15.023J / 12.848J / ESD.128J Global Climate Change: Economics, Science, and Policy
Spring 2008

THE CLIMATE MACHINE V: INTEGRATED ASSESSMENT I
Sensitivity Studies and Uncertainty Analysis using the Integrated Global System Model

R. PRINN, April 14, 2008

1. Structural & Parametric Uncertainty
2. Sensitivity Analysis
3. Uncertainty Analysis: IGSM 1
4. Uncertainty Analysis: IGSM 2.2
5. Communicating Uncertainty

TWO TYPES OF UNCERTAINTY

STRUCTURAL UNCERTAINTY

PARAMETRIC UNCERTAINTY

TWO TYPES OF ANALYSIS

SENSITIVITY

UNCERTAINTY

- **SENSITIVITY ANALYSIS**

$$dY = \sum_i \frac{\partial Y}{\partial x_i} dx_i$$

$$(dY)^2 = \sum_i \left(\frac{\partial Y}{\partial x_i} dx_i \right)^2 + \sum_{j \neq k} \frac{\partial Y}{\partial x_j} dx_j \frac{\partial Y}{\partial x_k} dx_k$$

$$= \sum_i \left(\frac{\partial Y}{\partial x_i} dx_i \right)^2$$

if errors due to x_j uncorrelated with errors due to x_k and errors have zero mean

- **UNCERTAINTY ANALYSIS**

$$CDF(Y) = P[Y' \leq Y]$$

$$PDF(Y) = \frac{dCDF(Y)}{dY}$$

e.g., Normal (Gaussian)

$$PDF(Y) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(Y-\mu)^2}{2\sigma^2} \right)$$

$\mu = \int Y' PDF(Y') dY'$ (first moment = mean or expected value)

$\sigma^2 = \int (Y'-\mu)^2 PDF(Y') dY'$ (second moment = variance = [std. dev]^2)

Sensitivity Analysis using the MIT INTEGRATED GLOBAL SYSTEM MODEL VERSION 1

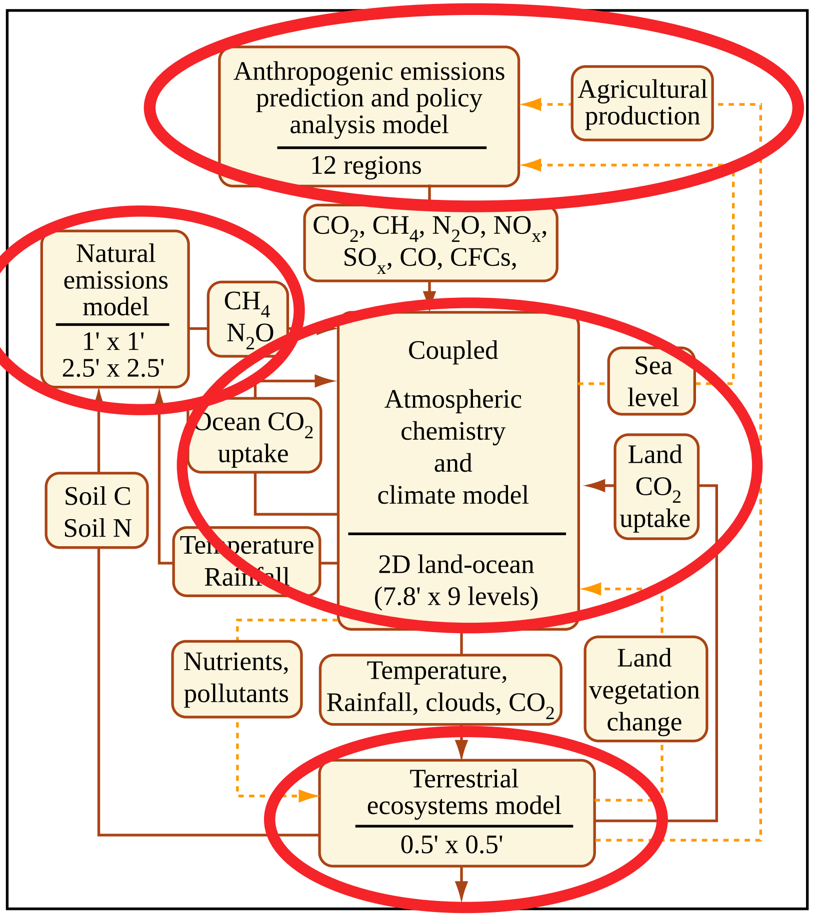


Figure by MIT OpenCourseWare.

Ref: Prinn et al, Climatic Change, 41, 469-546, 1999

SENSITIVITY ANALYSIS: *Defining the uncertain parameters*

Image removed due to copyright restrictions. See Table IV in:

Prinn, R., et al. "Integrated Global System Model for Climate Policy Assessment: Feedbacks and Sensitivity Studies." *Climatic Change* 41, no. 3/4 (1999): 469-546.

Schematic illustrating the seven runs performed for the Sensitivity Analysis of the IGSM 1. Open ellipses denote points in sequence where output is available, with the letters in the ellipse denoting the identifying symbol for the output.

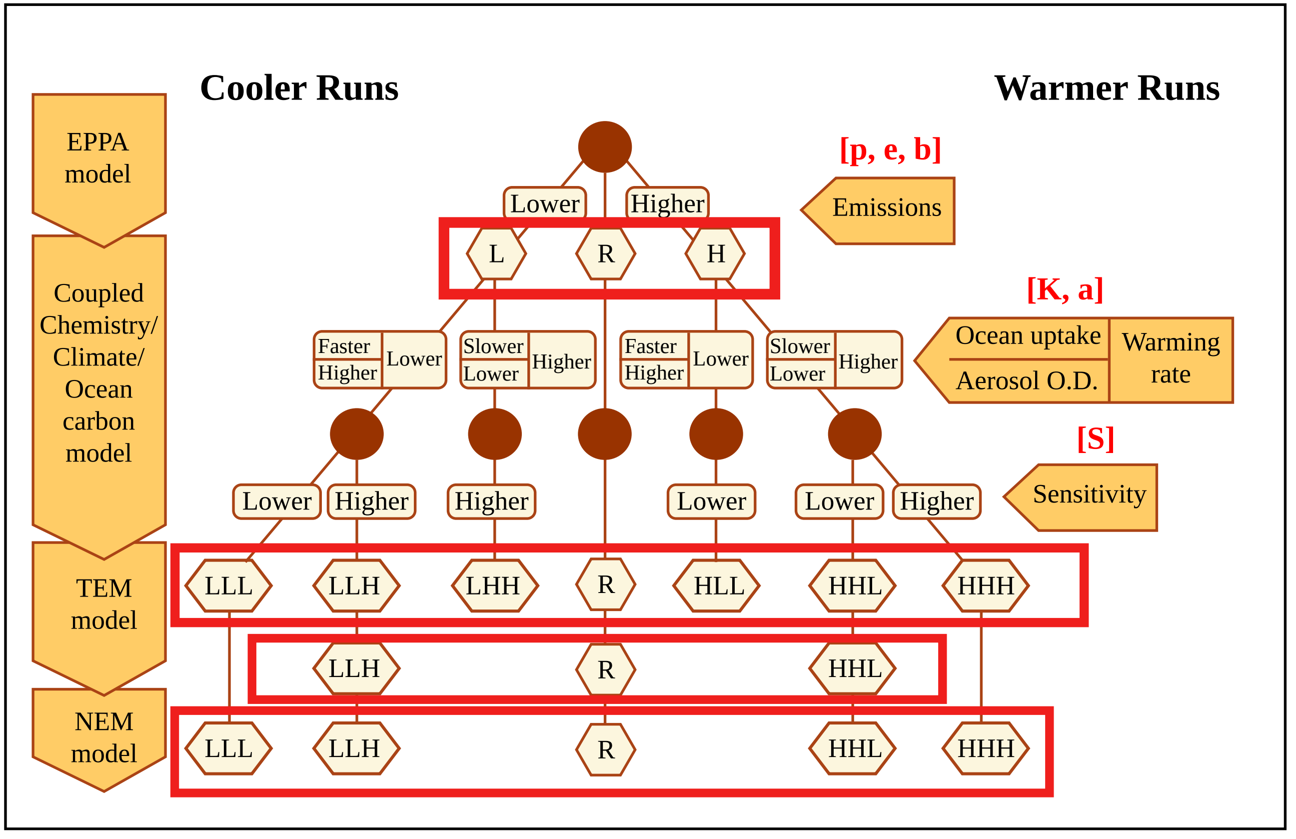


Figure by MIT OpenCourseWare.

