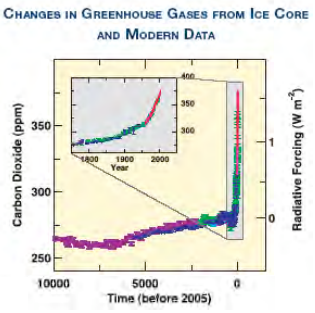
## Global Climate Change

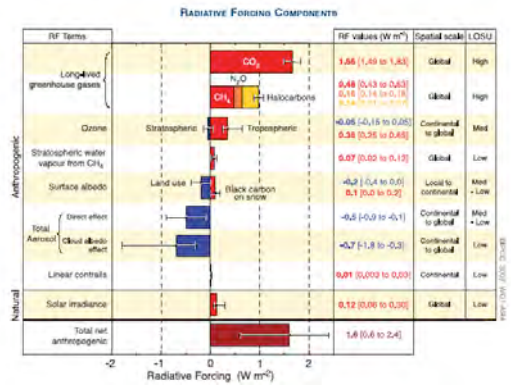
Observations of modern global change
Climate models
Projections of future global change

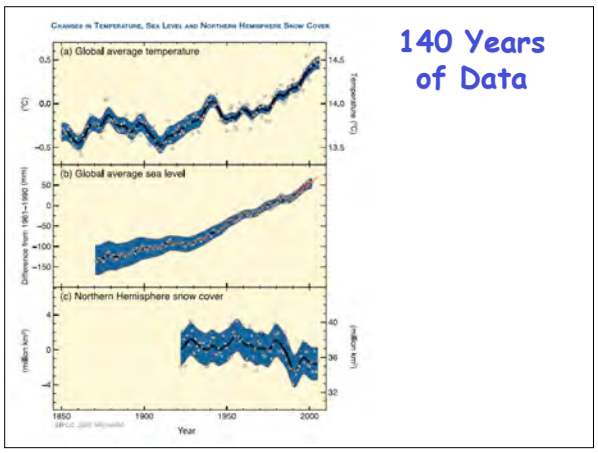
## Changing the Atmospheric Emissivity!



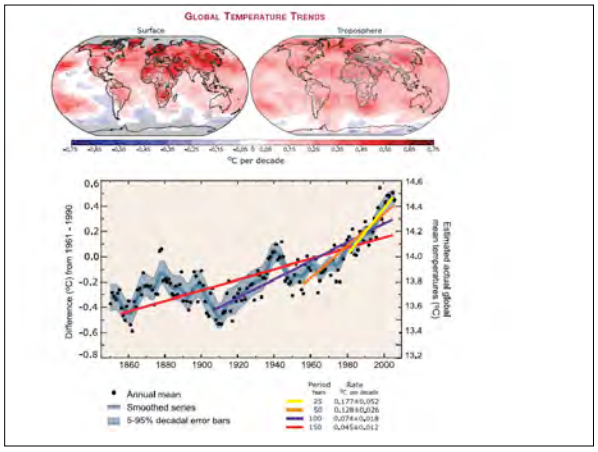

- After recovering from the last ice age, the atmospheric CO2 content was very steady
- Since the industrial revolution, it's increased from 278 ppm to 384 ppm
- Current radiative effect of 1.5 W $m^{-2}$
- What will happen in the next century?

