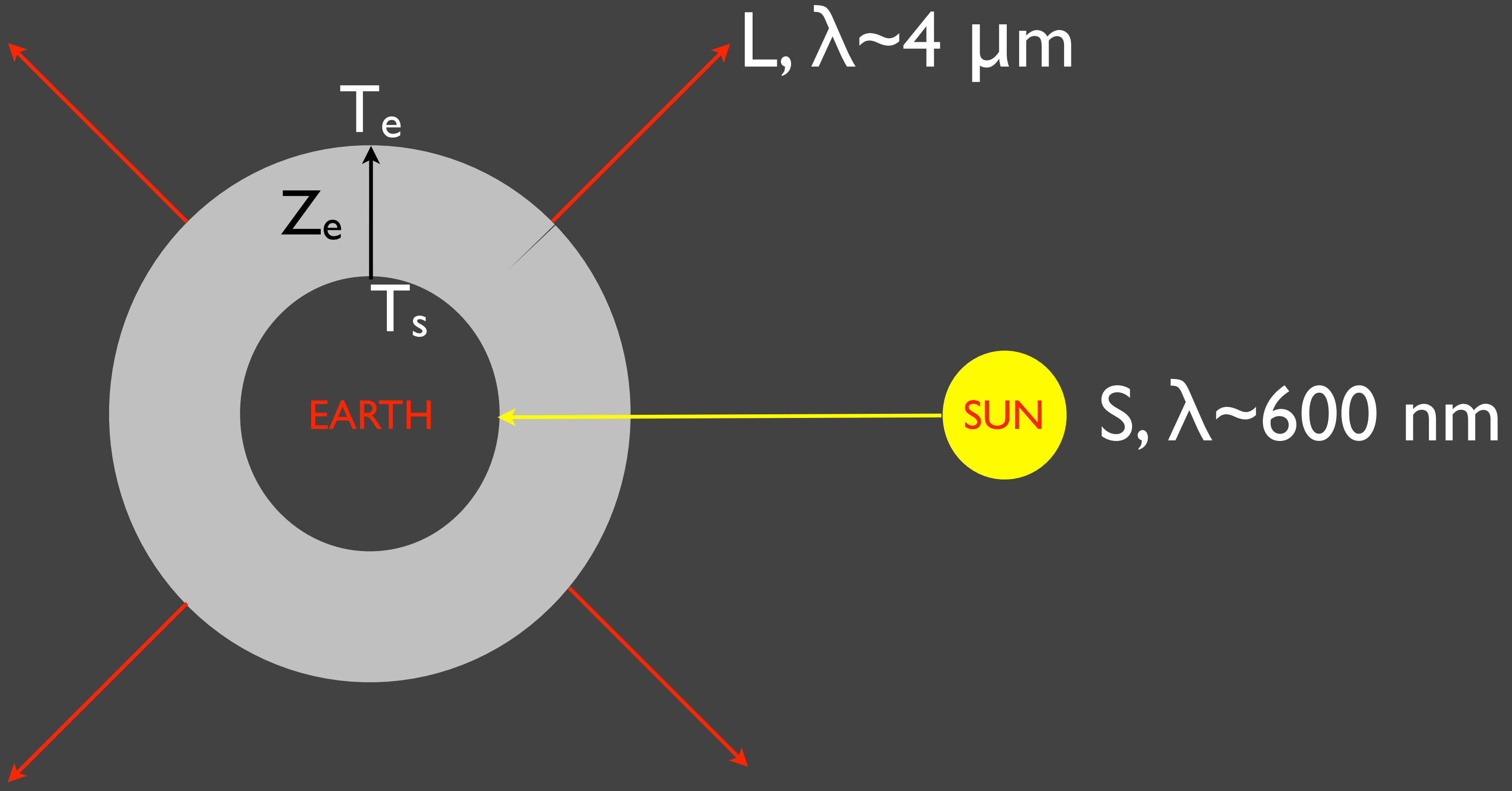


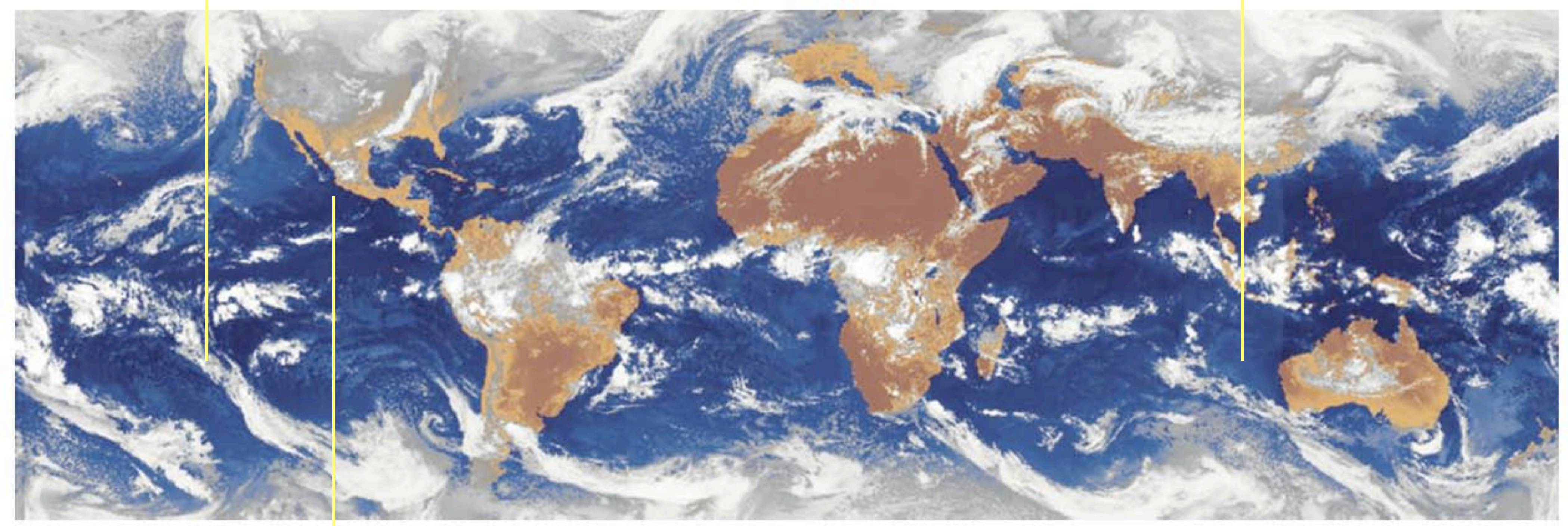
Radiative eq., blackbody

Net shortwave flux

Emission Temperature

$$
\begin{aligned}
S &= L = \sigma T_e^4 \\
S &= 240\,\mathrm{W/m^2} \\
T_e &= T(Z = Z_e) = \left(\frac{S}{\sigma}\right)^{1/4} \approx 255\mathrm{K}
\end{aligned}
$$

Emitted Longwave Radiation



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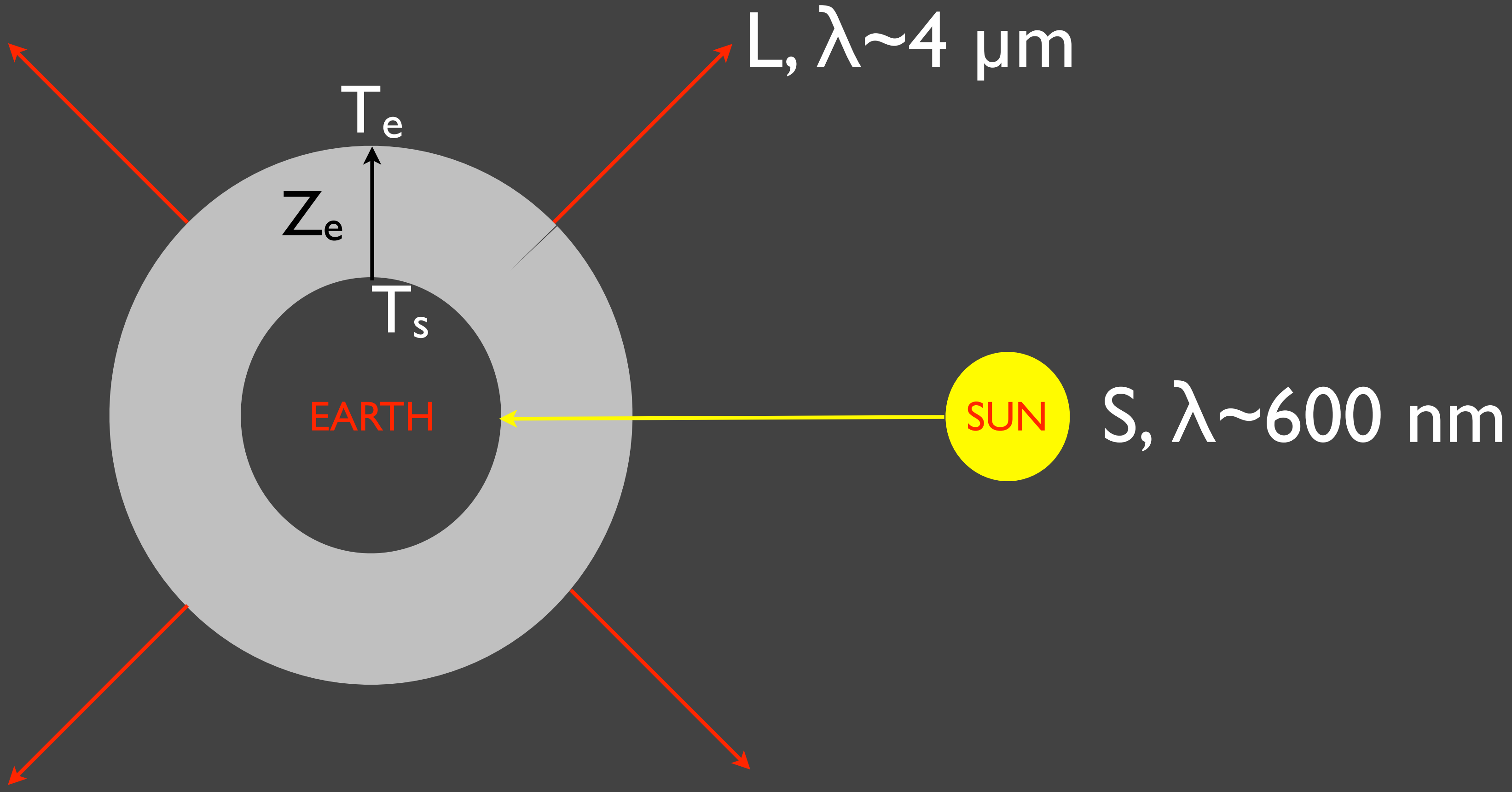
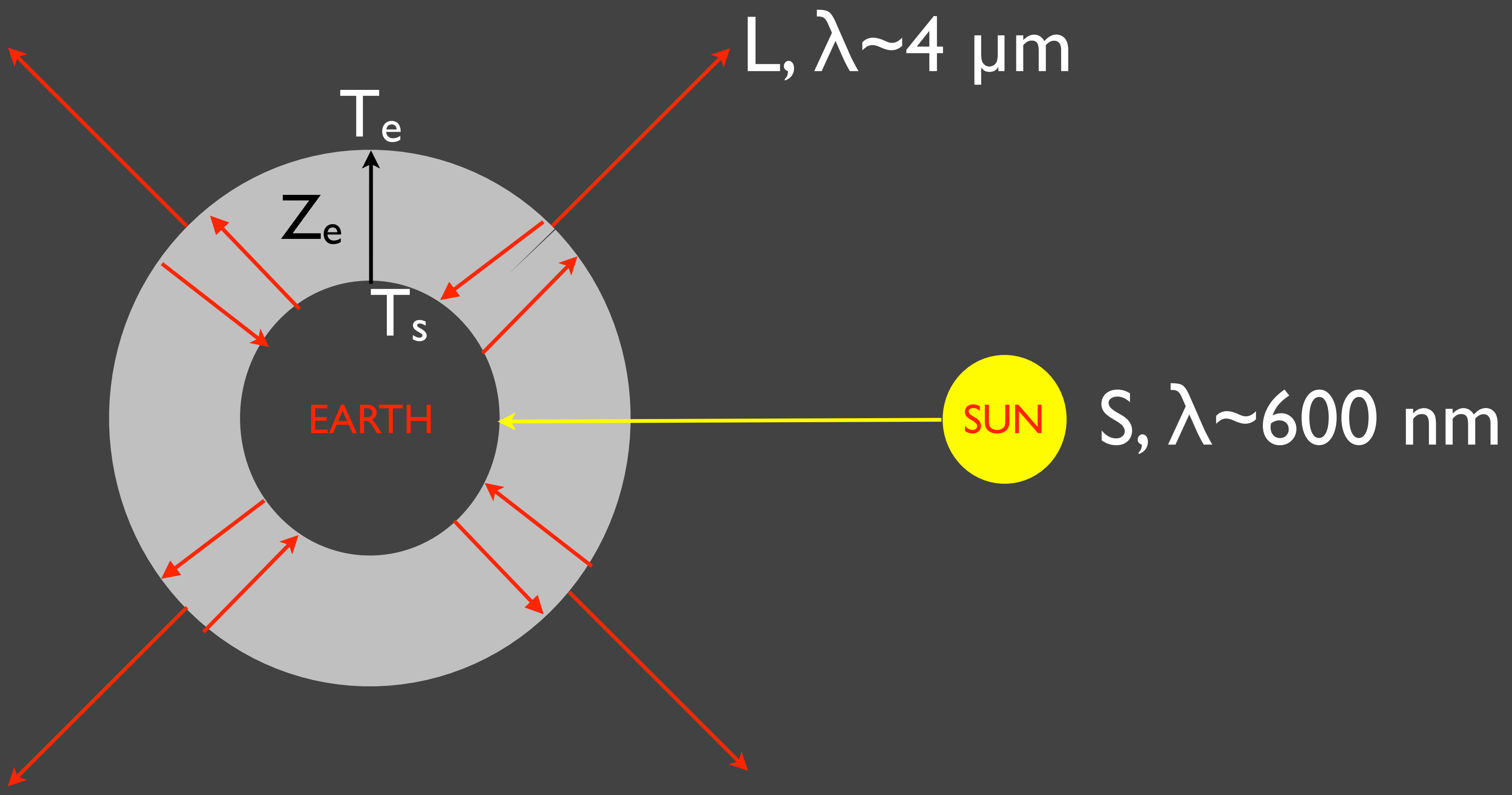