Ref: Prinn et al, Climatic Change, 41, 469-546, 1999

Sensitivity of Temperature Change from 1990 to 2100 to assumed: Emissions (p, e, b); Ocean Heat & Carbon Uptake and Aerosol Forcing (K, a); & Climate Sensitivity (s)

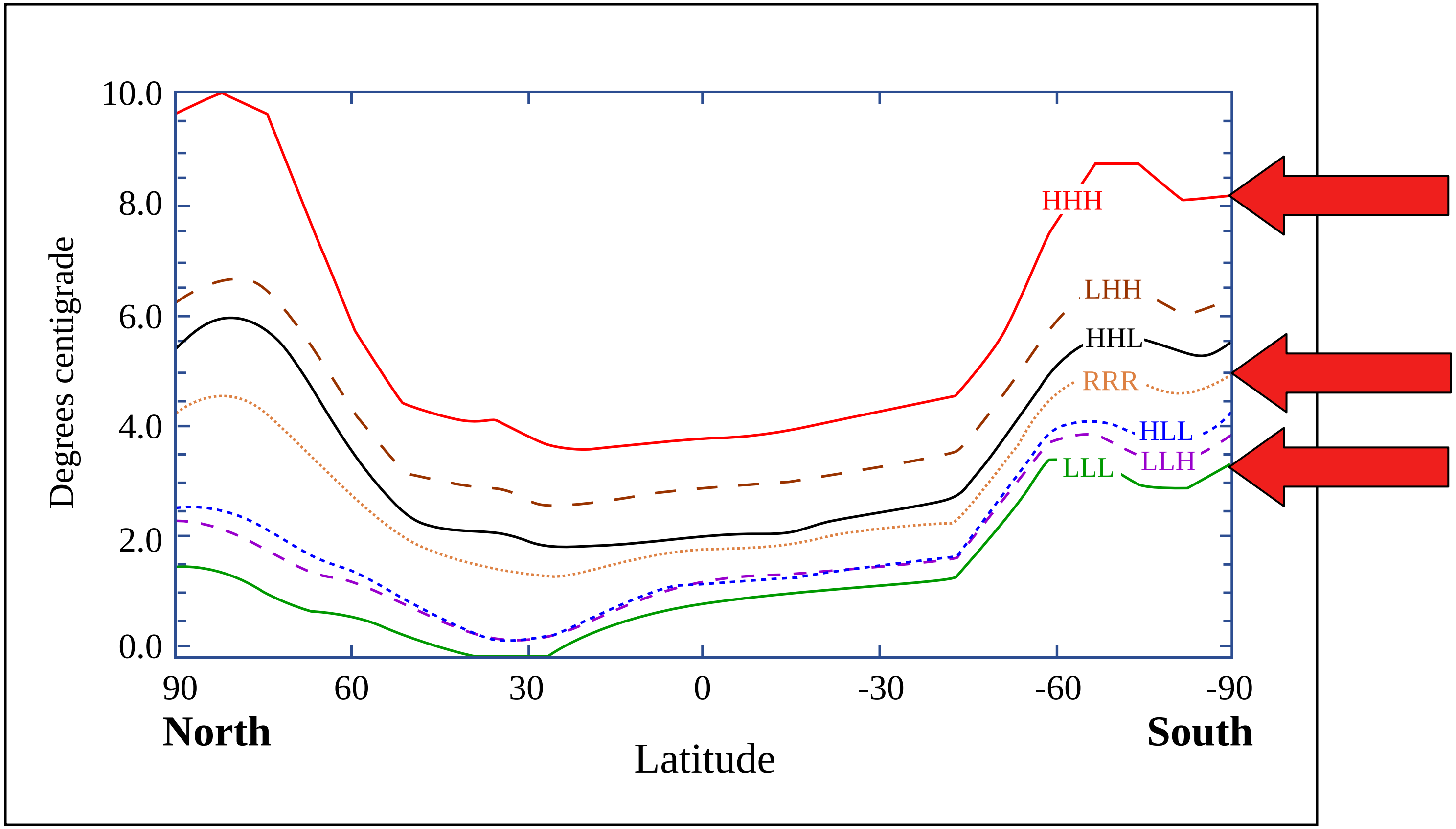


Figure by MIT OpenCourseWare.

Ref: Prinn et al, Climatic Change, 41, 469-546, 1999

Uncertainty Analysis using the MIT INTEGRATED GLOBAL SYSTEM MODEL VERSION 1

THE MAJOR CLIMATE FORECAST MODEL UNCERTAINTIES INVOLVE CLOUDS, OCEAN MIXING & AEROSOL FORCING.

THESE UNCERTAINTIES ARE CONSTRAINED BY OBSERVATIONS

ADDED TO THESE ARE SUBSTANTIAL UNCERTAINTIES IN EMISSION FORECASTING

TO ESTIMATE THE PDFs OF VARIOUS MEASURES OF CLIMATE CHANGE, WE USE VERY LARGE ENSEMBLES OF IGSM RUNS ,EACH WITH RANDOMLY CHOSEN EQUAL PROBABILITY CHOICES FOR THE UNCERTAIN MODEL PARAMETERS.

Uncertainty Analysis Method

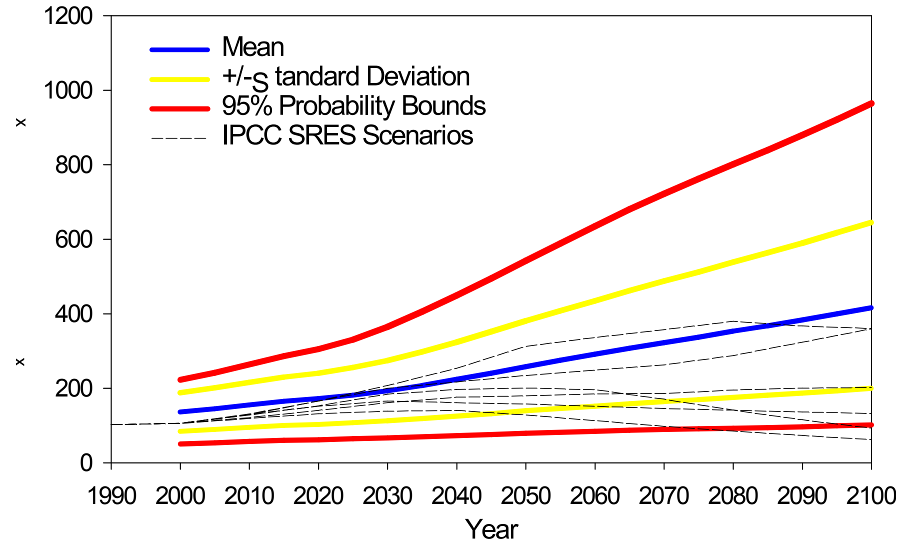
- 250 runs of the MIT IGSM with Latin hypercube sampling of uncertain model parameters
- No explicit policy and stringent policy (at or below 550ppm CO_2 equivalent) cases
- Policy should lower probability of damaging outcomes

