Using Simple to Intermediate Climate Models to Understand Climate Change and other stuff

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NCAR Workshop on Mathematics of Climate Change
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Math & ClimateChange Nexus

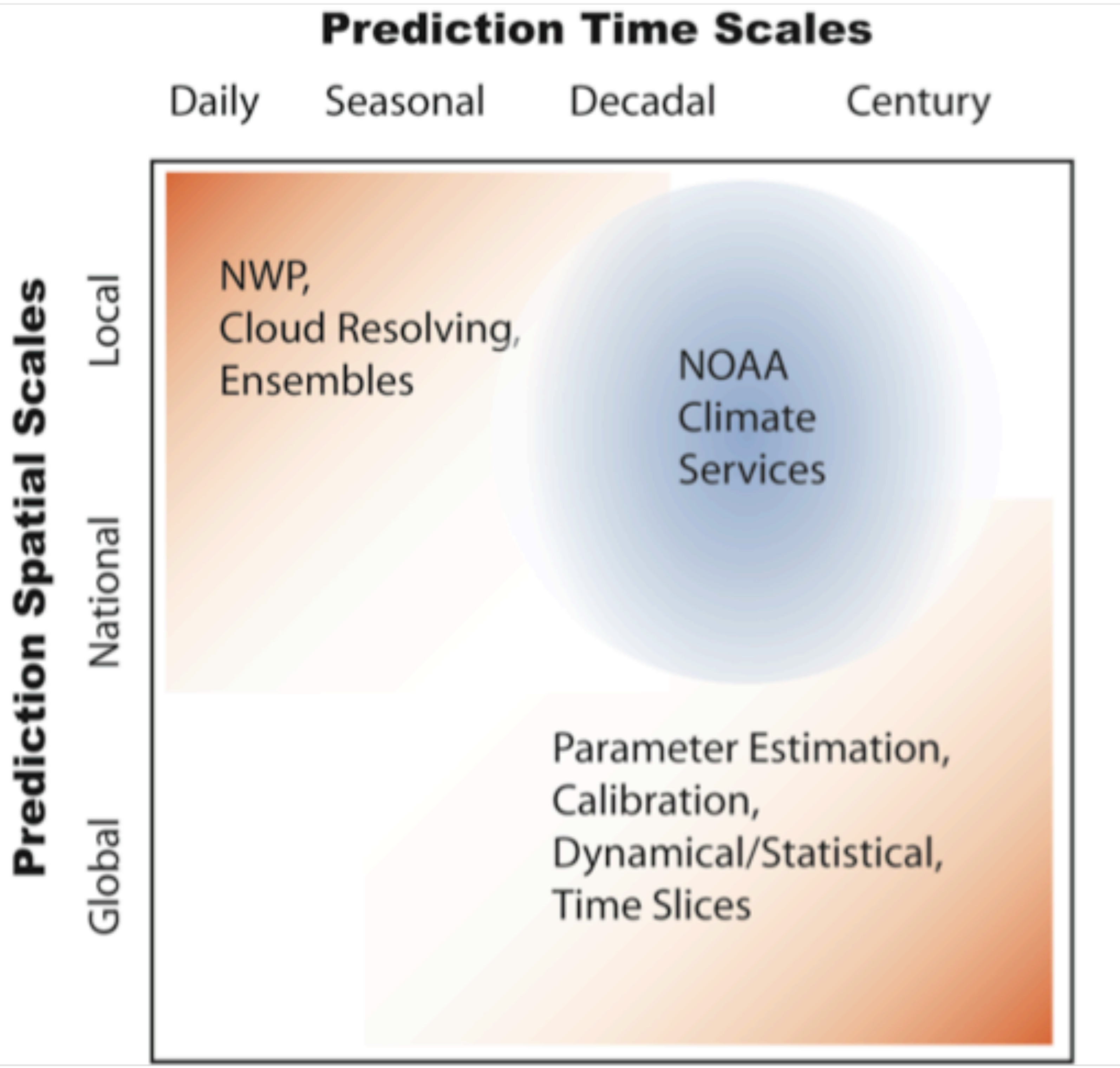
- **Model parameter estimation and calibration for predictions**
  - Prediction: Time-scales? Spatial scales? Variables? Model errors?
- **D&A Issues:** Variability on long time-scales, Attribution of climate change
- **Dynamics v. Response - What are we learning from data analysis? (properties v. parameters?)**
- **Tools for Uncertainty Estimation**
  - **Sampling, Parameters, Structure, ...**

Assessing Uncertainty in Regional Climate Change Projections

- **Factors affecting regional climate**
  - **Large-scale response of atmospheric circulation**
  - **Topography, tropical SSTs, local and global environment, etc.**
- **Motivation**
  - **Need to characterize differences in climate models by building *simplified models* to capture uncertainty**

Getting from global to regional scales

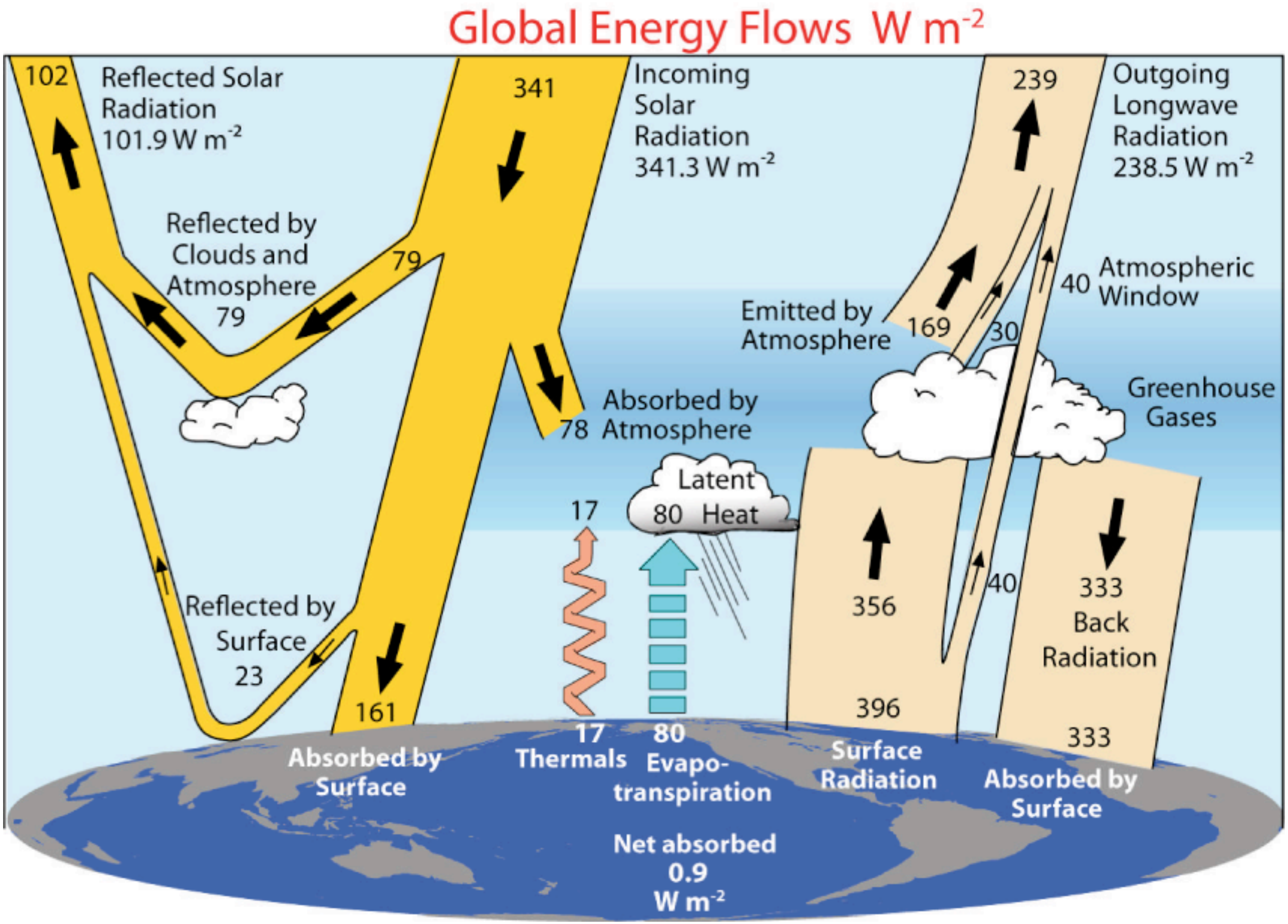
The regional climate prediction capabilities are not in sync with the state of the art forecasting methods



Forest et al. - White Paper on NOAA Climate Services

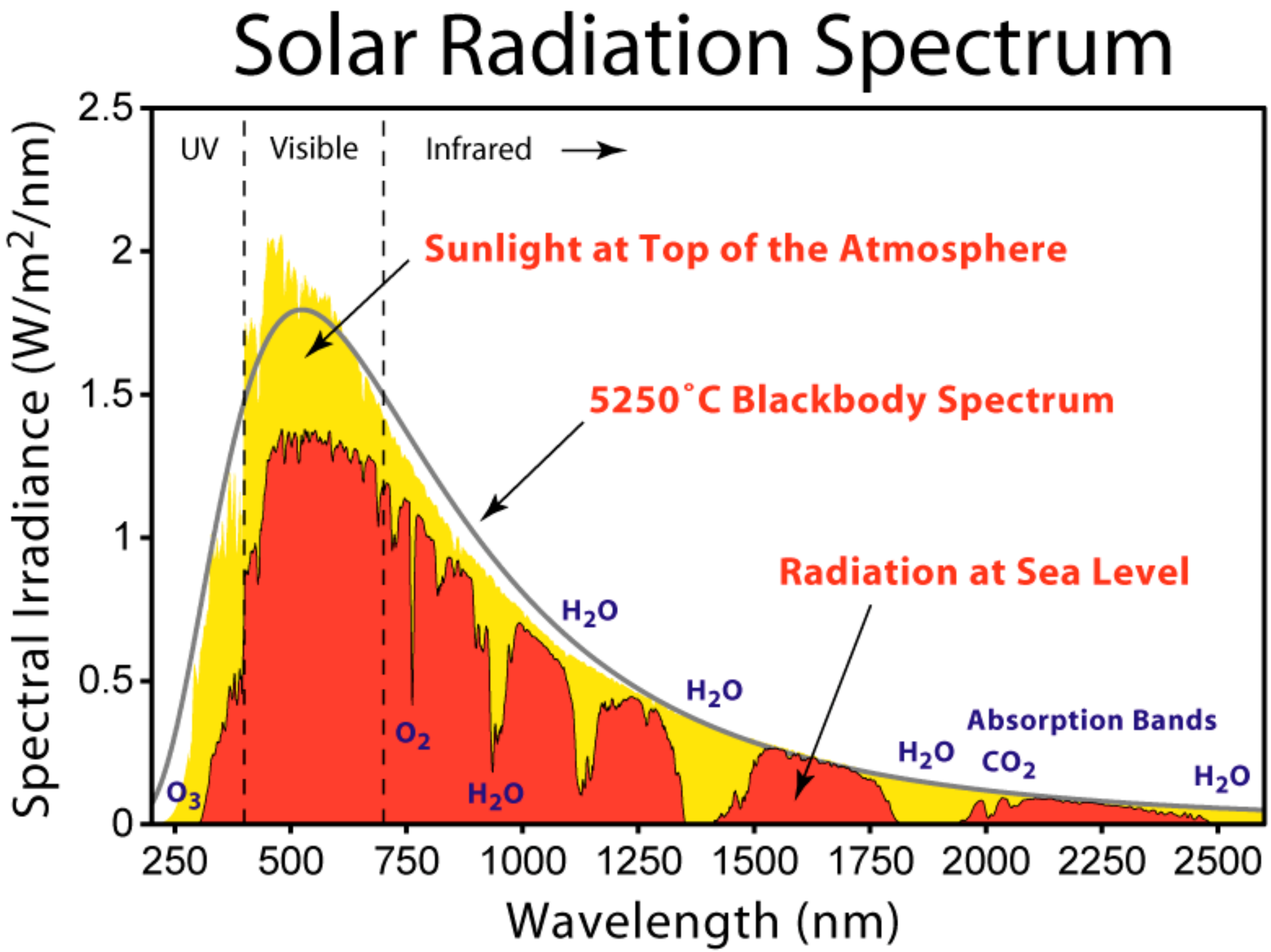
Overview

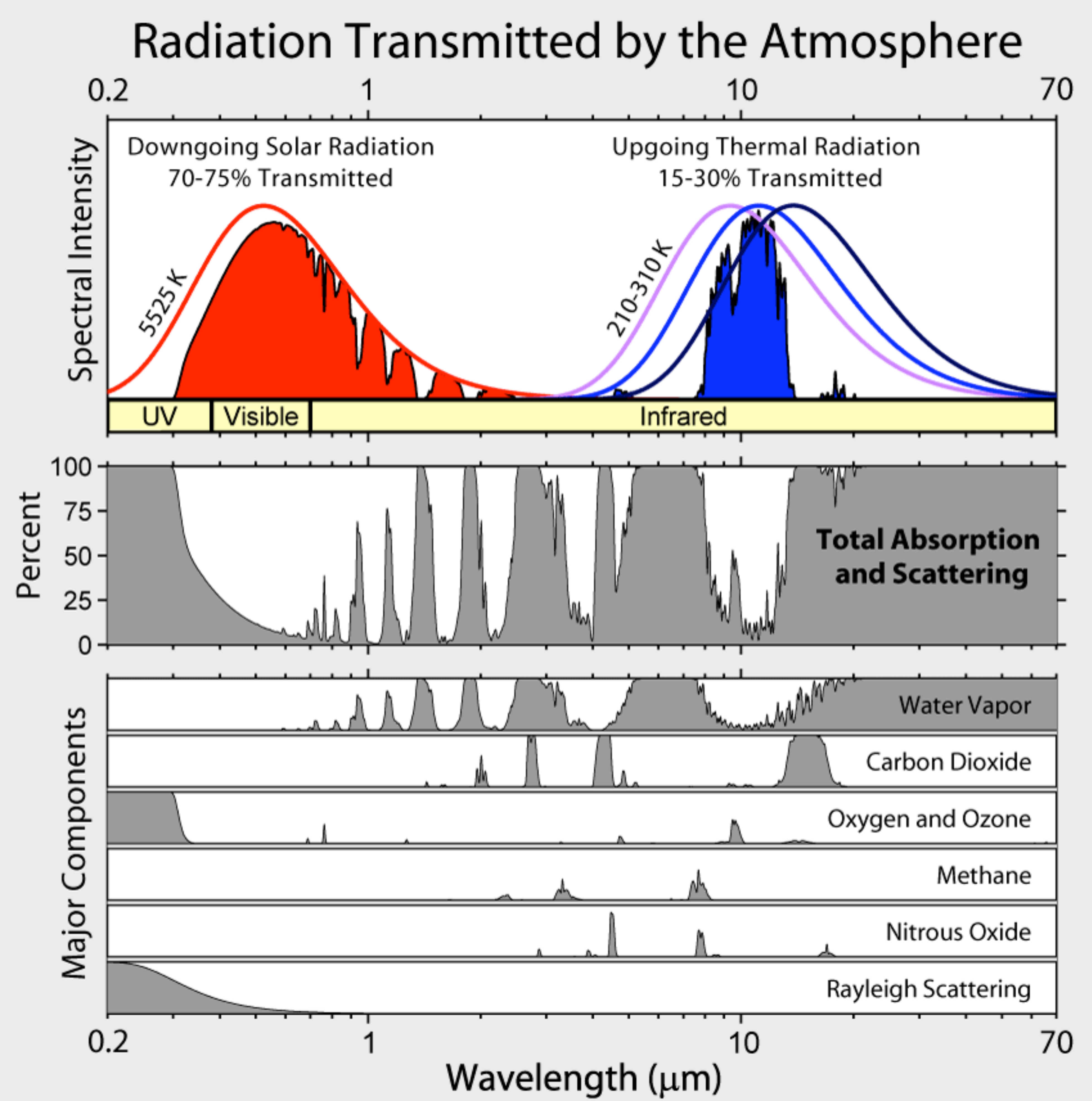
- **Other Simple Models**
  - **0D climate model**
  - **Stommel Box model (not discussed)**
- **Introduction to Earth/Climate Models of Intermediate Complexity (EMICs)**
- **Intro to MIT IGSM**
- **Uses of the MIT IGSM**
  - **Reproducing 20th century record**
  - **Future Climate Change**
  - **Understanding AOGCM behavior**



From Trenberth et al. (2009)

Is the atmosphere transparent to Solar wavelengths?





Radiation Transmitted by the Atmosphere
0.2
1
10
70
Spectral Intensity
Downgoing Solar Radiation
70-75% Transmitted
Upgoing Thermal Radiation
15-30% Transmitted
5525 K
210-310 K
UV
Visible
Infrared
Percent
100
75
50
25
0
Total Absorption
and Scattering
Major Components
Water Vapor
Carbon Dioxide
Oxygen and Ozone
Methane
Nitrous Oxide
Rayleigh Scattering
Wavelength (μm)

0D Climate Model

- **Incoming absorbed solar = outgoing IR**

$$Q_o = \frac{S_o(1-\alpha)}{4.} = \sigma T_e^4$$

- **where T_e = Effective blackbody temperature of Earth required to balance incoming radiation**

$$T_e = \left(\frac{S_o(1-\alpha)}{4\sigma}\right)^{\frac{1}{4}} = 255K$$

Simplest Greenhouse Model

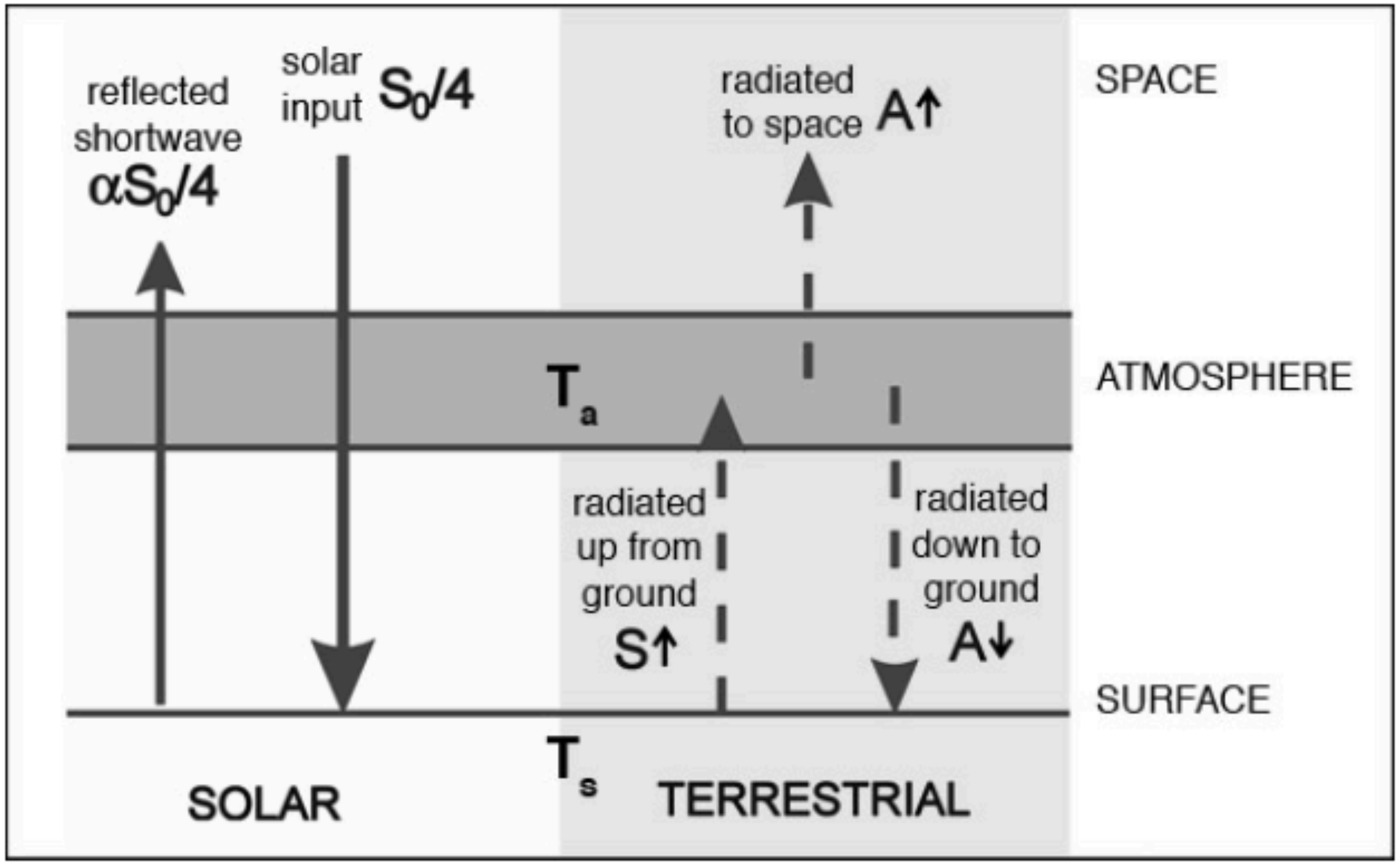
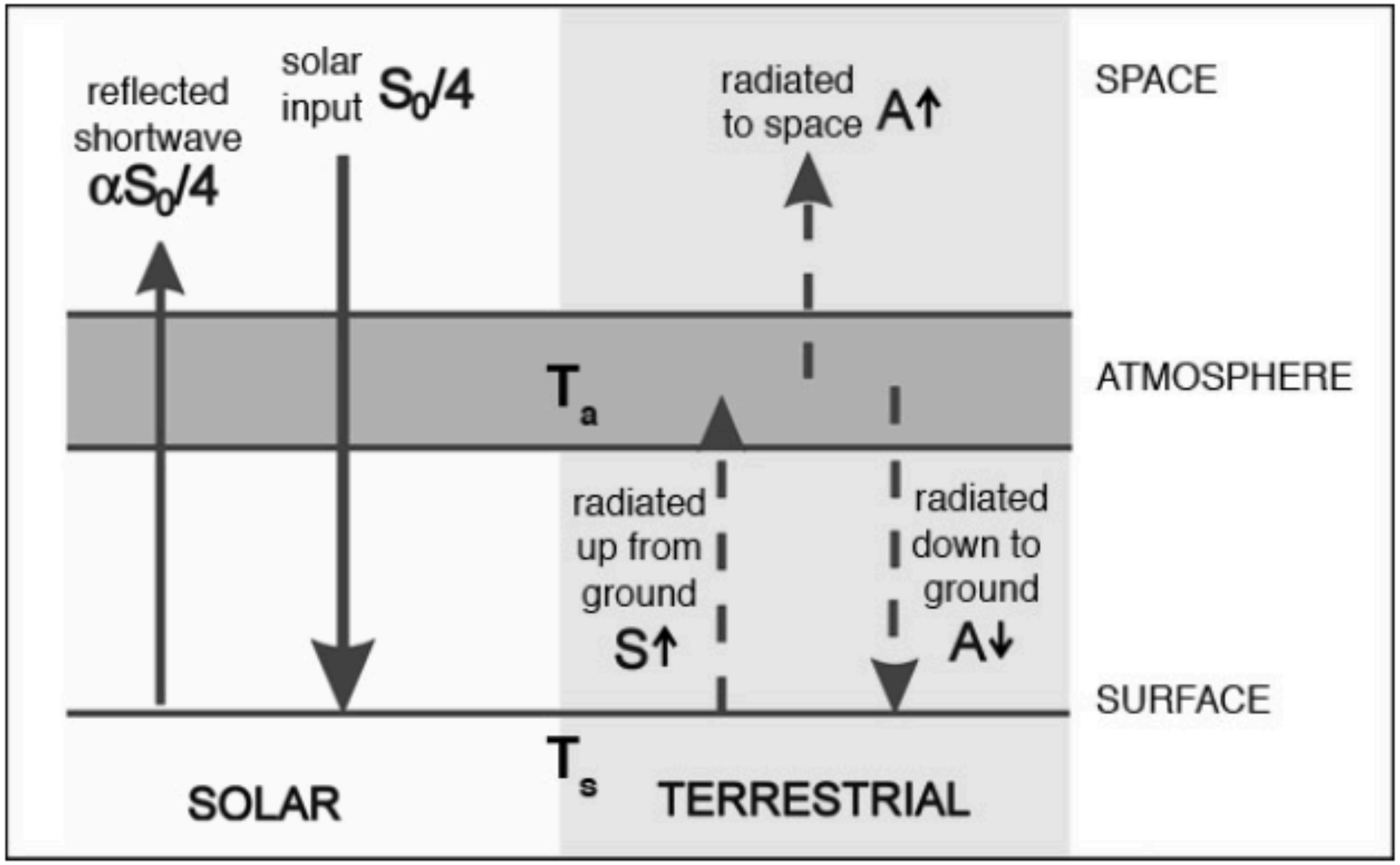


Figure 2.7: The simplest greenhouse model, comprising a surface at temperature T_s, and an atmospheric layer at temperature T_a, subject to incoming solar radiation $\frac{S_o}{4}$. The terrestrial radiation upwelling from the ground is assumed to be completely absorbed by the atmospheric layer.