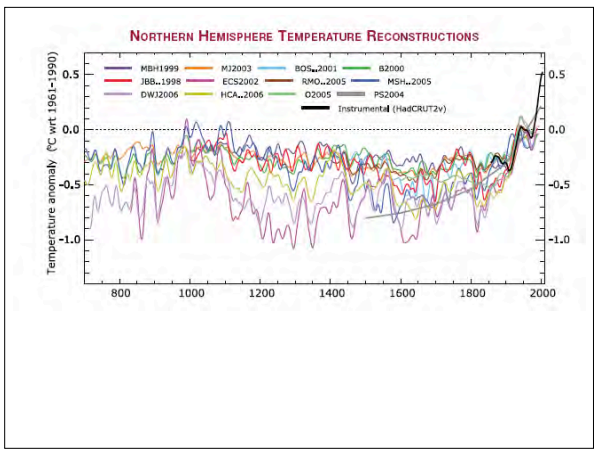
## Anthropogenic Forcing

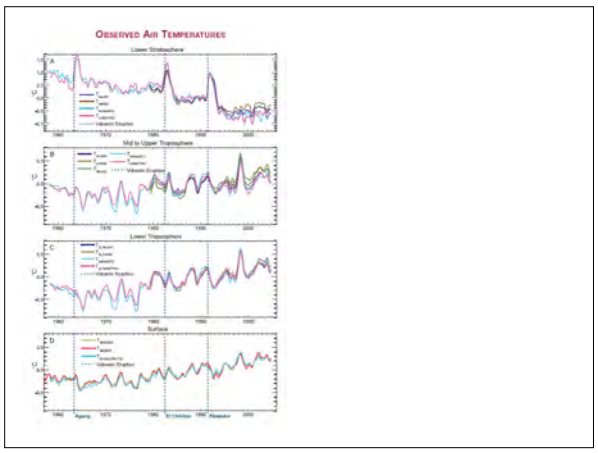


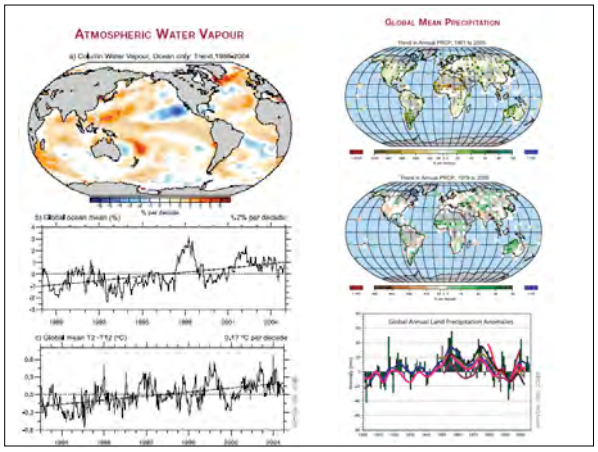


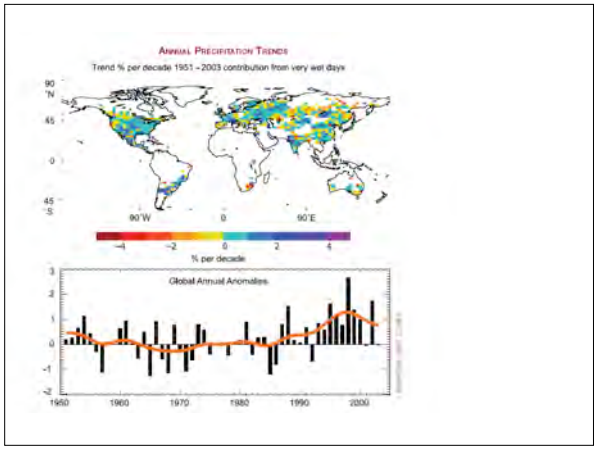

140 Years of Data

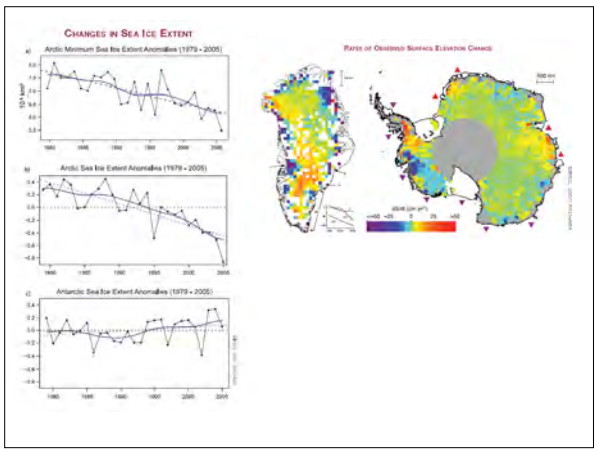


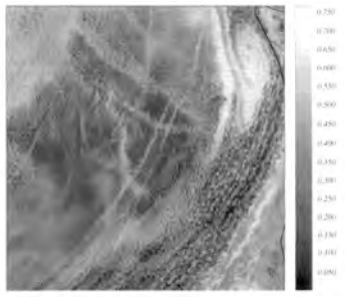

Observed Air Temperatures


Atmospheric Water Vapour
Global Mean Precipitation

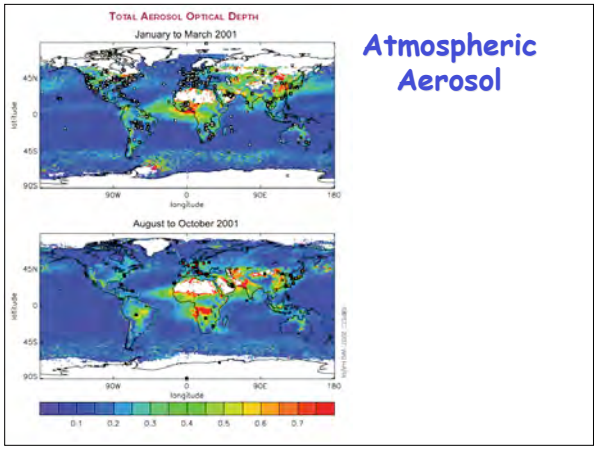

Annual Precipitation Trends
Trend % per decade 1951 – 2003 contribution from very wet days
% per decade
Global Annual Anomalies