TO ADDRESS UNCERTAINTY MIT CLIMATE MODEL HAS FLEXIBLE SENSITIVITY, OCEAN MIXING & AEROSOL FORCING WHOSE UNCERTAINTIES ARE CONSTRAINED BY OBSERVATIONS

Images removed due to copyright restrictions. See Figure 4 in:

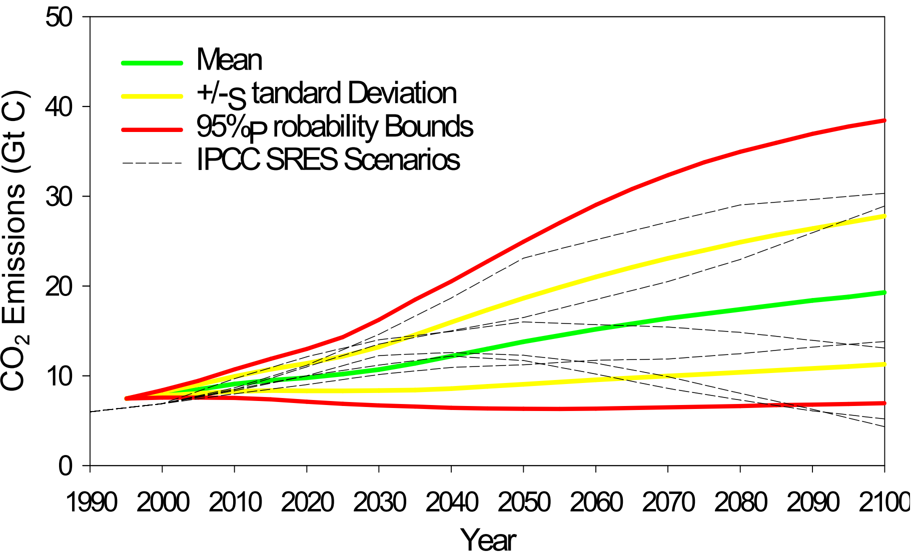
Forest, Chris, et al. "Quantifying Uncertainties in Climate System Properties with the Use of Recent Climate Observations." *Science* 295 (2002): 113-117.

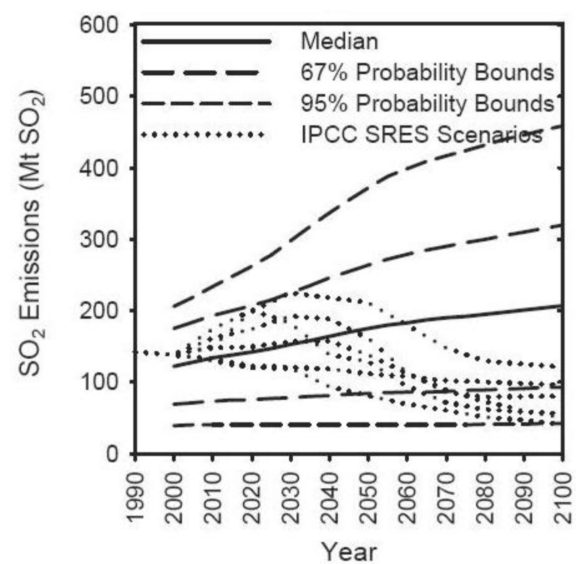
PROBABILITY RANGES FOR NO-POLICY CASE OF EMISSIONS OF SELECTED CLIMATE-FORCING & POLLUTING GASES (EPPA cf. SRES)



Global NO_x Emissions (Tg/yr)

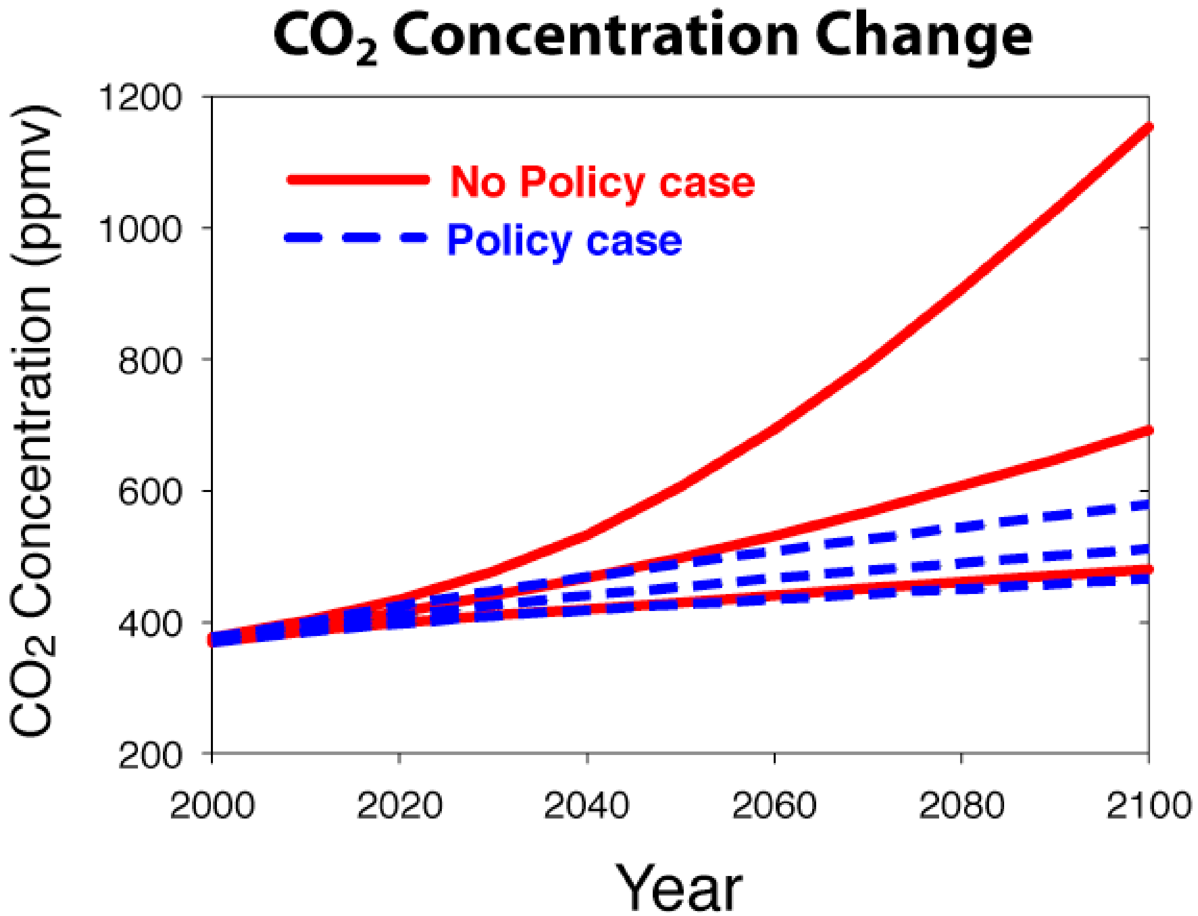
Global CO_2 Emissions (PgC/yr)





