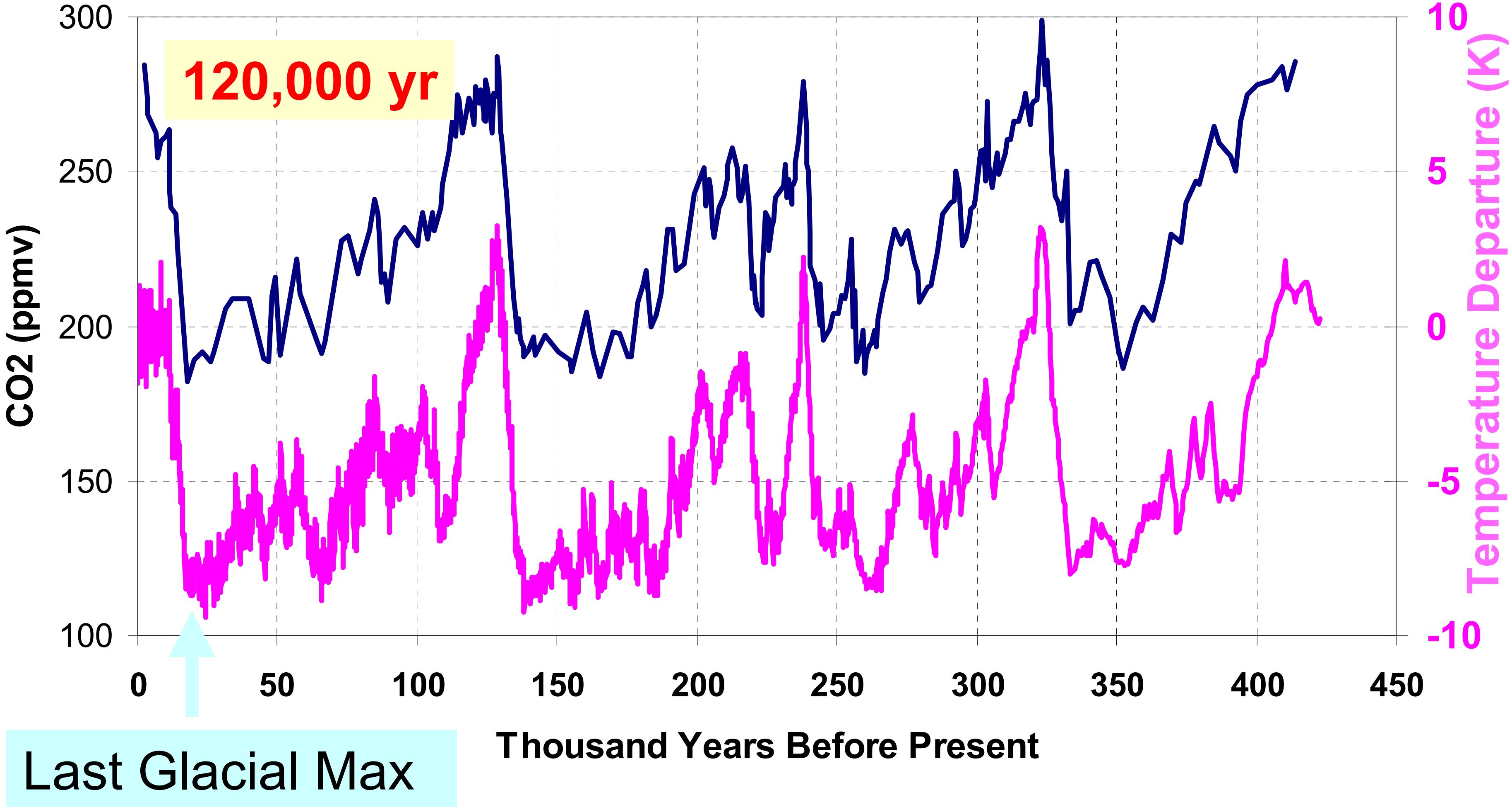
Climate Change: What Do We Really Know?