## Aerosol-Cloud Albedo Feedback

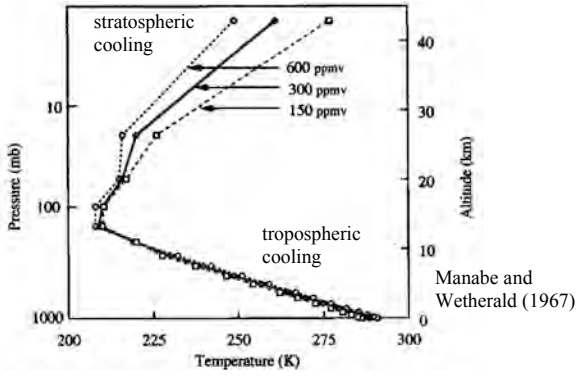


- Ship tracks off west coast
- Aerosol serves as CCN
- Makes more/smaller cloud drops
- Higher albedo



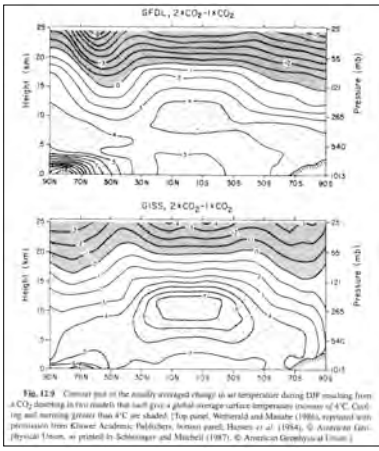

## Atmospheric Aerosol

## Radiative-Convective Equilibrium



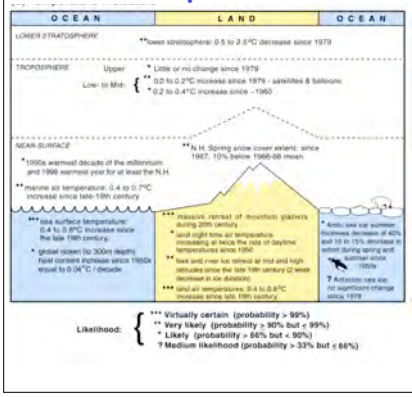

Manabe and Wetherald (1967)

## Vertical Structure

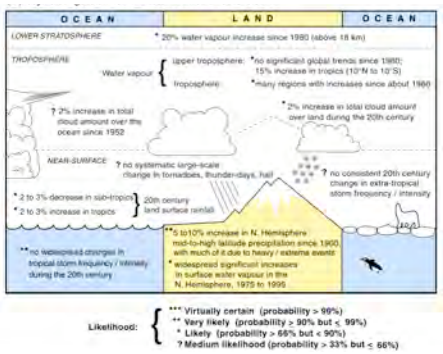


- Greenhouse "signature" is tropospheric warming and stratospheric cooling

## Temperature Indicators



## Hydrologic Indicators




## Climate Models

## Climate Model Structure

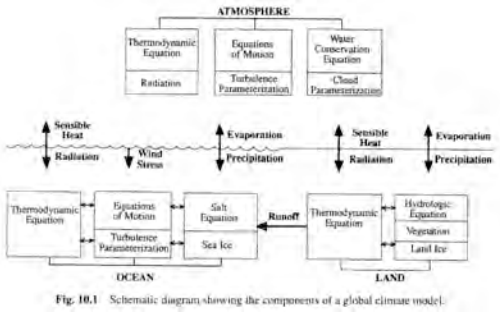
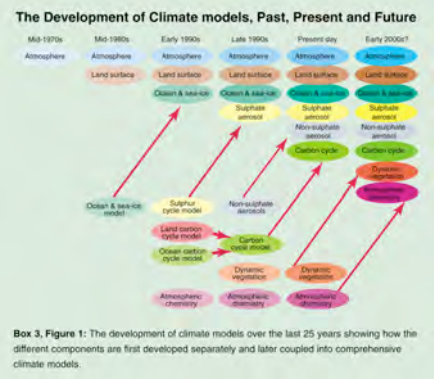
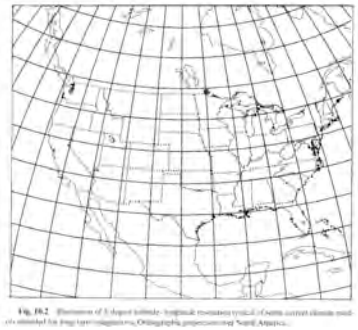



Fig. 10.1 Schematic diagram showing the components of a global climate model.