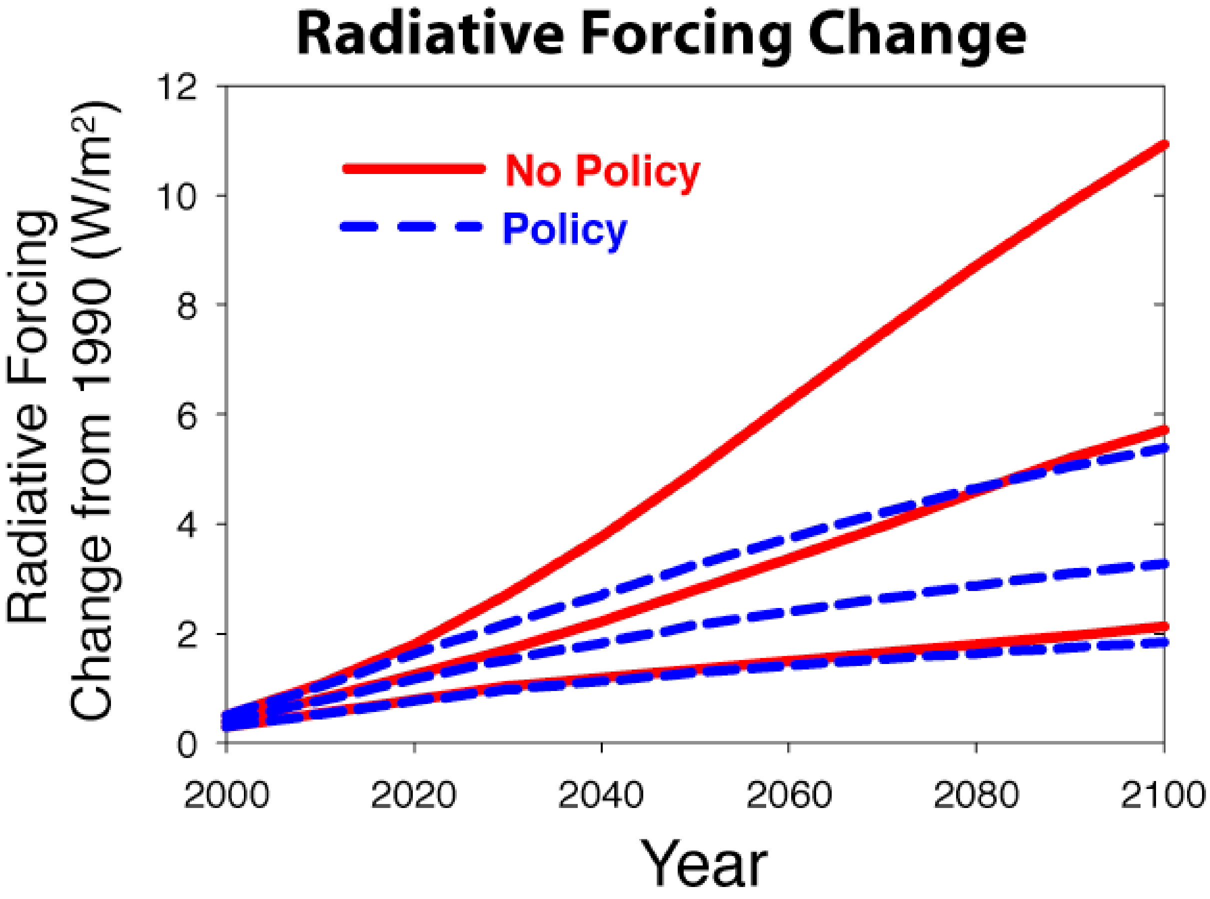
Global SO_2 Emissions (Tg/yr)

Ref: Webster et al, Atmos. Environ.,2002



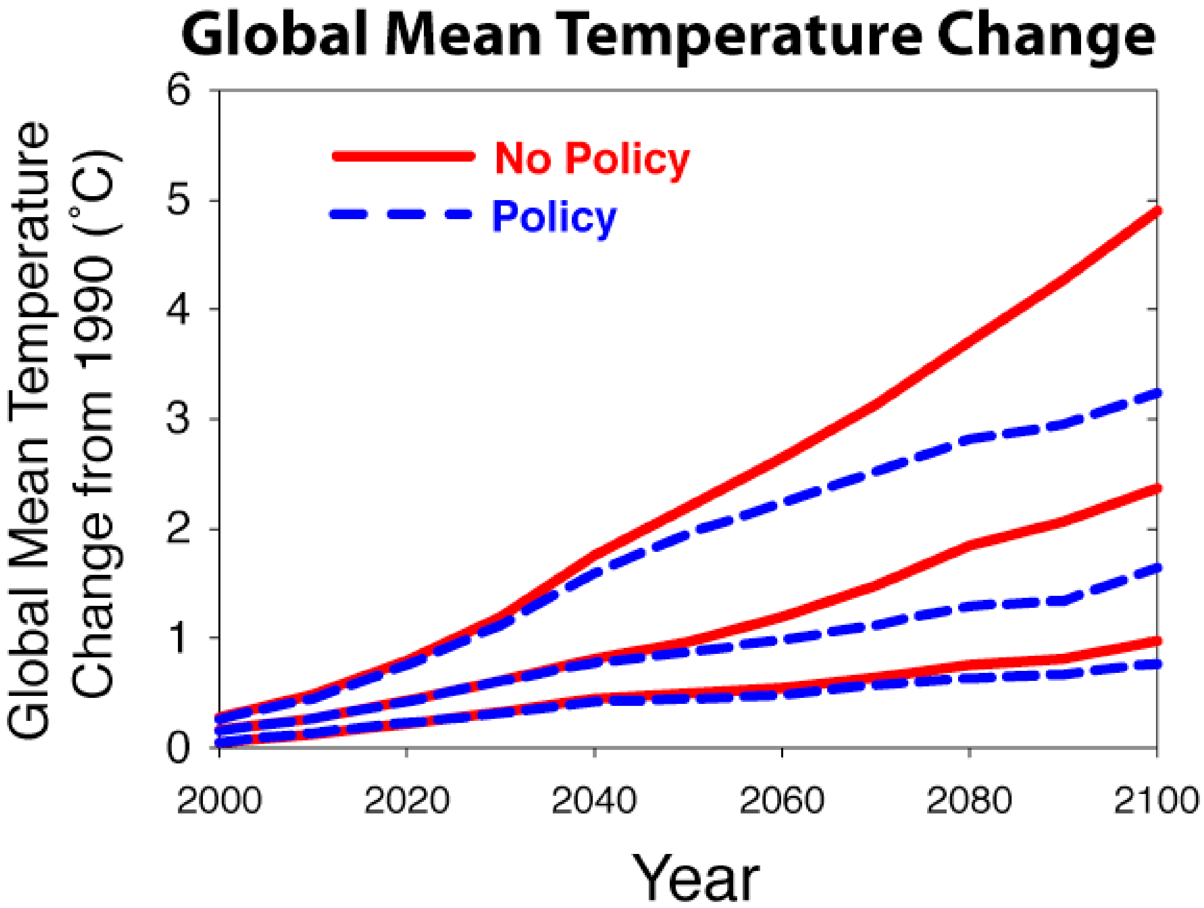
Projected changes in atmospheric CO_2 concentrations relative to 1990. Solid lines show the lower 95%, median, and upper 95% in the absence of greenhouse gas restrictions, and dashed lines show the lower 95%, median, and upper 95% under a policy that approximately stabilizes CO_2 concentrations at 550 ppm.