Observed emission height $T = T_e \text{ at } Z_e \approx 5\,\text{km}$

Observed surface temperature $T_s = T(Z=0) \approx 288\,\text{K} = T_e + 33\text{K}$

0-D Radiative Model for Temperature



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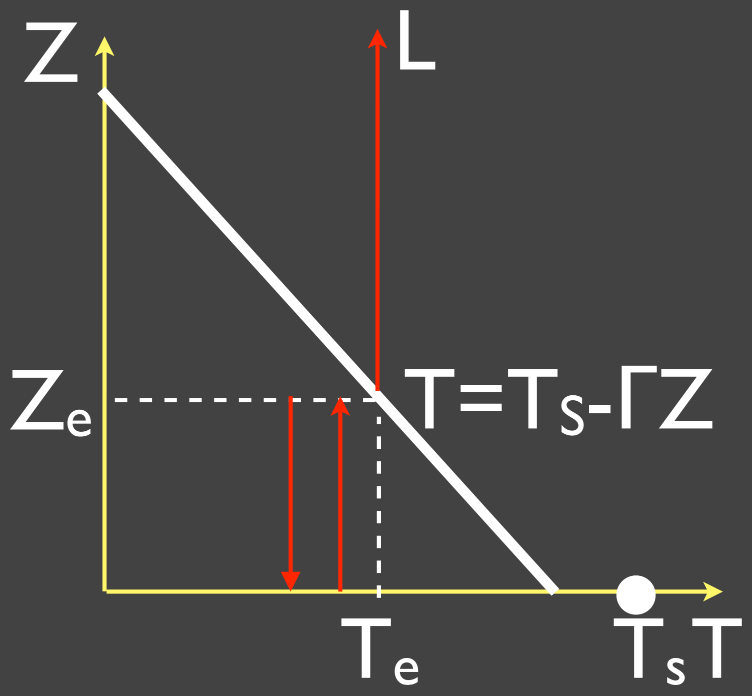
Greenhouse effect (Fourier et al.) from radiatively active gases (CO2, H20, CFCs) accounts for the extra 33K.

One-D Radiative Model for T(Z)



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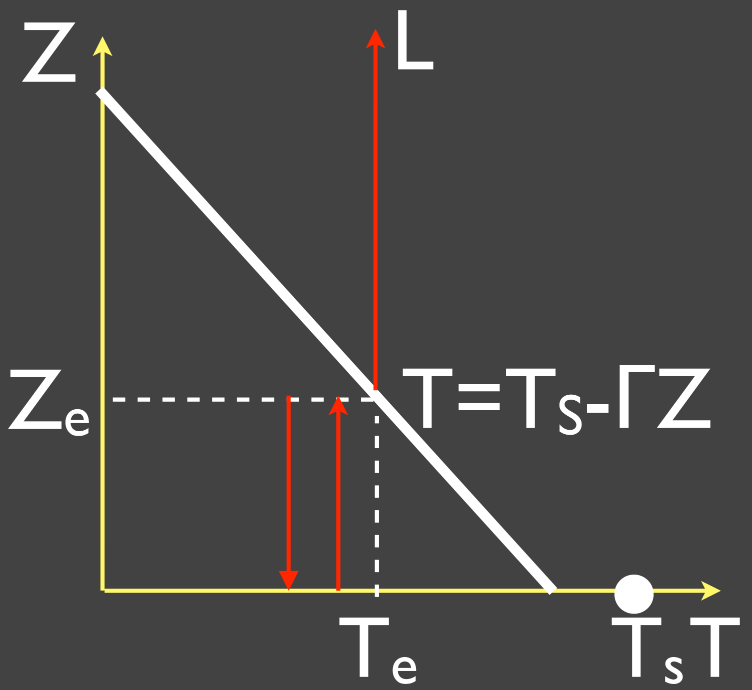
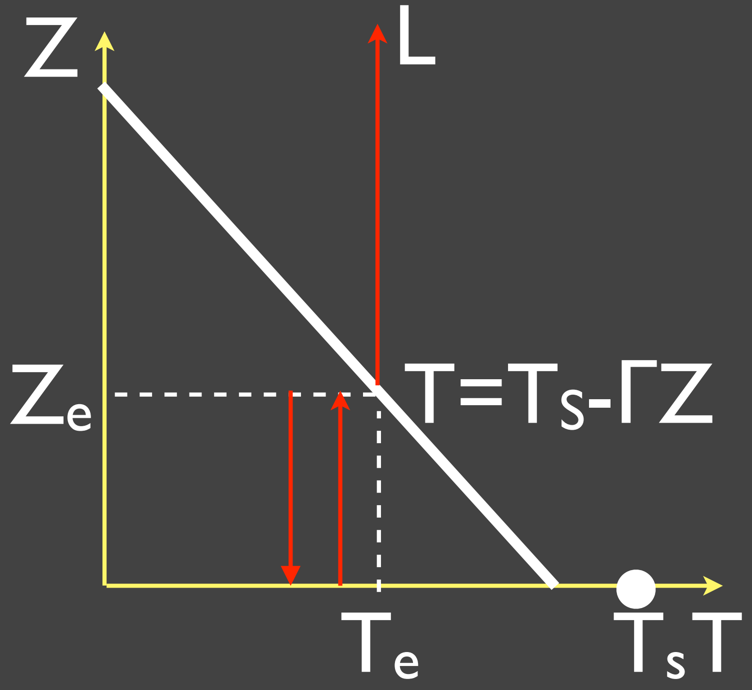


Lapse rate $\Gamma = -dT/dZ$

Greenhouse gas optical thickness τ

One-D Radiative Model for T(Z)



Lapse rate $\Gamma = -dT/dZ$

Greenhouse gas optical thickness τ

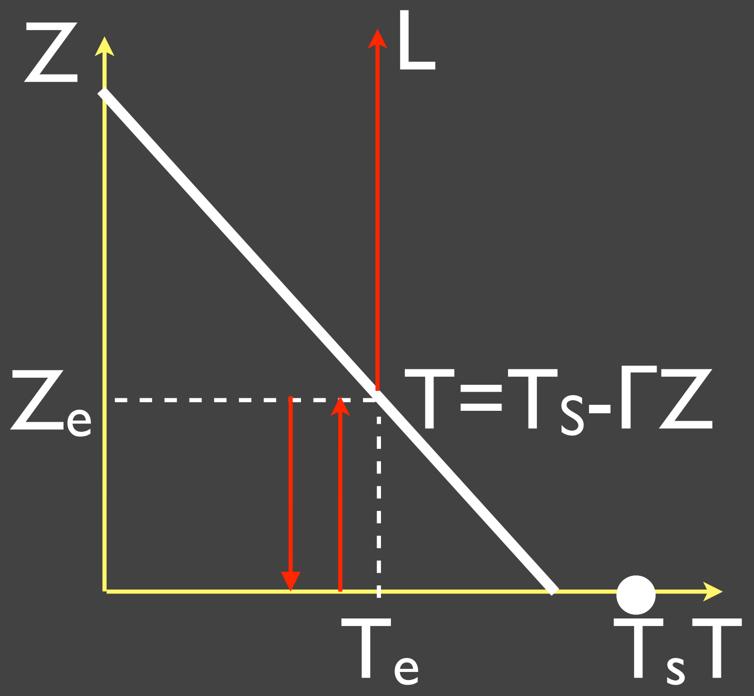
Surface T jump (small τ)

$$\frac{T(Z=0)}{T_s} = c\tau$$

Radiative lapse rate

$$\Gamma_{\text{rad}} = \frac{a\tau}{\tau + b}.$$

One-D Radiative Model for T(Z)



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Surface T jump (small τ)
$$\frac{T(Z=0)}{T_s} = c\tau$$
Convectively unstable

Radiative lapse rate
$$\Gamma_{\rm rad} = \frac{a\tau}{\tau + b}.$$
Convectively unstable if $\Gamma_{rad} > \Gamma_{ad} = g/c_p$

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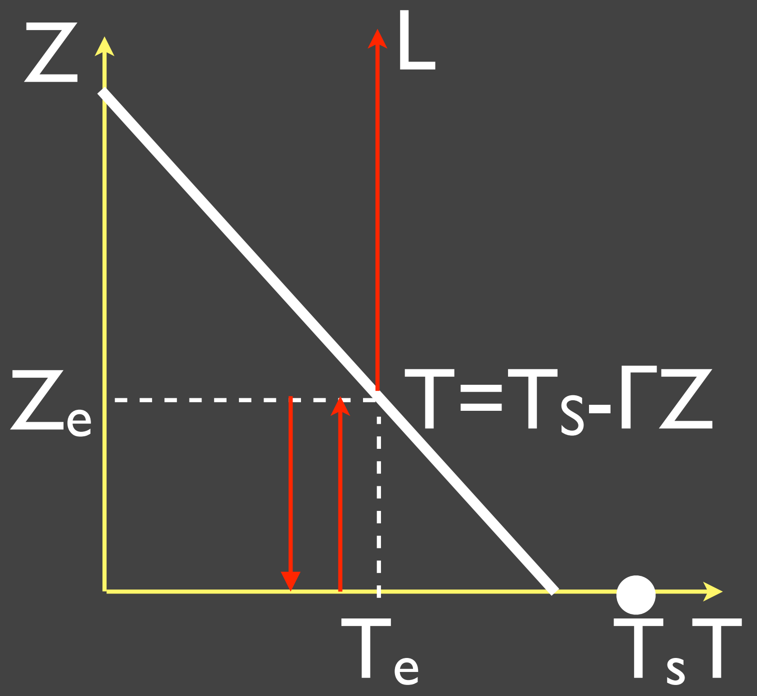