Inez Fung
UC Berkeley

International Sherwood Fusion Theory Conference,
Missoula, MT April 26 2004

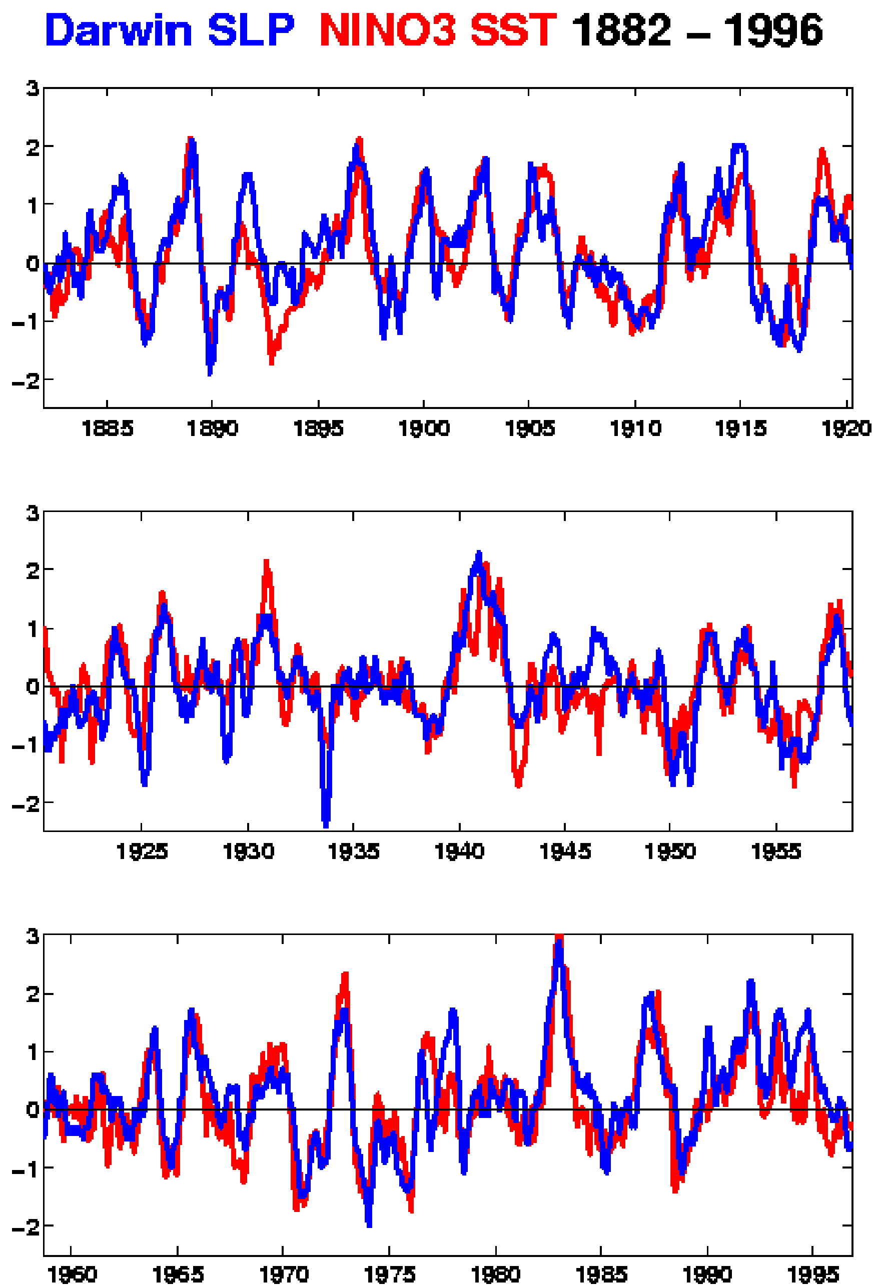
Milankovitch Cycles: Orbital Variations → "external" forcing of climate variability



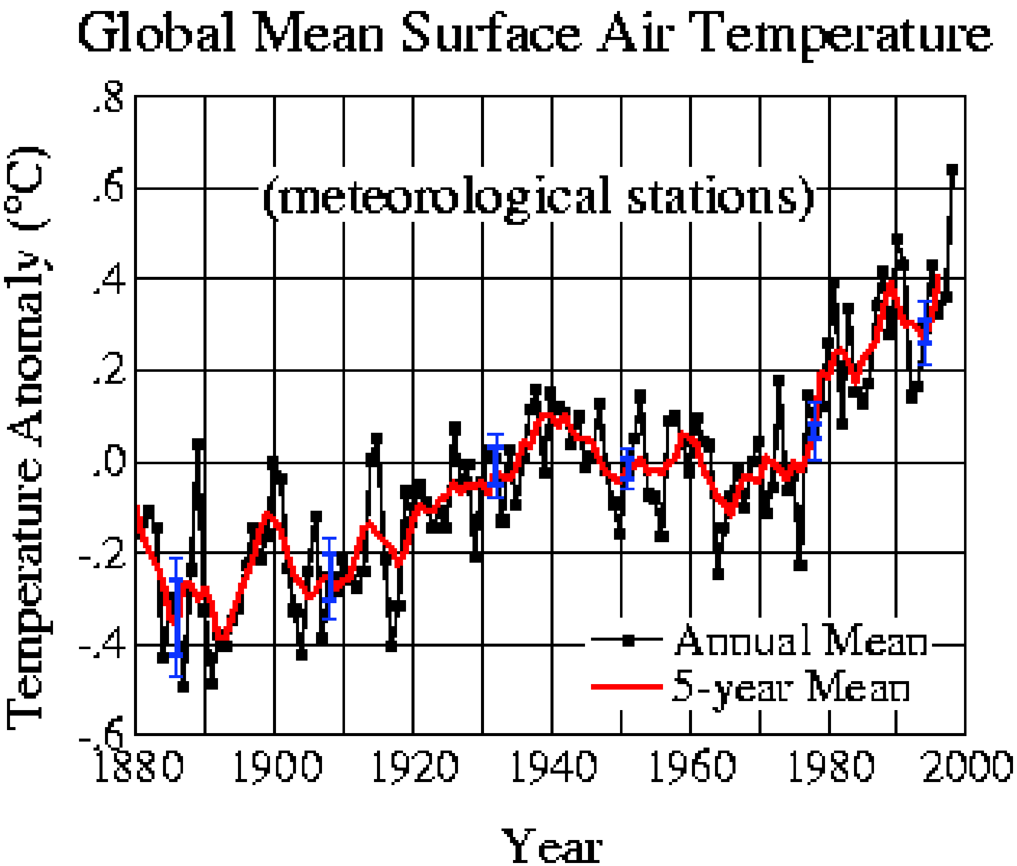
Co-Variations of CO_2 and Climate

"Internal" Variability of the Climate System

- El-Nino / Southern Oscillation
- Instability of the air-sea system in the equatorial pacific
- Irregular
- 2-7 year



Climate and Climate Change: External forcing + internal variability



- Baseline: avg atm state 1950-1980

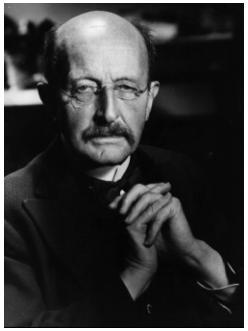
- Focus: last 200 yr, since industrial rev
- Instrumental record

- Projection: Next 100 yr

Climate and Climate Change

- **Physics of Climate**
- Climate Forcing
- Climate Processes
- Climate Change Response
- Climate Projections & Uncertainties