Source: Webster *et al.*, ***Climatic Change***, 2003 (MIT JPSPGC Report No. 95)



Projected changes in radiative forcing relative to 1990 due to all greenhouse gases. Solid lines show the lower 95%, median, and upper 95% in the absence of greenhouse gas restrictions, and dashed lines show the lower 95%, median, and upper 95% under a policy that approximately stabilizes CO_2 concentrations at 550 ppm.

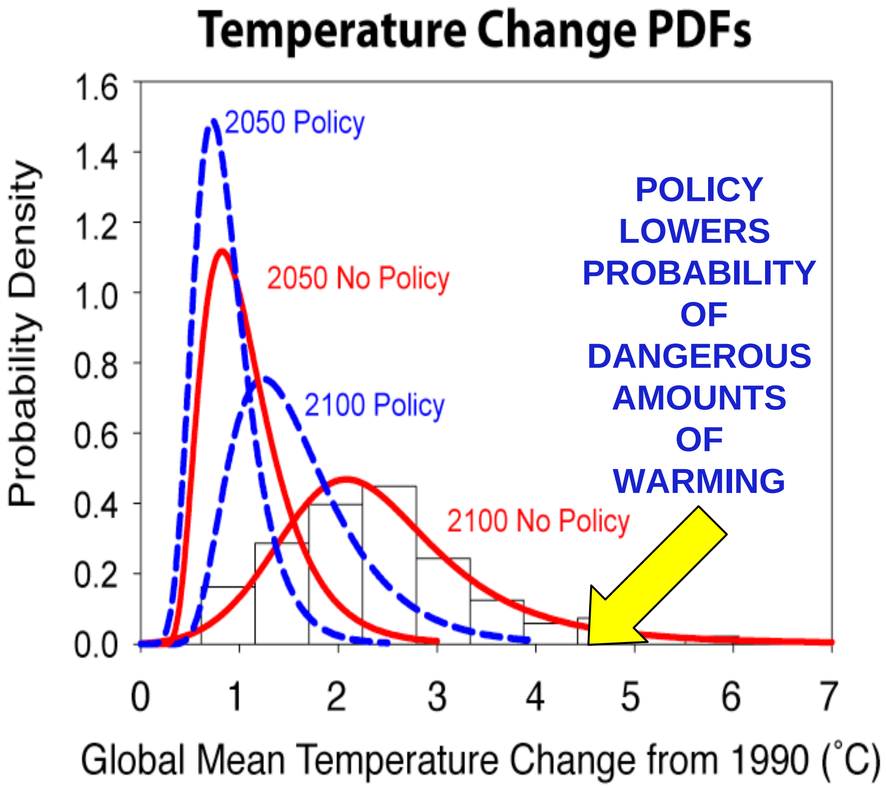
Source: Webster *et al.*, ***Climatic Change***, 2003 (MIT JPSPGC Report No. 95)

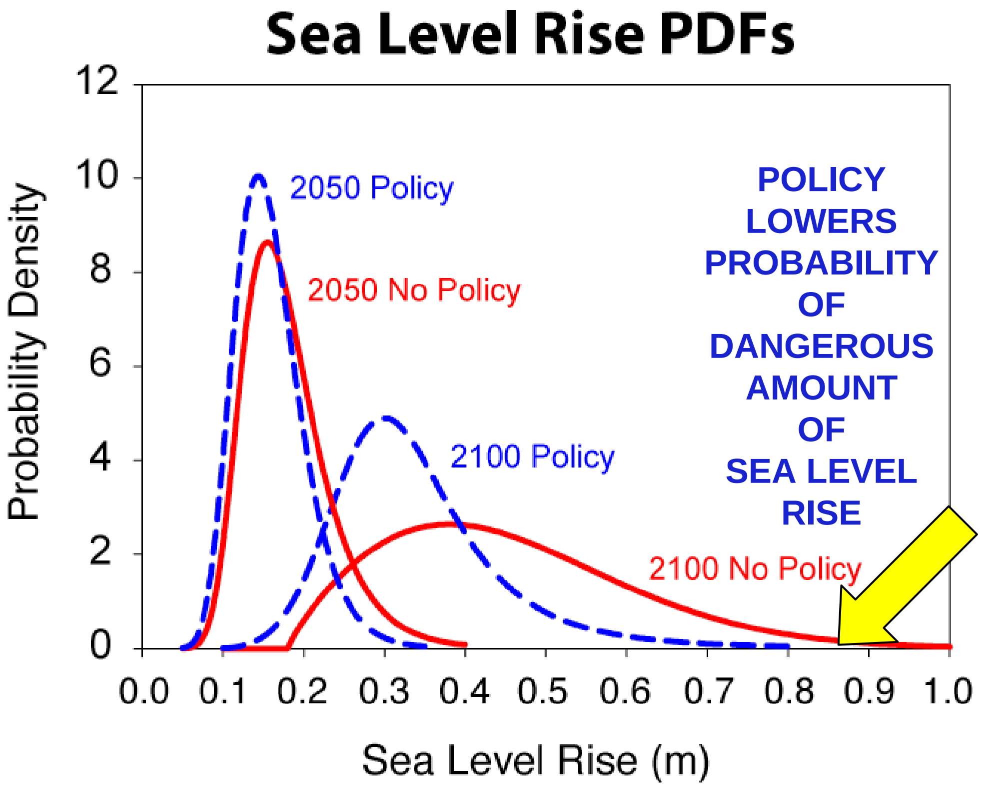


Projected changes in global mean surface temperature relative to 1990. Solid lines show the lower 95%, median, and upper 95% in the absence of greenhouse gas restrictions, and dashed lines show the lower 95%, median, and upper 95% under a policy that approximately stabilizes CO_2 concentrations at 550 ppm.

Source: Webster *et al.*, ***Climatic Change***, 2003 (MIT JPSPGC Report No. 95)

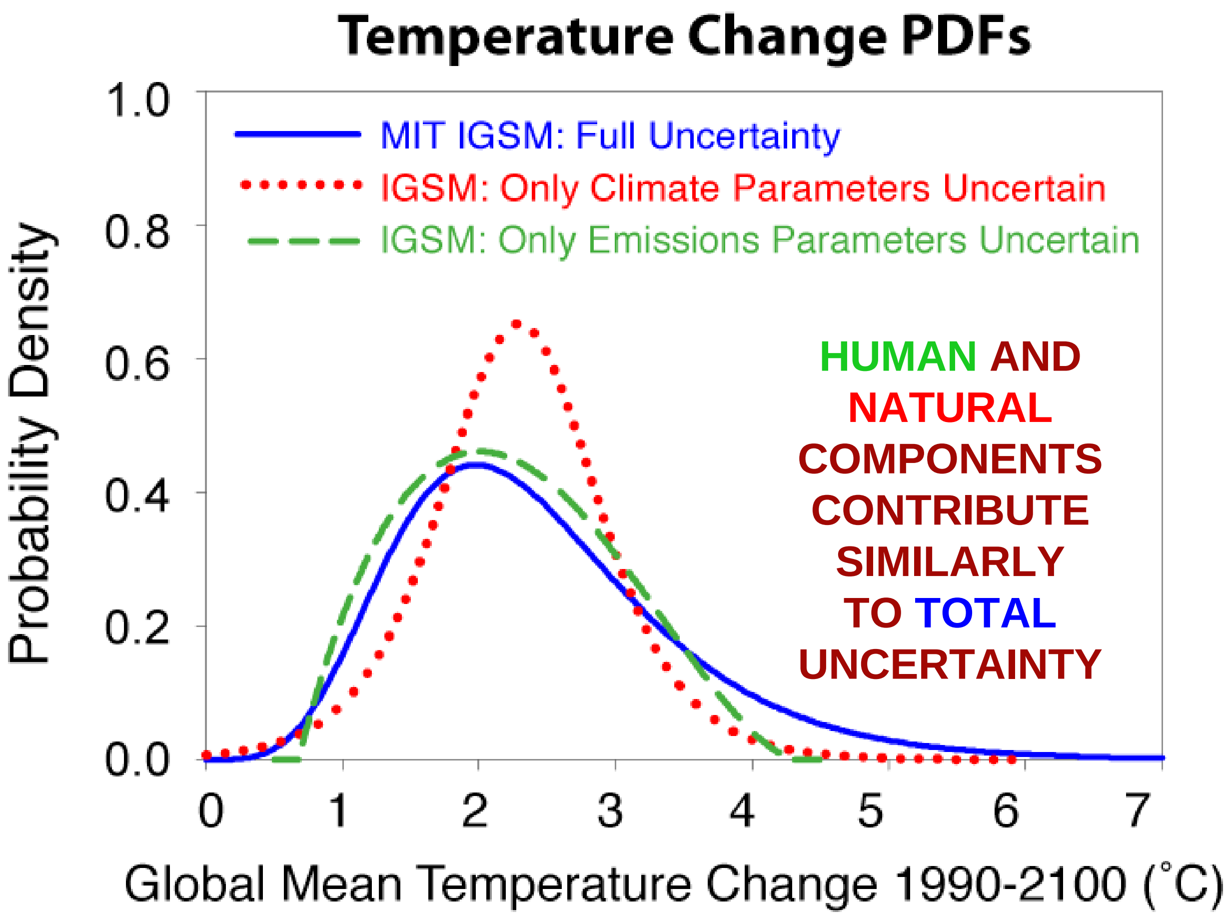
FULL PDF'S OF KEY MEASURES OF CLIMATE CHANGE for 1990-2100, WITH & WITHOUT the (550 ppm) POLICY