Marshall and Plumb: AOCD

Simplest Greenhouse Model



Top Energy Balance: $\frac{S_o}{4}(1-\alpha) = \sigma T_e^4$

Sfc Energy Balance: $\frac{S_o}{4}(1-\alpha) = \sigma(T_s^4 - T_e^4)$

Rearranging: $T_s = 2^{\frac{1}{4}} T_e = 1.19 * 255 = 303.K$

Marshall and Plumb: AOCD

Simple 1D climate model

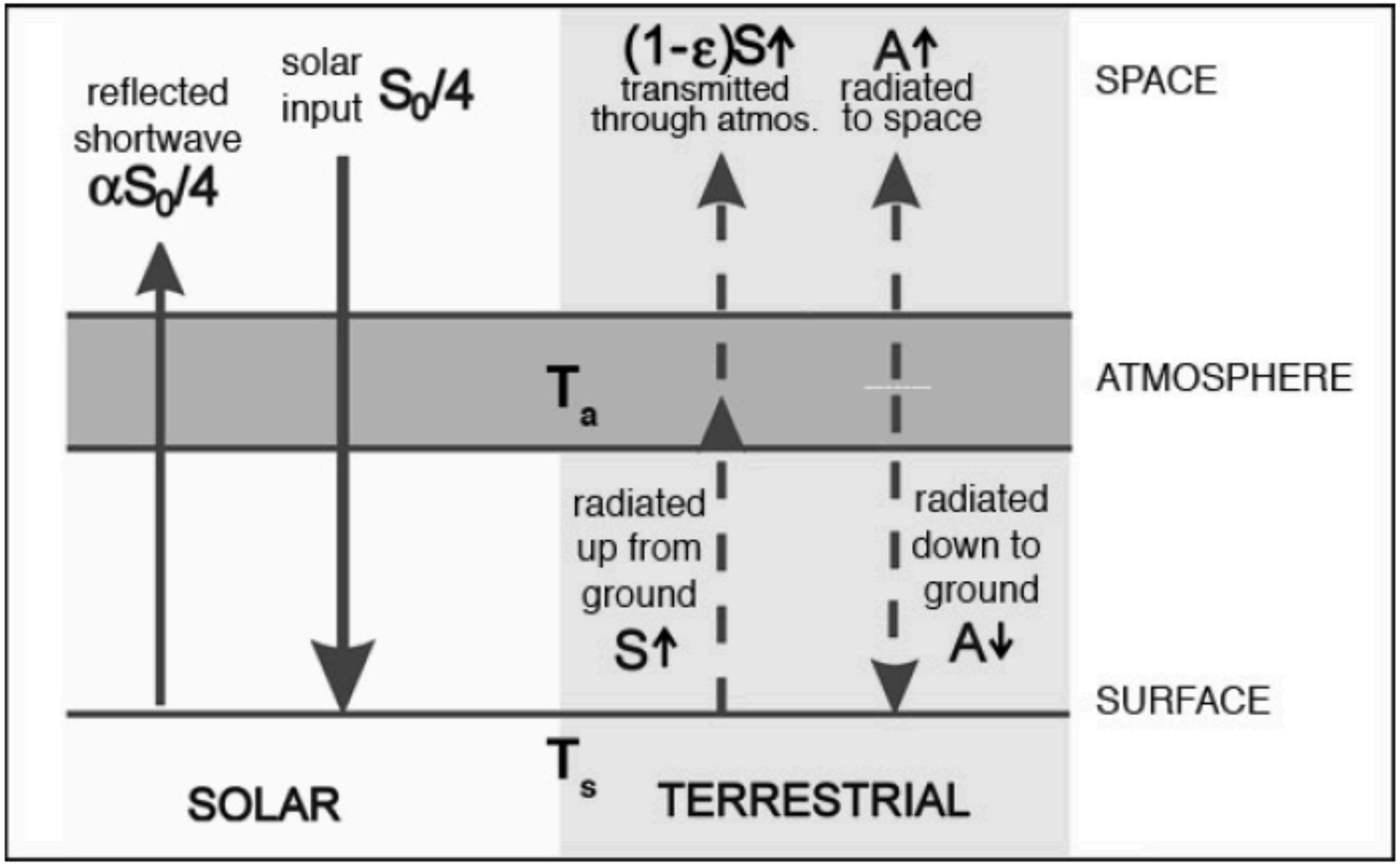
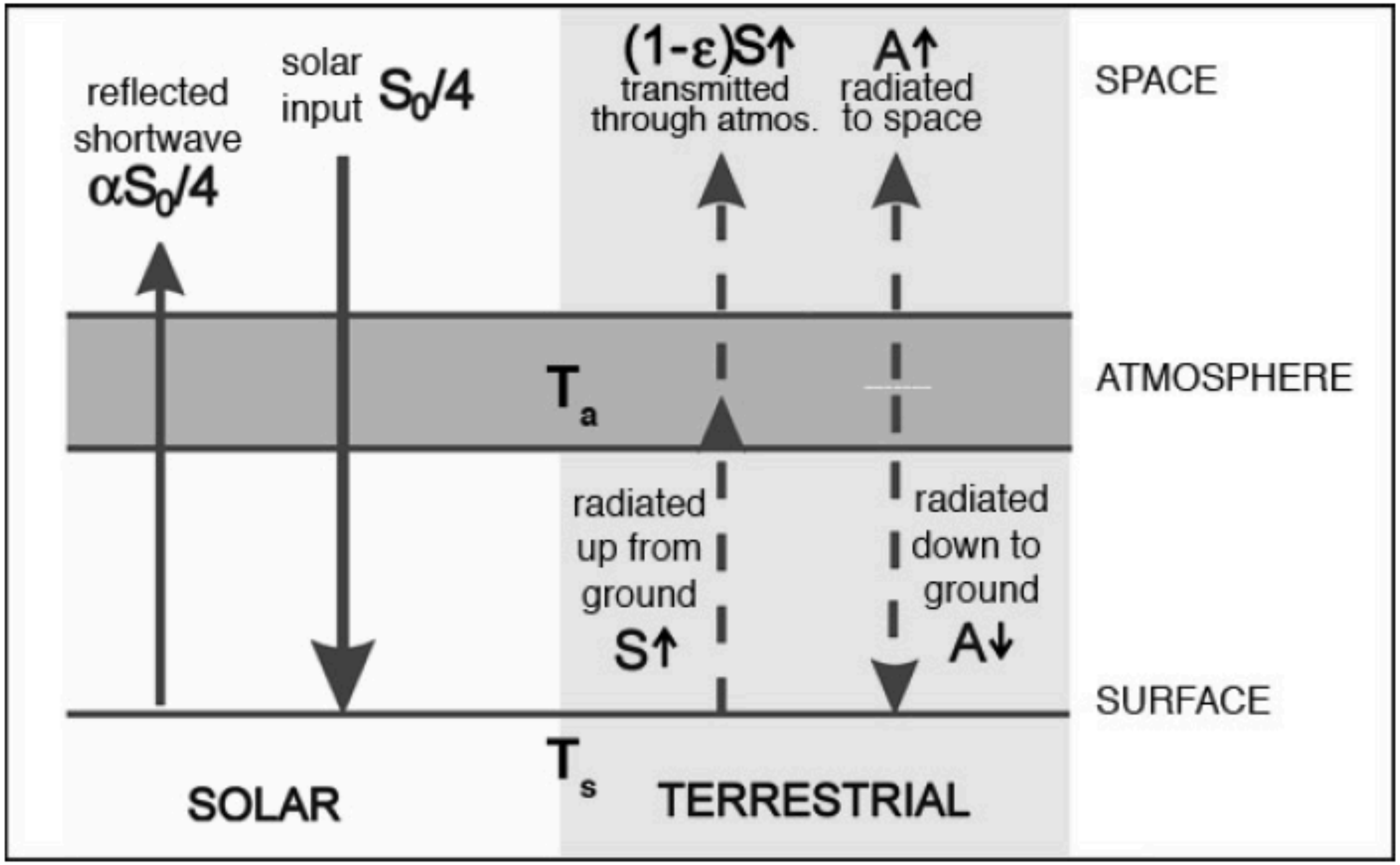


Figure 2.8: A leaky greenhouse. In contrast to Fig.2.7, the atmosphere now absorbs only a fraction, ε, of the terrestrial radiation upwelling from the ground.

Marshall and Plumb: AOCD

Simple 1D climate model



$$T_s = (\frac{1}{1-\epsilon/2})^{\frac{1}{4}} T_e = 1.136 * 255 = 289K$$

Marshall and Plumb: AOCD

Simple 1D climate model

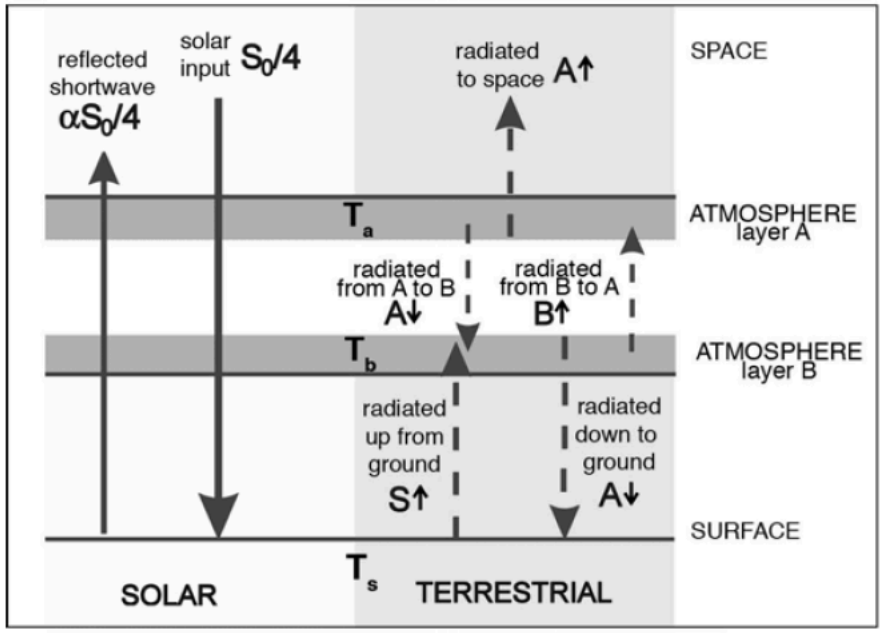


Figure 2.9: An 'opaque' greenhouse made up of two layers of atmosphere. Each layer completely absorbs the IR radiation impinging on it.

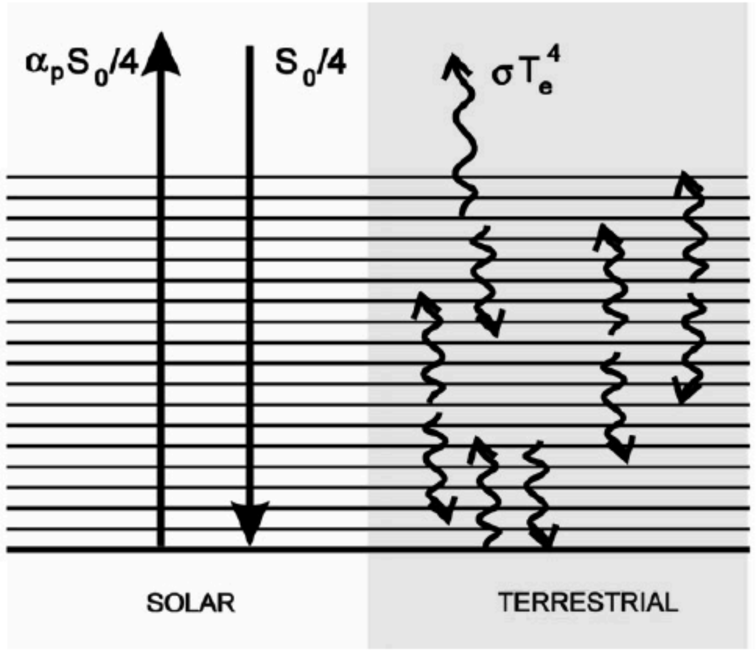


Figure 2.10: Schematic of radiative transfer model with many layers.

Marshall and Plumb: AOCD

Introducing Climate Sensitivity

Climate sensitivity was introduced to measure the global response of the climate system to a change in the radiative forcing inputs to the system.

"To make progress on a problem with the intimidating complexity of climate change, the proper response of a scientist is to begin by considering simple questions and then add complexity as understanding is gained. The lessons drawn from these simple models must be taken seriously, but with full realization that they may not be a faithful representation of nature."

Quote from Hartmann, GPC, Chapter 9, p. 229

A Quick Estimate of Climate Sensitivity

- Defined as: $$\frac{dT_s}{dQ} = \frac{\partial T_s}{\partial Q} + \frac{\partial T_s}{\partial y_i}\frac{dy_i}{dQ}$$
- This is the response in surface temperature to a change in the energy increase.
- Now let's return to the "leaky" atmosphere model and consider the sensitivity to the emissivity.

$$\frac{\partial T_s}{\partial \epsilon} = -\frac{T_e}{2}(1-\epsilon/2)^{-\frac{5}{4}}$$

- Suppose emissivity decreases by 1% (e.g., doubled [CO_2]), this implies a temperature change of 2.4 K

A Hierarchy of Climate Models

- "Horses for Courses" - Jake Jacoby
  - Models suited for specific purposes
- Energy Balance Models
  - great for concepts, good for uncertainty
  - okay for feedbacks with other components
- Global Climate Models
  - great for processes/feedbacks, good for predictions, but poor for uncertainty (just too expensive)
- Need for Intermediate Complexity
  - Difficult to define these days...

The 16th slide
(via Google Images search)

EMICs: A History

Climate Dynamics (2002) 18: 579–586
DOI 10.1007/s00382-001-0200-1

M. Claussen · L. A. Mysak · A. J. Weaver · M. Crucifix
T. Fichefet · M.-F. Loutre · S. L. Weber · J. Alcamo
V. A. Alexeev · A. Berger · R. Calov · A. Ganopolski
H. Goosse · G. Lohmann · F. Lunkeit · I. I. Mokhov
V. Petoukhov · P. Stone · Z. Wang

Earth system models of intermediate complexity: closing the gap in the spectrum of climate system models

EMICs: A History

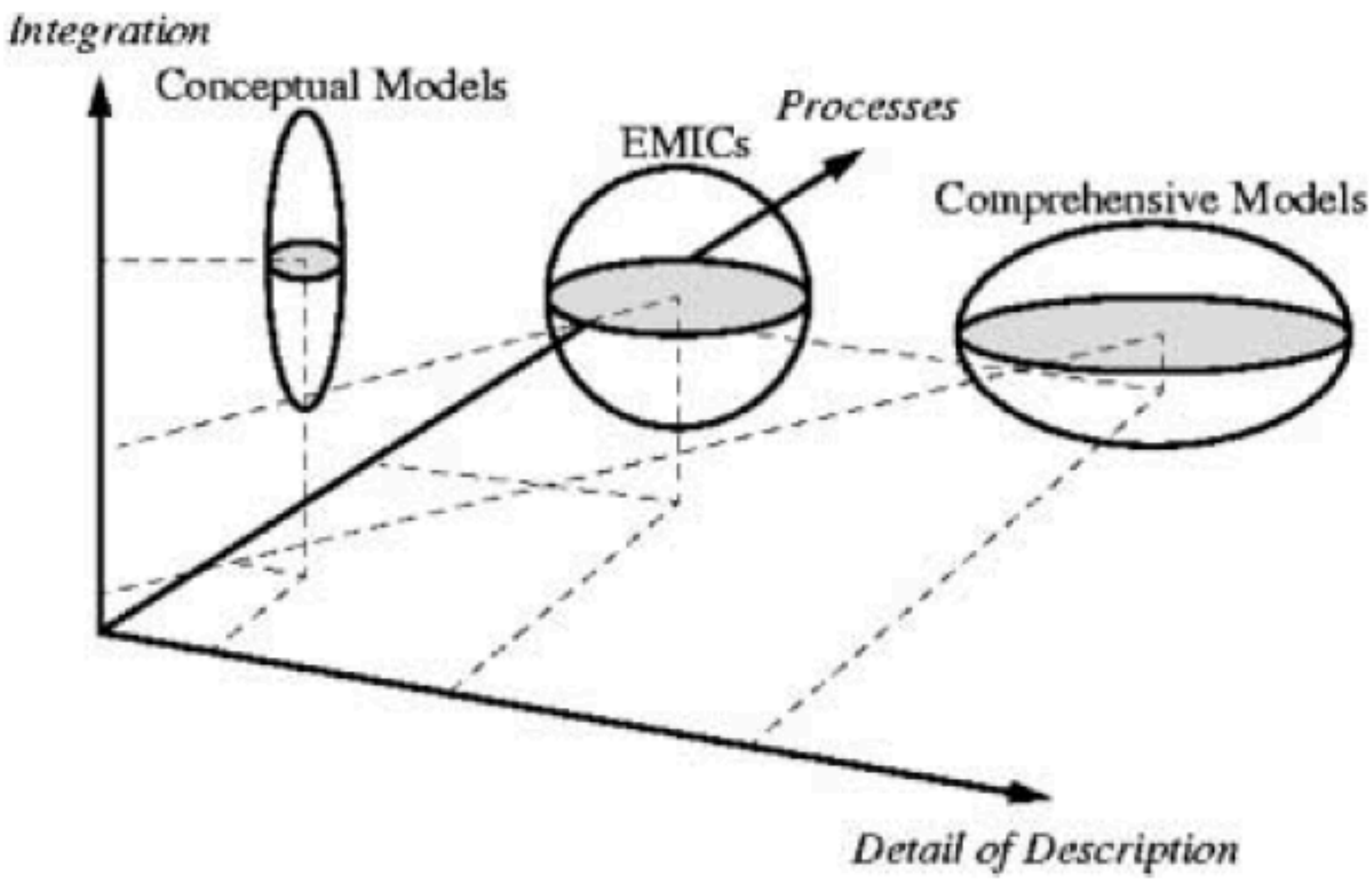


Fig. 1. Pictorial definition of EMICs. Adapted from Claussen (2000)

Claussen et al (2002)

EMICs: A History

Table 1. References to EMICs

Model	Short list of references
1: Bern 2.5D	Stocker et al. (1992), Marchal et al. (1998)
2: CLIMBER-2	Petoukhov et al. (2000), Ganopolski et al. (2000)
3: EcBilt	Opsteegh et al. (1998)
4: EcBilt-CLIO	Goosse et al. (2000)
5: IAP RAS	Petoukhov et al. (1998), Handorf et al. (1999), Mokhov et al. (2000)
6: MPM	Wang and Mysak (2000), Mysak and Wang (2000)
7: MIT	Prinn et al. (1999), Kamenkovich et al. (2000)
8: MoBidiC	Crucifix et al. (2000a)(2000b)
9: PUMA	Fraedrich et al. (1998), Maier-Reimer et al. (1993)
10: Uvic	Weaver et al. (2000)
11: IMAGE 2	Alcamo (1994), Alcamo et al. (1996)

Claussen et al (2002)

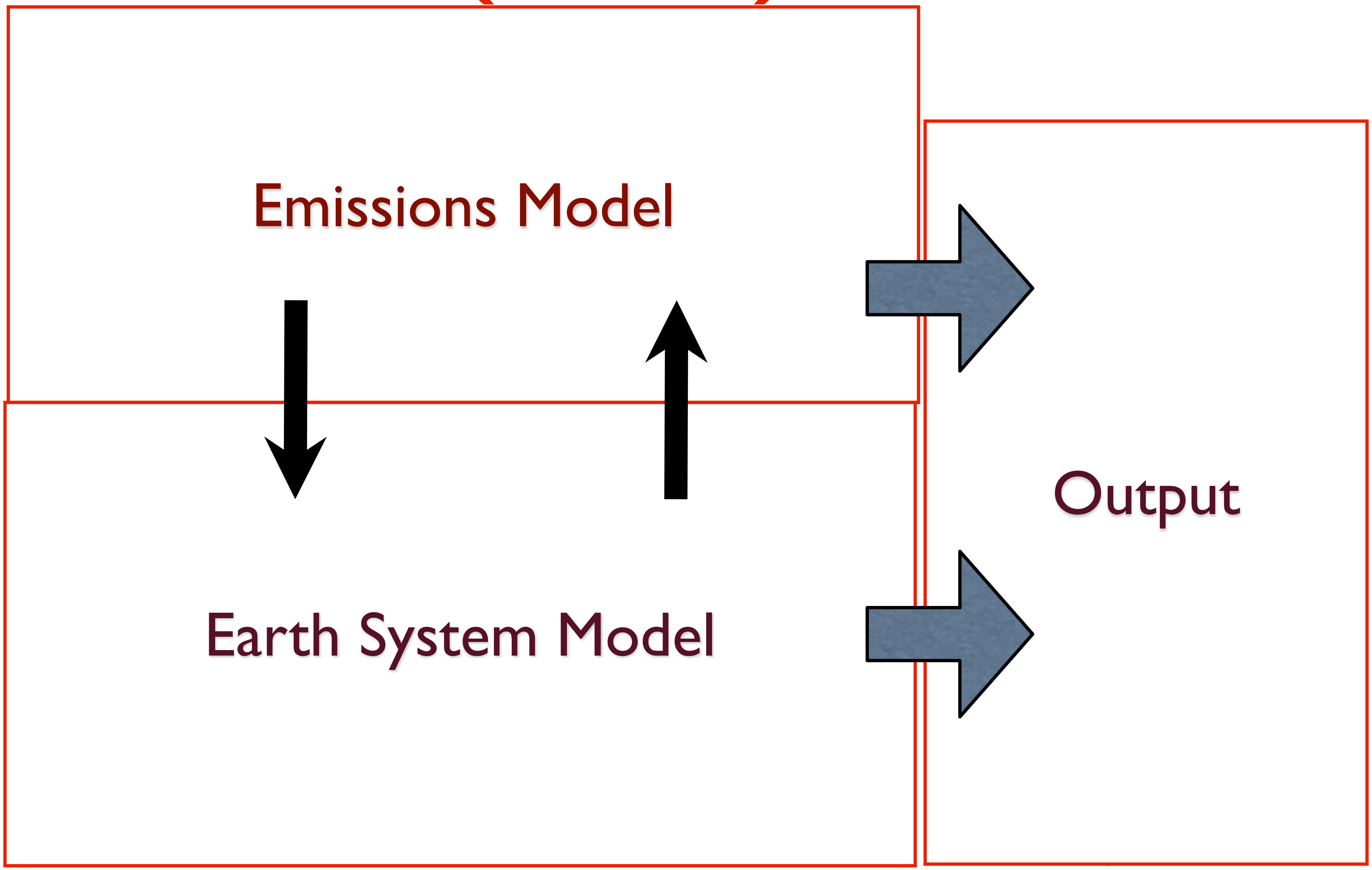
EMICs: A History

Table 2. Interactive components of the climate system being implemented into EMICs (for explana

Model	Atmosphere	Ocean	Biosphere
1	EMBM, 1-D(φ)	2-D(φ, z), 3 basins	B_o, B_T
2	SDM, 2-D(φ, λ)-mL	2-D(φ, z) 3 basins	B_o, B_T, B_V
3	QG, 3-D, T21, L3	3-D, 5.6°×5.6°, L12	
4	QG, 3-D, T21-L3	3-D, 3°×3°	B_T, B_V
5	SDM, 3-D 4.5°×6°, L8	SDM, 2-D(φ, λ) 4.5°×6°, L3 fixed salinity	
6	EMBM, 1-D(φ), land/ocean boxes	2-D(φ, z), 3 basins	
7	SDM, 2-D(φ, z)/atmospheric chemistry	3-D, 4°×1.25° to 3.75°, L15	B_T
8	QG, 2-D(φ, z)-L2	2-D(φ, z), 3 basins	B_o, B_T, B_V
9	GCM, 3-D, T21, L5	3-D, 5°×5°, L11	B_o
10	DEMBM, 2-D(φ, λ)	3-D, 3.6°×1.8°, L 19	
11	DEMBM, 2-D(φ, λ)/atmospheric chemistry	2-D(φ, z), 2 basins	B_o, B_T, B_V