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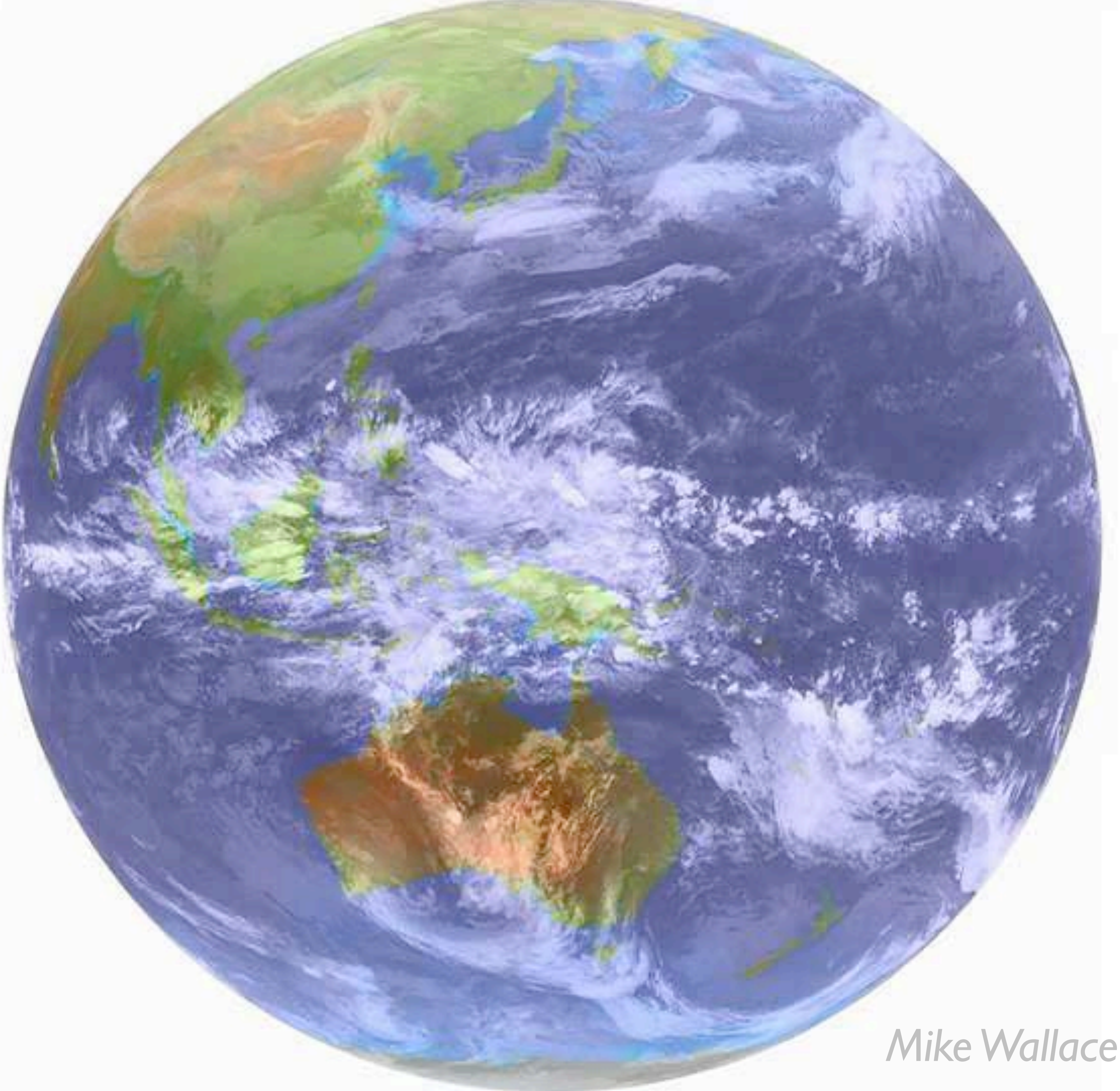
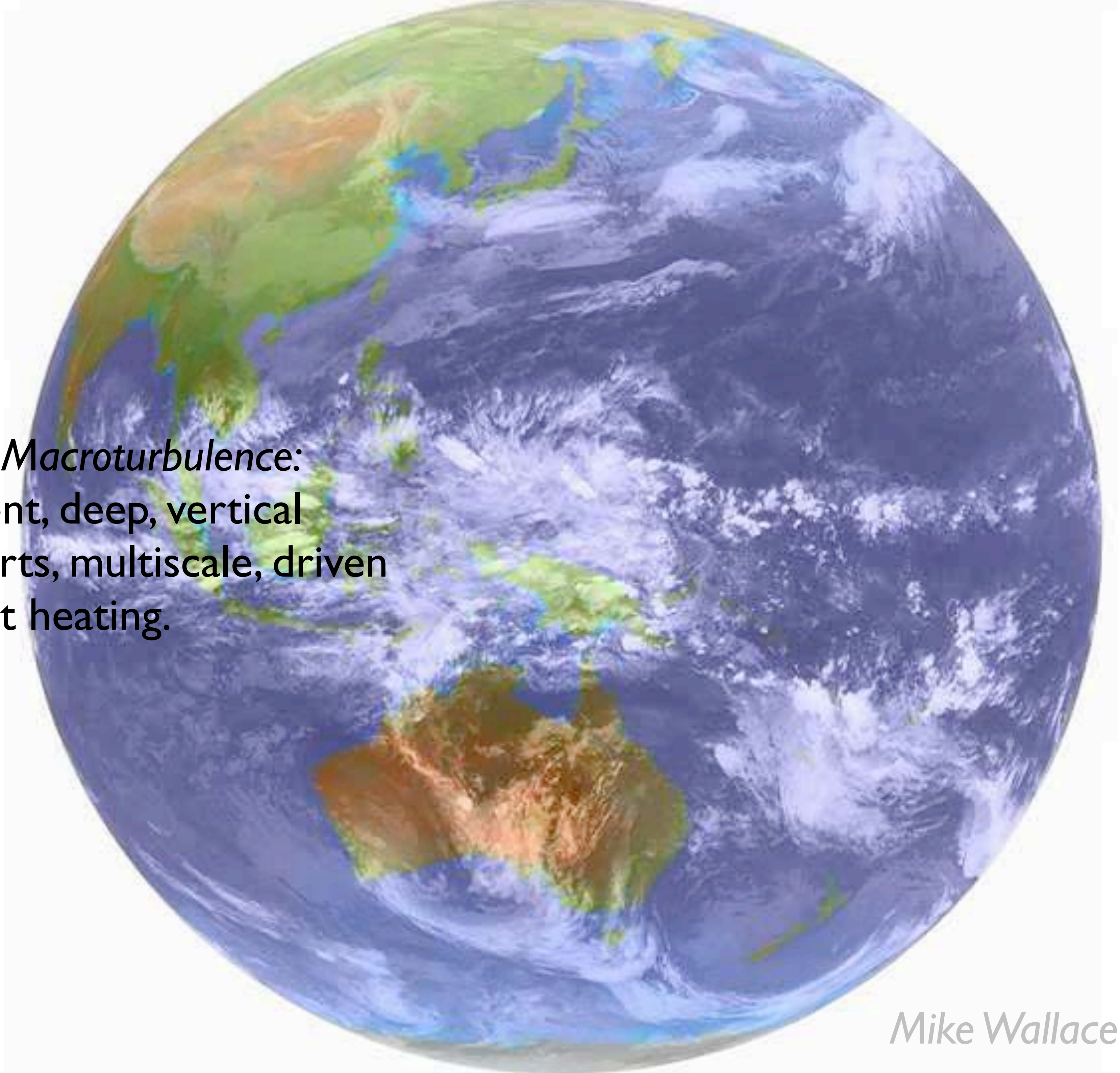
Convectively unstable

Convectively unstable if $\Gamma_{rad} > \Gamma_{ad} = g/c_p$

To understand response of T_s and Γ to radiative destabilization, we briefly consider tropical and extratropical general circulation.

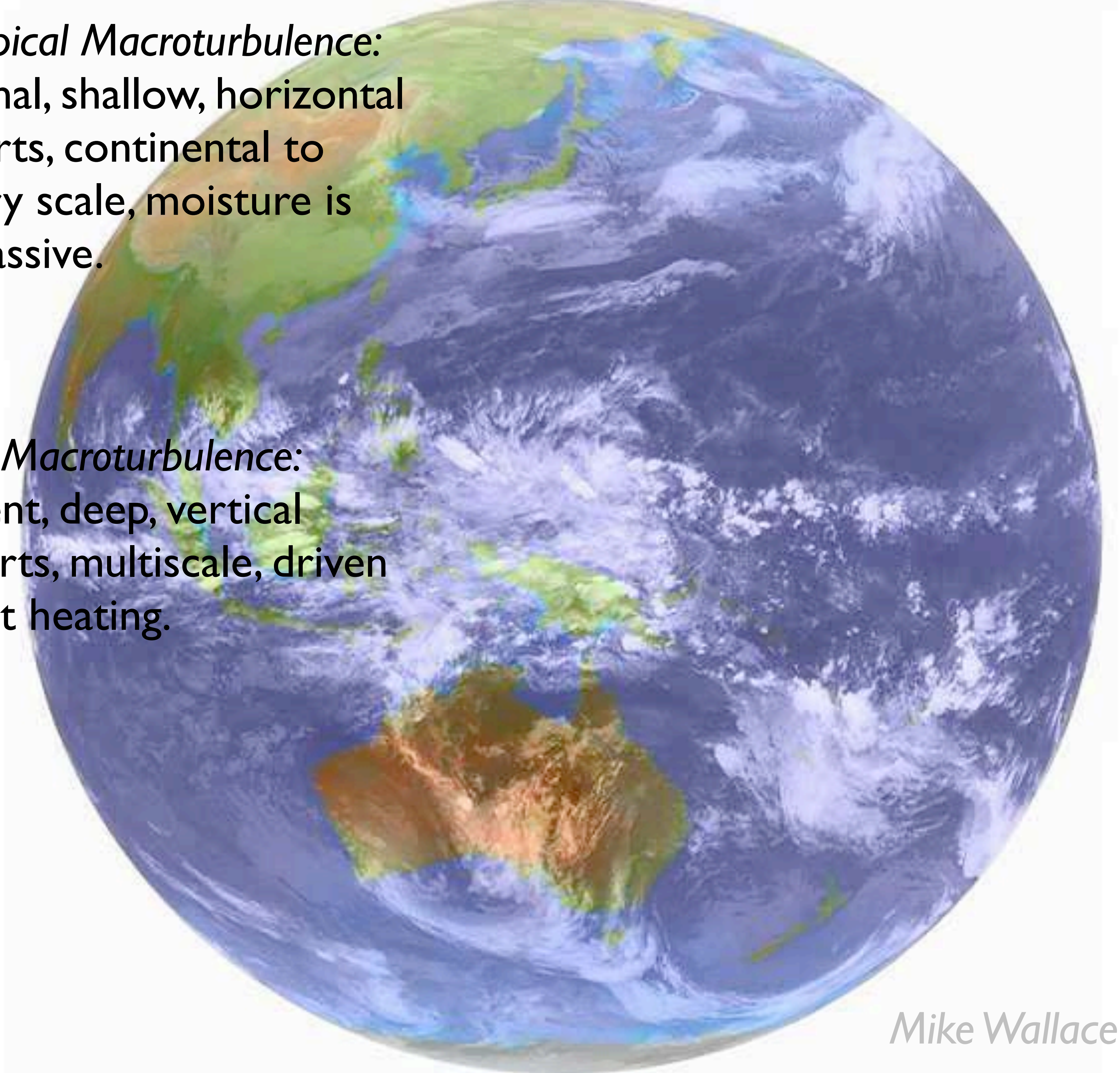


Mike Wallace



Tropical Macroturbulence:
Divergent, deep, vertical transports, multiscale, driven by moist heating.

Mike Wallace

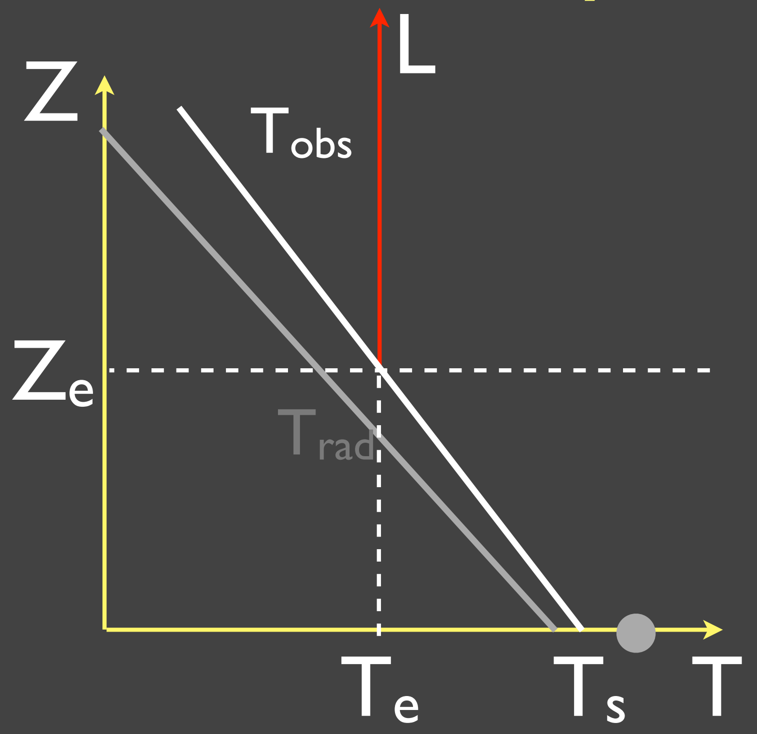


Extratropical Macroturbulence:
Rotational, shallow, horizontal transports, continental to planetary scale, moisture is more passive.

Tropical Macroturbulence:
Divergent, deep, vertical transports, multiscale, driven by moist heating.