Source: Webster *et al.*, ***Climatic Change***, 2003 (MIT JPSPGC Report No. 95)

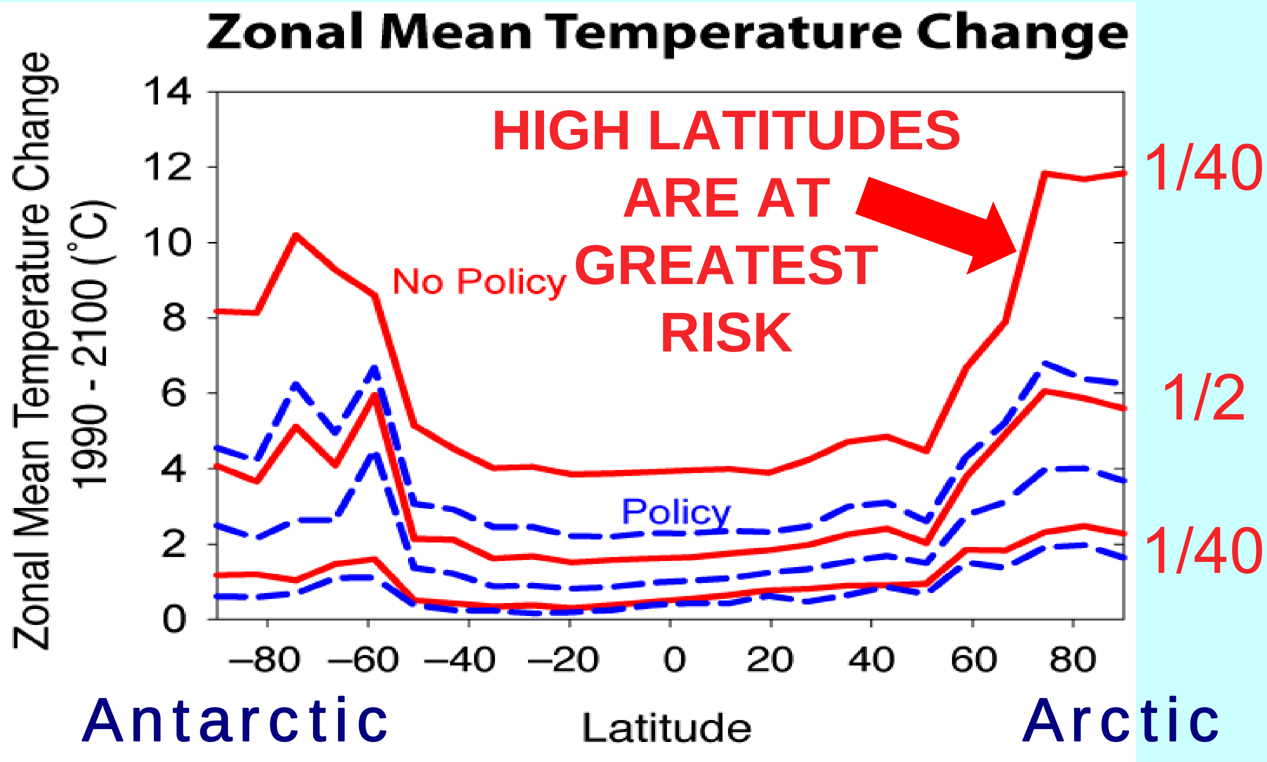
INFLUENCE OF EMISSIONS VS. CLIMATE ON THE PDF's



Probability distributions of global mean surface temperature change from 1990 to 2100 from all uncertain parameters (solid blue), only climate model parameters uncertain and emissions fixed (dotted red), and only emissions uncertain with climate model parameters fixed (dashed green).

Source: Webster *et al.*, ***Climatic Change***, 2003 (MIT JPSPGC Report No. 95)