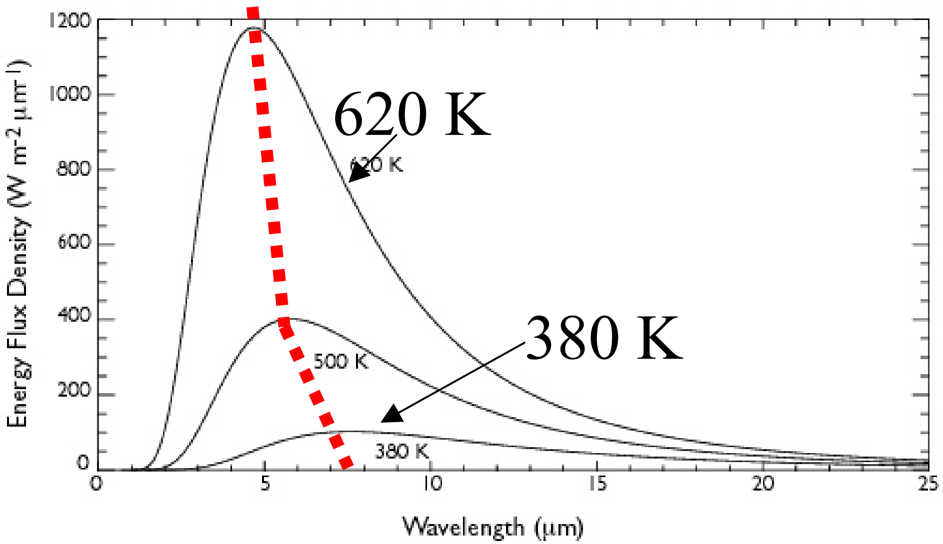
Blackbody Radiation



Max Planck (1858 – 1947)
Nobel Prize 1918

Planck's Law:

The amount and spectrum of radiation emitted by a blackbody is uniquely determined by its temperature

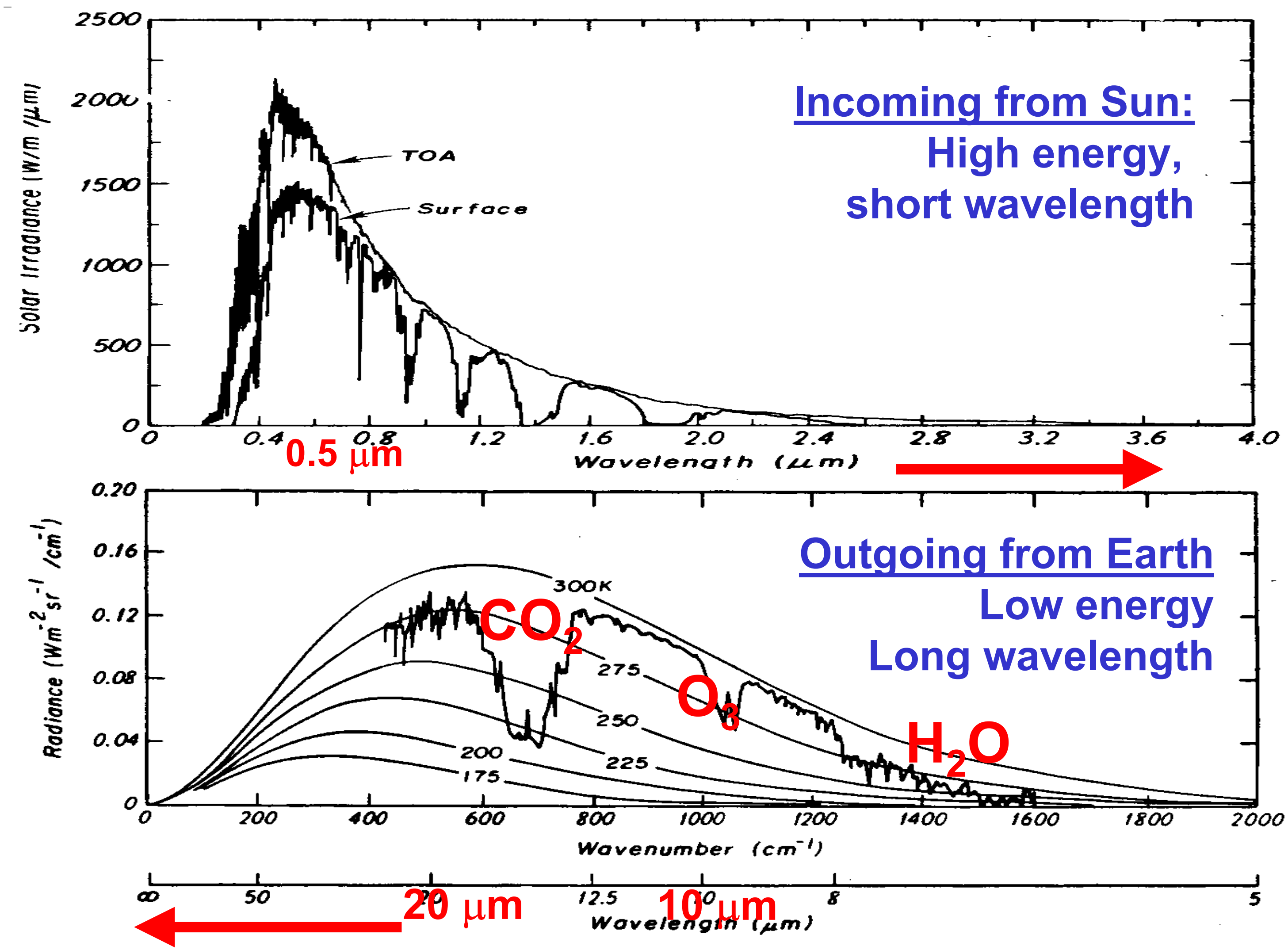


wavelength

Sun: 6000K → peak emission at 0.5 μm "Short wave"