## Evolution of Climate Models

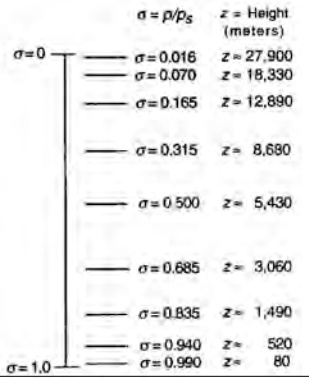



## Climate Model Grid Cells



- Recent global NWP models typically use dx ~ 50 km
- Typical climate models dx ~ 200 km

## Climate Model Vertical Structure



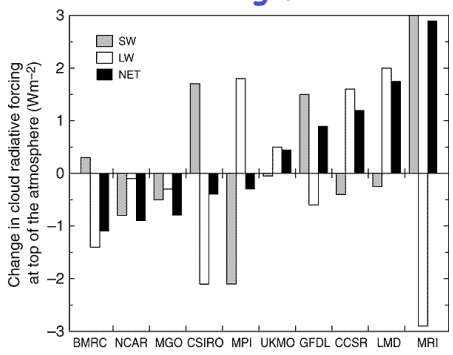

- 9-level model c. 1970
- Recent weather prediction models use ~60 levels, up to 1 mb
- Climate models typically somewhat coarser

## Resolution and Parameterization

## CMMAP

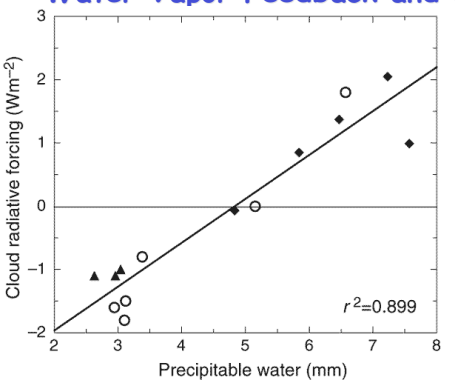
## CCSM

## Change in TOA Cloud Radiative Forcing for 2xCO2




*Change in the Top of the Atmosphere (TOA) Cloud Radiative Forcing (CRF) associated with a $CO_2$ doubling (from a review by Le Treut and McAvaney, 2000). The models are coupled to a slab ocean mixed layer and are brought to equilibrium for present climatic conditions and for a double $CO_2$ climate. The sign is positive when an increase of the CRF (from present to double $CO_2$ conditions) increases the warming, negative when it reduces it.*

## Water Vapor Feedback and Clouds

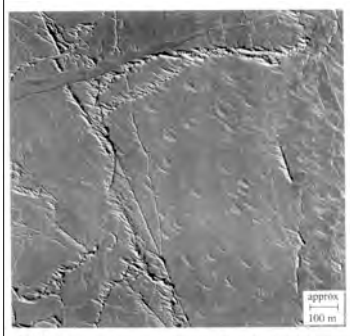



*Relationship between simulated global annually averaged variation of net cloud radiative forcing at the top of the atmosphere and precipitable water due to $CO_2$ doubling produced in simulations with different parameteriz-ations of cloud related processes.*

## Ocean-Atmosphere Coupling

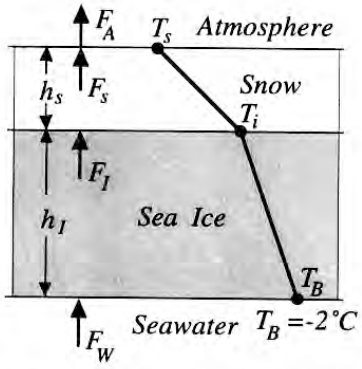
- CFL Stability criteria
- Spatial scales
- Time scales
- Asynchronous coupling
- Flux correction