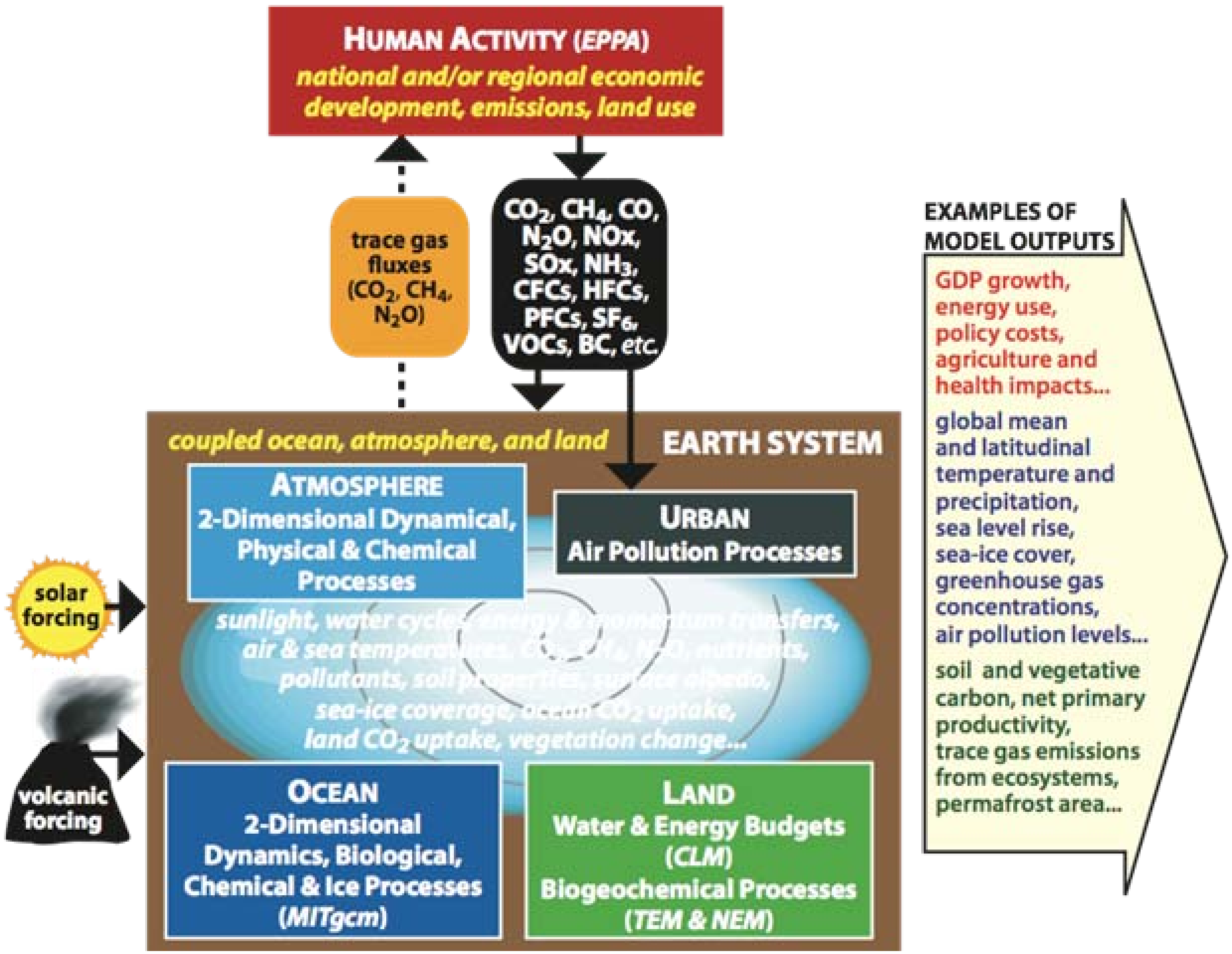
WHAT IS THE PROBABILITY OF VARIOUS AMOUNTS OF CLIMATE CHANGE BY LATITUDE for 1990-2100, WITH & WITHOUT A (550 ppm CO_2-equivalent) POLICY?



Projected change in surface warming by latitude band between 1990 and 2100. The median value, and lower 95% and upper 95% bounds are shown. Solid lines show distributions resulting from no emissions restrictions and dashed lines are distributions under the sample policy.

Source: Webster *et al.*, ***Climatic Change***, 2003 (MIT JPSPGC Report No. 95)

Uncertainty Analysis of MIT IGSM 2.2 under No Policy and Stabilization Scenarios



Ref: Sokolov, Forest, et al, 2008 and Webster et al, 2008, Joint Program, in preparation

Methodology

- Estimate probability distributions for input parameters controlling the emissions and climate projections-system models

(1) Emissions Uncertainties

(2) Climate System Response Uncertainties:

Climate Sensitivity

Rate of Heat uptake by Deep Ocean

Radiative Forcing Strength of Aerosols

(3) Greenhouse Gas Cycle Uncertainties:

CO_2 Fertilization Effect on Ecosystem Sink

Rate of Carbon Uptake by Deep-Ocean

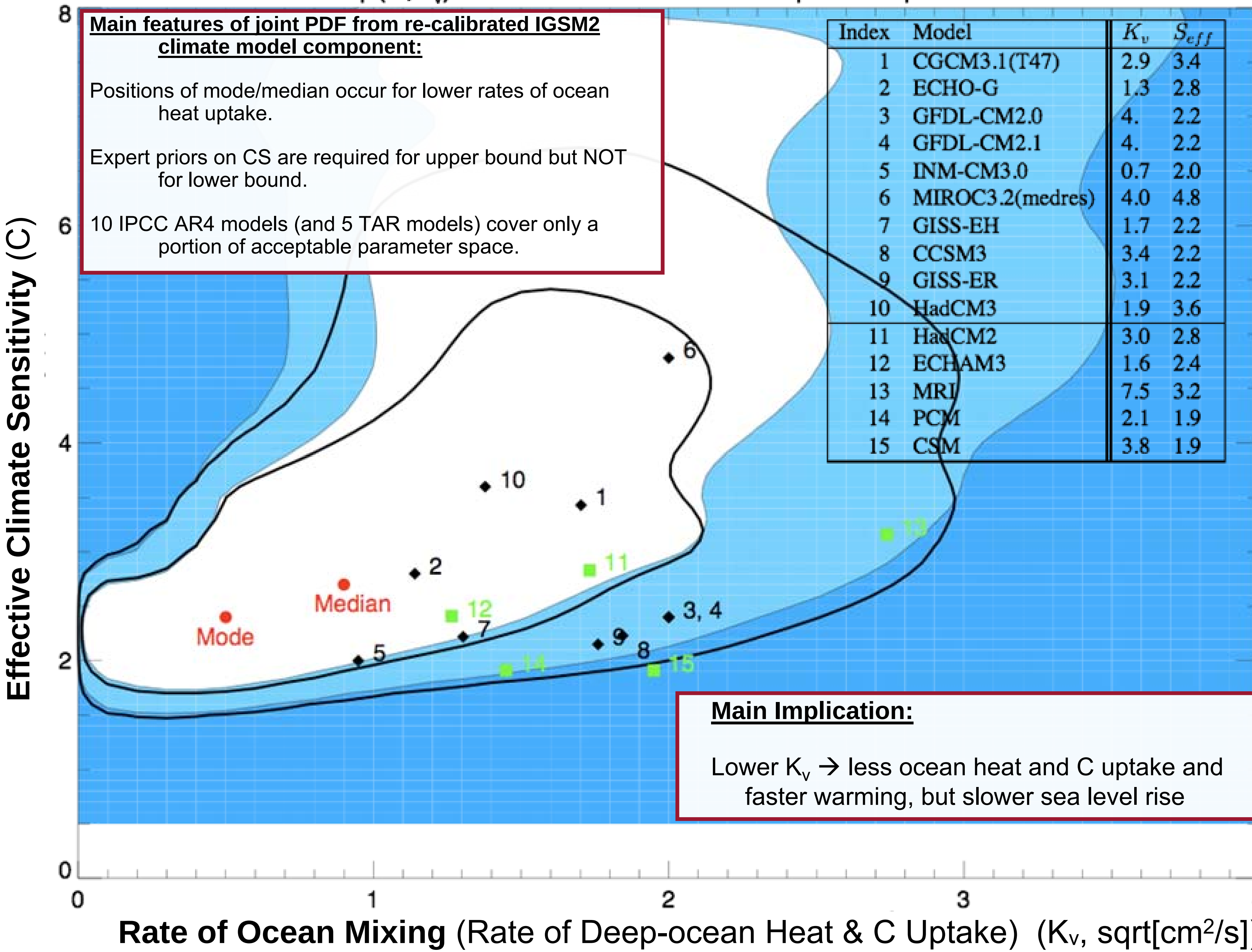
Trends in Rainfall Frequency on CH_4 + N_2O

- Generate 400 member ensembles to represent Monte Carlo sample
- Simulate Reference (i.e., No Policy) and Four Stabilization Scenarios (450, 550, 650, and 750 ppm)

Ref: Sokolov, Forest, et al, 2008 and Webster et al, 2008, Joint Program, in preparation

$p(S,K_v)$: IGSM2.2 Uniform and Expert CS priors

Ref: Forest, et al, 2008



Main features of joint PDF from re-calibrated IGSM2 climate model component:

Positions of mode/median occur for lower rates of ocean heat uptake.

Expert priors on CS are required for upper bound but NOT for lower bound.