Claussen et al (2002)

MIT Integrated Global System Model (IGSM2)



Sokolov et al. (2005, JP-Report 124)

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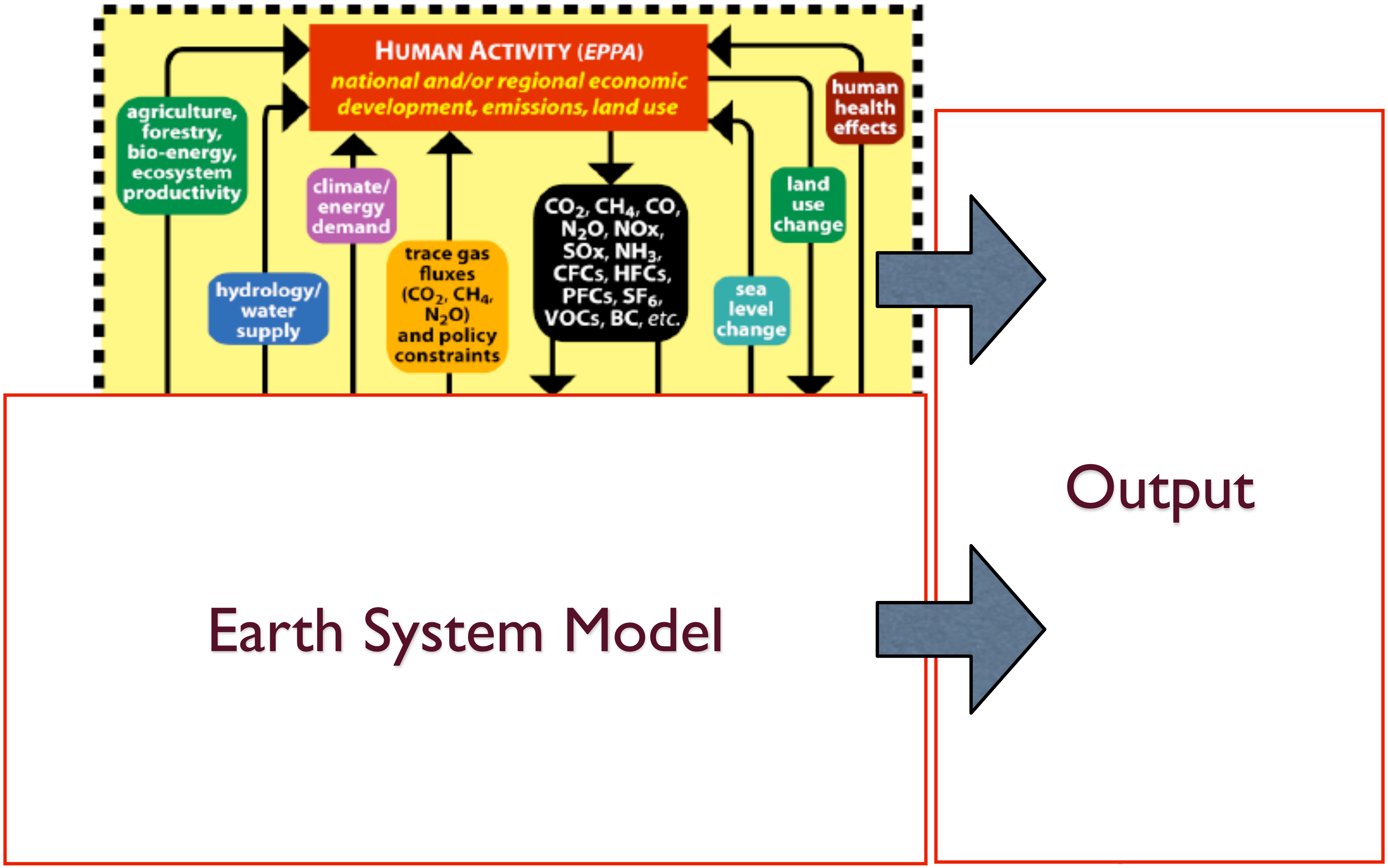

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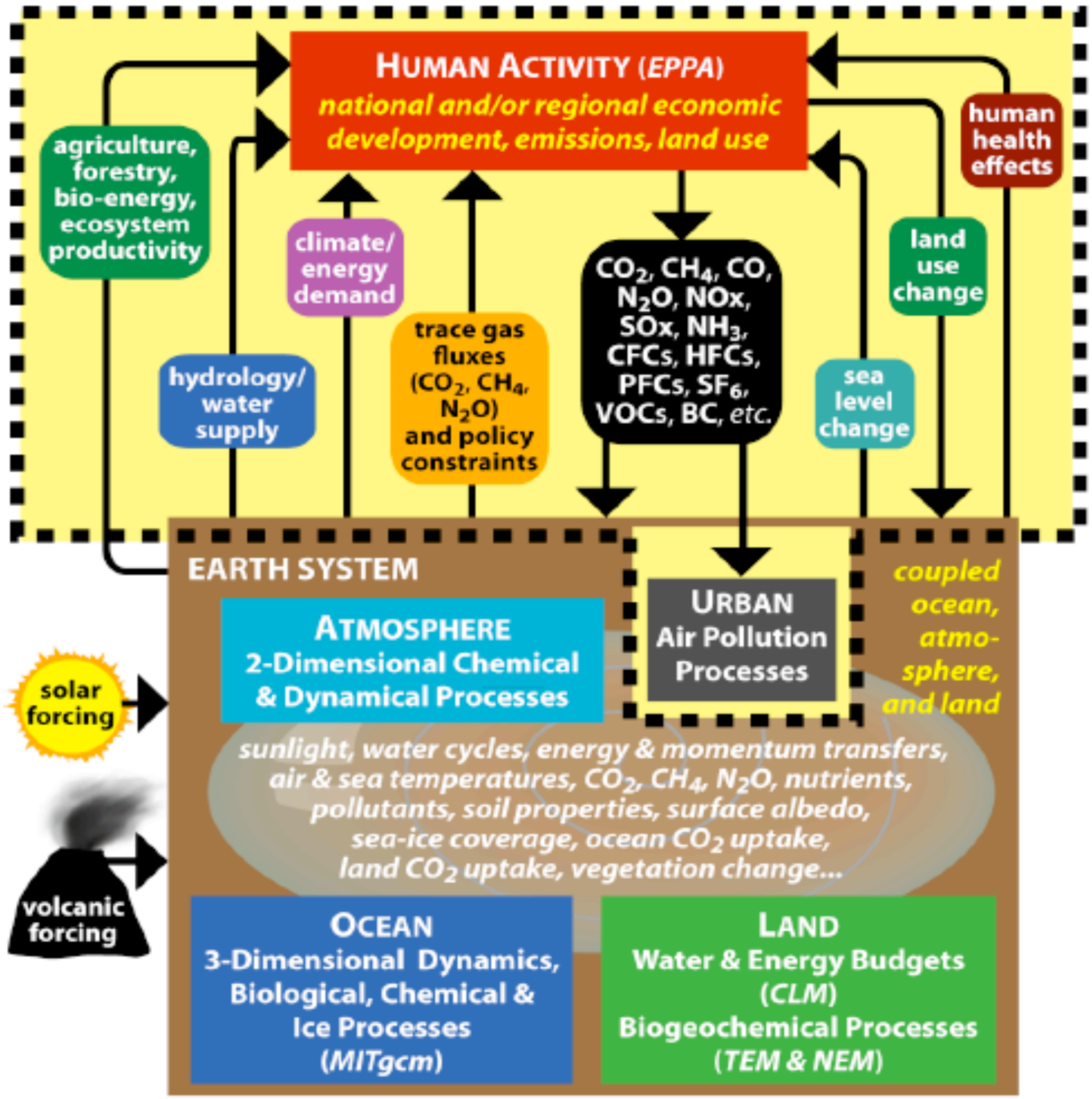

Output

Sokolov et al. (2005, JP-Report 124)

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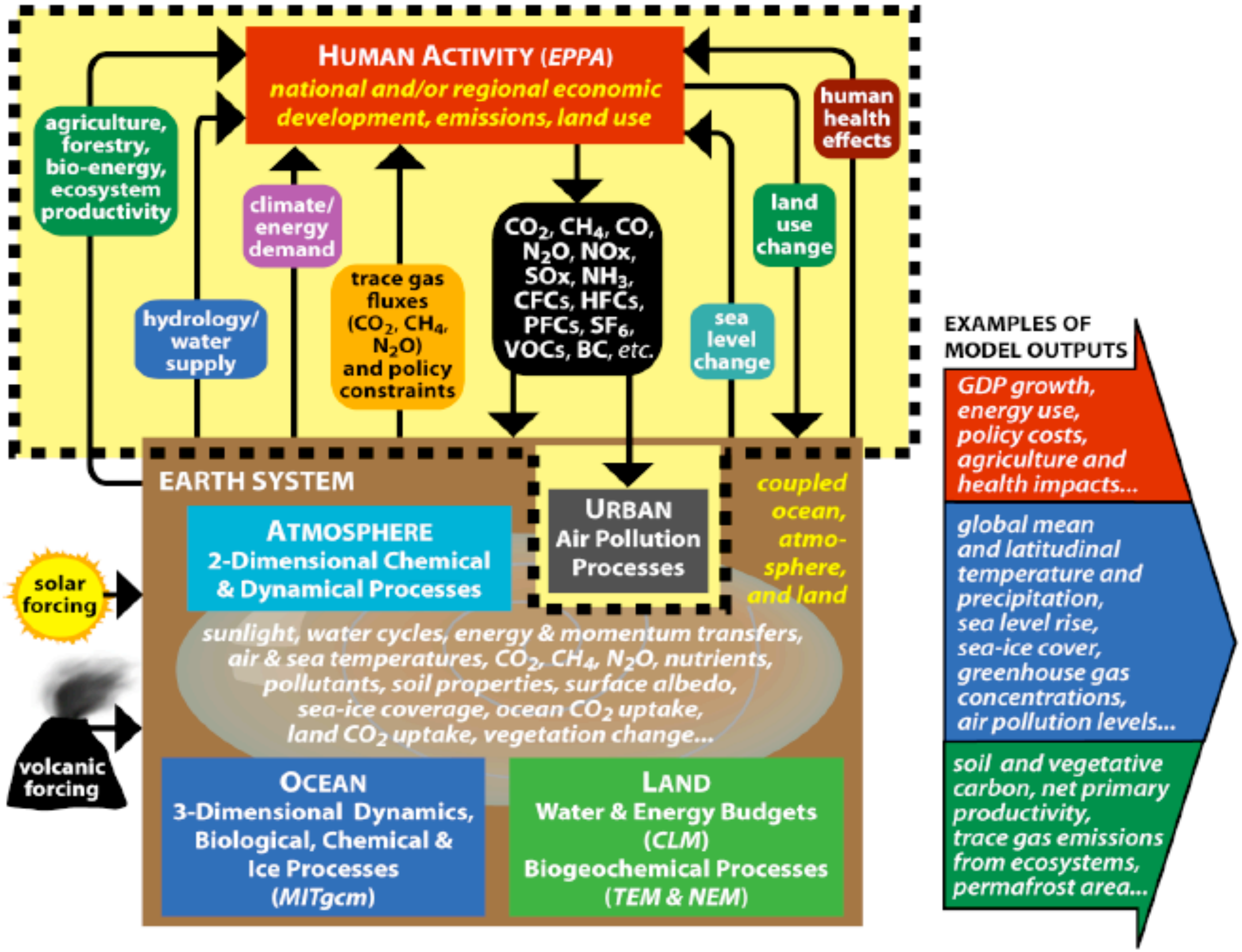


Sokolov et al. (2005, JP-Report 124)

MIT IGSM Overview

- Atmospheric Model (latitude-height)
  - Statistical Dynamic Model
  - Physical and Chemical Model
- Ocean/Sea Ice Model (2D or 3D)
  - Physical, Biogeochemical, Biological Models
- Land Model
  - Physical, Biological, Biogeochemical
  - Terrestrial Ecosystem Model (Melillo et al.)
- MIT EPPA - Economic Model

GISS Model II (8x10 grid)
(basis for MIT IGSM Climate Model)

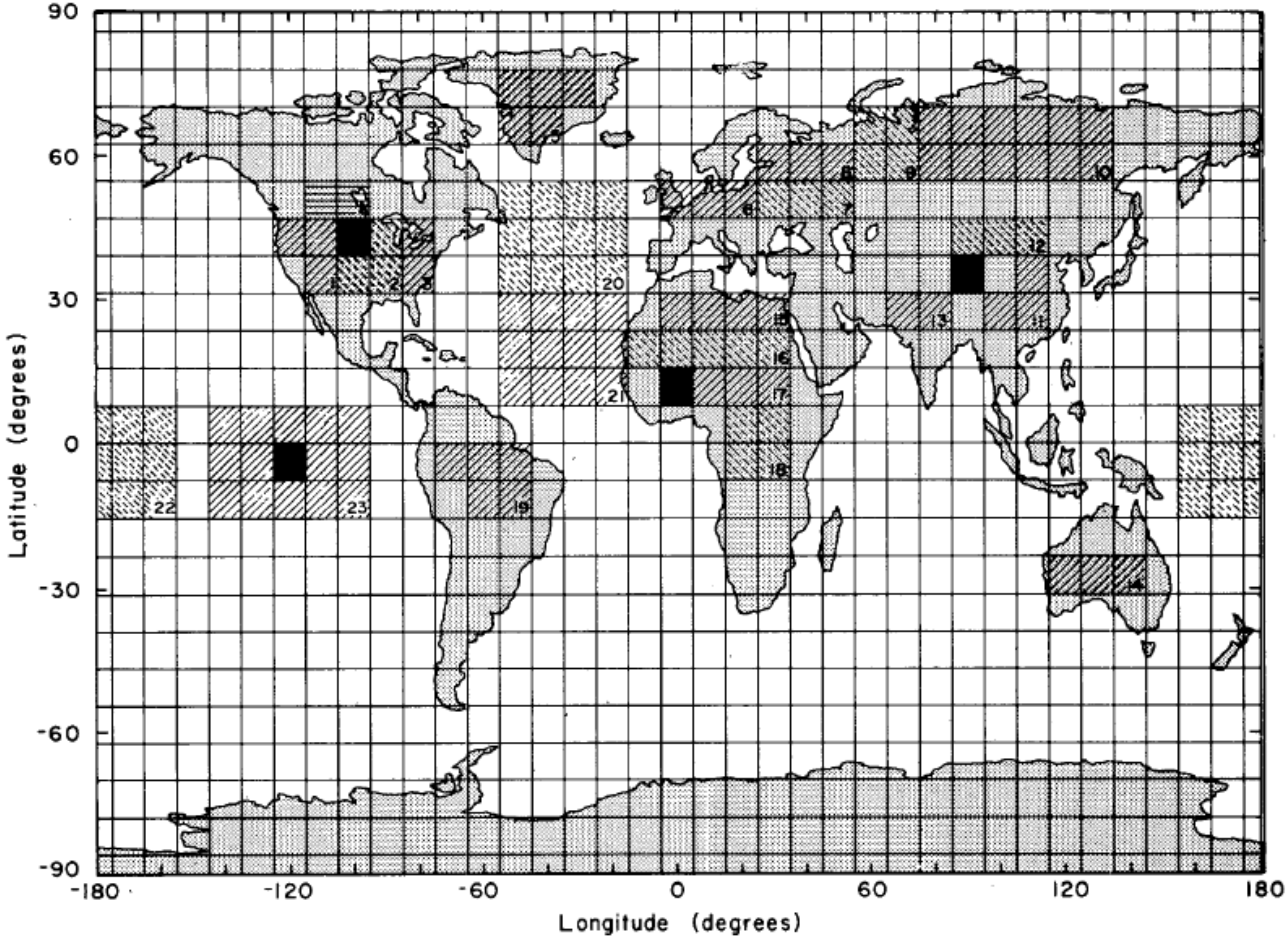


FIG. 1. Grid spacing for 8° × 10° model. Shadings indicate one choice of regions for special monthly diagnostics. The four black regions are a particular choice of gridboxes for hourly diagnostics.

Hansen et al. (1983)

IGSM Pressure Levels (9 levels)

Number of boxes:
24x36x9 = 7776

Current models:
~10^7

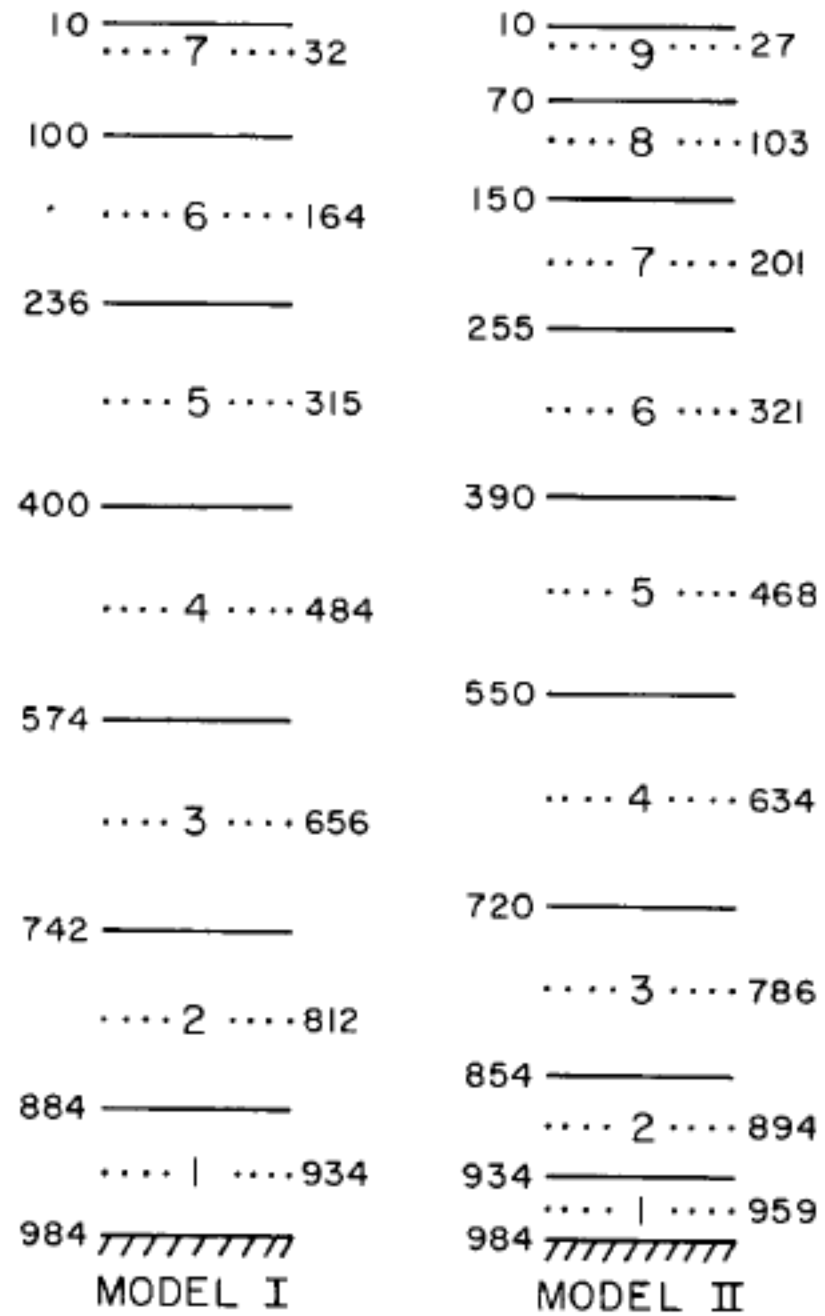


FIG. 2. Global-mean pressure levels (mb) for 7-layer Model I and 9-layer Model II. Layer edges are solid lines, and interior levels are dotted.

Hansen et al. (1983)

GISS/IGSM Model Grid Box

Statistical Components of Model
- Clouds
- Precipitation

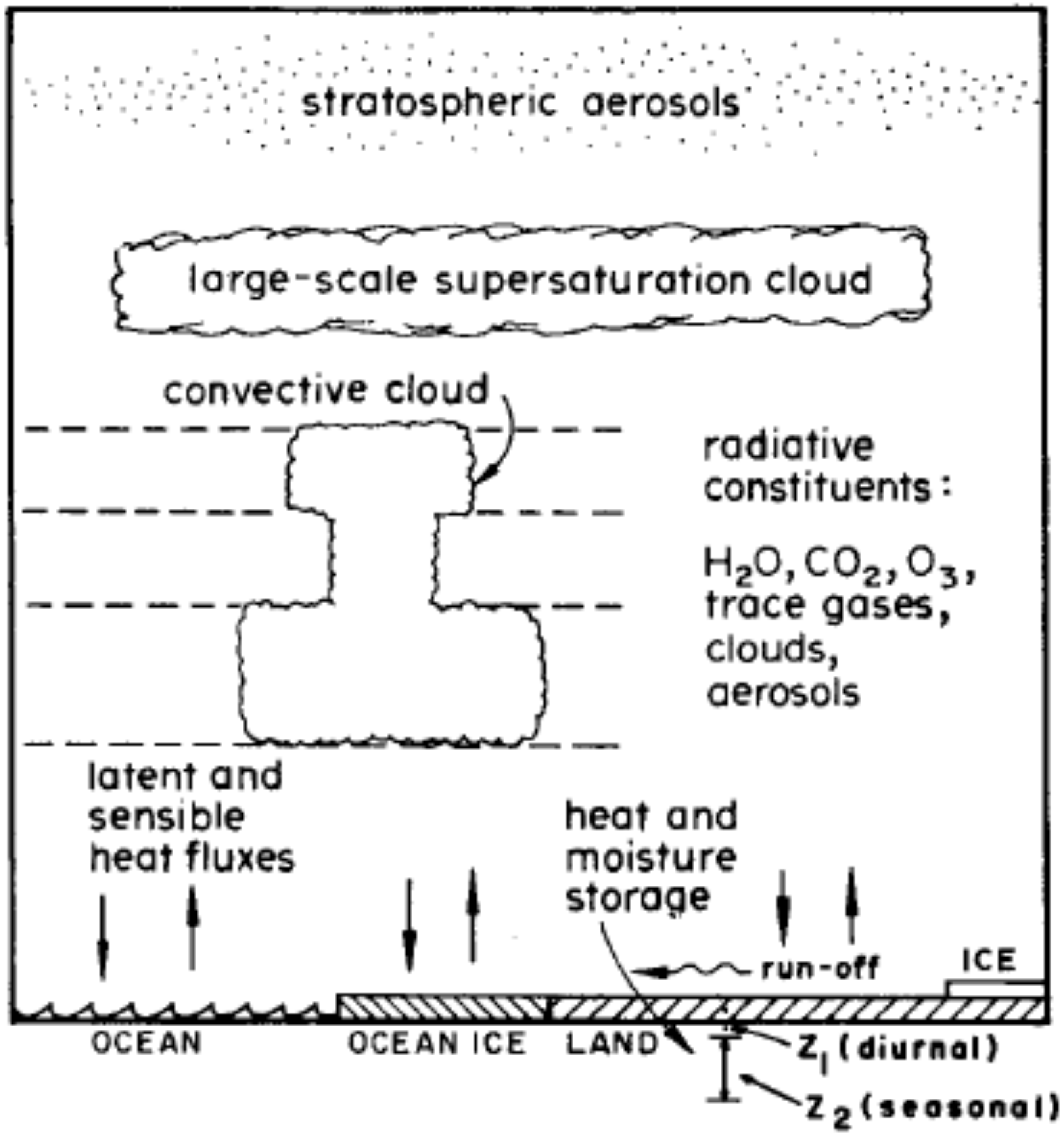


FIG. 3. Schematic illustration of model structure at a single gridbox.

Hansen et al. (1983)

GISS Model Equations (needed to include eddy fluxes)

TABLE 2. Approximate form of fundamental equations employed in computations.