Mike Wallace

One-D Radiative-Dynamical Model for T(Z)

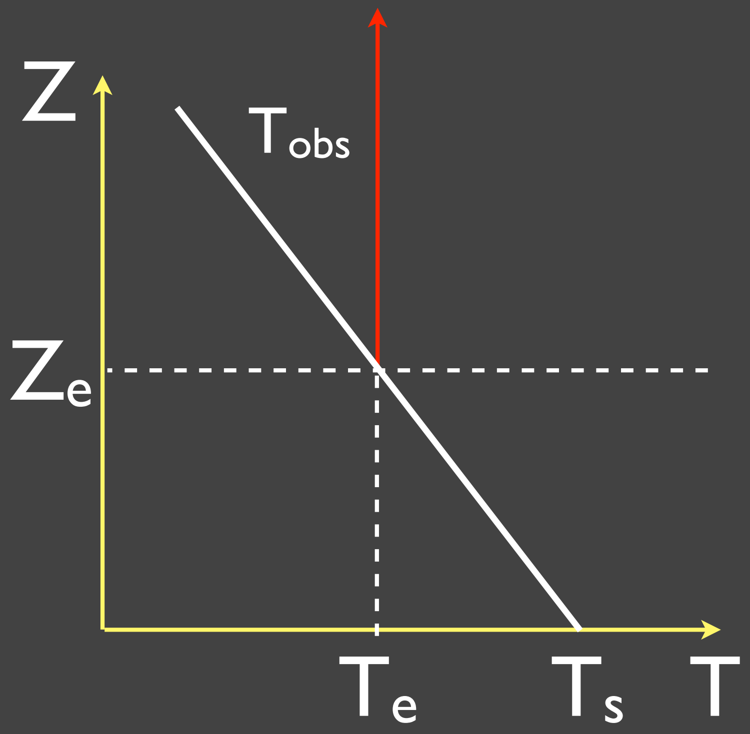


Observed lapse rates are neutral (adiabatic) or subcritical.

In the tropics, radiative destabilization relieved by vertical convective motions, involving moisture: "radiative-convective equilibrium".

In the extratropics, both vertical convection and large-scale horizontal motions are active.

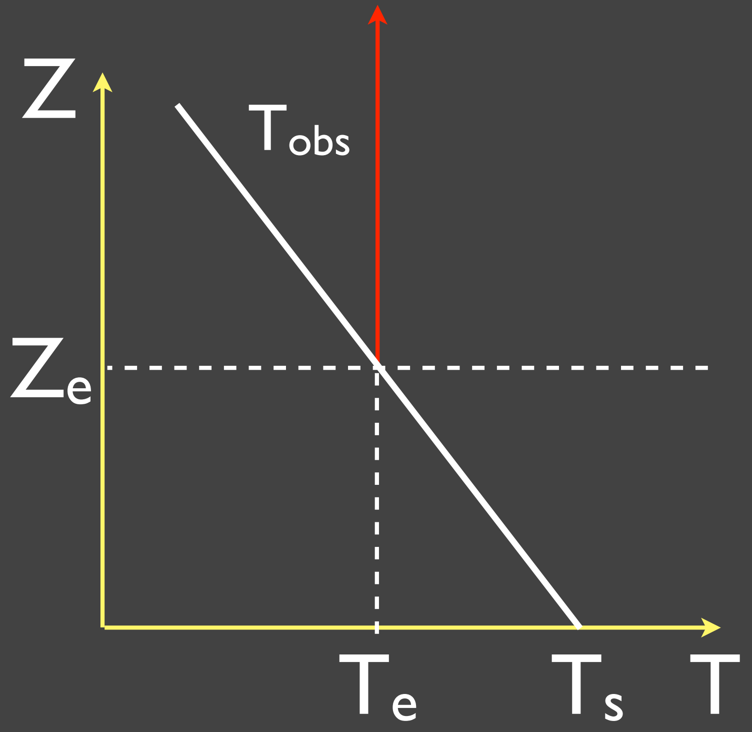
Greenhouse Warming



Suppose we add more CO_2. Let's keep Γ and S fixed.

What would happen to the emission temperature T_e?

Greenhouse Warming



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What would happen to the emission temperature T_e?

Nothing! But the troposphere would become more optically thick, and Z_e would increase.

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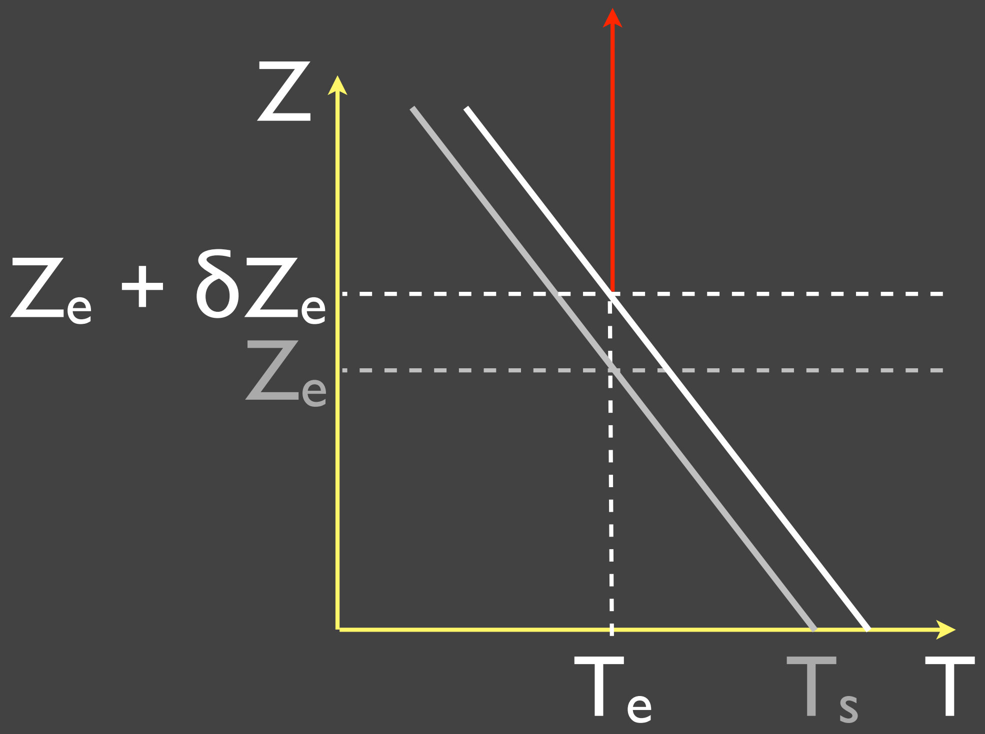

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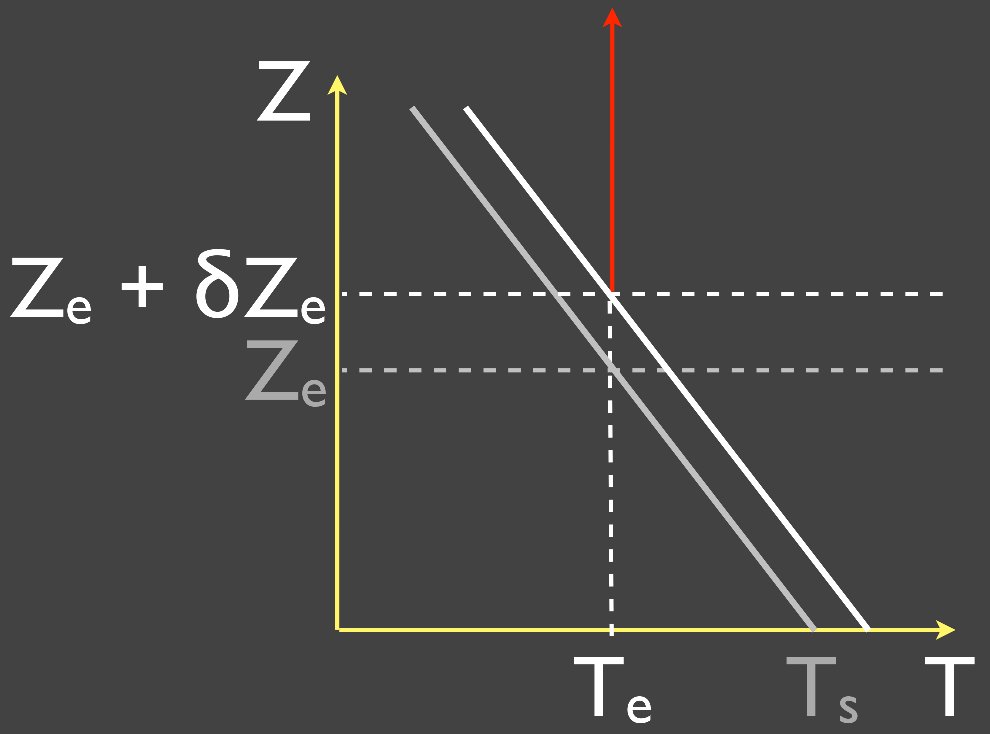

δZ_e~100 m for $2XCO_2$

Suppose we add more CO_2. Let's keep Γ and S fixed.

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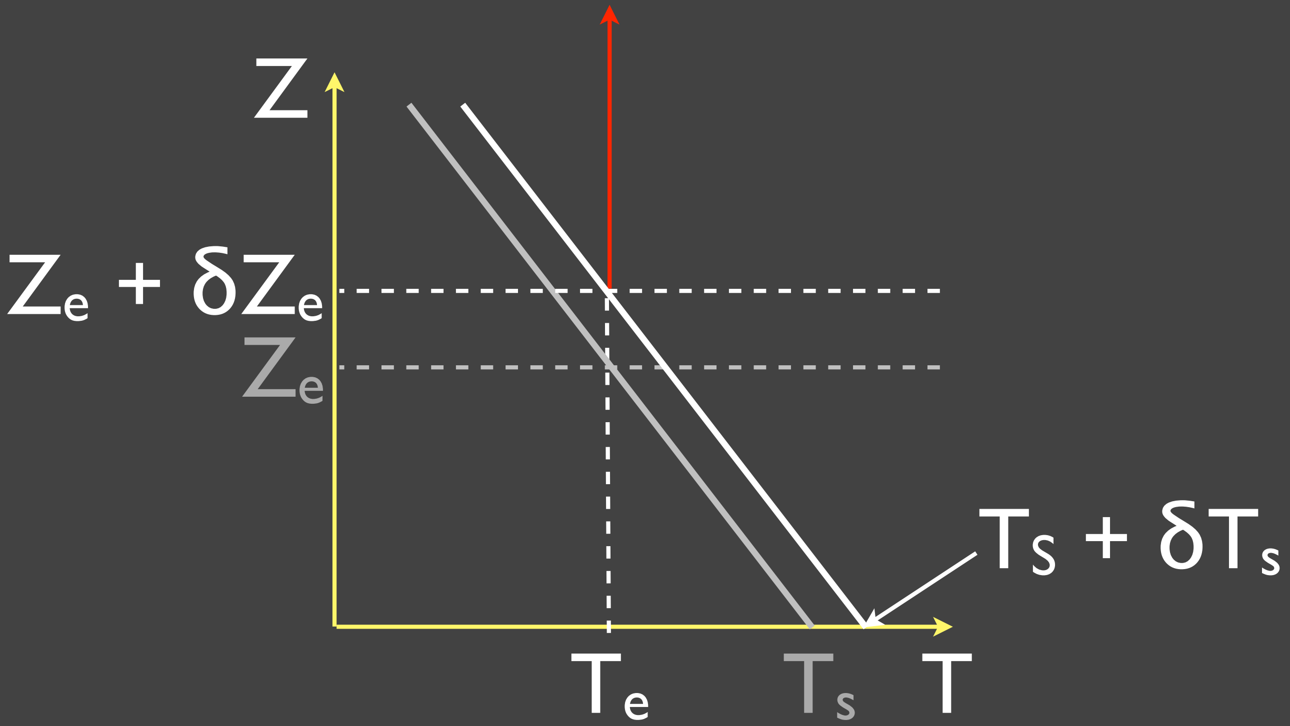
Nothing! But the troposphere would become more optically thick, and Z_e would increase.

Greenhouse Warming



Suppose we add more CO_2. Let's keep Γ and S fixed.

What would happen to the emission temperature T_e?

Nothing! But the troposphere would become more optically thick, and Z_e would increase.

Then, given the assumptions, so would T_s. Let's calculate δT_s

Reference Climate Sensitivity

L and *S* depend on atmospheric structure and composition.

Define radiative imbalance:

$$R = L - S = R(T_s, \Gamma, \log_2 \mathrm{CO}_2, \mathrm{H_2O}, C, I, V, \ldots)$$

Under radiative equilibrium

$$R = 0.$$

How do variations in CO_2 affect surface temperature if everything else is fixed?

Reference Climate Sensitivity

$$\begin{aligned} \log_2 CO2 &\rightarrow \log_2 CO2 + \delta \log_2 CO2 \\ T_s &\rightarrow T_s + \delta T_s \end{aligned}$$

A gedanken experiment: realizable in principle.