## Sea Ice is Complicated!

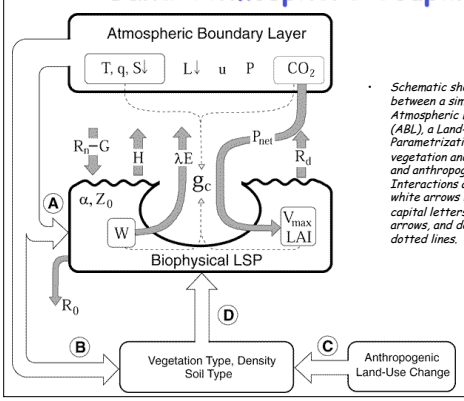



- Changes in albedo, thickness, heat fluxes, water vapor flux at sfc
- Freezing, thawing, advection, interaction with ocean currents

## Sea Ice Temperatures and Heat Fluxes

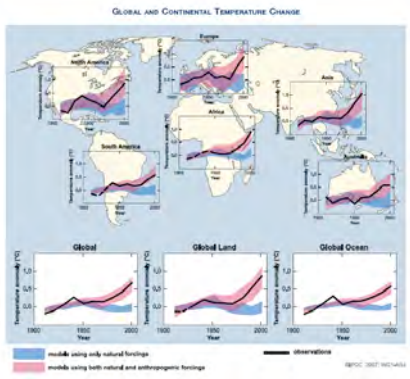


## Land-Atmosphere Coupling




- *Schematic showing relationships between a simulation of the Atmospheric Boundary Layer (ABL), a Land-Surface Parametrization (LSP), vegetation and soil properties, and anthropogenic change. Interactions are shown by broad white arrows marked with capital letters, fluxes by grey arrows, and dependencies by dotted lines.*

## Predicting the past




Models can reproduce observed changes. Both anthropogenic and natural forcing (e.g., solar and volcanic aerosol) are required to explain historical changes.

## Signal:Noise

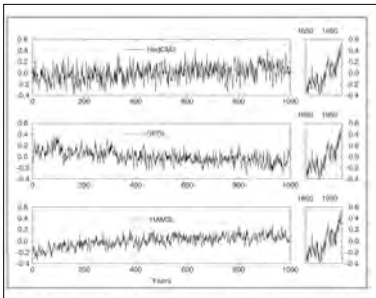
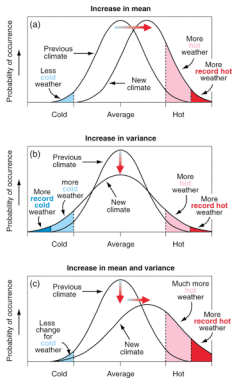


**Figure 14**: Global mean surface air temperature anomalies from 1,000 year control simulations with three different climate models, – Hadley, Geophysical Fluid Dynamics Laboratory and Hamburg, compared to the recent instrumental record. No model control simulation shows a trend in surface air temperature as large as the observed trend. If internal variability is correct in these models, the recent warming is likely not due to variability produced within the climate system alone. [Based on Figure 12.1]

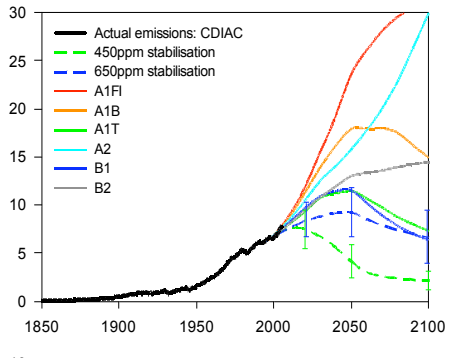
## Projections of the Future



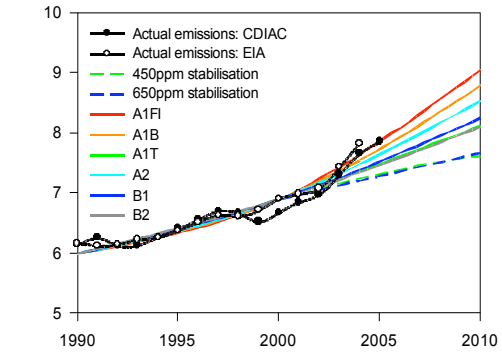

## Means and Variances

*Schematic showing the effect on extreme temperatures when (a) the mean temperature increases, (b) the variance increases, and (c) when both the mean and variance increase for a normal distribution of temperature.*