Equation	Dependent variable	Equation
$\frac{\partial \pi \mathbf{U}}{\partial t} = -\nabla \cdot \pi \mathbf{U}\mathbf{U} - \frac{\partial \pi \dot{\sigma} \mathbf{U}}{\partial \sigma} - \left(f + \frac{\tan\phi}{a} u\right)\mathbf{k} \times \pi \mathbf{U} - \pi \nabla \Phi - \frac{\sigma \pi}{\rho} \nabla \pi + \pi \mathbf{F}_\sigma$	$\mathbf{U}$	(T5)
$\frac{\partial \pi}{\partial t} = -\nabla \cdot \pi \mathbf{U} - \frac{\partial \pi \dot{\sigma}}{\partial \sigma}$	π, $\dot{\sigma}$	(T6)
$\frac{\partial \pi \Theta}{\partial t} = -\nabla \cdot \pi \mathbf{U} \Theta - \frac{\partial \pi \dot{\sigma} \Theta}{\partial \sigma} + \frac{\pi \Theta}{c_p T} Q$	Θ	(T7)
$\frac{\partial \pi q}{\partial t} = -\nabla \cdot \pi \mathbf{U} q - \frac{\partial \pi \dot{\sigma} q}{\partial \sigma} + \pi(E - C)$	q	(T8)
$\frac{\partial \Phi}{\partial \sigma} = -\frac{\pi}{\rho}$	Φ	(T9)
$p = \rho R T$	ρ	(T4)

Additional notation

$\mathbf{U}$	horizontal velocity in σ coordinates, with components (u, v)
$\nabla \cdot \pi \mathbf{U}\mathbf{U}$	vector with components $[\nabla \cdot (\pi \mathbf{U} u), \nabla \cdot (\pi \mathbf{U} v)]$
$\nabla \cdot A\mathbf{U}$	horizontal divergence $\left[= \frac{1}{a \cos\phi}\left(\frac{\partial A u}{\partial \lambda} + \frac{\partial A v \cos\phi}{\partial \phi}\right)\right]$
∇A	horizontal gradient $\left[= \frac{1}{a}\left(\frac{1}{\cos\phi}\frac{\partial A}{\partial \lambda}, \frac{\partial A}{\partial \phi}\right)\right]$
a	mean planetary radius
ϕ	latitude in radians
λ	longitude in radians
σ	vertical coordinate $[=(p - p_t)/\pi]$
E	rate of evaporation
$\dot{\sigma}$	$d\sigma/dt$
π	$p_s - p_t$, where p_s is the surface pressure and p_t the constant pressure at the model's upper boundary
Θ	potential temperature $[=T(p_{00}/p)^\kappa$, where $\kappa = R/c_p$ and $p_{00} = 1000$ mb]
Φ	geopotential [$=gz$, where z is height above sea level]
f	Coriolis parameter $[=2\Omega \sin\phi]$
c_p	specific heat at constant pressure
F_σ	horizontal frictional force
q	water vapor mixing ratio
C	rate of condensation.

Hansen et al. (1983)

Development of 2D MIT Model required Eddy Flux parameterization

Development of a Two-Dimensional Zonally Averaged Statistical–Dynamical Model. Part I: The Parameterization of Moist Convection and its Role in the General Circulation

Development of a Two-Dimensional Zonally Averaged Statistical–Dynamical Model. Part II: The Role of Eddy Momentum Fluxes in the General Circulation and their Parameterization

Development of a Two-Dimensional Zonally Averaged Statistical–Dynamical Model. Part III: The Parameterization of the Eddy Fluxes of Heat and Moisture

PETER H. STONE

Center for Meteorology and Physical Oceanography, Massachusetts Institute of Technology, Cambridge, Massachusetts and NASA/Goddard Space Flight Center, Institute for Space Studies, New York, New York

MAO-SUNG YAO

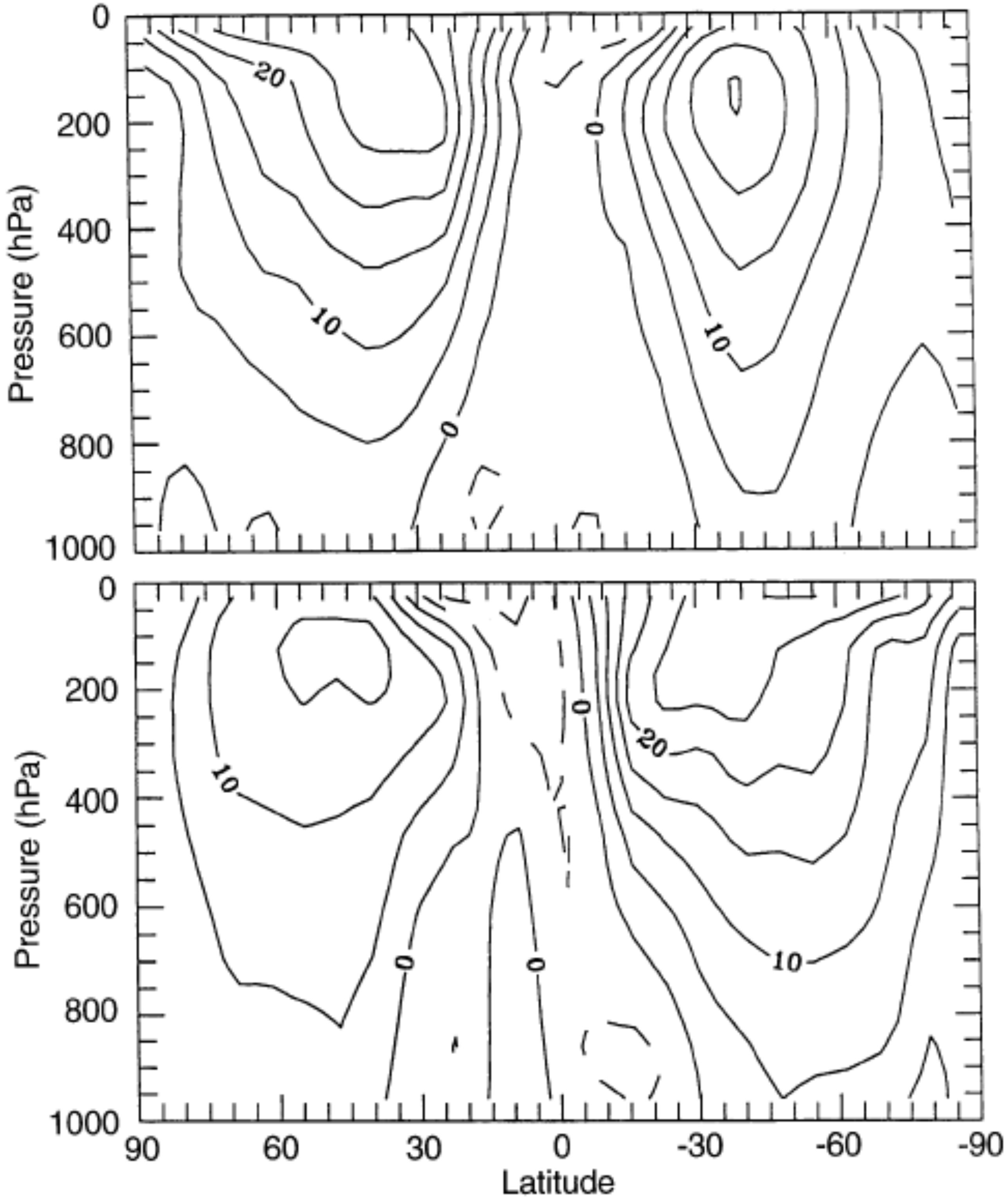
Centel Federal Services Corporation, NASA/Goddard Space Flight Center, Institute for Space Studies, New York, New York

(Manuscript received 25 May 1989, in final form 16 November 1989)

MIT 2D Climate Model Description

- 2D statistical-dynamical atmospheric model derived from 3D GISS II AGCM (Sokolov and Stone, 1998) 46x11 (lat-height)
- Q-flux mixed layer ocean model where temperature anomalies are mixed into deep-ocean. Q-flux held fixed in transient runs.
- Adjustable model properties:
  - Climate Sensitivity (via adjustable cloud feedback)
  - Rate of deep-ocean heat uptake (via diffusivity)
  - Net Aerosol Forcing (via scattering cross-section or loading)

Wind fields from IGSM (Sokolov & Stone, 1998)



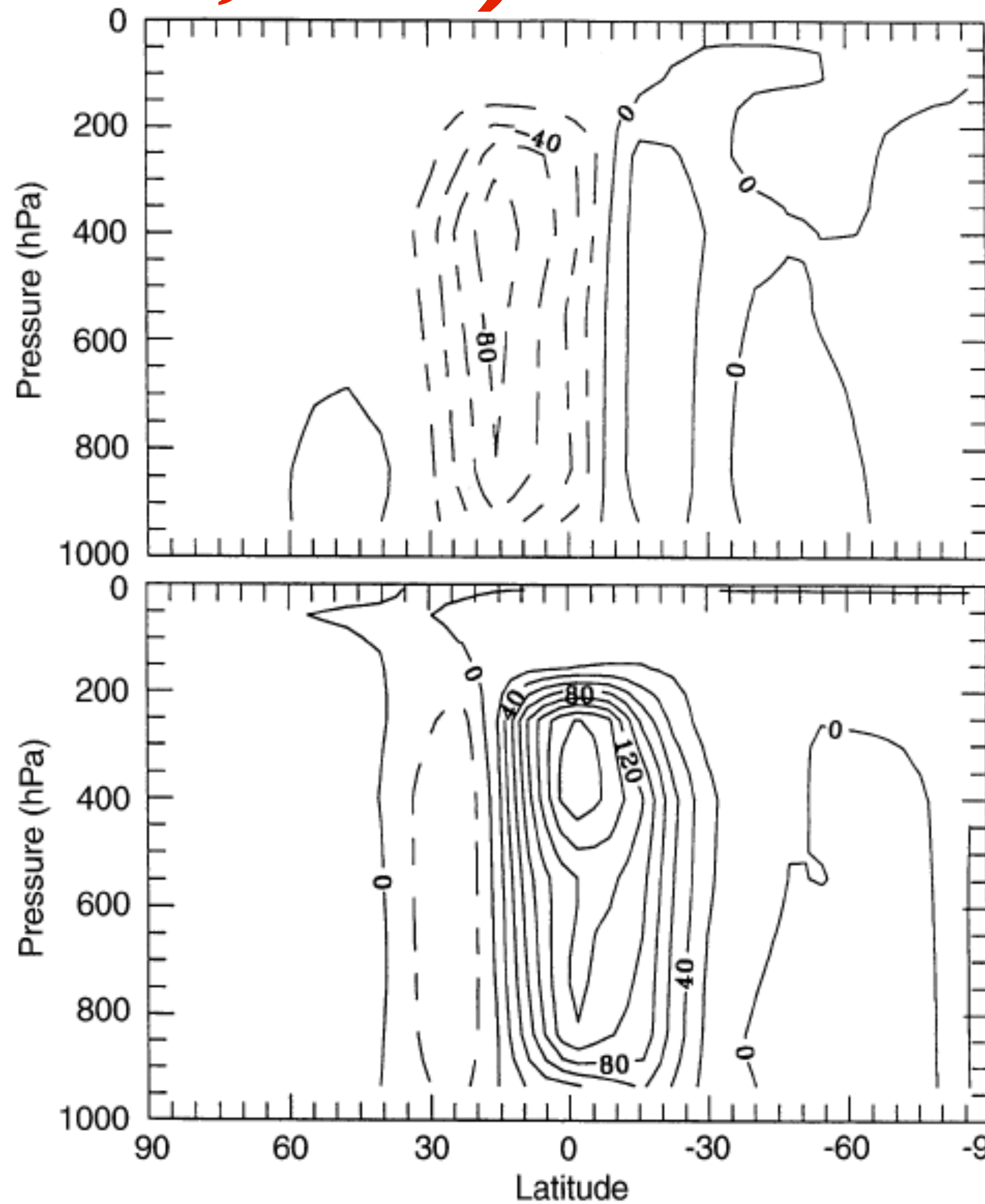


Fig. 1 Height-latitude cross section of zonal wind for DJF (*top*) and JJA (*bottom*) from the MIT 2-D model

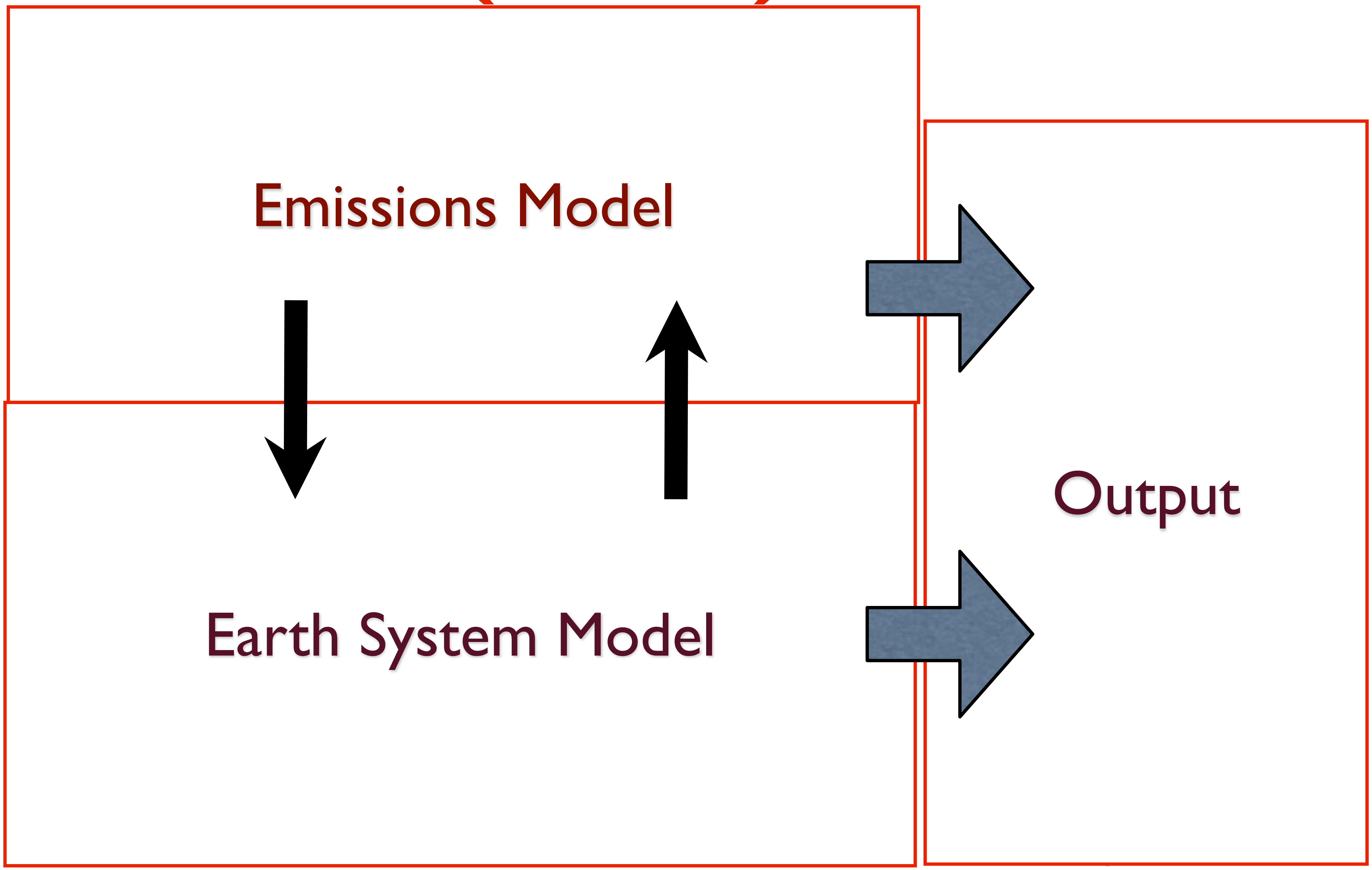
Fig. 2 As Fig. 1, but for meridional streamfunction

LUNCH BREAK

POST LUNCH BREAK

- Using the IGSM
  - Uncertainty Analysis
  - Parameter/Property Estimation
  - Climate Model Evaluations
  - Scenario Analyses
  - Feedbacks and Response

MIT Integrated Global System Model (IGSM2)



Sokolov et al. (2005, JP-Report 124)

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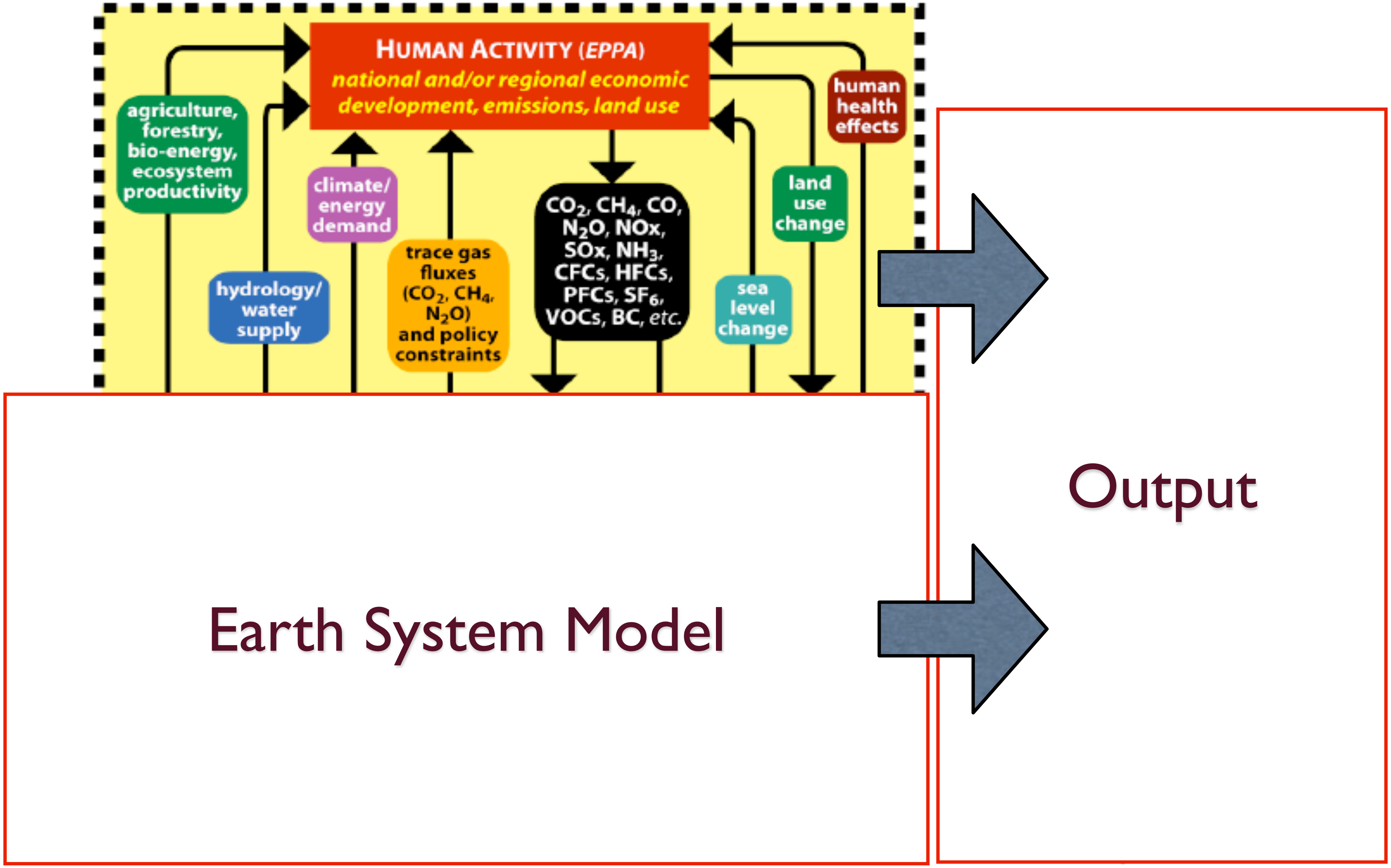

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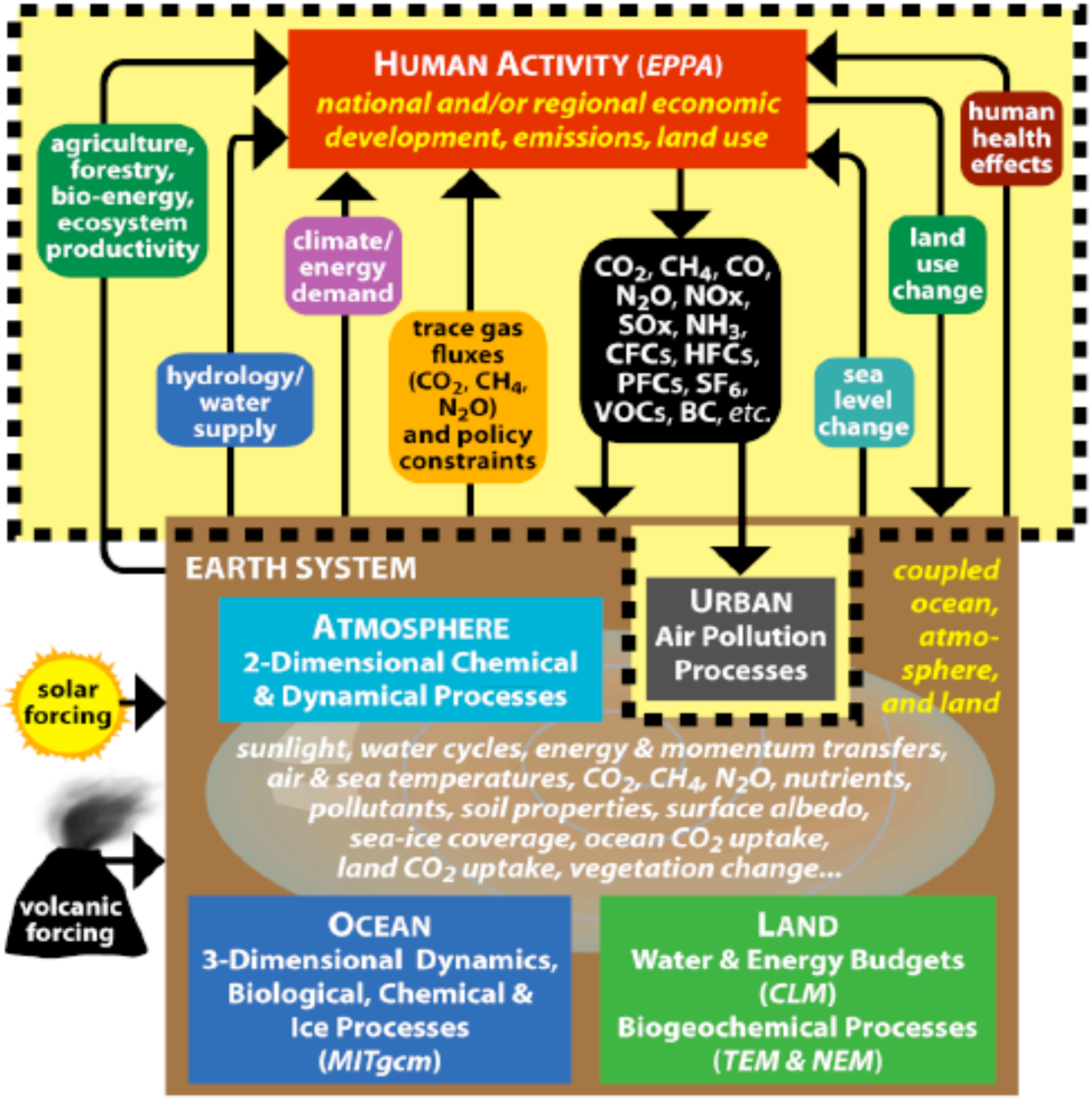