Under radiative equilibrium,

$$\begin{aligned} 0 &= \delta R \\ &= R\left[T_s + \delta T_s, \log_2 \mathrm{CO}_2 + \delta\left(\log_2 \mathrm{CO}_2\right), E\right] - R\left[T_s, \log_2 \mathrm{CO}_2, E\right] \\ &\approx \left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO}_2, E} \delta T_s + \left(\frac{\partial R}{\partial \log_2 \mathrm{CO}_2}\right)_{T_s, E} \delta\left(\log_2 \mathrm{CO}_2\right). \end{aligned}$$

Thus, if the linearization is valid:

$$\delta T_s = -\left(\frac{\partial T_s}{\partial R}\right)_{\log_2 \mathrm{CO}_2, E} \left(\frac{\partial R}{\partial \log_2 \mathrm{CO}_2}\right)_{T_s, E} \delta\left(\log_2 \mathrm{CO}_2\right) = \left(\frac{\partial T_s}{\partial \log_2 \mathrm{CO}_2}\right)_{R, E} \delta\left(\log_2 \mathrm{CO}_2\right)$$

(by the chain rule for partial derivatives.)

Reference Climate Sensitivity

From Stefan-Boltzmann

$$\left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO}_2, E} \approx +4\mathrm{W}/(\mathrm{m}^2 \cdot \mathrm{K})$$

Greenhouse, from radiative transfer

$$\left(\frac{\partial R}{\partial \log_2 \mathrm{CO}_2}\right)_{T_s, E} \approx -4\mathrm{W}/\mathrm{m}^2$$

Reference sensitivity

$$\left(\frac{\partial T_s}{\partial \log_2 \mathrm{CO}_2}\right)_{R, E} \equiv \Delta_0 \approx +1\,\mathrm{K}$$

The reference sensitivity is small: 1K per doubling of CO2

But other changes will occur that affect temperature and radiation: feedbacks.

Climate Feedbacks

“Feedback” involves any quantity that is affected by T_s and affects R.

E.g. allow water vapor, a powerful greenhouse gas, to vary: $H_20 = H_20(T_s)$

$$\begin{aligned}
\log_2 \mathrm{CO_2} &\rightarrow \log_2 \mathrm{CO_2} + \delta\left(\log_2 \mathrm{CO_2}\right) \\
T_s &\rightarrow T_s + \delta T_s \\
\mathrm{H_2O}(T_s) &\rightarrow \mathrm{H_2O}(T_s + \delta T_s) \approx \mathrm{H_2O}(T_s) + \frac{d\mathrm{H_2O}}{dT_s}\delta T_s .
\end{aligned}$$

Climate Feedbacks

Using the same variational method, the sensitivity with water vapor feedback is

Sensitivity:

$$\Delta^{\mathrm{H_2O}} \equiv \left(\frac{\partial T_s}{\partial \log_2 \mathrm{CO_2}}\right)_{R,E}^{\mathrm{H_2O}} = \frac{\Delta_0}{1 - g_{H20}}$$

Gain factor:

$$g_{H20} = -\left[\frac{\left(\frac{\partial R}{\partial \mathrm{H_2O}}\right)_{\log_2 \mathrm{CO_2}, T_s, E}}{\left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO_2}, \mathrm{H_2O}, E}}\right]\left(\frac{d\mathrm{H_2O}}{dT_s}\right)$$

Climate Feedbacks

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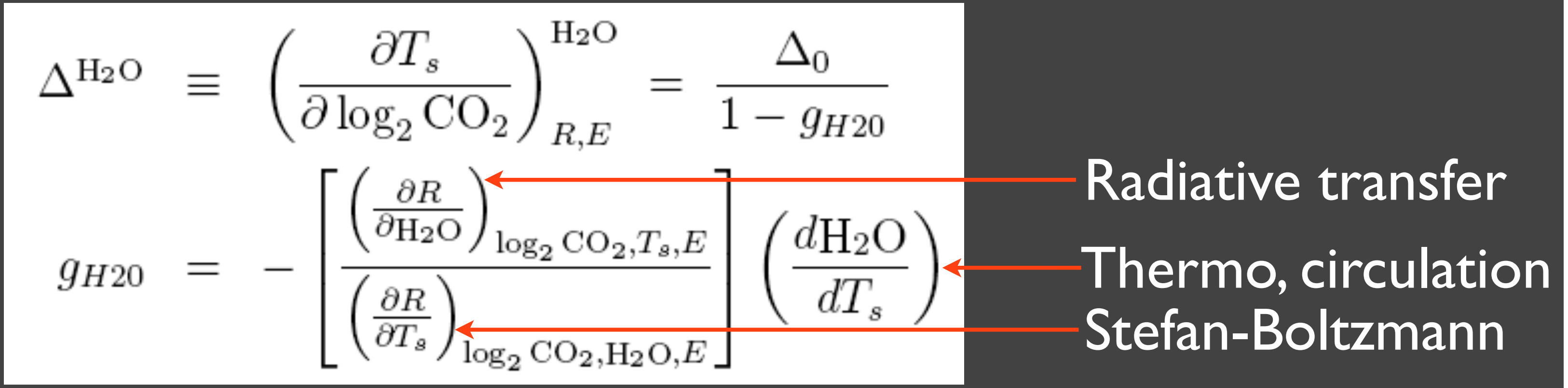

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Gain factor:

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Radiative transfer

Thermo, circulation

Stefan-Boltzmann

Climate Feedbacks

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Gain factor:

$$g_{H20} = -\left[\frac{\left(\frac{\partial R}{\partial \mathrm{H_2O}}\right)_{\log_2 \mathrm{CO_2},T_s,E}}{\left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO_2},\mathrm{H_2O},E}}\right]\left(\frac{d\mathrm{H_2O}}{dT_s}\right)$$

Radiative transfer

Thermo, circulation

Stefan-Boltzmann

–ve feedback	$g_{\mathrm{H_2O}} < 0$
No feedback	$g_{\mathrm{H_2O}} = 0$
+ve feedback	$g_{\mathrm{H_2O}} > 0$
Estimated	$g_{\mathrm{H_2O}} \sim 0.4$
Runaway	$g_{\mathrm{H_2O}} \geq 1$

Climate Feedbacks

Using the same variational method, the sensitivity with water vapor feedback is

Sensitivity:

$$\Delta^{\mathrm{H_2O}} \equiv \left(\frac{\partial T_s}{\partial \log_2 \mathrm{CO_2}}\right)^{\mathrm{H_2O}}_{R,E} = \frac{\Delta_0}{1 - g_{H20}}$$

Gain factor:

$$g_{H20} = -\left[\frac{\left(\frac{\partial R}{\partial \mathrm{H_2O}}\right)_{\log_2 \mathrm{CO_2}, T_s, E}}{\left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO_2}, \mathrm{H_2O}, E}}\right]\left(\frac{d\mathrm{H_2O}}{dT_s}\right)$$

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Estimated	$g_{\mathrm{H_2O}} \sim 0.4$
Runaway	$g_{\mathrm{H_2O}} \geq 1$

This feedback increases climate sensitivity by 2/3:

$$g_{\mathrm{H_2O}} \sim 0.4 \quad \rightarrow \quad \Delta^{\mathrm{H_2O}} = \frac{\Delta_0}{1 - 0.4} \approx 1.7\,\mathrm{K}$$

Climate Feedbacks

We can incorporate additional feedbacks:

$$\Delta^{\mathrm{H_2O},\Gamma,C,I,\ldots} = \left(\frac{\partial T_s}{\partial \log_2 \mathrm{CO_2}}\right)_{R,E}^{\mathrm{H_2O},\Gamma,C,I,\ldots} = \frac{\Delta_0}{1 - g_{\mathrm{H_2O}} - g_{\Gamma} - g_{C} - g_{I} - g_{\ldots}}$$

The gains are additive, and many of them are understood to be positive.

Indirect feedbacks on CO_2, e.g. from the biosphere, can be included formally.

Current generation climate models provide quantitative estimates of the factors.

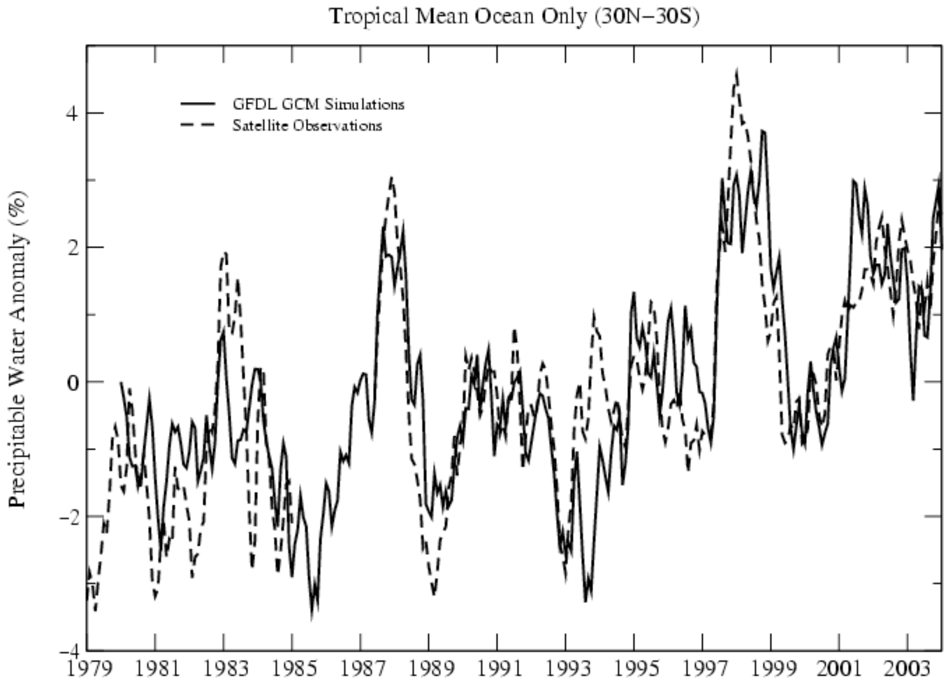
Climate Sensitivity in Climate Models

We can evaluate how models capture feedback related processes.

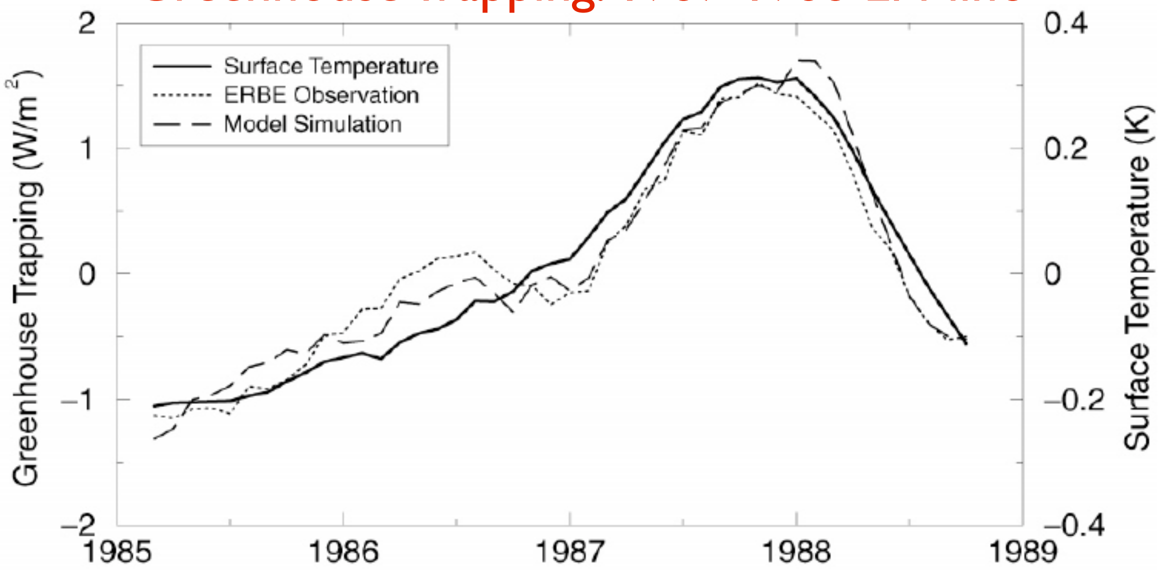
But climate sensitivity is difficult to infer from observations, so we lean heavily on the models for this.

We will now highlight recent advances in calculations of climate sensitivity in climate models.

Model vs. Observed Water Vapor



Greenhouse Trapping: 1987-1988 El Niño



Soden and Held

Climate Sensitivity Calculation Methods

The variational approach we have used can be implemented in climate models in a non-interactive calculation: "radiative kernels" (Manabe & Wetherald, Held, Soden, Coleman et al.)

Another approach is to suppress feedbacks in an interactive calculation (Hall & Manabe).

There are other approaches, and all have strengths and weaknesses.