## Emission Scenarios

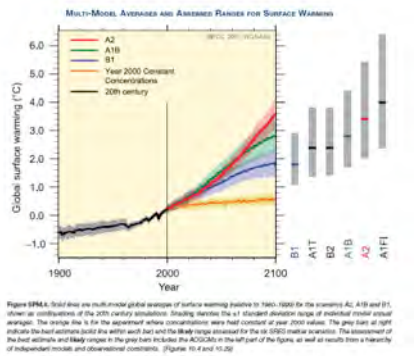


## Emission Scenarios vs Reality

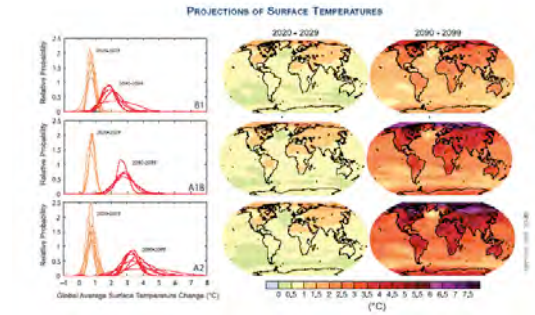



Raupach et al. 2007 PNAS

## Future Climate Simulations




- Some warming is "committed"
- Emissions
- Uncertainty



## Accelerated Hydrologic Cycle

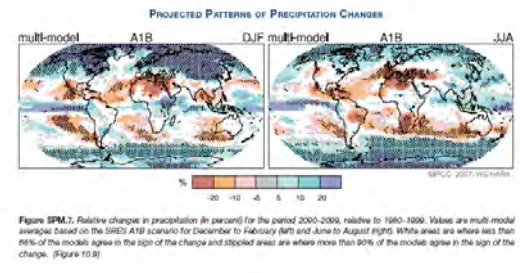


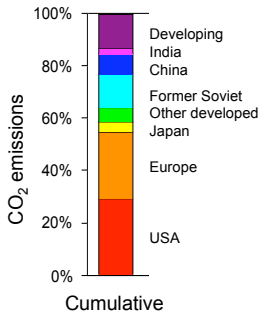

Figure SPM.7. Relative changes in precipitation (in percent) for the period 2090-2099, relative to 1980-1999. Values are multi-model average based on the SRES A1B scenario for December to February (left) and June to August (right). White areas are where less than 66% of the models agree in the sign of the change and stippled areas are where more than 90% of the models agree in the sign of the change. (Figure 10.9)

Wet places get wetter (ITCZ, midlats), and dry places get drier (subtropical highs)

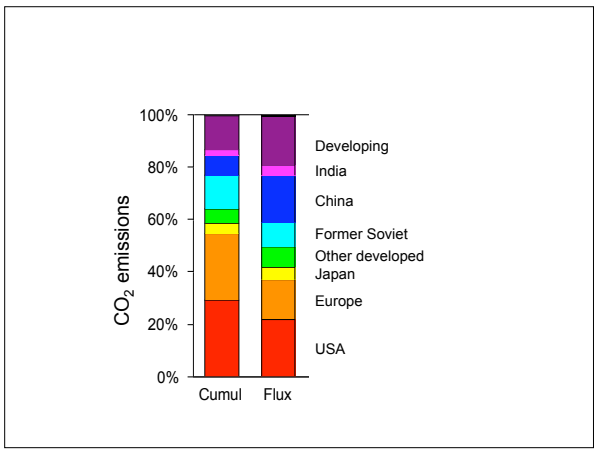
## Climate Impacts

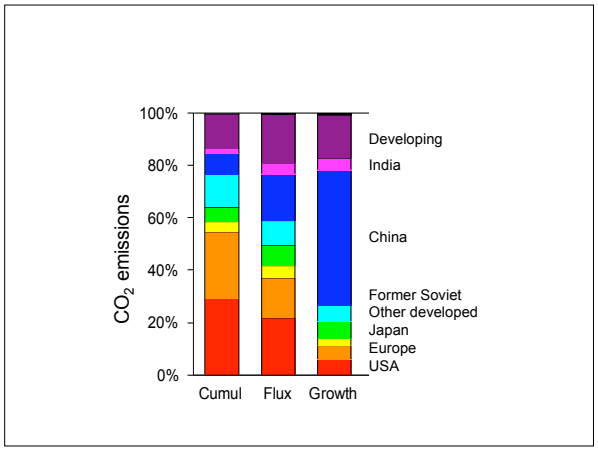
| Phenomenon and direction of trend | Likelihood that trend occurred in late 20th century (typically post 1960) | Likelihood of a human contribution to observed trend | Likelihood of future trends based on projections for 21st century using SRES scenarios |
|---|---|---|---|
| Warmer and fewer cold days and nights over most land areas | Very likely | Likely | Virtually certain |
| Warmer and more frequent hot days and nights over most land areas | Very likely | Likely (nights) | Virtually certain |
| Warm spells/heat waves. Frequency increases over most land areas | Likely | More likely than not | Very likely |
| Heavy precipitation events. Frequency (or proportion of total rainfall from heavy falls) increases over most areas | Likely | More likely than not | Very likely |
| Area affected by droughts increases | Likely in many regions since 1970s | More likely than not | Likely |
| Intense tropical cyclone activity increases | Likely in some regions since 1970 | More likely than not | Likely |
| Increased incidence of extreme high sea level (excludes tsunamis) | Likely | More likely than not | Likely |