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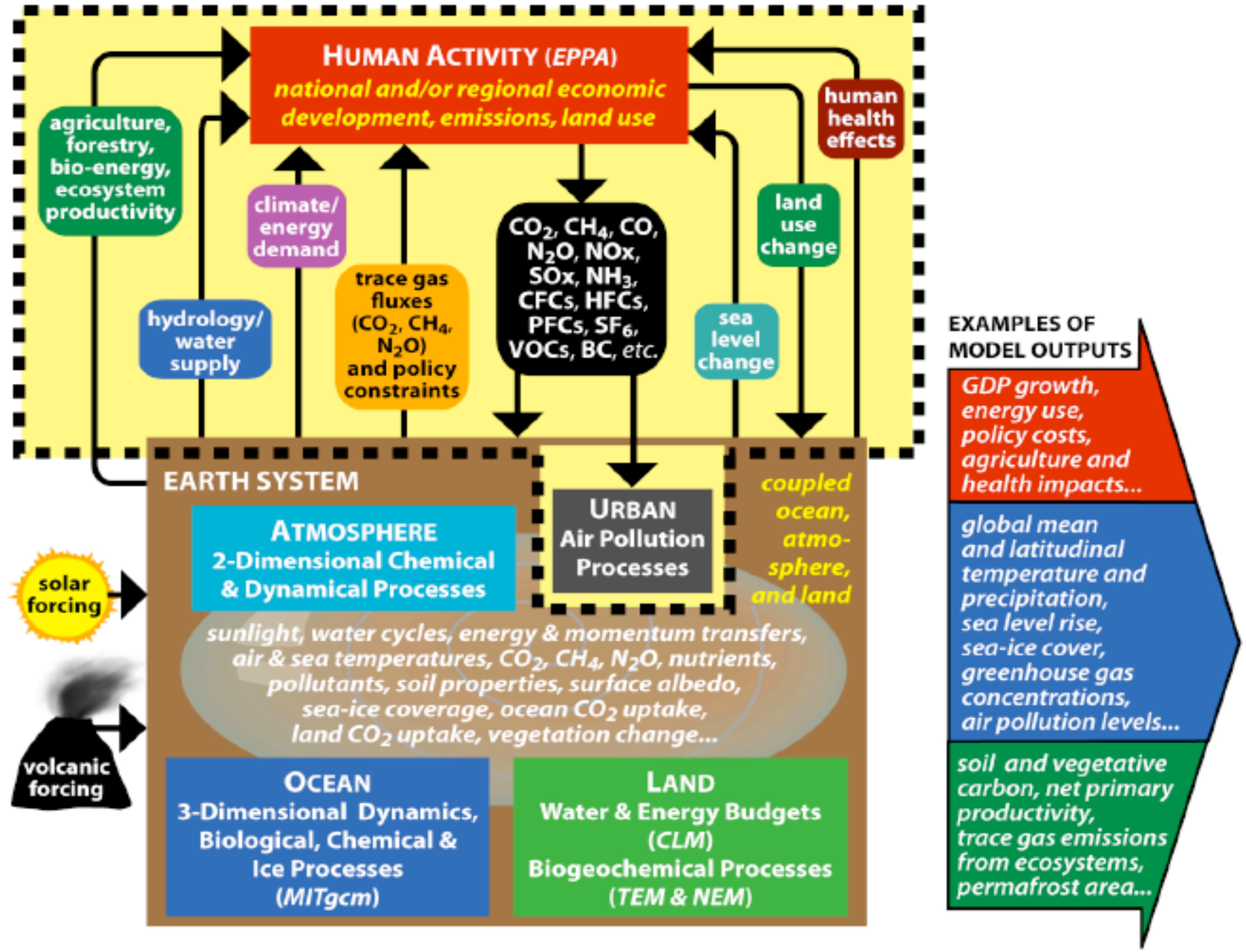
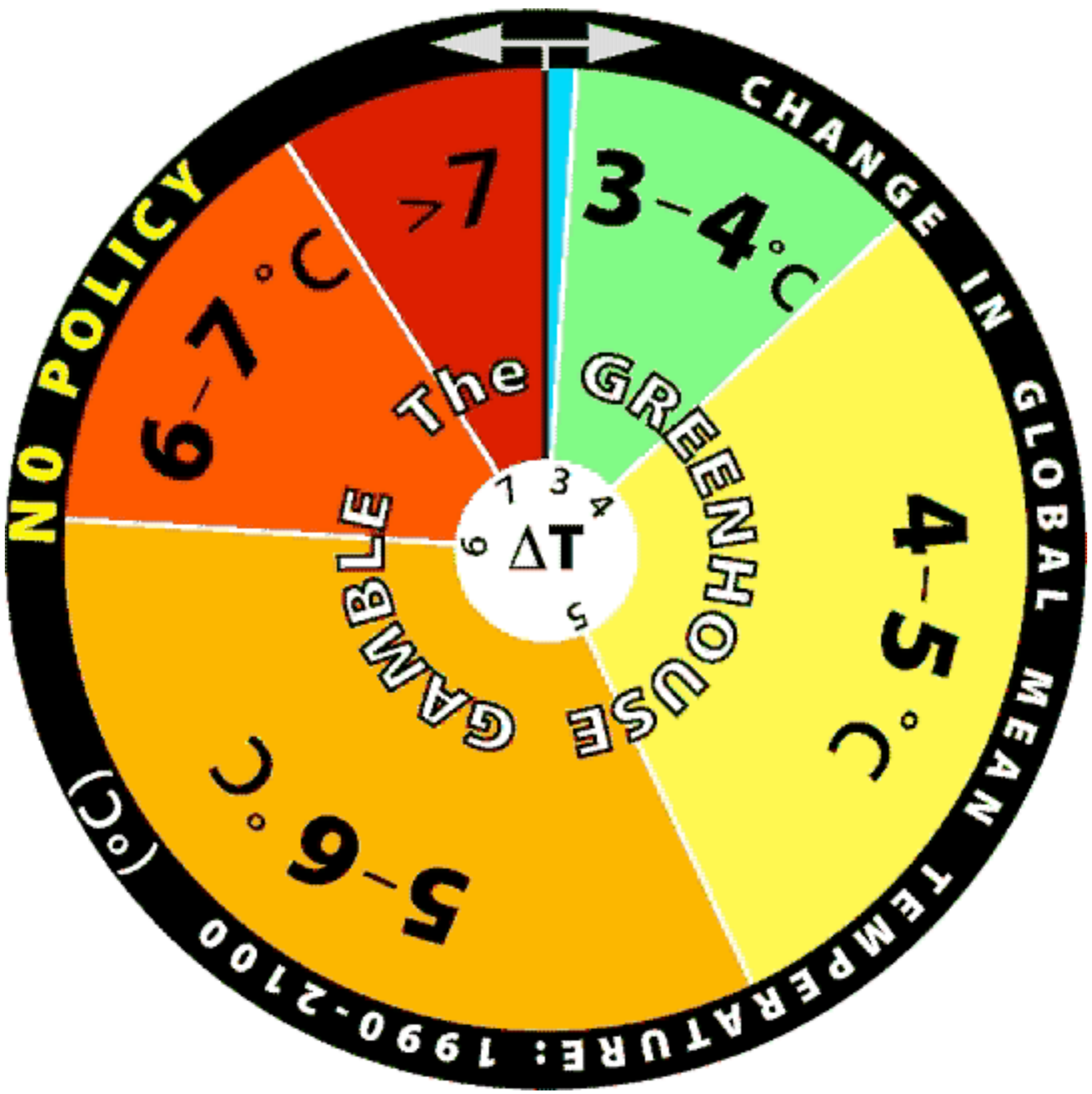
Sokolov et al. (2005, JP-Report 124)

MIT Integrated Global System Model (IGSM2)



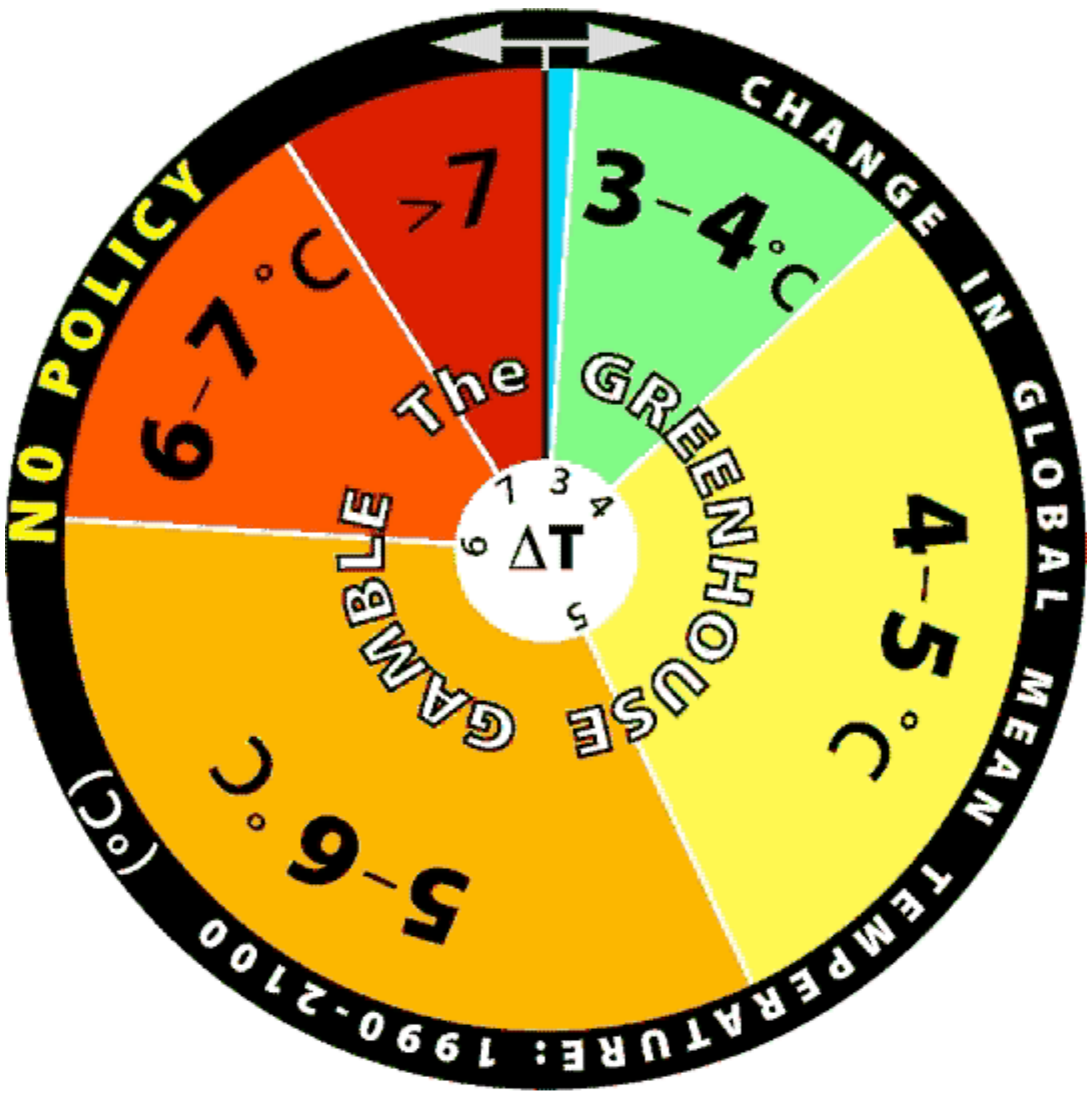
Sokolov et al. (2005, JP-Report 124)

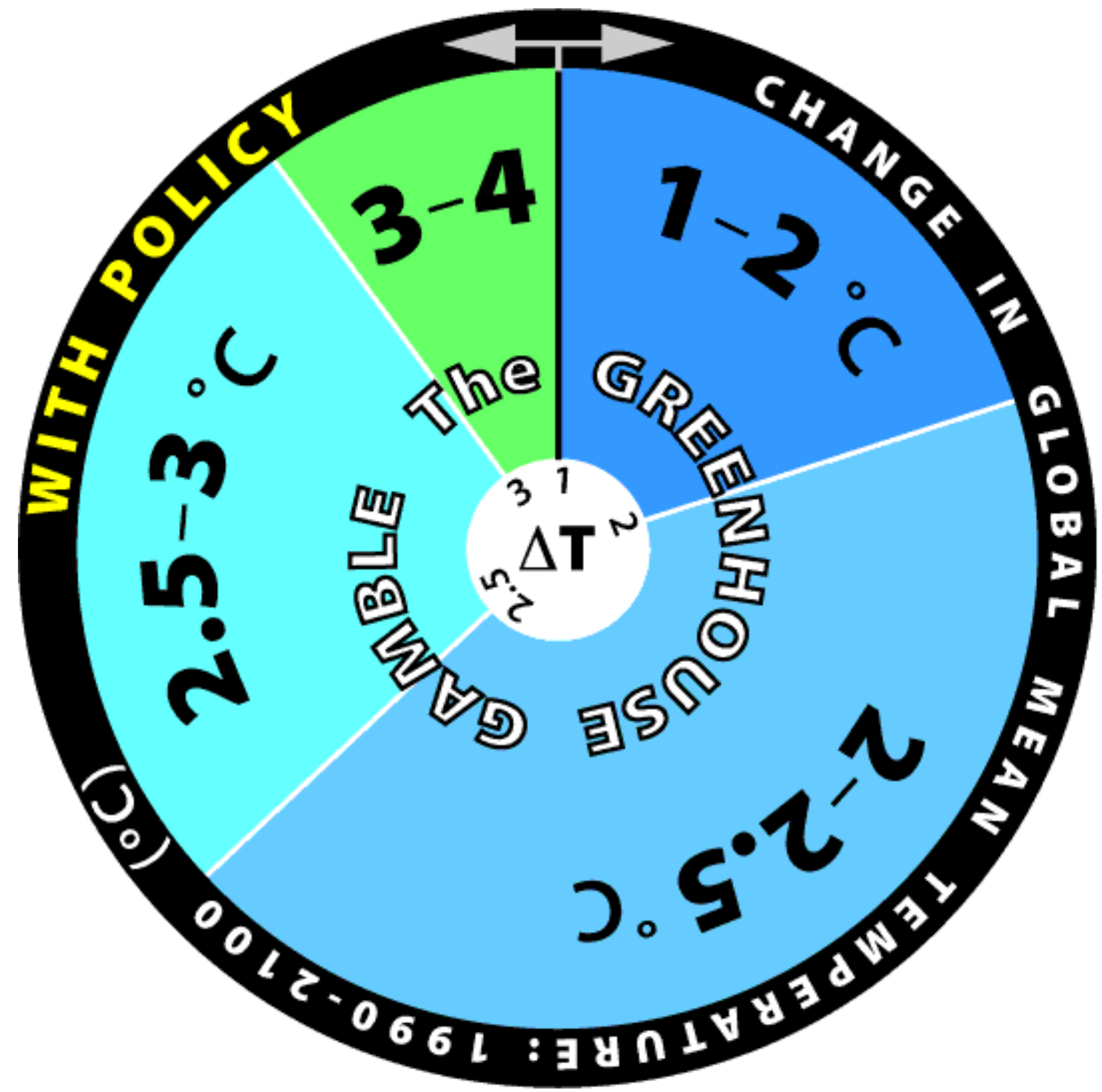
The Greenhouse Gamble



http://globalchange.mit.edu/resources/gamble/

The Greenhouse Gamble





http://globalchange.mit.edu/resources/gamble/

Major Climate Projection Uncertainties

Consider the energy balance equation for the global-mean surface temperature anomaly (ΔT):

$$c_p \frac{d\Delta T(t)}{dt} = F(t) - \lambda \Delta T(t) - \Phi_o(K_v)$$

Major Climate Projection Uncertainties

Consider the energy balance equation for the global-mean surface temperature anomaly (ΔT):

$$c_p \frac{d\Delta T(t)}{dt} = F(t) - \lambda \Delta T(t) - \Phi_o(K_v)$$

Change in global mean heat content

Major Climate Projection Uncertainties

Consider the energy balance equation for the global-mean surface temperature anomaly (*ΔT*):

$$c_p \frac{d\Delta T(t)}{dt} = F(t) - \lambda \Delta T(t) - \Phi_o(K_v)$$

Change in global mean heat content

Future Forcings

Major Climate Projection Uncertainties

Consider the energy balance equation for the global-mean surface temperature anomaly (ΔT):

$$c_p \frac{d\Delta T(t)}{dt} = F(t) - \lambda \Delta T(t) - \Phi_o(K_v)$$

Change in global mean heat content

Future Forcings

Net Feedbacks
$\lambda = 1/S$

Major Climate Projection Uncertainties

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Change in global mean heat content

Future Forcings

Net Feedbacks
$\lambda = 1/S$

Flux of heat into deep-ocean

Major Climate Projection Uncertainties

Consider the energy balance equation for the global-mean surface temperature anomaly (ΔT):

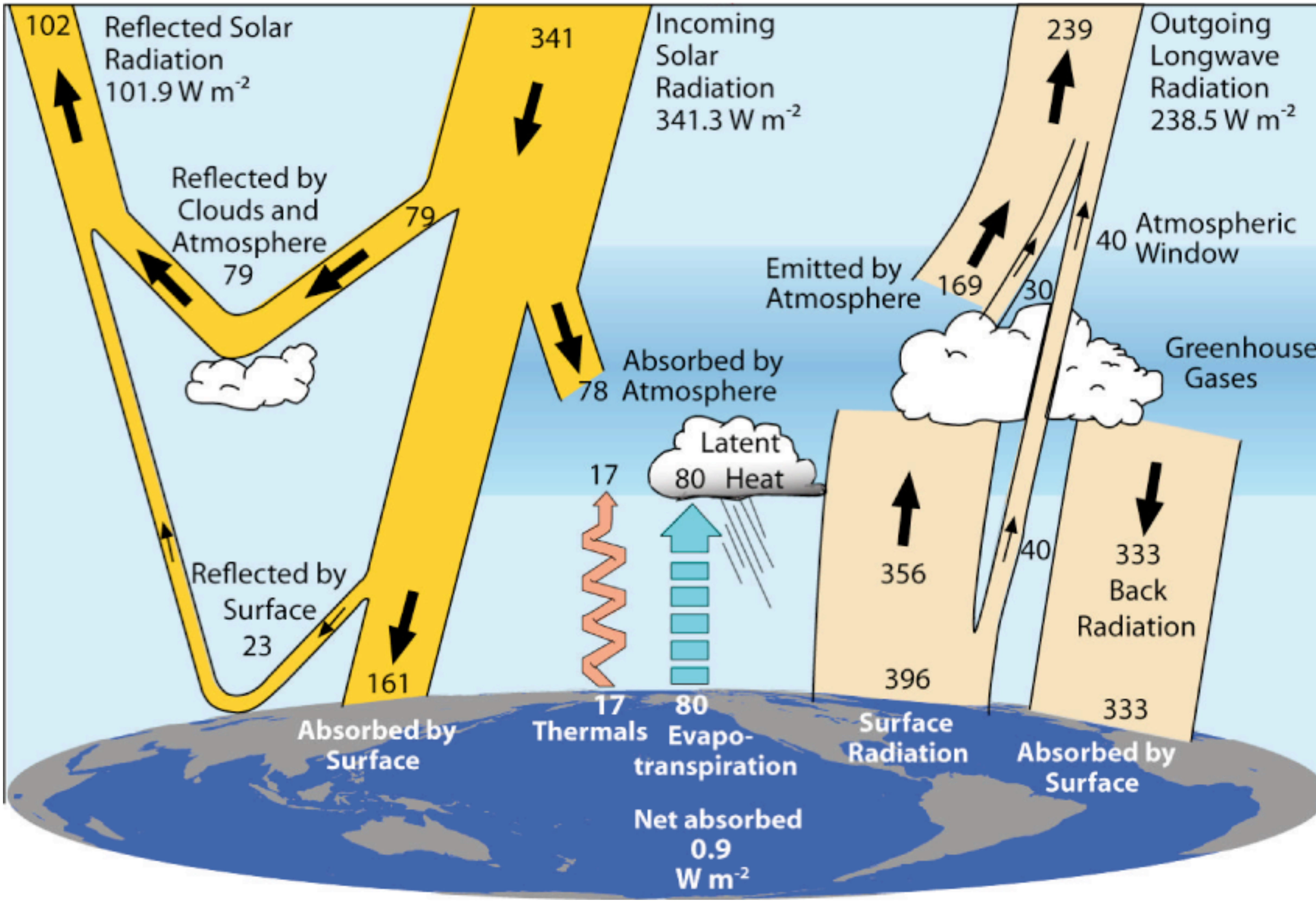
$$c_p \frac{d\Delta T(t)}{dt} = F(t) - \lambda \Delta T(t) - \Phi_o(K_v)$$

Change in global mean heat content	Future Forcings	Net Feedbacks $\lambda = 1/S$	Flux of heat into deep-ocean

Conceptually: This is a good framework for organizing where the uncertainty exists.

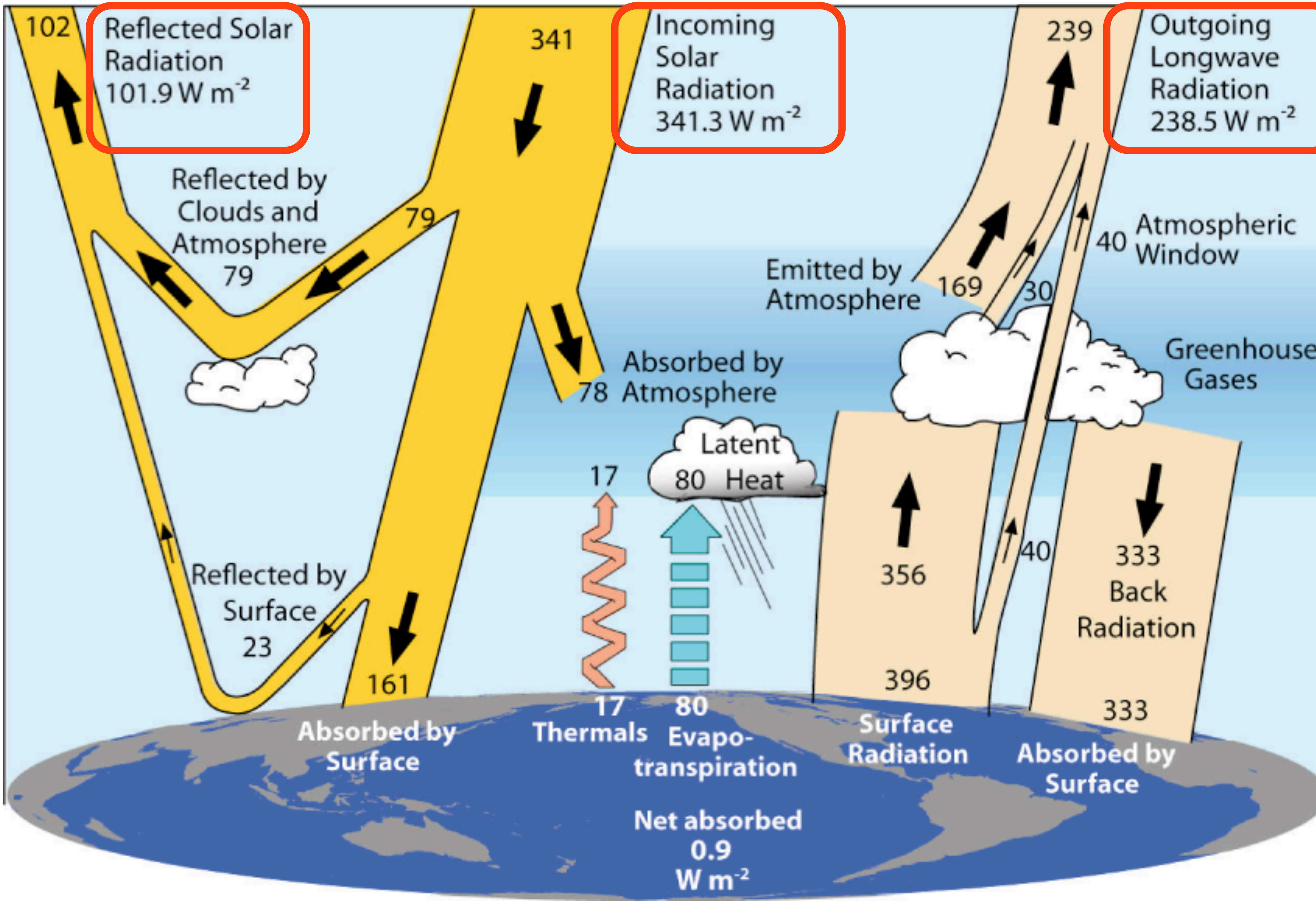
In practice: For state-of-the-art models, each uncertainty is an aggregate quantity and cannot be identified with any one specific model component or process.