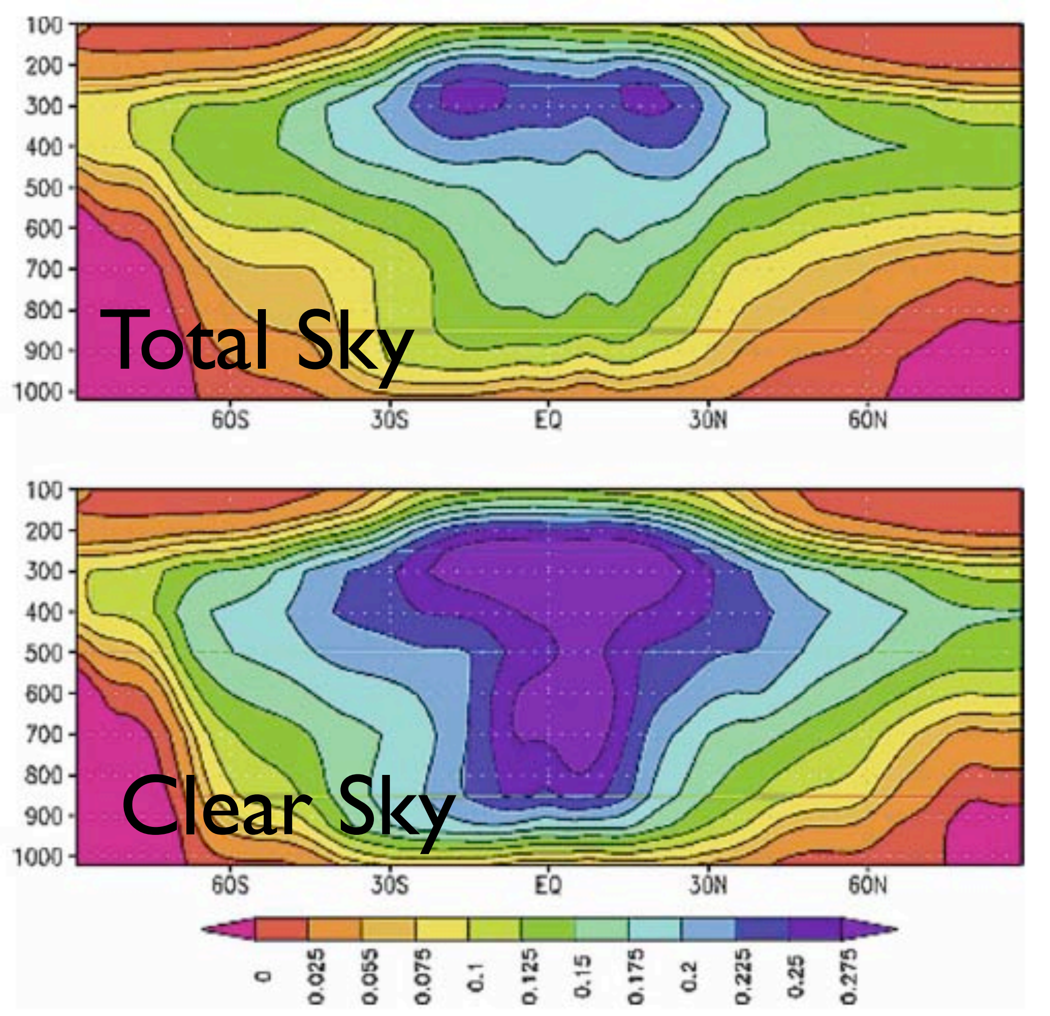
Using Models to Build a Theory of Climate Sensitivity

$$\left(\frac{\partial R}{\partial \mathrm{H_2O}}\right)_{\log_2 \mathrm{CO_2}, T_s, E} \xrightarrow[\text{Kernel}]{\text{Radiative}} \begin{aligned} &\overline{R(w_A + \delta\overline{w}, T_A, c_A, a_A)} - \overline{R(w_A, T_A, c_A, a_A)} \\ &\approx \sum_i \overline{\frac{\partial R}{\partial w_i}} \delta\overline{w}_i \equiv \sum_i K_i^w \delta\overline{w}_i. \end{aligned}$$

Our simple ideas can lead to insightful quantitative calculations.

The sensitive regions for water vapor are in some of the dry regions of the atmosphere.

Circulation and clouds have an important influence.



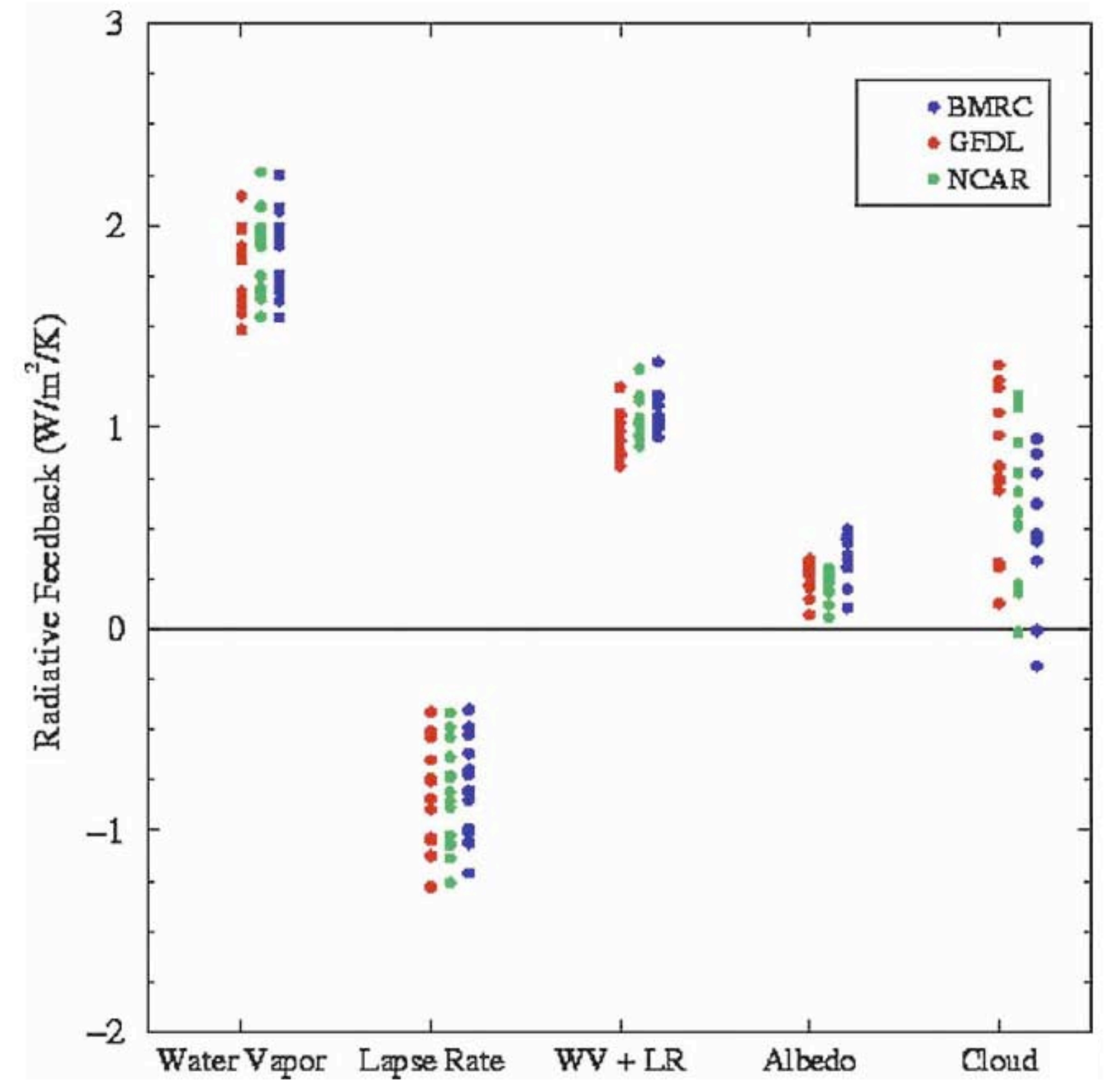
Soden et al. 2008

Current Estimates of Individual Feedbacks

The figure shows the latest calculations of feedback factors for IPCC AR4; using our notation:

$$\left(\frac{\partial R}{\partial X}\right)_{\log_2 \mathrm{CO}_2, T_s, E} \left(\frac{dX}{dT_s}\right)$$

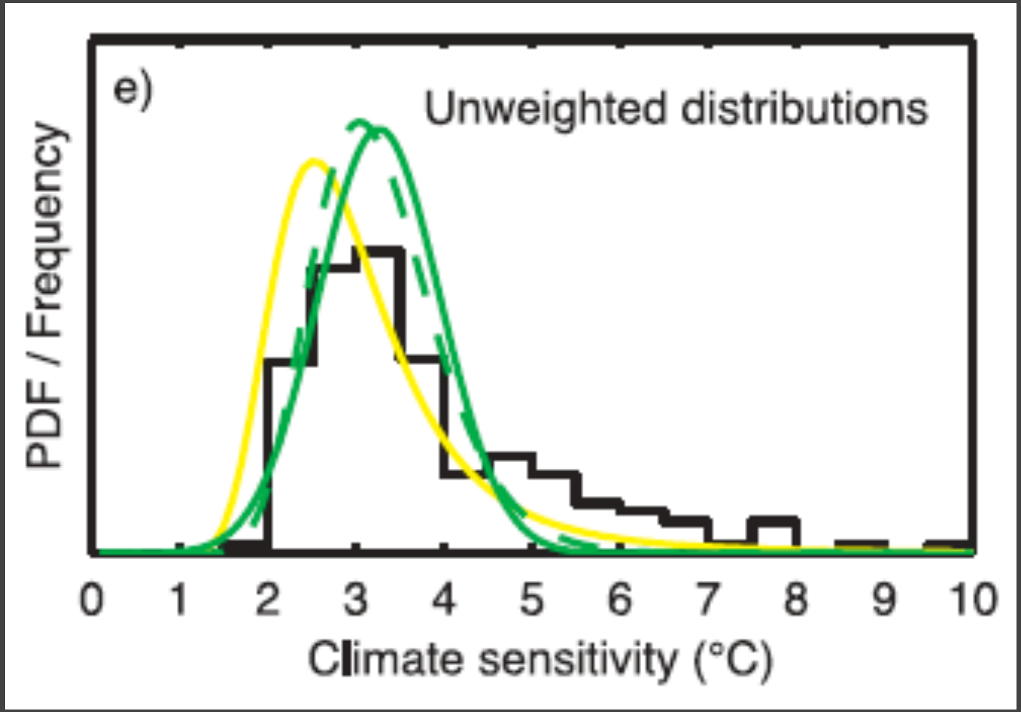
Clouds remain a key uncertainty, but Soden et al. show that the cloud gain is positive.



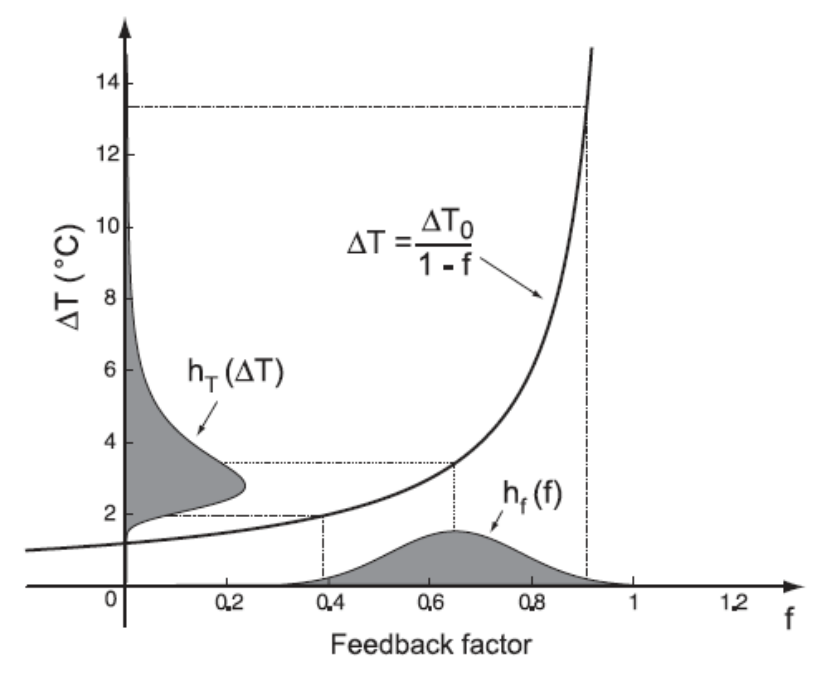
Soden et al. 2008

Distribution of Climate Sensitivity

Uncertainty in gain factors is normally distributed. Thus, uncertainty in climate sensitivity is right skewed.



IPCC 2007



Roe & Baker 2007

Thus, there is a significant probability of large climate change from additional direct feedbacks.