## Dramatic contrast – history versus future




Raupach et al. PNAS 2007


100%
80%
60%
40%
20%
0%
$CO_2$ emissions
Cumul
Flux
Developing
India
China
Former Soviet
Other developed
Japan
Europe
USA


100%
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Cumul
Flux
Growth
Developing
India
China
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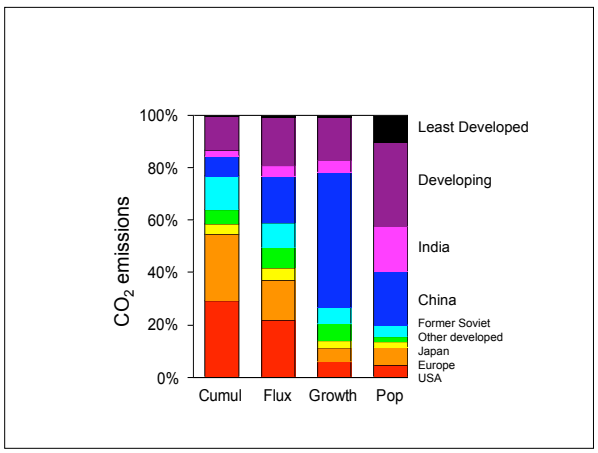
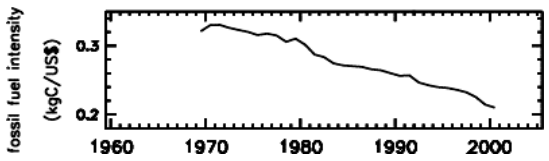
Japan
Europe
USA

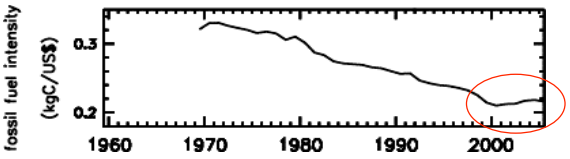

100%
80%
60%
40%
20%
0%
$CO_2$ emissions
Cumul
Flux
Growth
Pop
Least Developed
Developing
India
China
Former Soviet
Other developed
Japan
Europe
USA

## Carbon intensity of the world economy fell steadily for 30 years



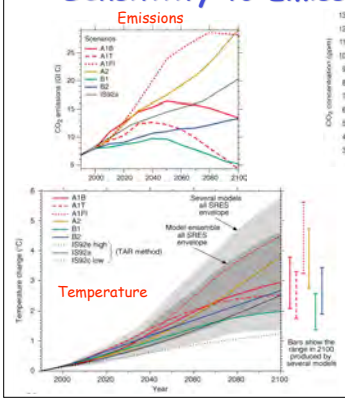

Canadell et al. 2007

## Until 2000!



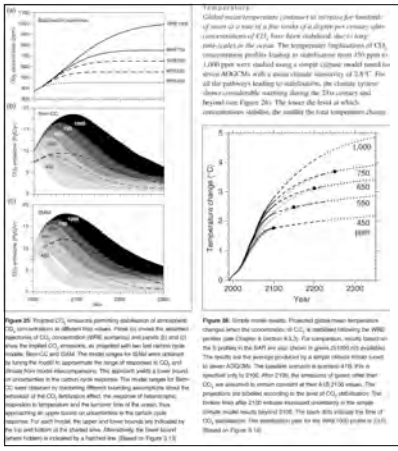

Canadell et al. 2007

## Sensitivity to Emission Scenarios



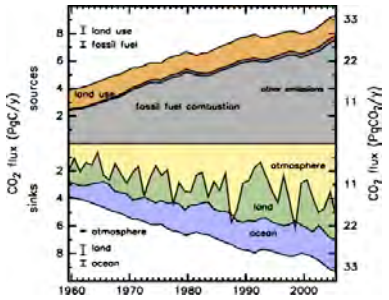

- Uncertainty about human decisions is a major driver of uncertainty in climate change
- Model ensemble simulated warming ranges ~ 2.5° K in 2100