Earth: ~300K → peak emission 10-20 μm "Longwave"

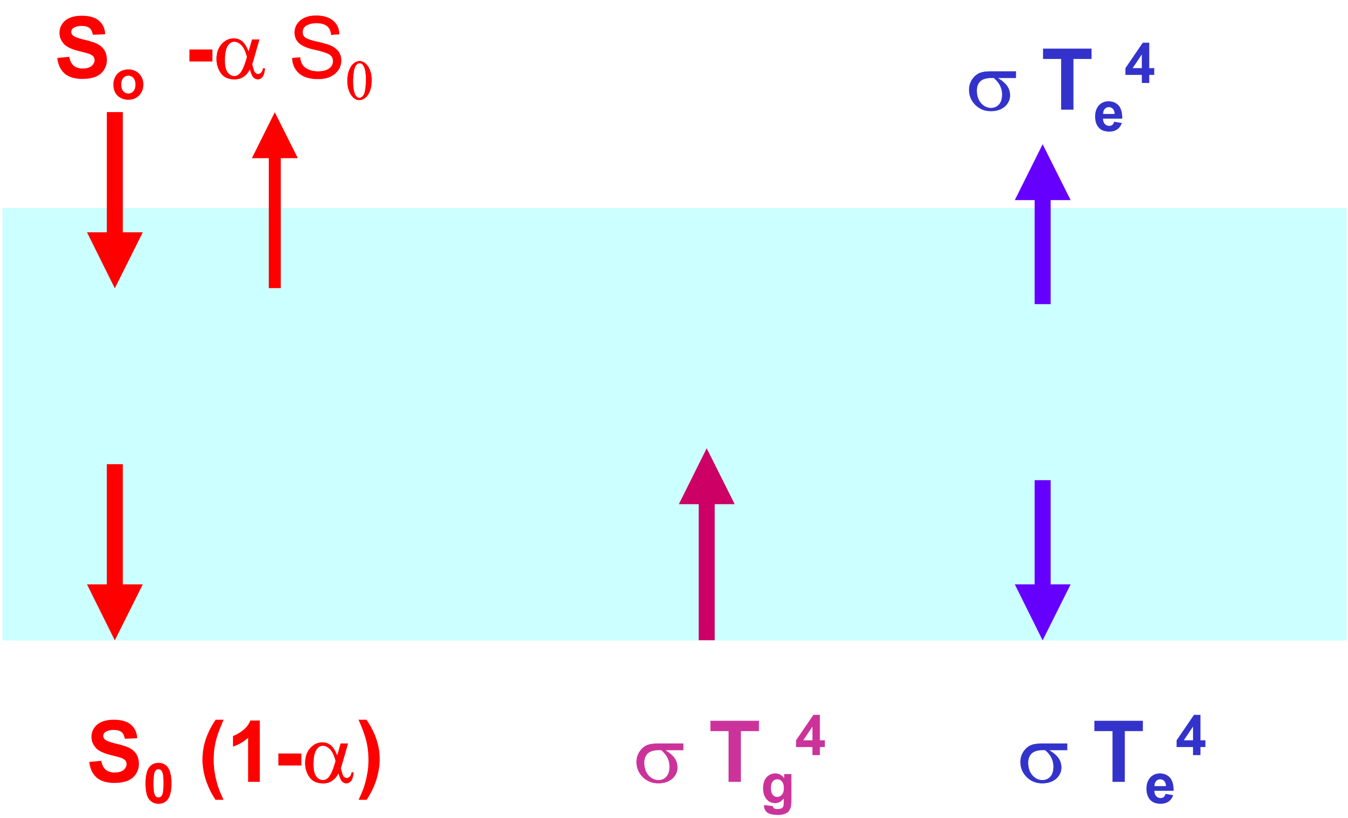
Earth Spectrum



Energy Balance:

incoming solar = outgoing terrestrial radiation

$$S_0/4\ (1-\alpha) = \sigma T^4$$



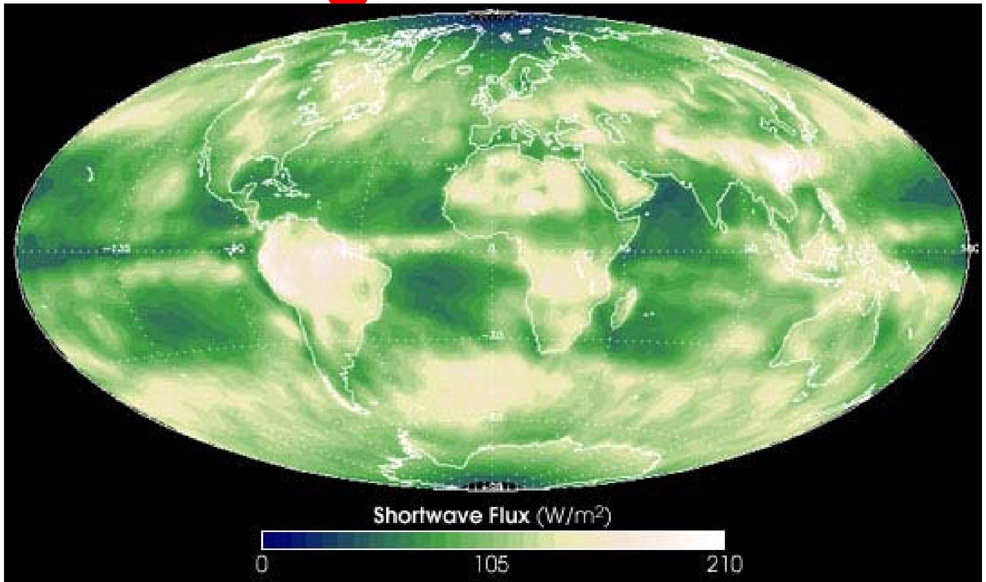
Simplest case:

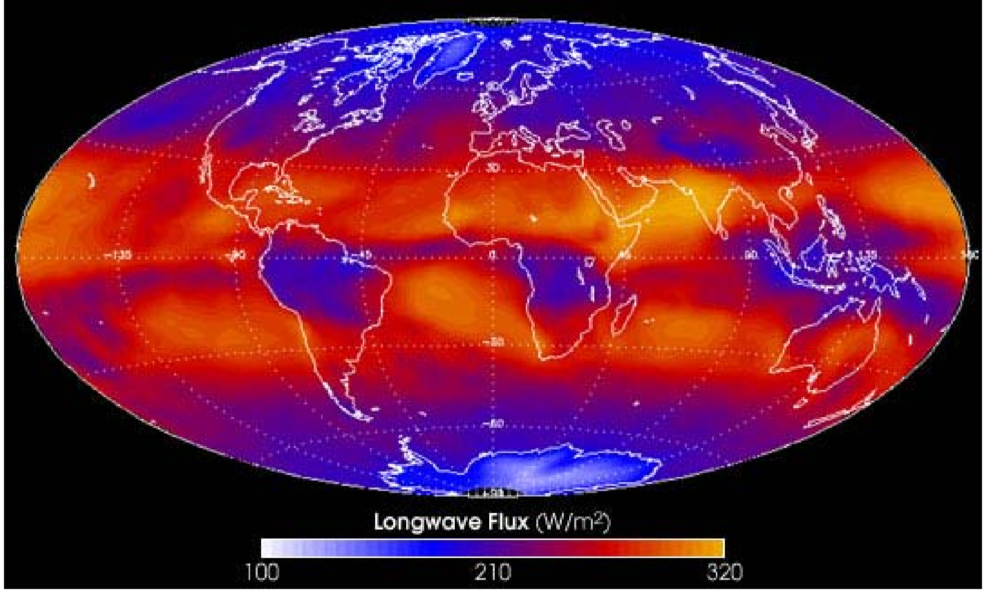
one layer atm; greenhouse gases;

No absorbers of shortwave radiation;

α=albedo

Energy Balance at Top of Atmosphere: incoming shortwave = outgoing longwave





Incoming Shortwave:

S_o (1 – albedo)

High albedo:

Clouds (~10 μm), ice, deserts

Outgoing longwave radiation: σT^4

High clouds radiate at lower T

Climate and Climate Change

- **Physics of Climate**
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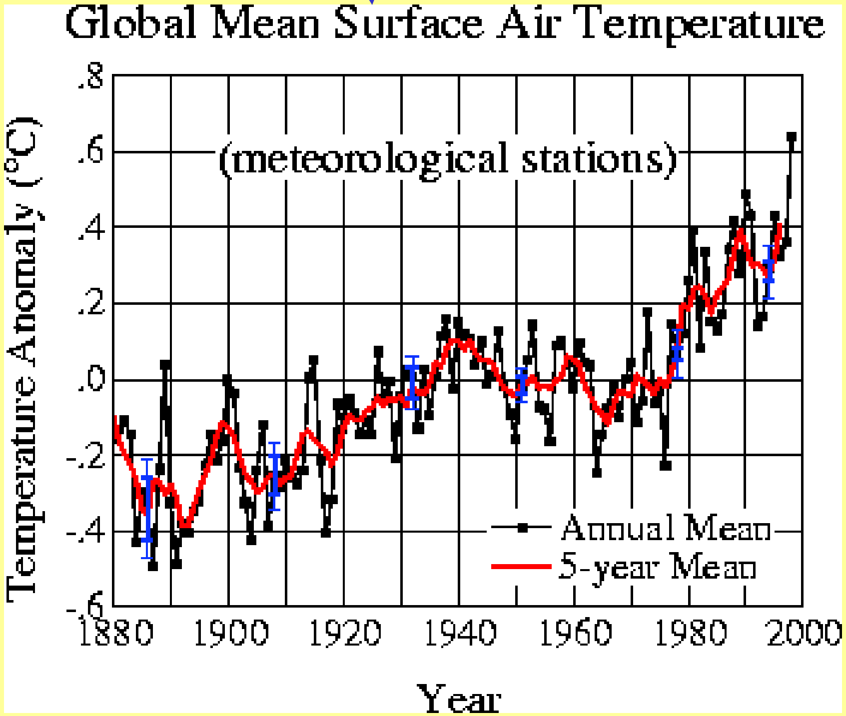
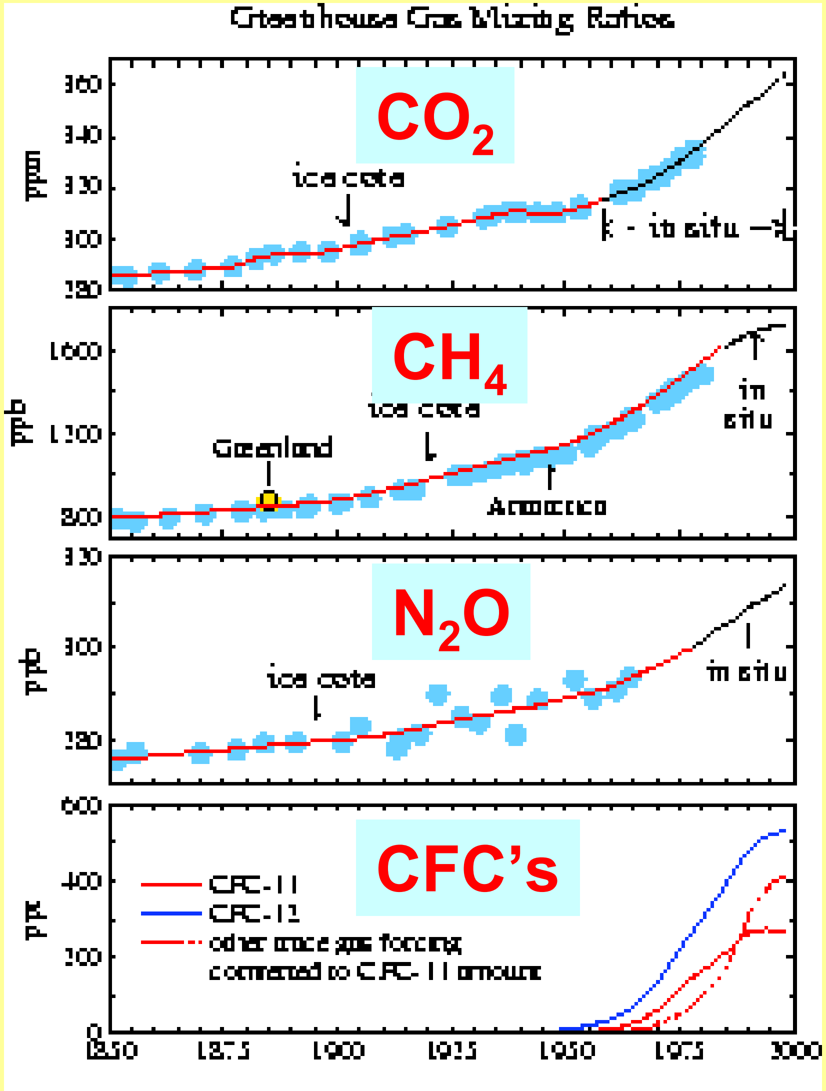
- Uncertainties