Case study:
Snow Albedo Feedback

With Chris Fletcher (Toronto),
Alex Hall & Qin Xu (UCLA)

Ice & Snow Albedo Feedback

Melting ice and snow expose a dark surface, which leads to further warming.

$$g_I \quad = \quad - \left[\frac{\left(\frac{\partial R}{\partial I}\right)_{\log_2 \mathrm{CO_2}, T_s, E}}{\left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO_2}, I, E}} \right] \left(\frac{dI}{dT_s} \right)$$

Northern Hemisphere Winter Albedo

Ice & Snow Albedo Feedback

Melting ice and snow expose a dark surface, which leads to further warming.

$$g_I = -\left[\frac{\left(\frac{\partial R}{\partial I}\right)_{\log_2 \mathrm{CO_2}, T_s, E}}{\left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO_2}, I, E}}\right]\left(\frac{dI}{dT_s}\right)$$

← Negative

Northern Hemisphere Winter Albedo

Ice & Snow Albedo Feedback

Melting ice and snow expose a dark surface, which leads to further warming.

Positive

$$g_I = -\left[\frac{\left(\frac{\partial R}{\partial I}\right)_{\log_2 \mathrm{CO_2}, T_s, E}}{\left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO_2}, I, E}}\right]\left(\frac{dI}{dT_s}\right)$$

Negative

Northern Hemisphere Winter Albedo

Ice & Snow Albedo Feedback

Melting ice and snow expose a dark surface, which leads to further warming.

Positive

$$g_I = -\left[\frac{\left(\frac{\partial R}{\partial I}\right)_{\log_2 \mathrm{CO}_2, T_s, E}}{\left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO}_2, I, E}}\right]\left(\frac{dI}{dT_s}\right)$$

Negative

Positive

Northern Hemisphere Winter Albedo

Ice & Snow Albedo Feedback

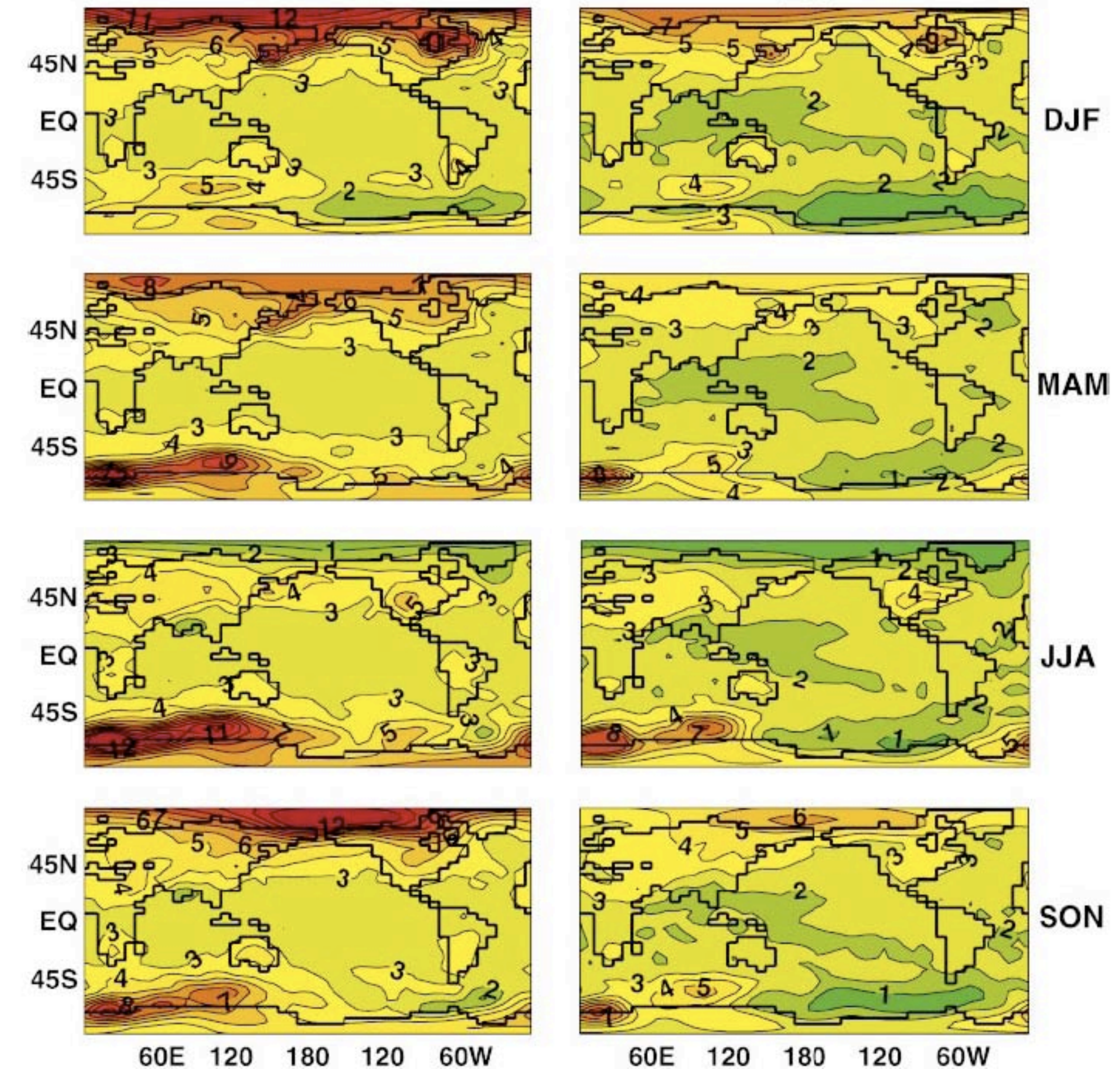
Melting ice and snow expose a dark surface, which leads to further warming.

$$\underset{\substack{\uparrow\\ \text{Positive}}}{g_I} = -\left[\frac{\overset{\substack{\text{Positive}\\ \downarrow}}{\left(\frac{\partial R}{\partial I}\right)_{\log_2 \mathrm{CO_2}, T_s, E}}}{\underset{\substack{\uparrow\\ \text{Positive}}}{\left(\frac{\partial R}{\partial T_s}\right)_{\log_2 \mathrm{CO_2}, I, E}}}\right]\left(\frac{dI}{dT_s}\right) \leftarrow \text{Negative}$$

Northern Hemisphere Winter Albedo

Effect of Albedo Feedback on Global Warming

Standard Suppressed SAF

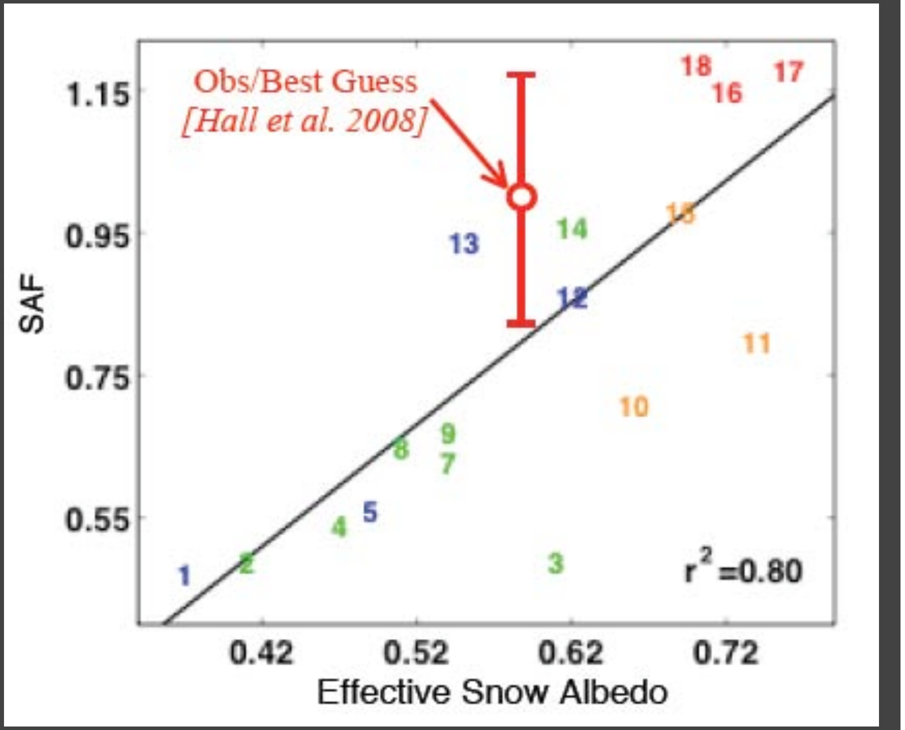


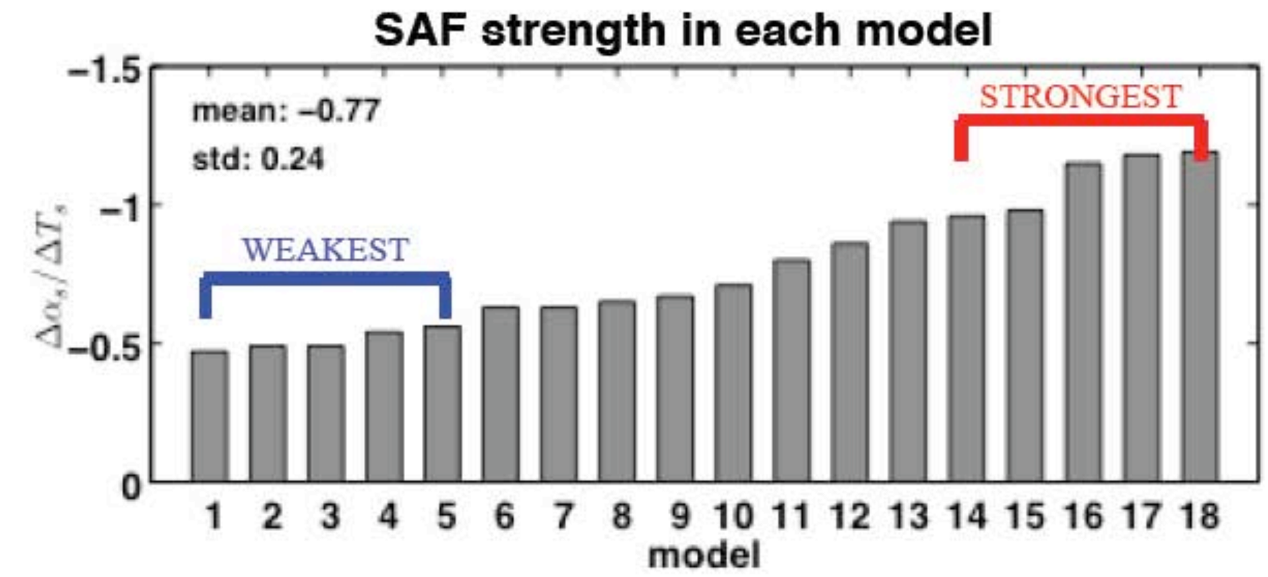
Hall 2004

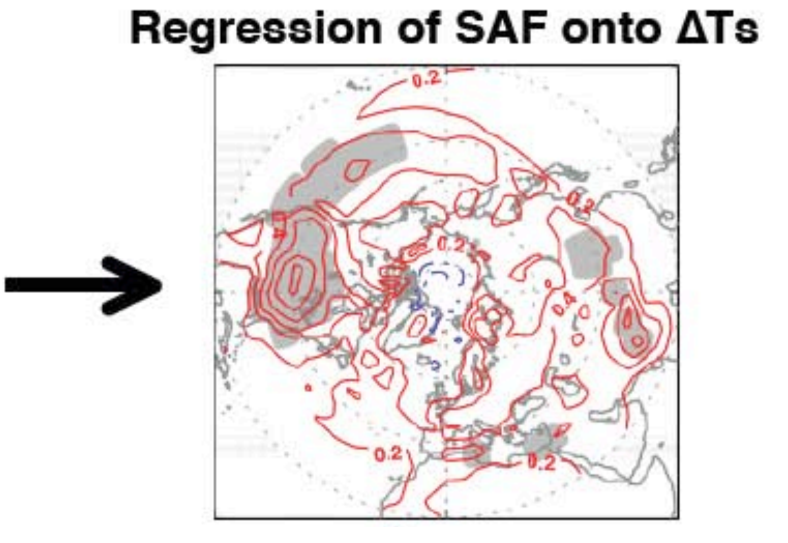
Models with bright snow have strong SAF (Hall et al. 2008)

The SAF is active at *low* latitudes and has signatures over the oceans.

This suggests that snow albedo feedbacks force a *teleconnection*.