Global Climate System Energy Fluxes



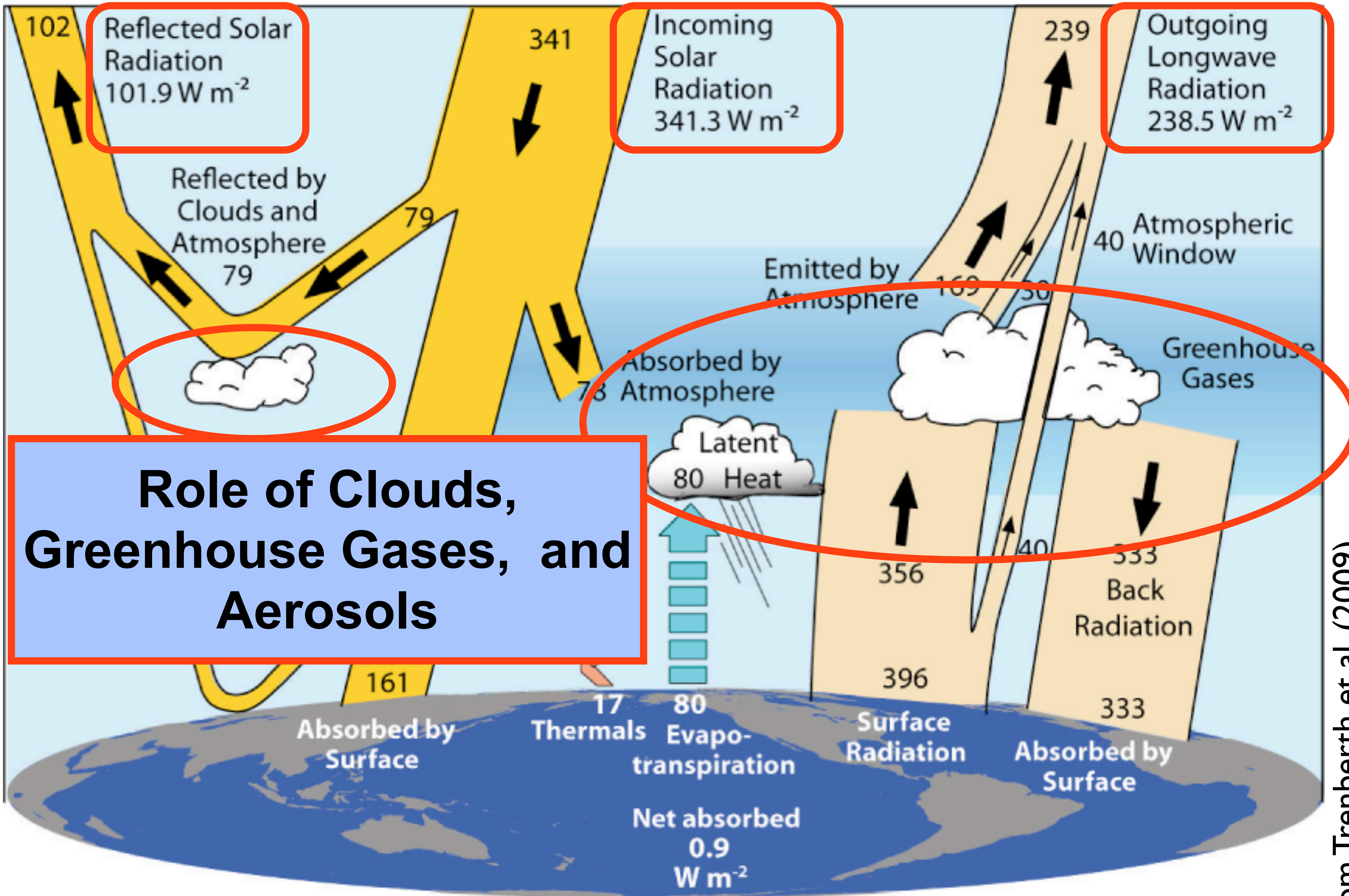
From Trenberth et al. (2009)

Global Climate System Energy Fluxes



From Trenberth et al. (2009)

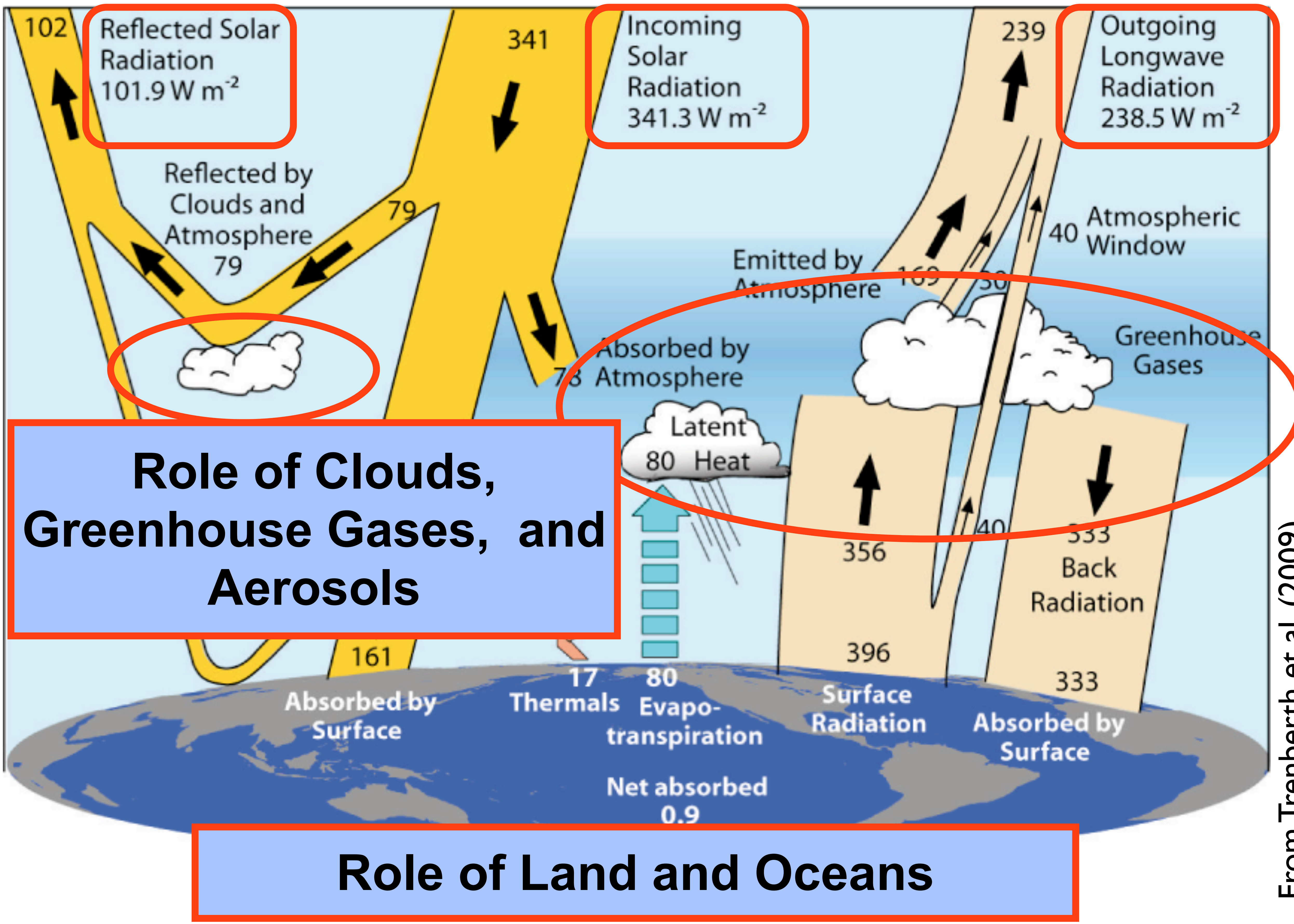
Global Climate System Energy Fluxes



Role of Clouds, Greenhouse Gases, and Aerosols

From Trenberth et al. (2009)

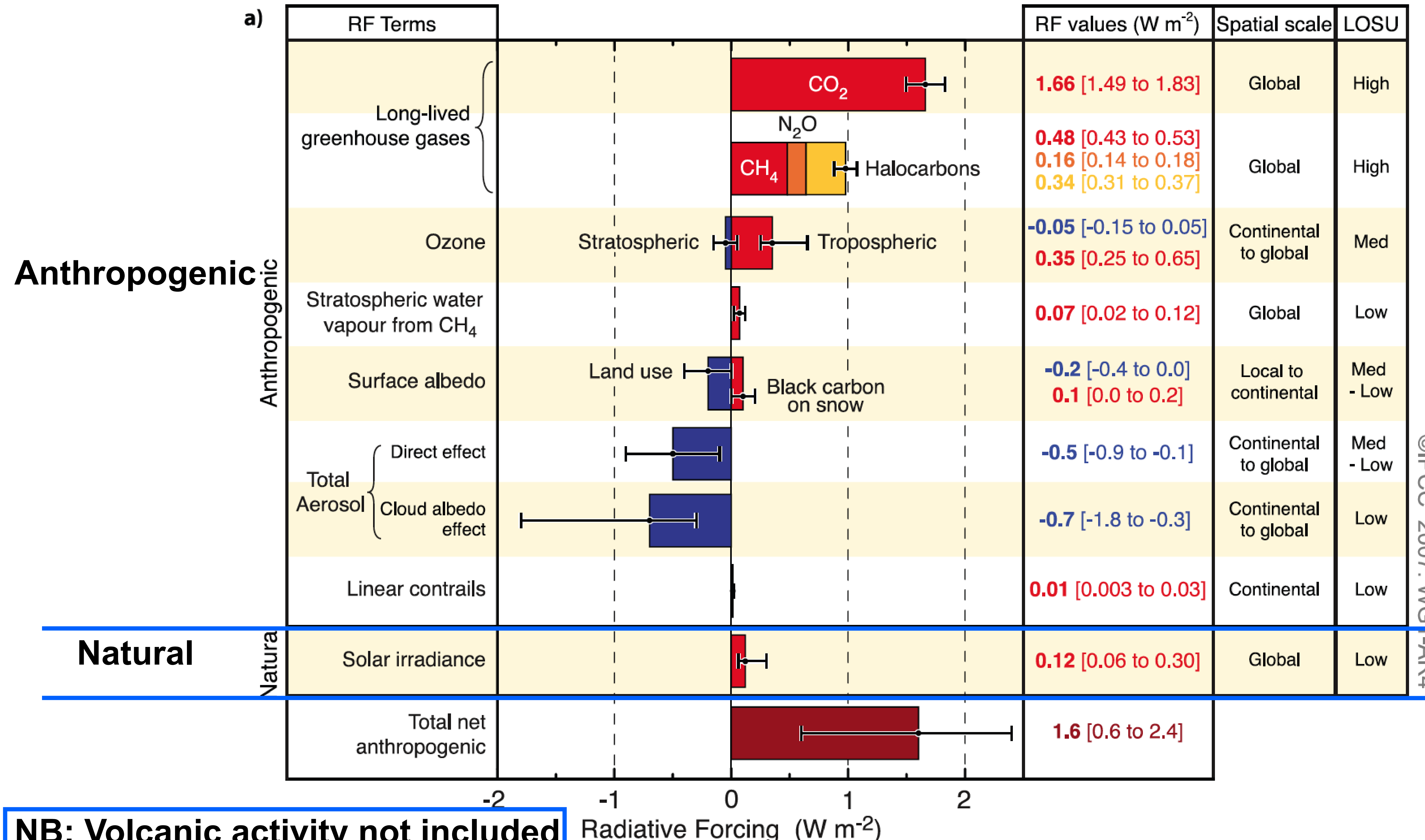
Global Climate System Energy Fluxes



From Trenberth et al. (2009)