Since 1800: Atm CO_2 has increased by 30%

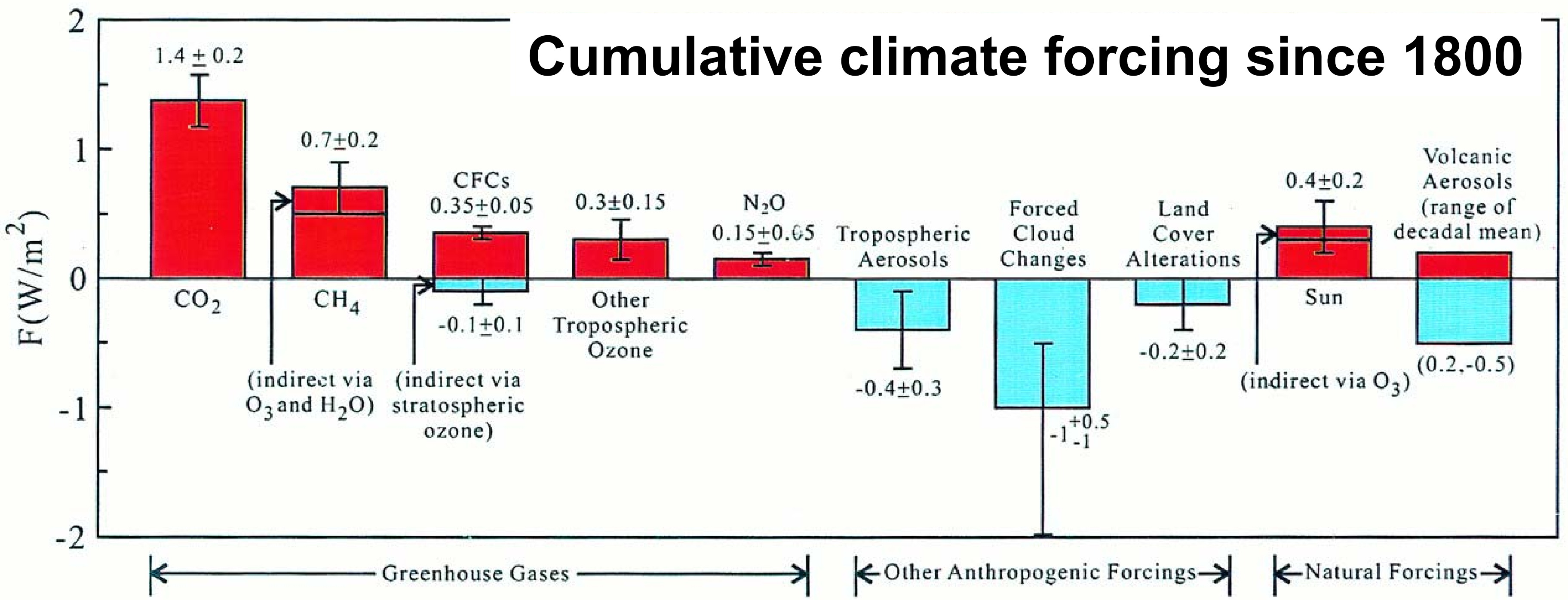
Increase in temperature // increase in greenhouse gases





Climate Forcing:

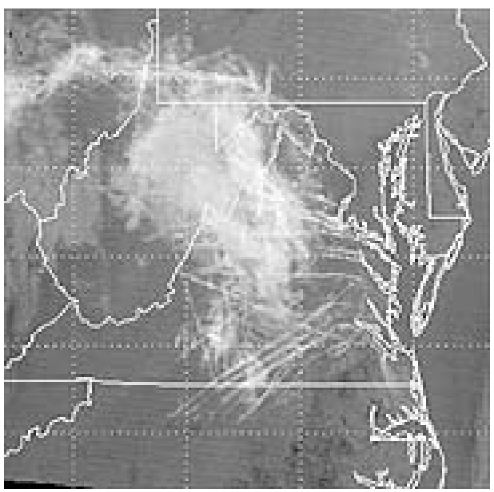
expressed as a change in radiative heating (W/m^2) at surface for a given change in trace gas composition or other change external to the climate system



Hansen PNAS 2001

Forced Cloud Changes:

anthropogenic aerosols may act as cloud condensation nuclei & change cover cover, cloud drop size, cloud lifetimes