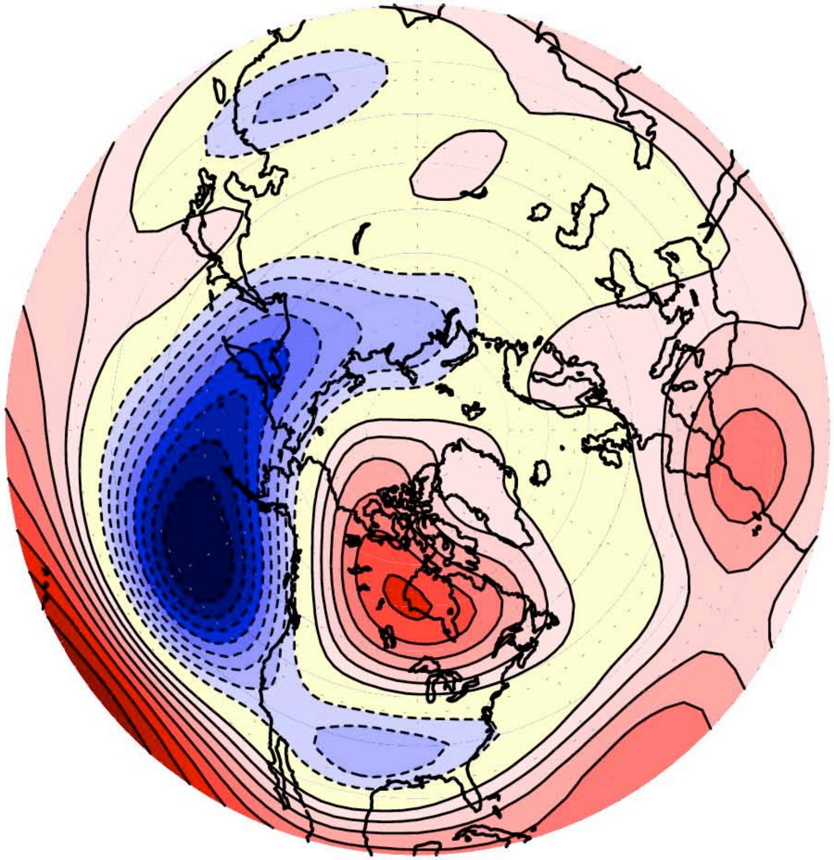




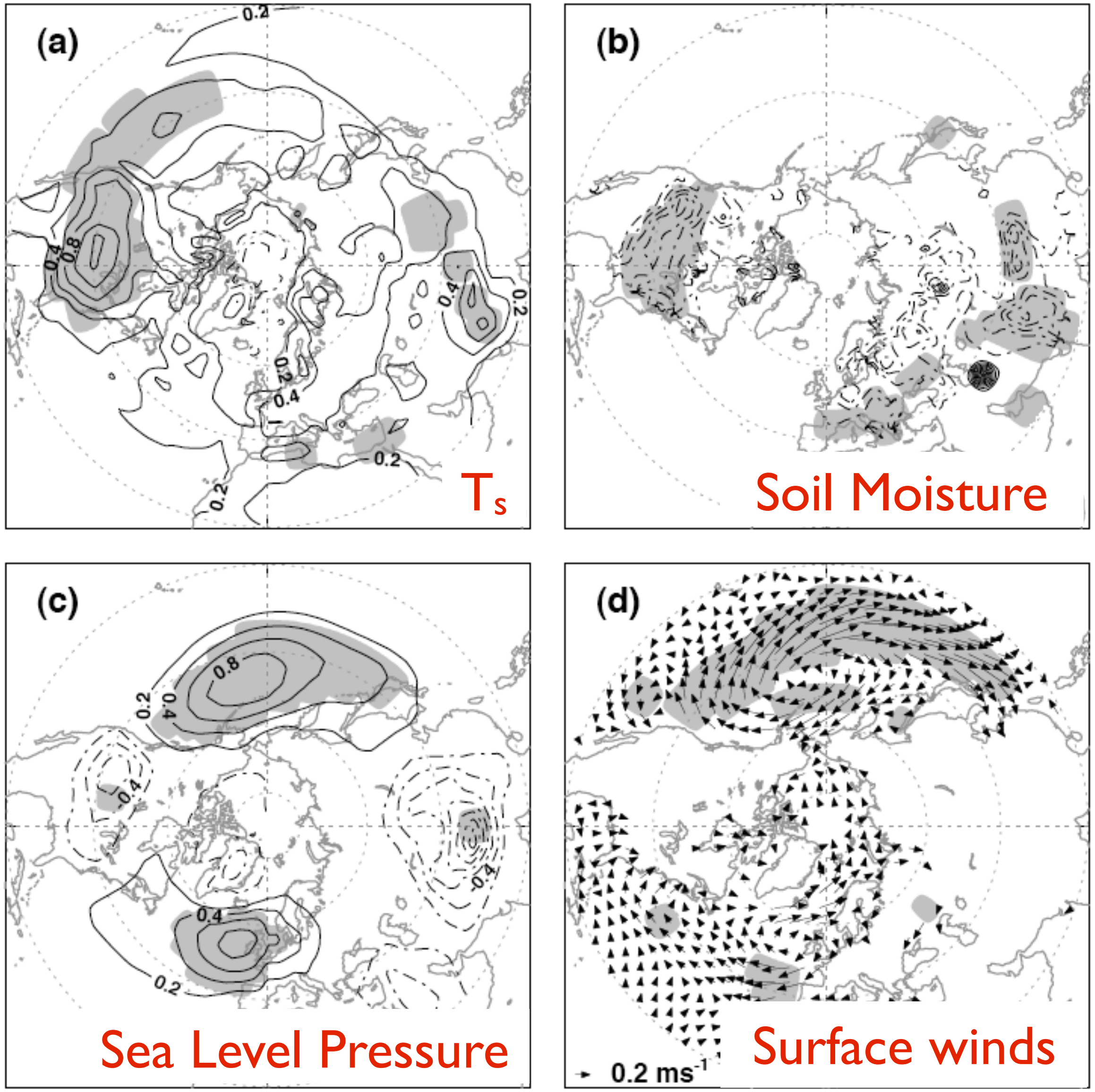


Teleconnections are long-range spatial correlation patterns involving planetary scale Rossby waves.

Atmospheric circulation pattern that is coherent with El Niño



Snow Albedo Feedback: Remote Signatures

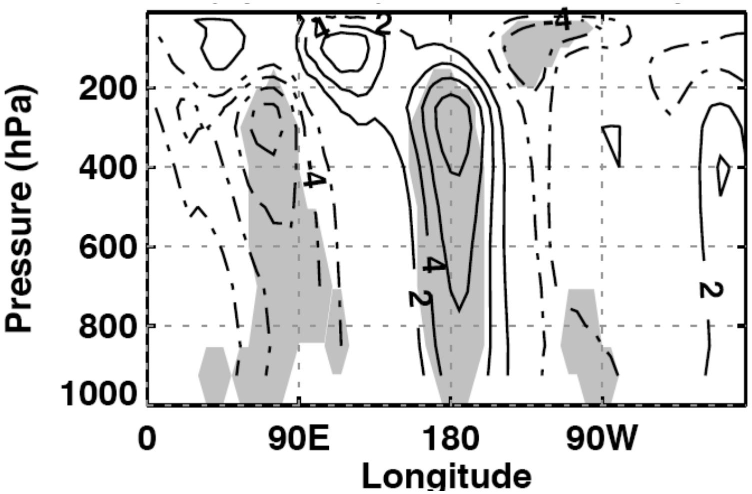


T_s

Soil Moisture

Sea Level Pressure

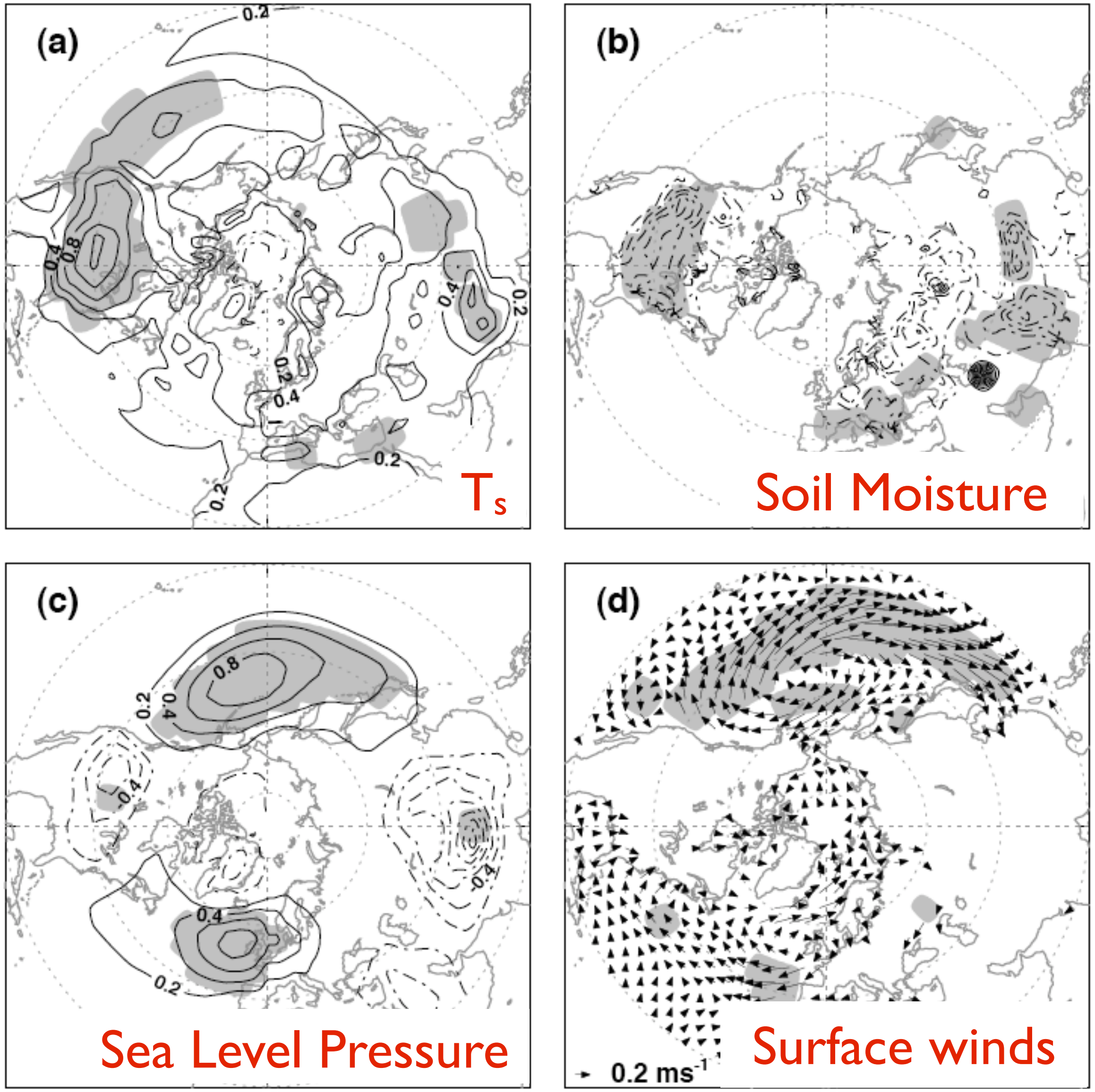
Surface winds

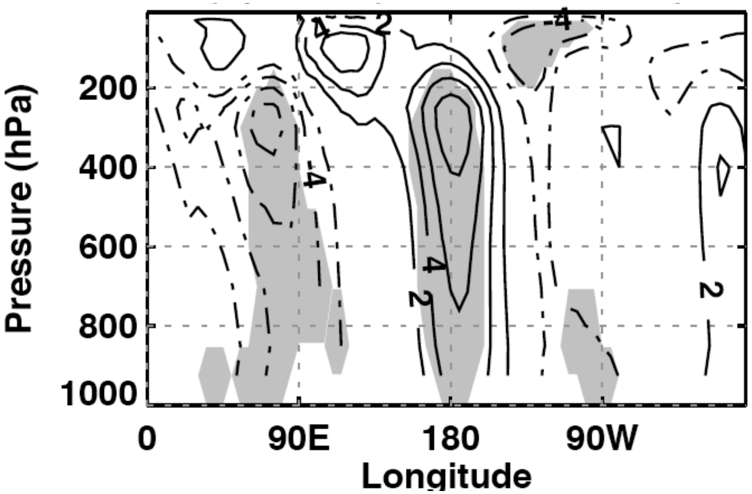


Vertical-longitudinal wave structure

The snow-albedo feedback is linked to planetary scale thermal, hydrological, and circulation signatures.

Snow Albedo Feedback: Remote Signatures





Vertical-longitudinal wave structure

Uncertainty in snow-albedo feedback has highly nonlocal consequences for regional climate change.

Conclusions

We are still faced with a wide range of predicted responses to climate change.

But climate modelling and sensitivity analysis have developed to the point where we can explain and constrain this spread.

It seems to me that we are closing in on a climate theory: starting from simple ideas, and building towards comprehensive models.

We can now explain previously confusing observational results, and tie regional uncertainties to feedback factors.

We are in a better position to study the full “Earth system”

Earth System = Physical Climate + BioGeoChem + Biosphere