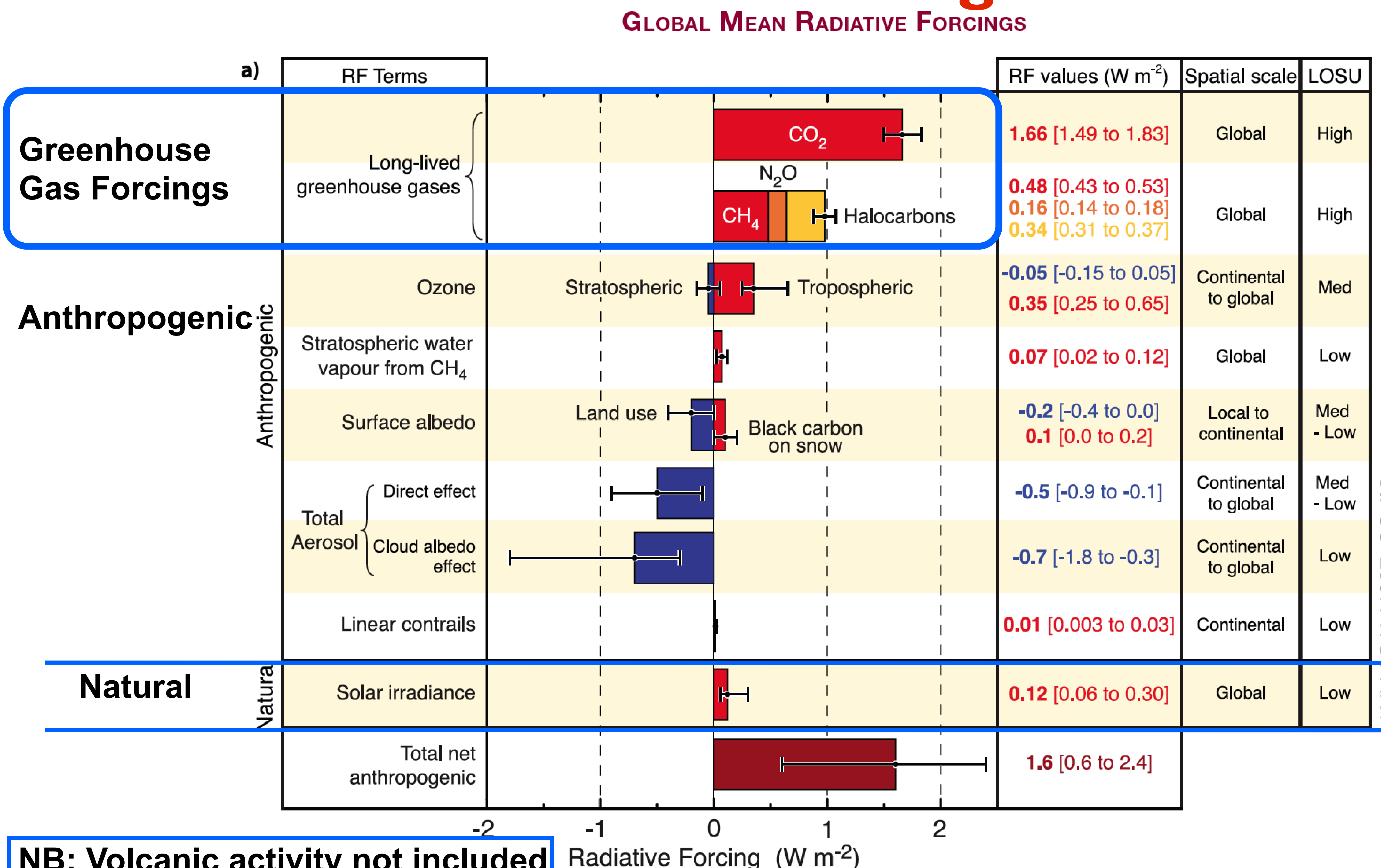
Historical Climate Forcing Factors

GLOBAL MEAN RADIATIVE FORCINGS



NB: Volcanic activity not included

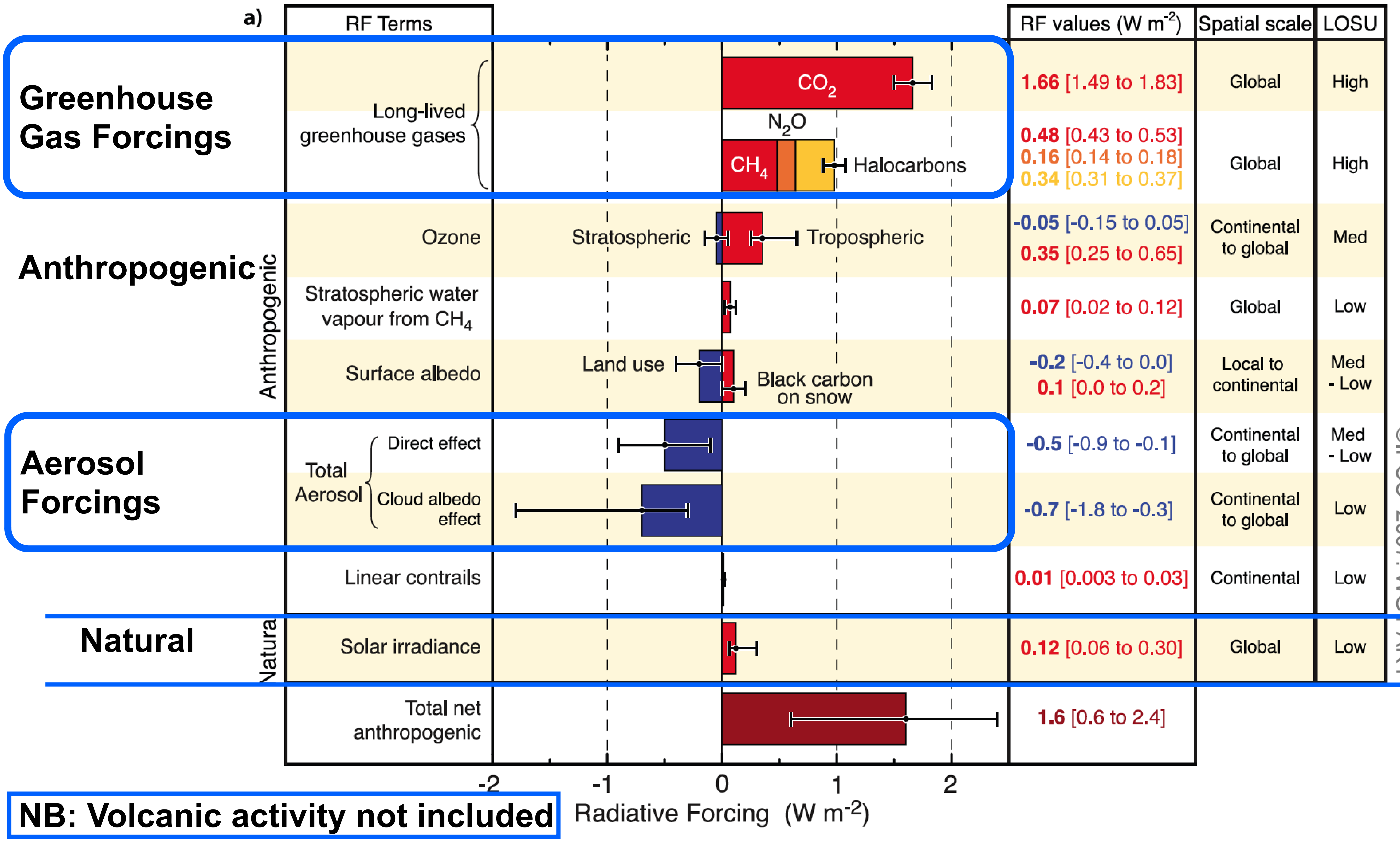
Historical Climate Forcing Factors



NB: Volcanic activity not included

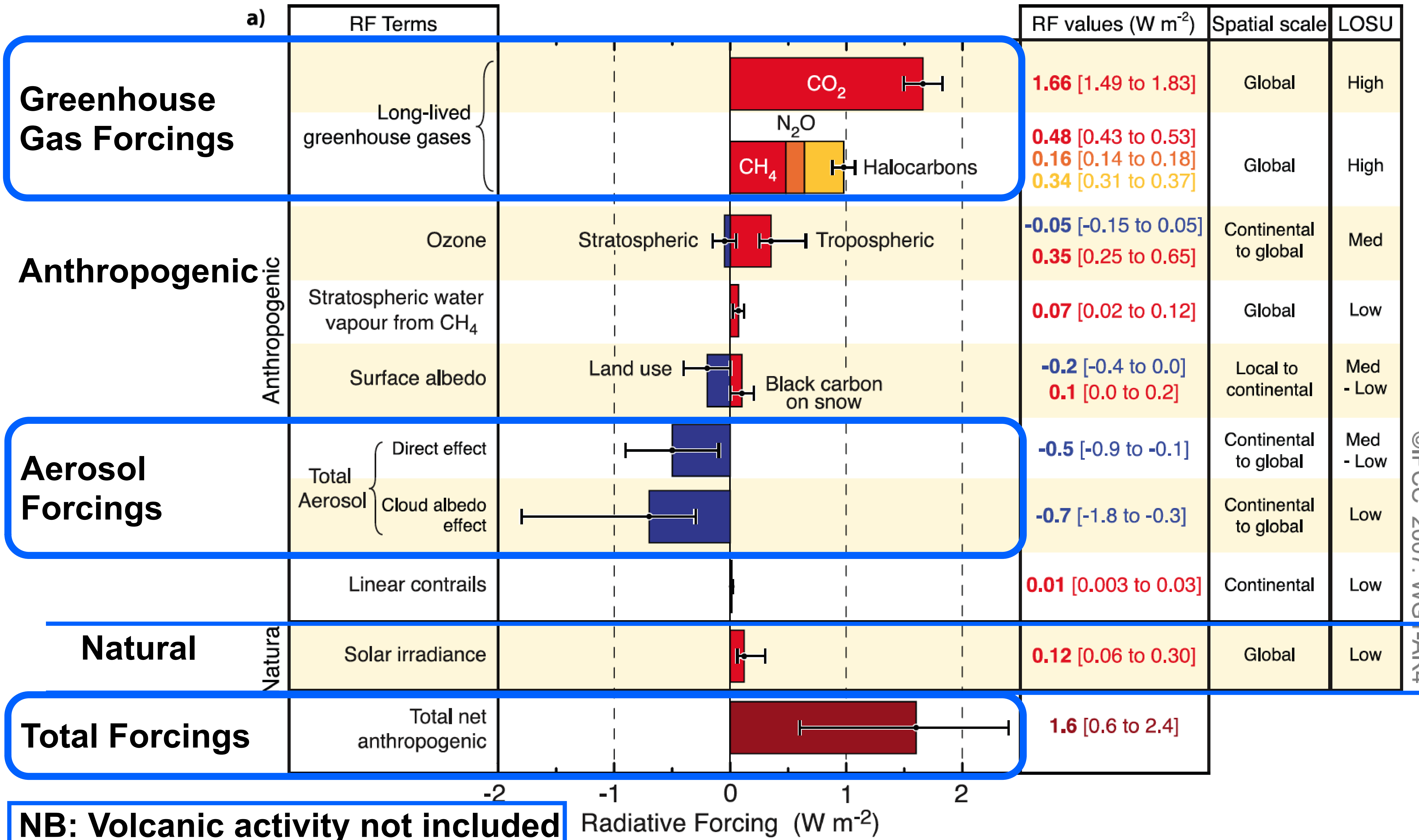
Historical Climate Forcing Factors

GLOBAL MEAN RADIATIVE FORCINGS



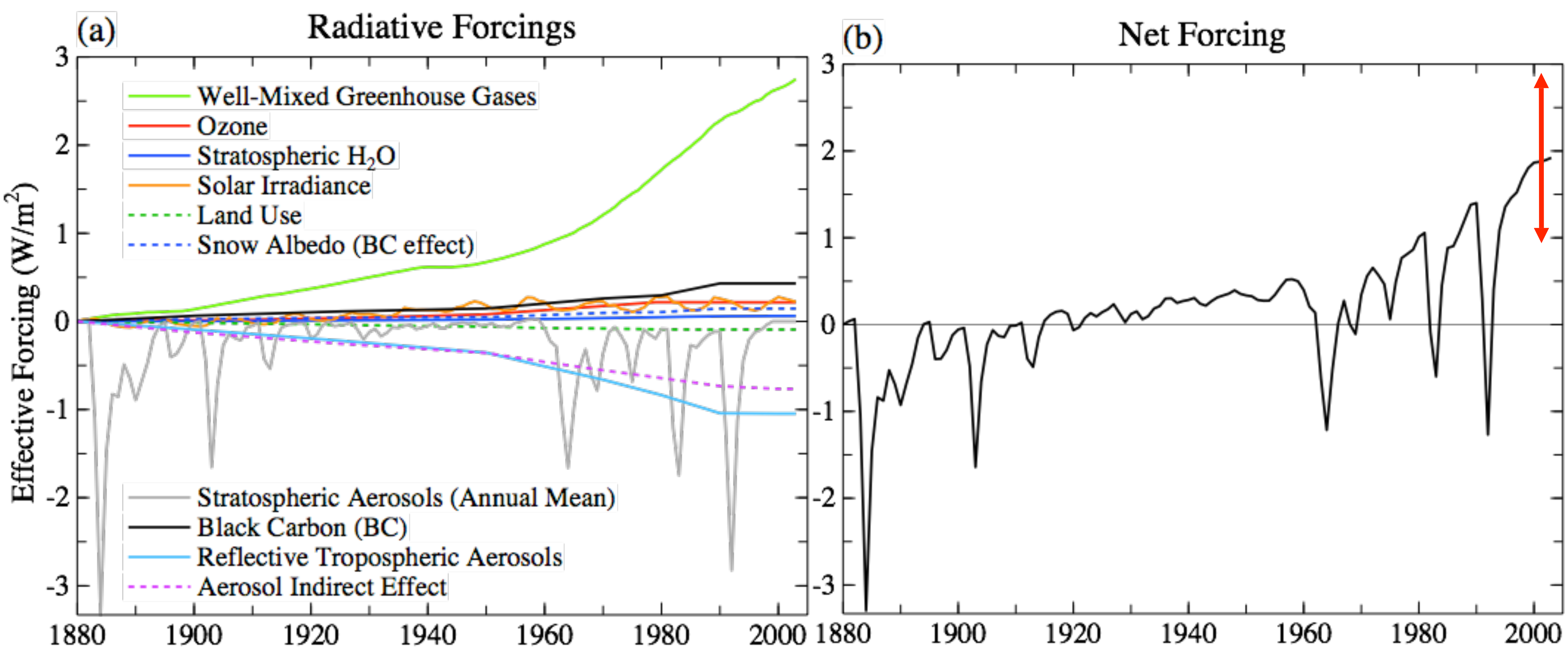
Historical Climate Forcing Factors

Global Mean Radiative Forcings



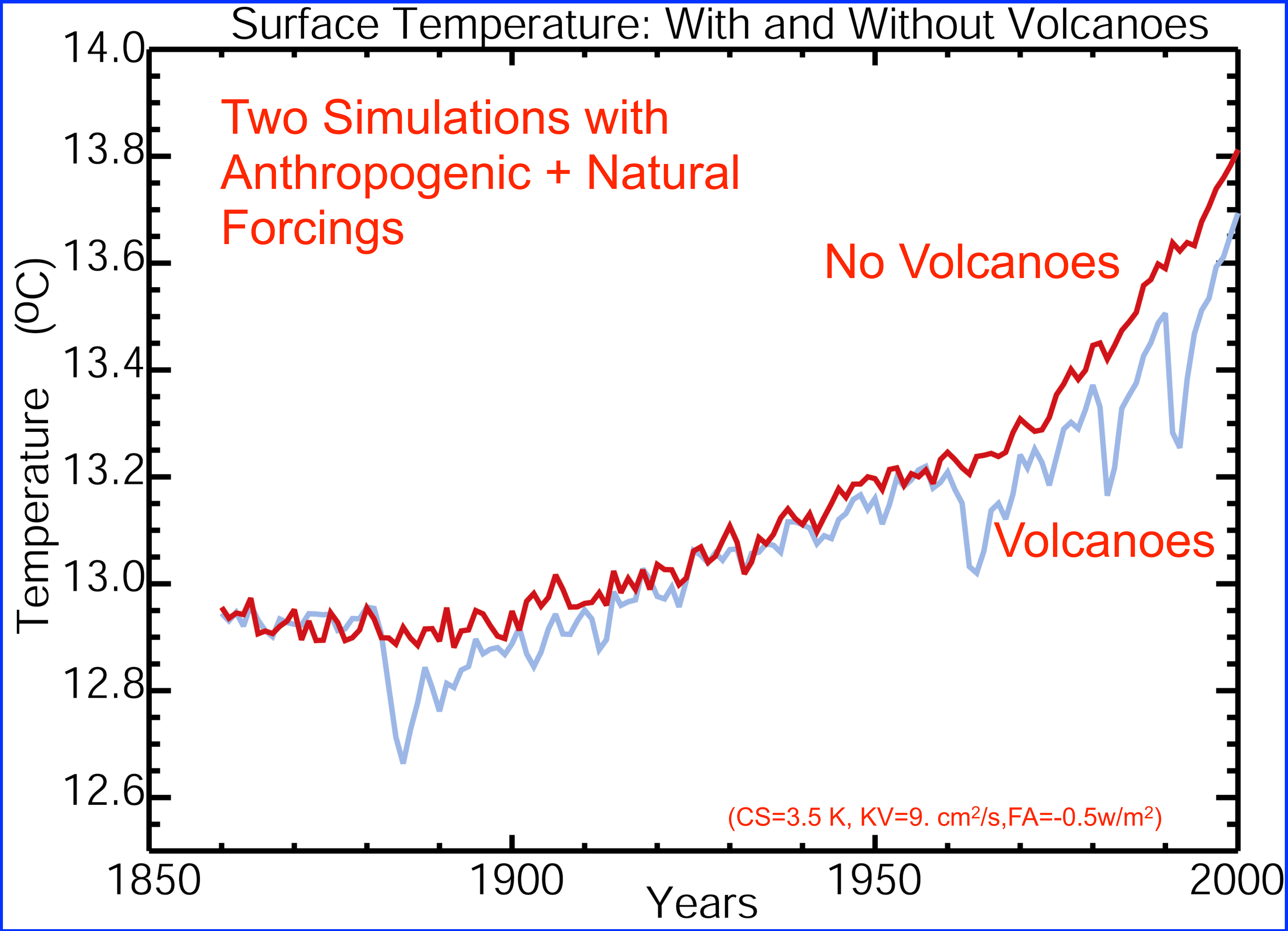
Historical Climate Forcing Factors

Estimated Time-series of Radiative Forcings
Total Uncertainty = +/- 1 W/m^2

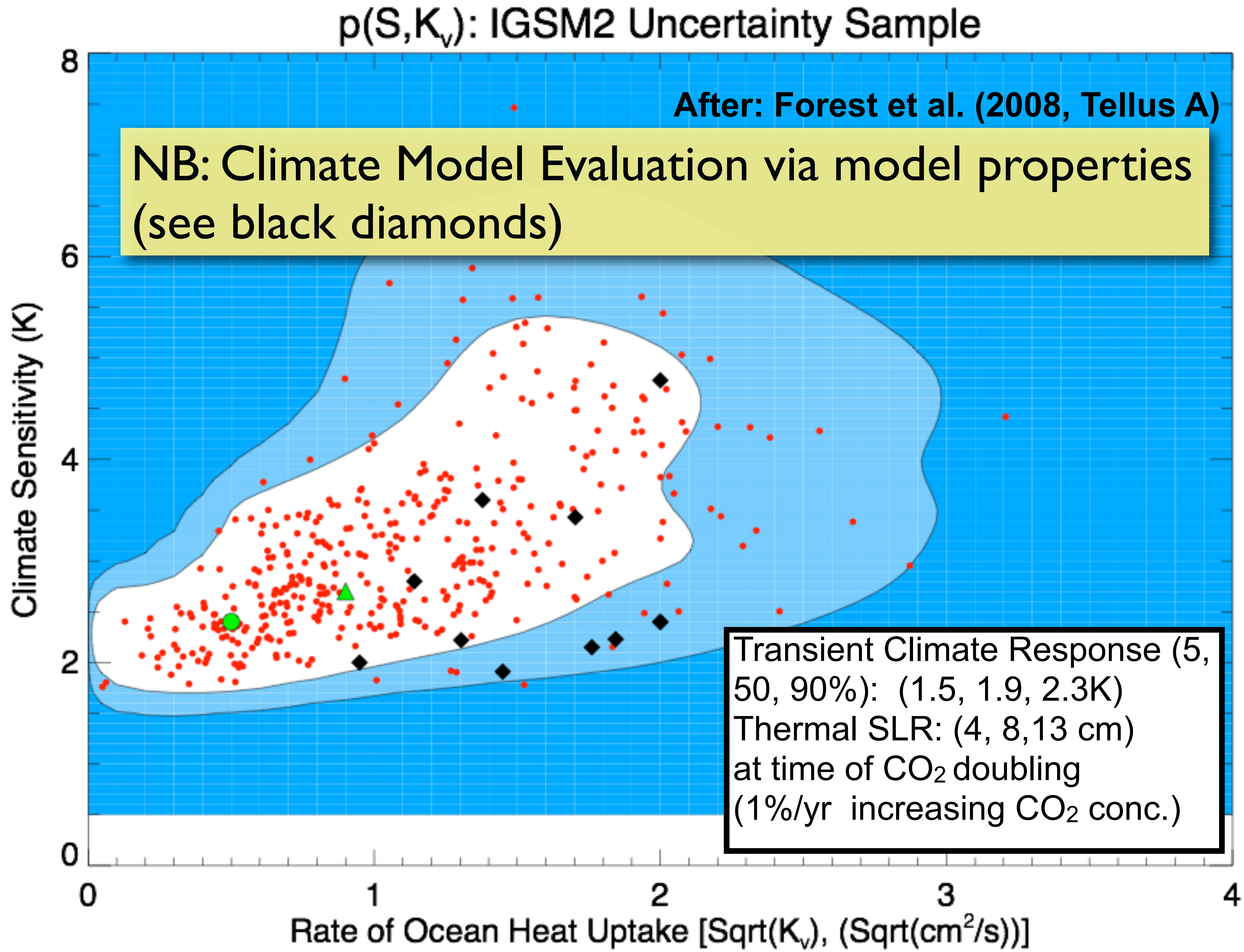


From NASA GISS: http://data.giss.nasa.gov/modelforce/

Major concern is getting the forcings right.



Latin Hypercube Sample (n=250)



Included Uncertainties

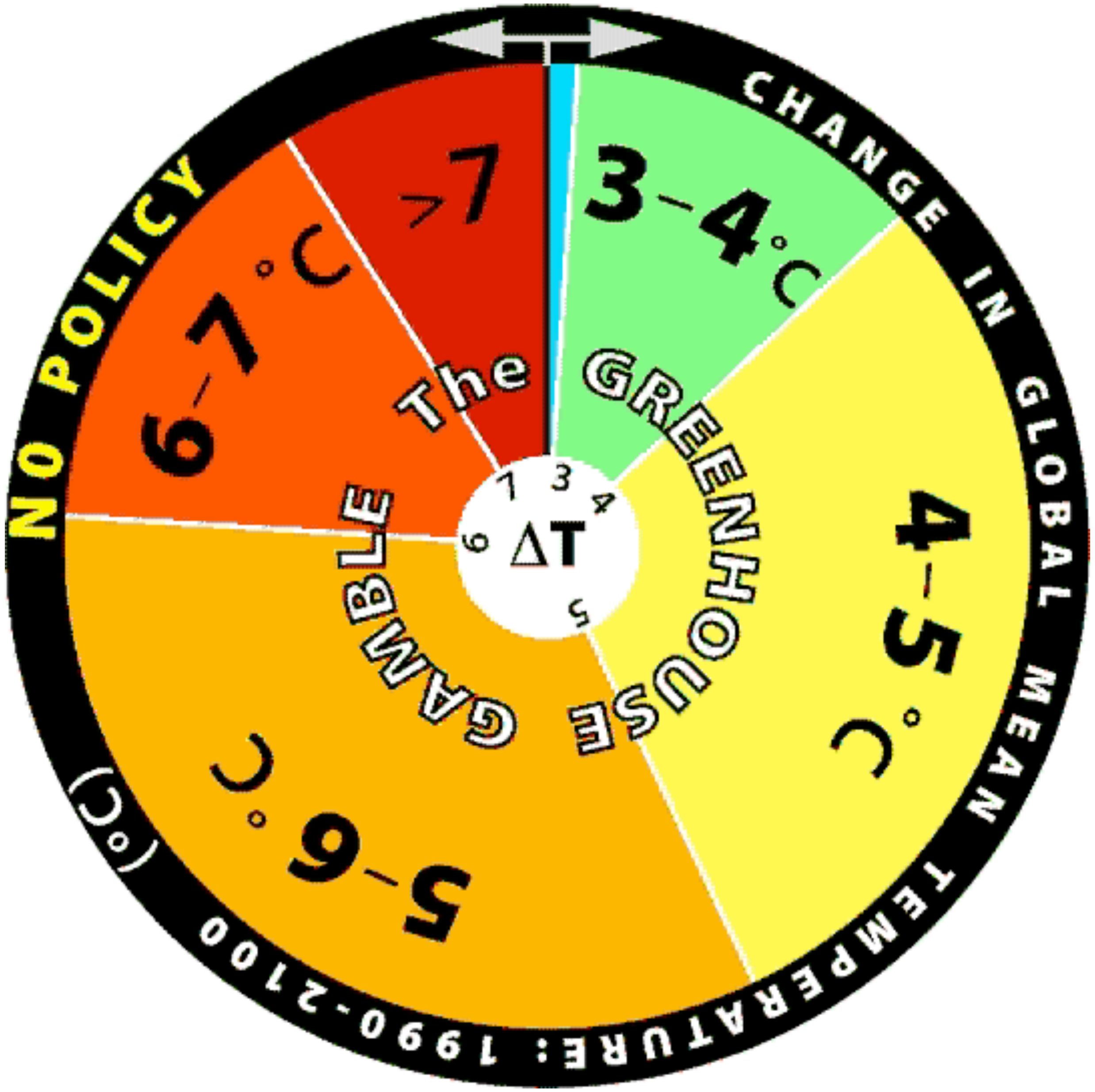
- **Emissions Uncertainty from MIT EPPA4**
  - Population: 6-13 billion, Energy Resources, Efficiency/ Technology
- **Climate System Response**

(Calibrated in Forest et al. 2008)

  – Climate Sensitivity
  – Rate of Heat uptake by Deep Ocean
  – Radiative Forcing Strength of Aerosols
- **Carbon Cycle Uncertainty**:
  – CO_2 Fertilization Effect on Ecosystem
  – Rate of Carbon Uptake by Deep-Ocean
- **Trends in Precip. Freq. on CH_4 + N_2O**

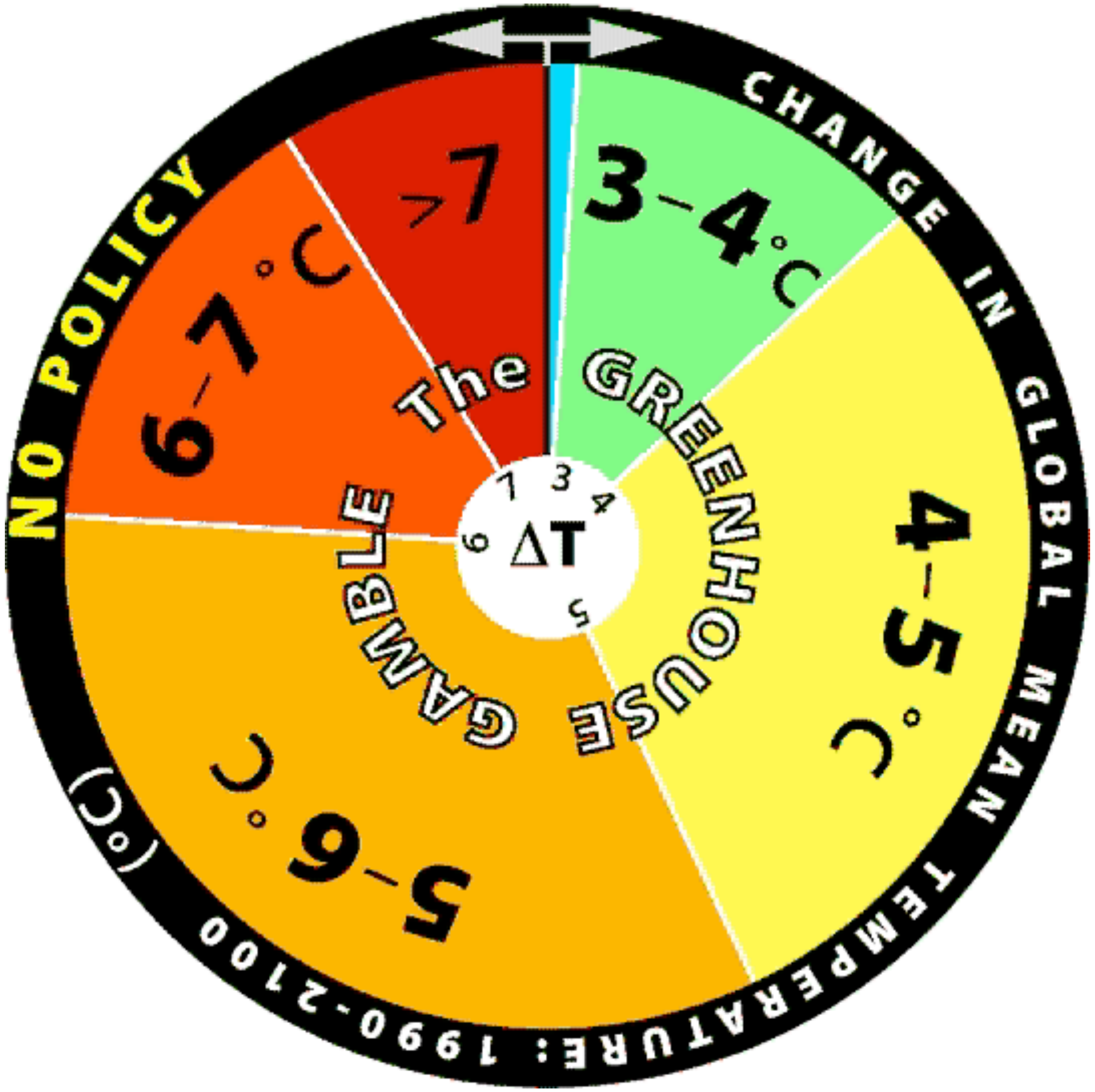
  (Statistics scaled using by AR4 model trends)

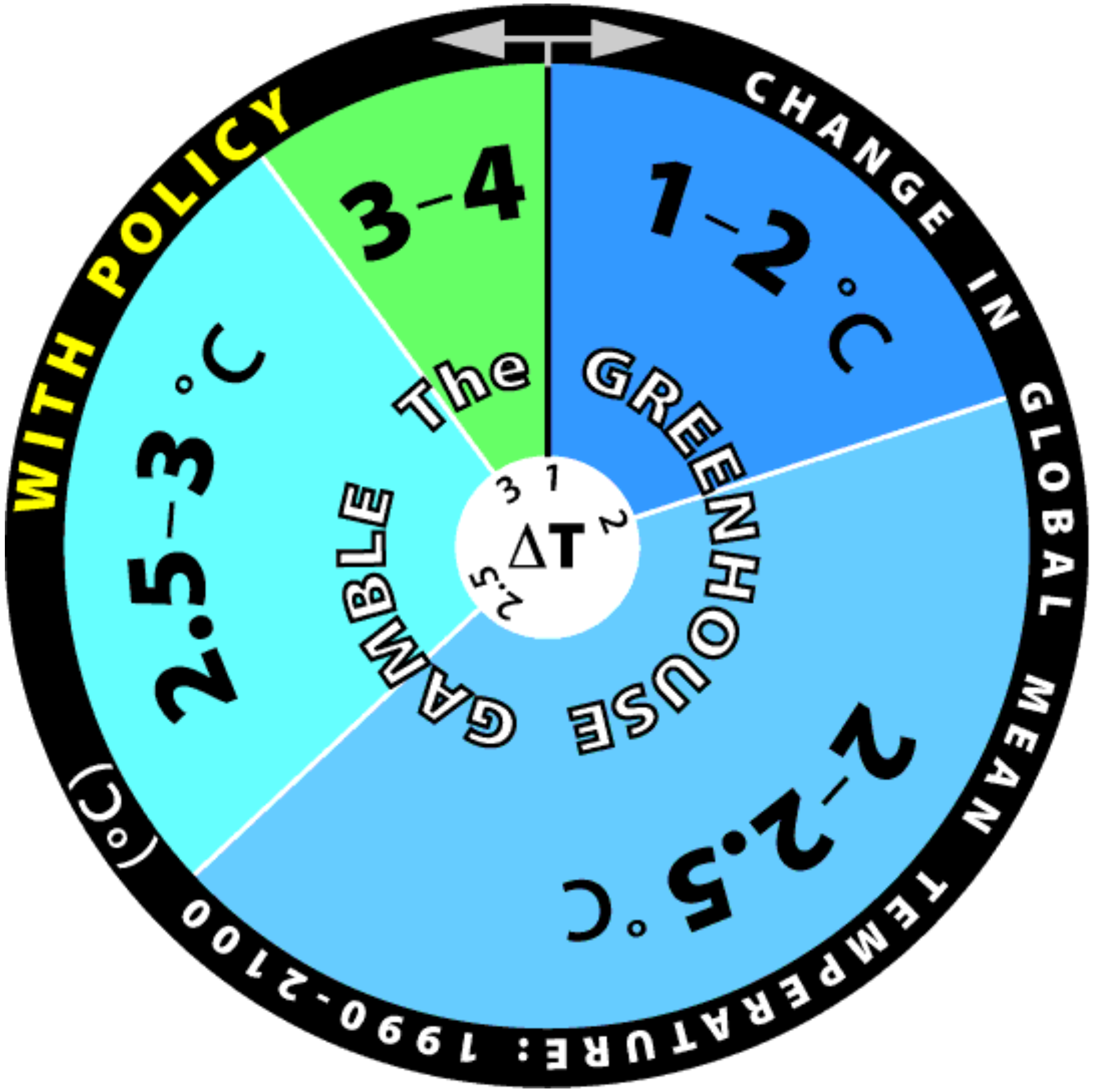
The Greenhouse Gamble



http://globalchange.mit.edu/resources/gamble/

The Greenhouse Gamble





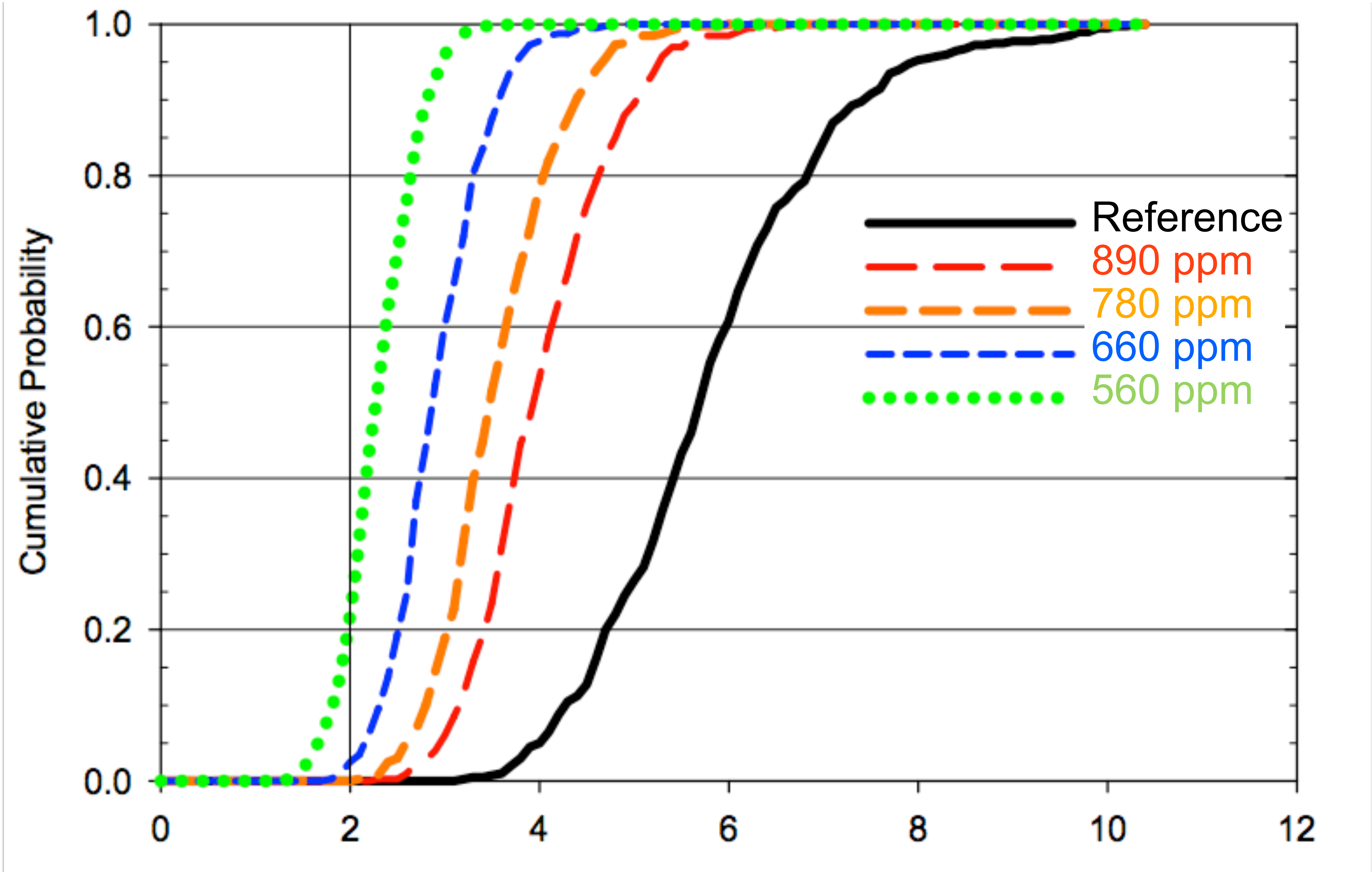
http://globalchange.mit.edu/resources/gamble/