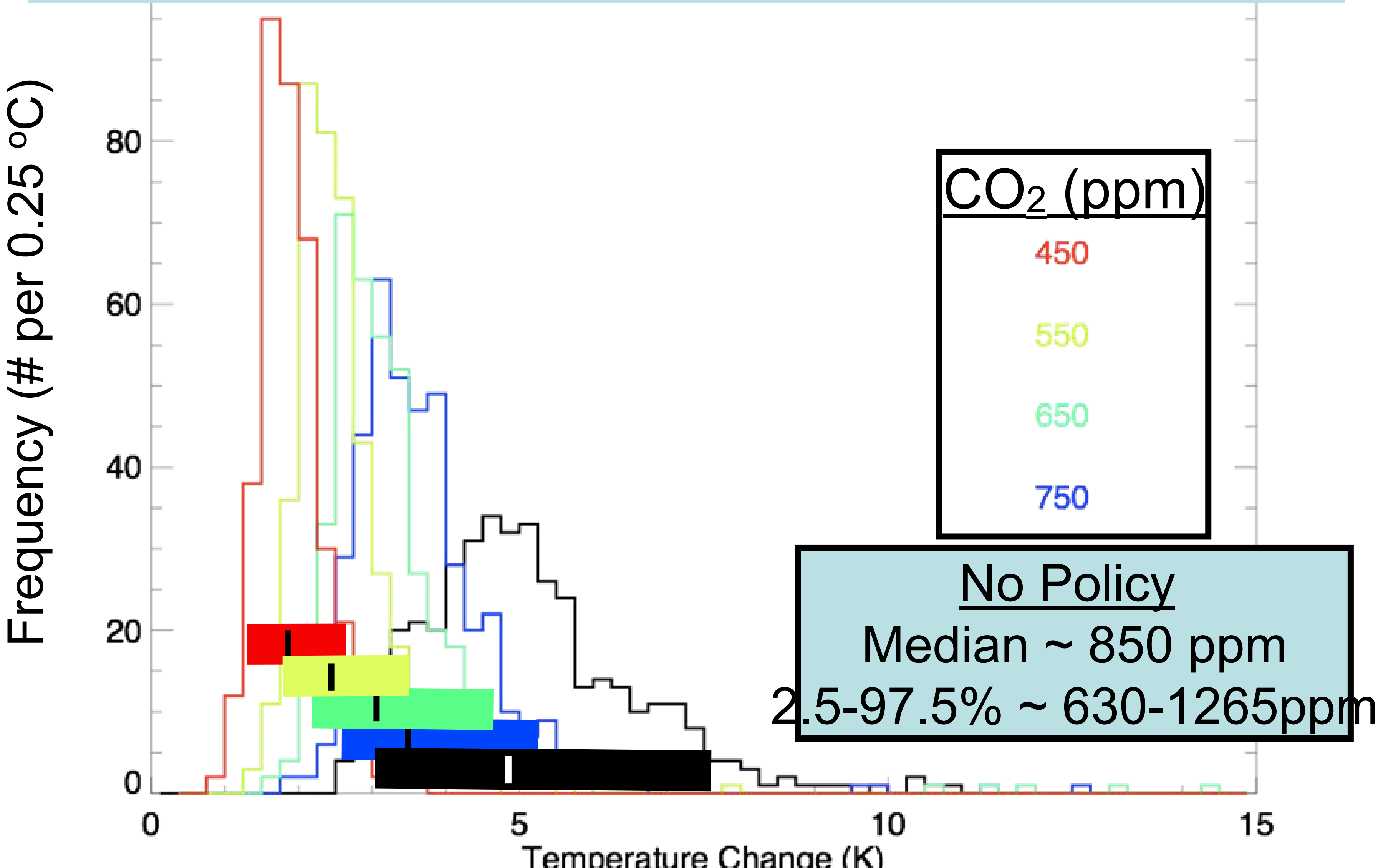
10 IPCC AR4 models (and 5 TAR models) cover only a portion of acceptable parameter space.

Index	Model	K_v	S_{eff}
1	CGCM3.1(T47)	2.9	3.4
2	ECHO-G	1.3	2.8
3	GFDL-CM2.0	4.	2.2
4	GFDL-CM2.1	4.	2.2
5	INM-CM3.0	0.7	2.0
6	MIROC3.2(medres)	4.0	4.8
7	GISS-EH	1.7	2.2
8	CCSM3	3.4	2.2
9	GISS-ER	3.1	2.2
10	HadCM3	1.9	3.6
11	HadCM2	3.0	2.8
12	ECHAM3	1.6	2.4
13	MRI	7.5	3.2
14	PCM	2.1	1.9
15	CSM	3.8	1.9

Main Implication:

Lower K_v → less ocean heat and C uptake and faster warming, but slower sea level rise

Frequency Distributions for Temperature Change from 2000 to 2100 under **No Policy** and 4 CCSP **Stabilization** Scenarios



Ref: Sokolov, Forest, et al, 2008 and Webster et al, 2008, Joint Program, in preparation

COMMUNICATING UNCERTAINTY AND RISK

Risks of Global Mean Temperature Increase Since Preindustrial

	$\Delta T > 2^oC$	$\Delta T > 4^oC$	$\Delta T > 6^oC$
No Policy	400 in 400	4 in 5	1 in 3
Stabilize at 750	400 in 400	3 in 5	1 in 50
Stabilize at 650	98 in 100	1 in 5	1 in 200
Stabilize at 550	97 in 100	1 in 20	<1 in 400
Stabilize at 450	70 in 100	<1 in 400	<1 in 400

Ref: Sokolov, Forest, et al, 2008 and Webster et al, 2008, Joint Program, in preparation

COMMUNICATING UNCERTAINTY AND RISK

Risks of Ocean Impacts

	Sea Level Rise > 0.3m	Sea Level Rise > 0.6m
No Policy	19 in 20	8 in 50
Stabilize at 750	17 in 20	2 in 50
Stabilize at 650	15 in 20	1 in 50
Stabilize at 550	11 in 20	<1 in 400
Stabilize at 450	5 in 20	< 1 in 400

Ref: Sokolov, Forest, et al, 2008 and Webster et al, 2008, Joint Program, in preparation

Why is the Reference distribution shifted To higher temperatures?

- Radiative Forcing Increases?
  - Emissions (higher lower bound)
  - **Reduced Ocean Carbon Uptake**
  - Additional forcing such as Black Carbon & Tropospheric Ozone (additional forcing included but still calibrated by net aerosols in 1990s)
- Climate Model Response?
  - **Climate Model Parameters show higher response**
- **Learning?**
  - Distributions better defined
  - Distributions shifted higher

Ref: Sokolov, Forest, et al, 2008 and Webster et al, 2008, Joint Program, in preparation

Conclusions regarding odds of Future Climate Change from latest Analysis

- $\Delta T > 2^{o}K$ above pre-industrial
  - virtually certain under No Policy scenario
  - reduced to 7 in 10 chance with 450 ppm stabilization

- ΔSeaLevel > 0.3 meters above pre-industrial
  - 19 chances in 20 under No Policy scenario
  - reduced to 1 in 4 chance with 450 ppm stabilization

Ref: Sokolov, Forest, et al, 2008 and Webster et al, 2008, Joint Program, in preparation

Concluding Remarks

As with all investigations of complex and only partially understood systems the probability results must be treated with appropriate caution:

- Current knowledge of stability of great ice sheets, stability of thermo-haline circulation, ecosystem dynamics, climate-severe storm connections, future technological innovation, human population dynamics, political change, etc., is limited.

- Therefore, "surprises" not currently evident from model studies including uncertainty studies may occur.