## CO2 Stabilization ?



## Only about 40% of the emissions stay in the atmosphere

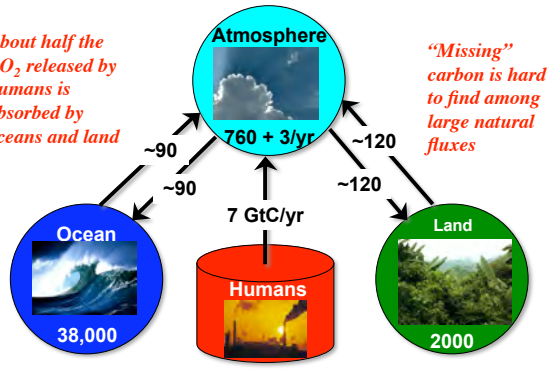
- Atmosphere = 42%
  - +0.0011/yr
- Oceans = 30%
  - -0.0005/yr
- Land =27%
  - -0.0006/yr
- Subsidy from land & oceans




Canadell et al. 2007

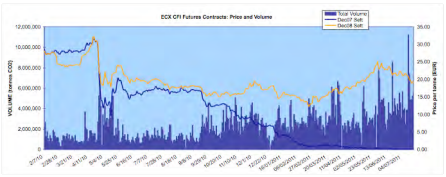
## The Global Carbon Cycle

*About half the $CO_2$ released by humans is absorbed by oceans and land*




*"Missing" carbon is hard to find among large natural fluxes*

## European Climate Exchange
### Futures Trading: Permits to Emit CO2




- European "cap-and-trade" market set up as described in Kyoto Protocol
- About €20/ton of CO2 = $101/ton of carbon

## The "Missing Sink"

- Terrestrial and marine exchanges currently remove more than 4 GtC per year from the atmosphere
- This free service provided by the planet constitutes an effective 50% emissions reduction, worth $400 Billion per year at today's price on the ECX!
- Science is currently unable to quantitatively account for
  - The locations at which these sinks operate
  - The mechanisms involved
  - How long the carbon will remain stored
  - How long the sinks will continue to operate
  - Whether there is anything we can do to make them work better or for a longer time

## Where Has All the Carbon Gone?

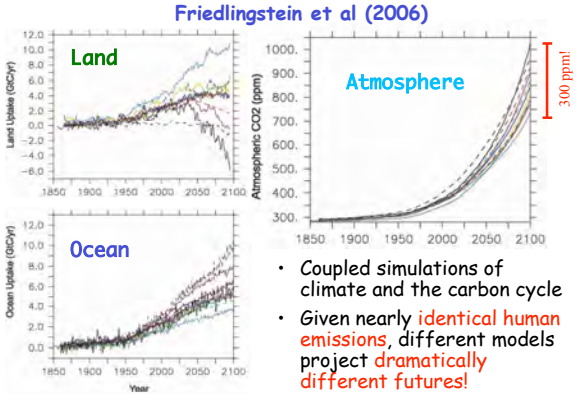
- Into the **oceans**
  - **Solubility pump** ($CO_2$ very soluble in cold water, but rates are limited by slow physical mixing)
  - **Biological pump** (slow "rain" of organic debris)
- Into the **land**
  - **$CO_2$ Fertilization** (plants eat CO2 … is more better?)
  - **Nutrient fertilization** (N-deposition and fertilizers)
  - **Land-use change** (forest regrowth, fire suppression, woody encroachment … but what about Wal-Marts?)
  - Response to **changing climate** (e.g., Boreal warming)

## Coupled Carbon Cycle Climate Modeling

- "Earth System" Climate Models
  - Atmospheric GCM
  - Ocean GCM with biology and chemistry
  - Land biophysics, biogeochemistry, biogeography
- Prescribe fossil fuel emissions, rather than CO2 concentration as usually done
- Integrate model from 1850-2100, predicting both CO2 and climate as they evolve
- Oceans, plants, and soils exchange CO2 with model atmosphere
- Climate affects ocean circulation and terrestrial biology, thus feeds back to carbon cycle

## Carbon-Climate Futures

Friedlingstein et al (2006)




- Coupled simulations of climate and the carbon cycle
- Given nearly identical human emissions, different models project dramatically different futures!