Risks of Global Mean Temperature Increase 1990-2100

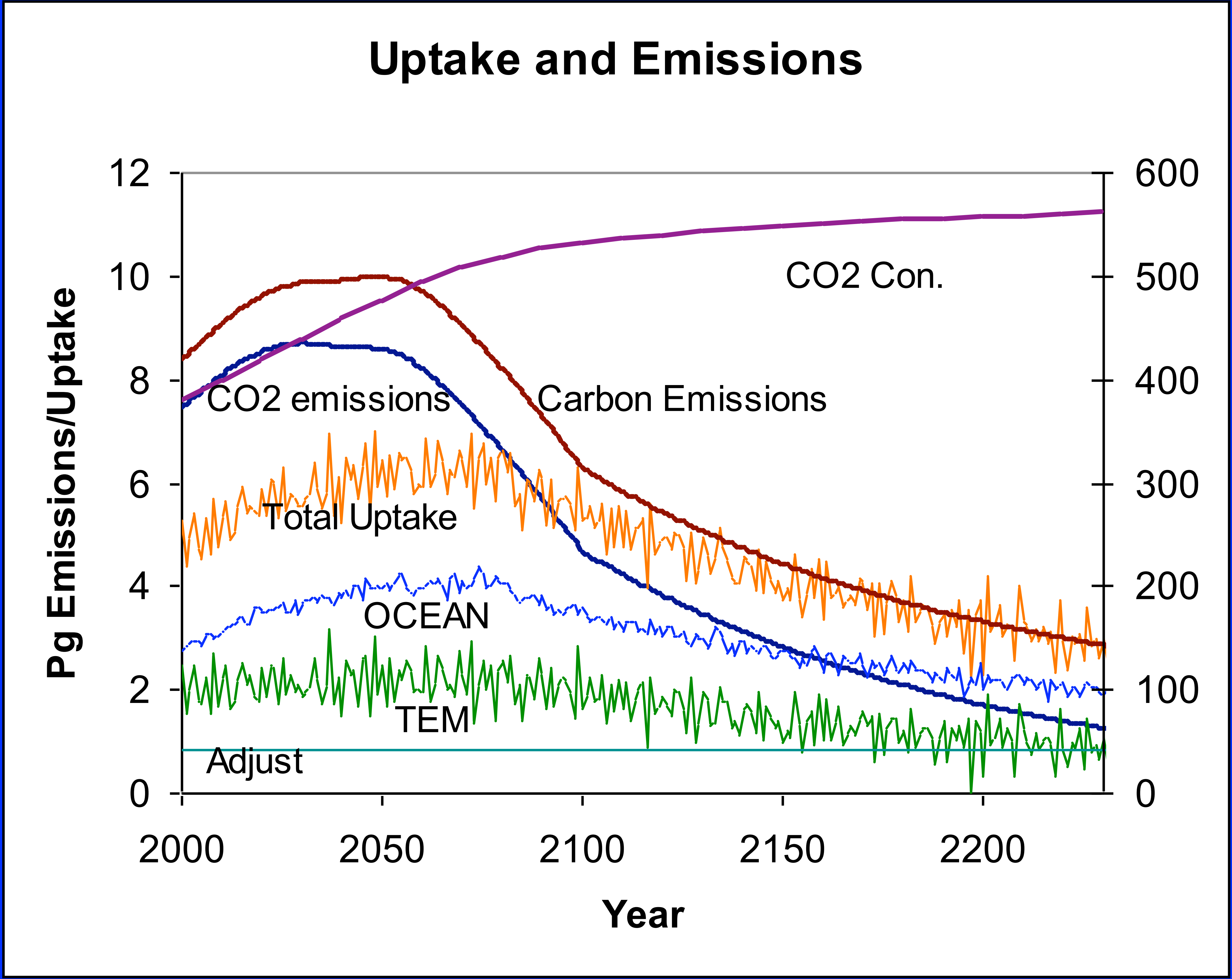
	$\Delta T > 2^oC$	$\Delta T > 4^oC$	$\Delta T > 6^oC$
No Policy	400 in 400	17 in 20	1 in 4
Stabilize at 750	400 in 400	1 in 4	1 in 400
Stabilize at 650	97 in 100	7 in 100	<1 in 400
Stabilize at 550	8 in 10	1 in 400	<1 in 400
Stabilize at 450	1 in 4	<1 in 400	<1 in 400

Sources: Sokolov et al. (2009, J. Climate); Webster et al. (2009, MIT JP Report 180)

Cumulative Probability of T_s in 2100 above Pre-industrial Temperature



Stabilization Scenario Example



Extra Slides

From: Sokolov et al. (2003, J. Climate)

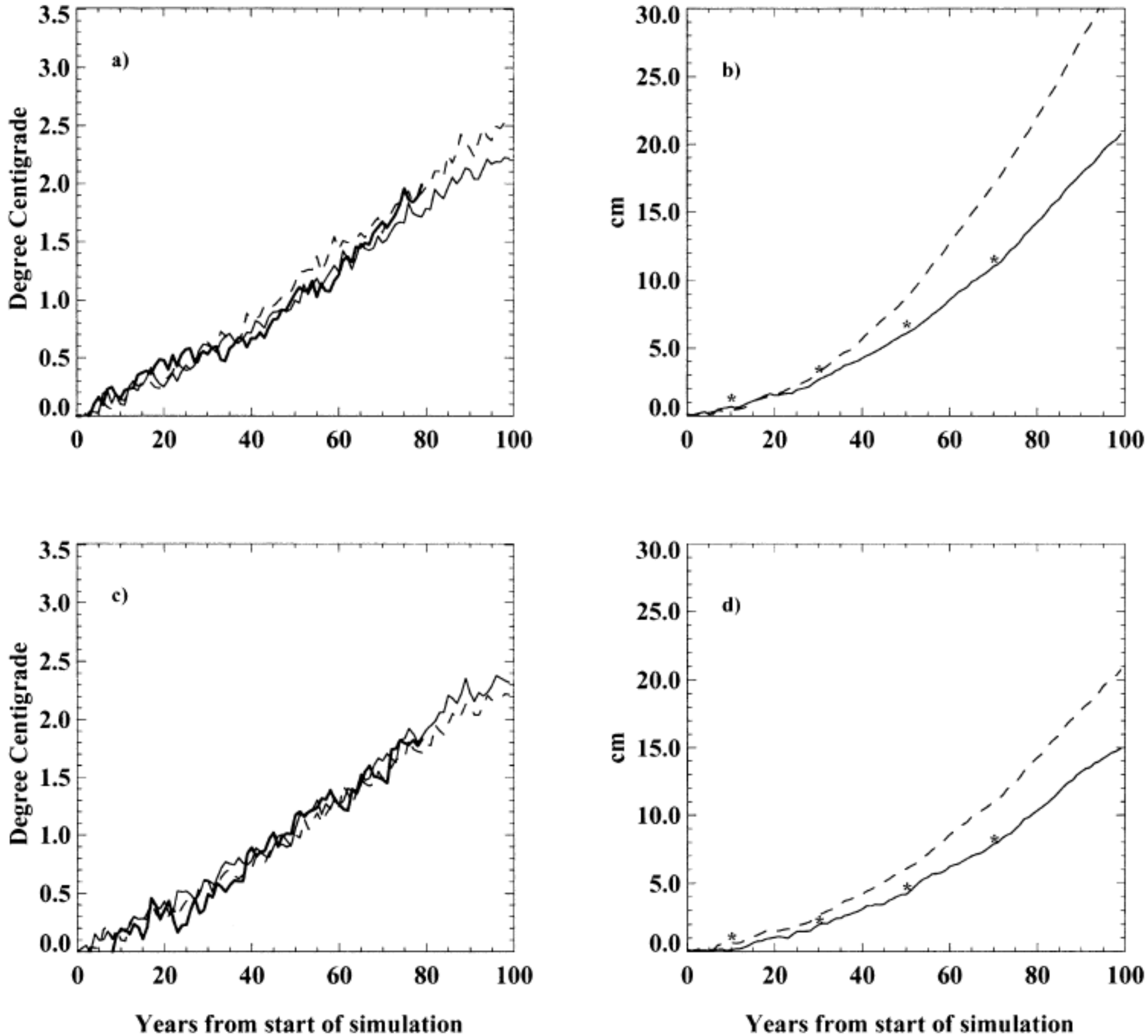


FIG. 2. Changes of annual mean global mean surface air temperature and sea level (thermal expansion) in simulations with the (a), (b) MRI1 and (c), (d) ECHAM3/LSG AOGCMs and in simulations with the versions of the MIT 2D climate model with effective (thin solid lines) and equilibrium (dashed lines) climate sensitivities. Data from CMIP2 simulations with AOGCMs are shown by thick solid line (SAT) and by asterisks (sea level). Unfortunately, while changes in SAT from these simulations are available on an annual basis, sea level rise due to thermal expansion of the ocean is not. The data required to calculate thermal expansion were saved as a 20-yr mean for four consecutive segments of the simulations. In this study we used data on sea level rise for these four periods provided by S. Raper (Raper et al. 2002).

From: Sokolov et al. (2003, J. Climate)

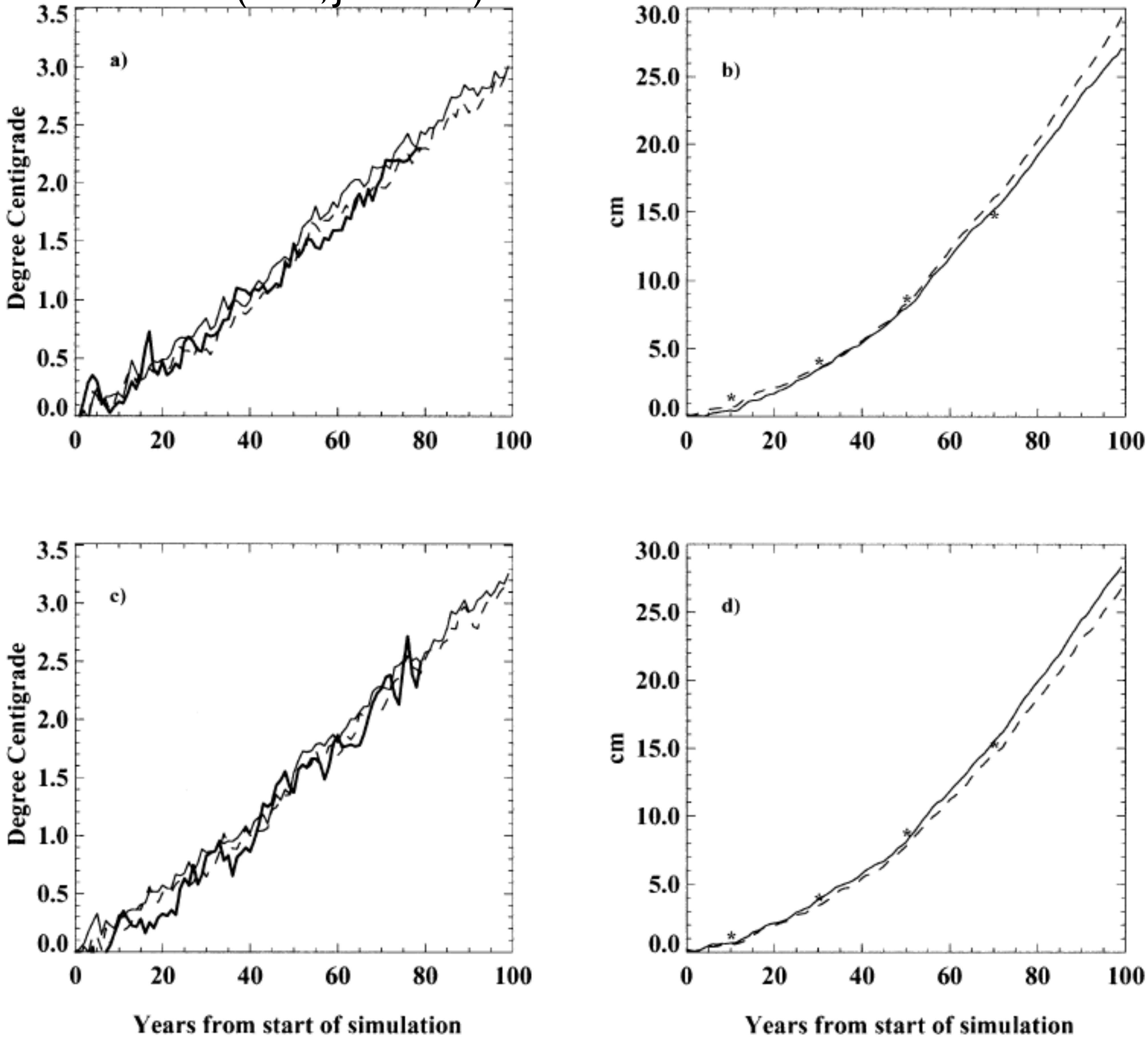
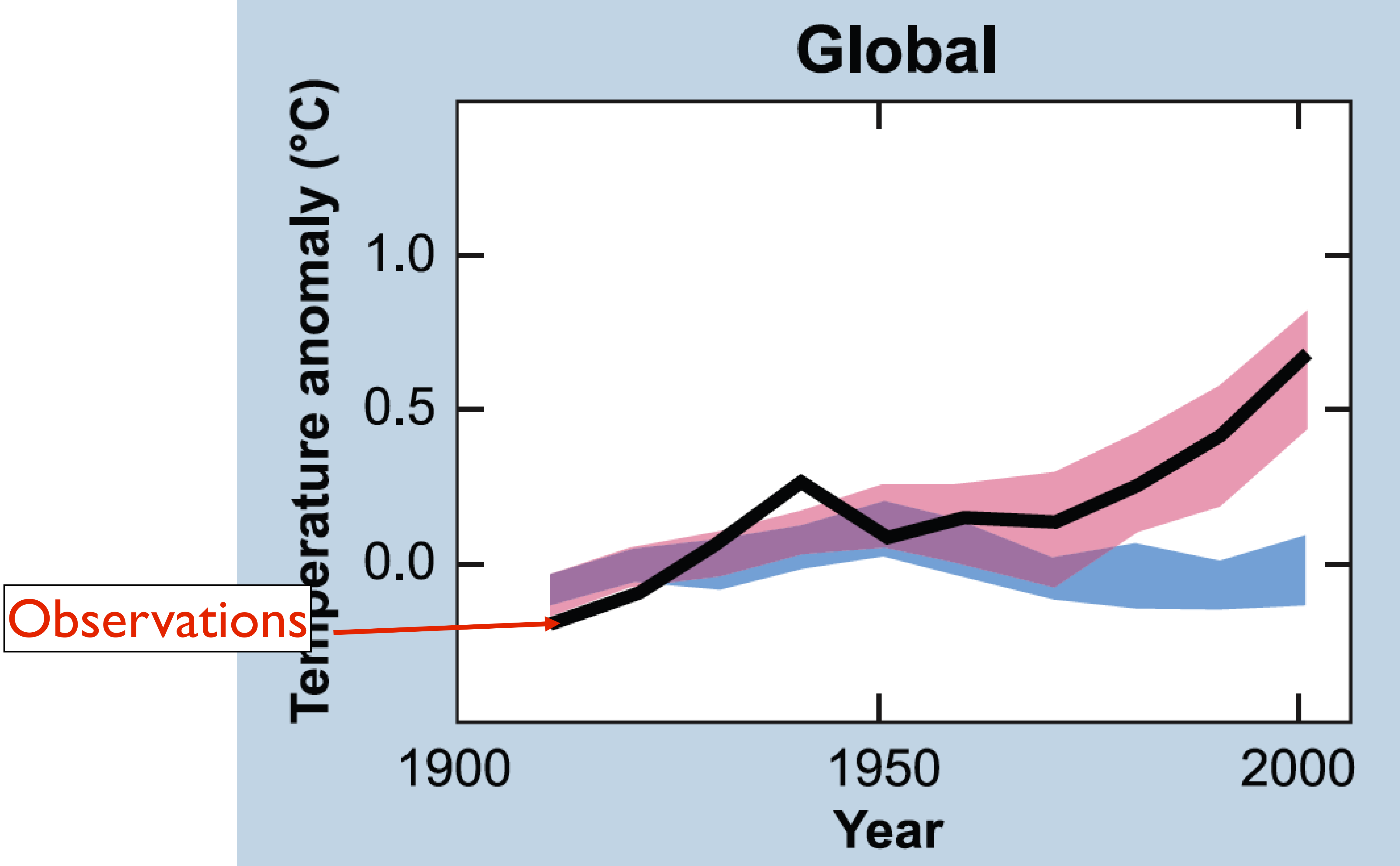


FIG. 3. As in Fig. 2 but for the (a), (b) CSIRO and (c), (d) GFDL R15 AOGCMs.

Climate Change Observations and Climate Model Hindcasts

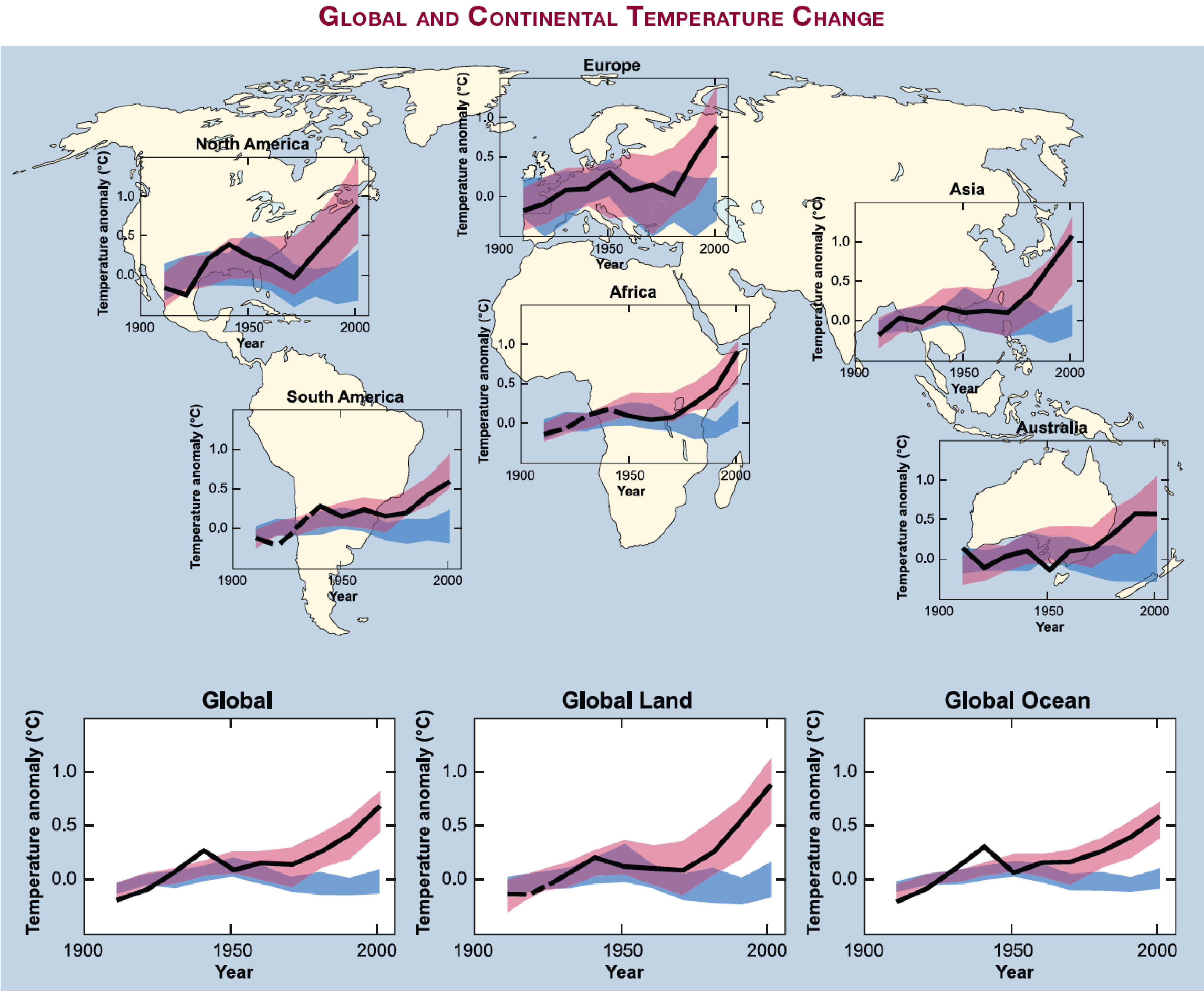


Models using only natural forcings (n~21)

Models using natural and anthropogenic forcings

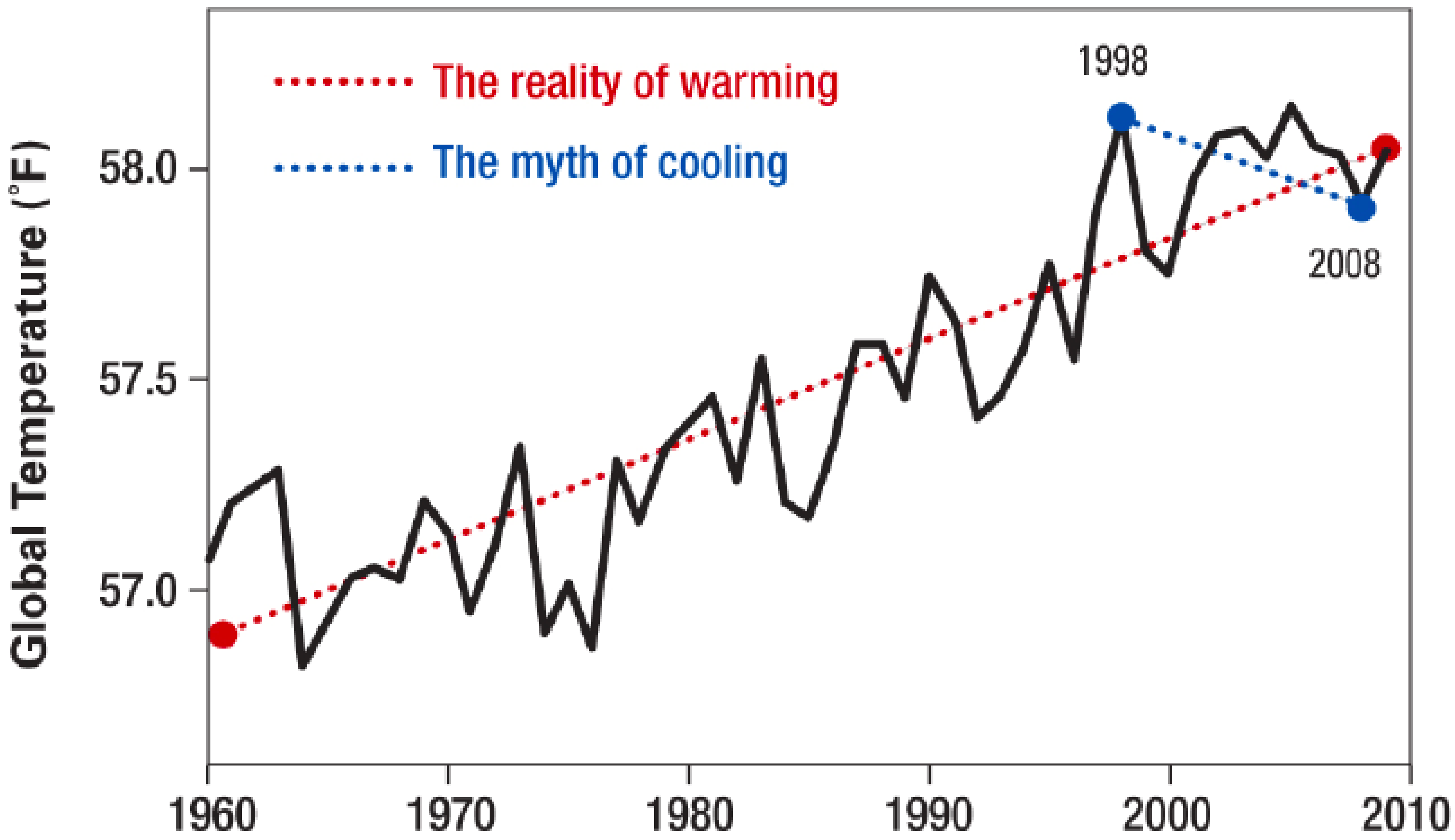
From IPCC AR4 Summary for Policymakers WG1

Climate Change Observations and Climate Model Hindcasts



From IPCC AR4 Summary for Policymakers WG I

Surface Temperature Records



Global Surface Temperature Over the Last Fifty Years

The year 1998 was particularly warm and has been used to falsely claim that the following decade has seen little change or a cooling in temperature. Red shows the correct trend from 1960 through 2008, blue is an erroneous trend over ten years resulting from "cherry-picking" the start and finish dates. Source: NOAA/NCDC data[1], design idea K. Hayhoe.

From http://www.ucsusa.org/climatescienceupdate

Surface Temperature Records