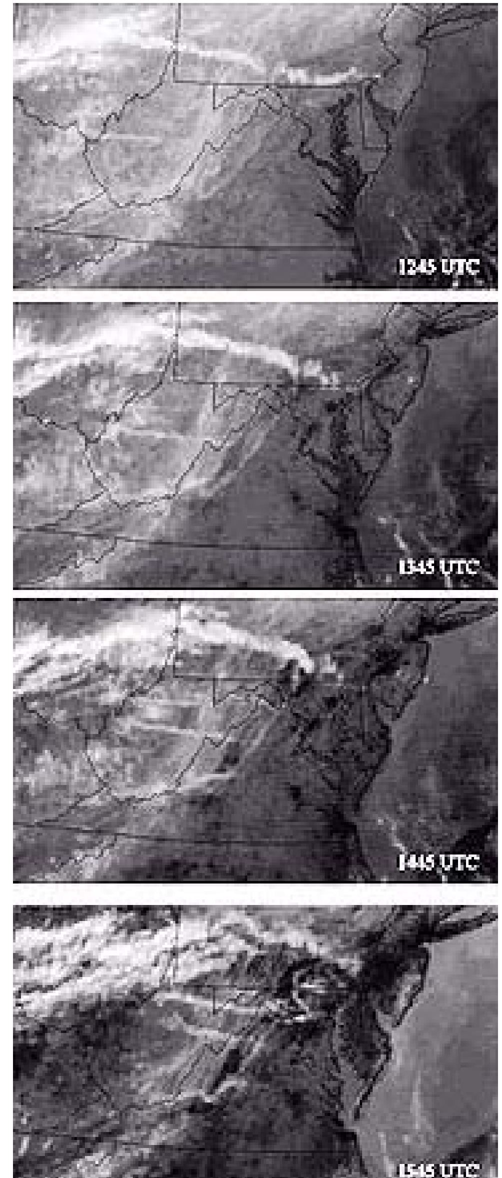


Jan 26 2001

Typical day: 700-800 planes

Sep 11 2001:

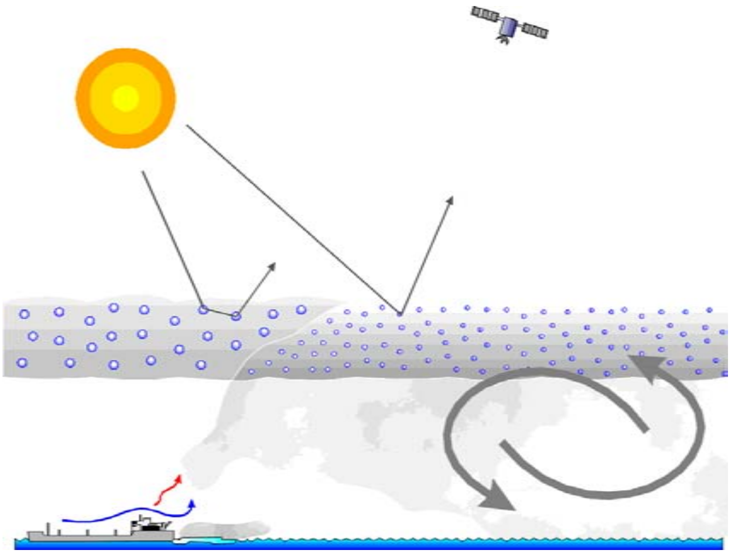
Air Force One + 9 military jets

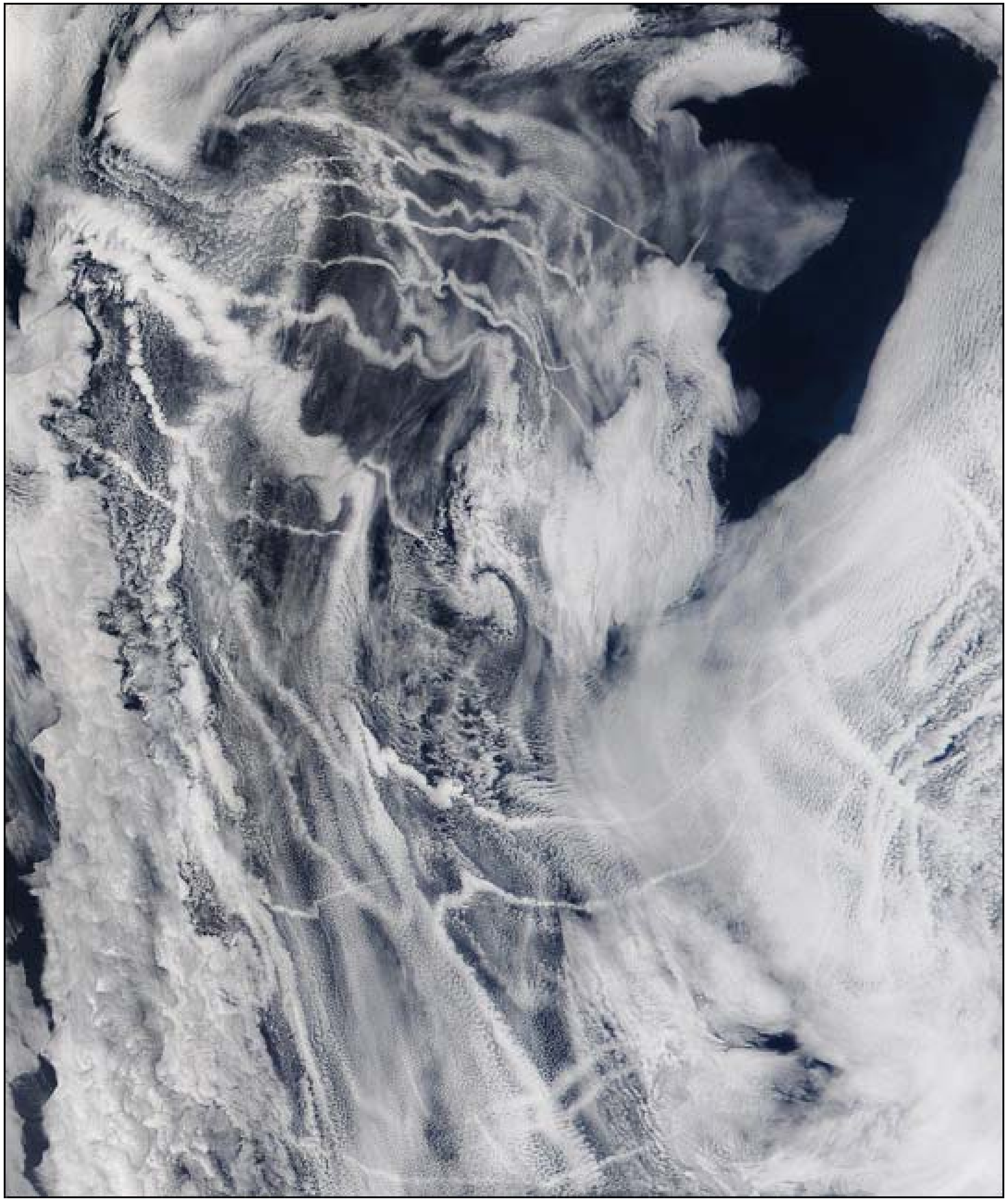


Jet contrails stimulated growth of cirrus clouds 5 hrs later

Ship Tracks:

- more cloud condensation nuclei
- smaller drops
- more drops
- more reflective





Climate and Climate Change

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Climate Processes

$$D/DT\,\vec{\mathbf{v}} - \mathbf{2}\,\Omega x \vec{v} = 1/\rho\,\nabla p - \vec{g} + \vec{F}$$

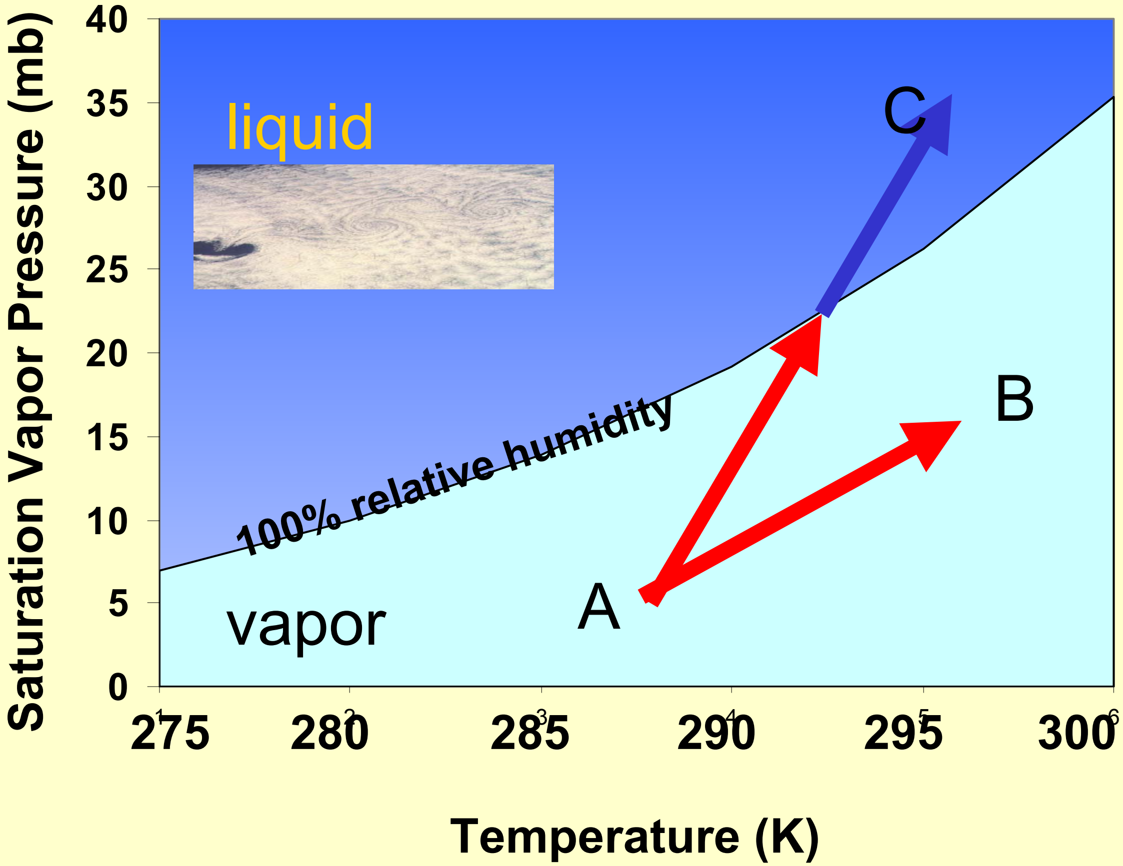
D/Dt (temperature)

= solar rad (clouds) + net IR rad (T, humidity) + sensible heat + latent heat

D/Dt (humidity) = evap - condensation

D/Dt (liq water) = condensation - evap

Climate Dial: Three phases of water



A → B

+ water vapor

+ greenhouse

Warming

A → C

+ water vapor

+ cloud cover

+ greenhouse

- absorption of sunlight

Ice → Liquid

+ absorption of sunlight

Climate Forcing, Climate Processes and Climate Feedbacks:

A given change in "external" climate forcing (e.g. 2xCO_2) will trigger changes in the hydrologic system, atm circulation. These "internal" changes will act to amplify or damp the initial forcing.

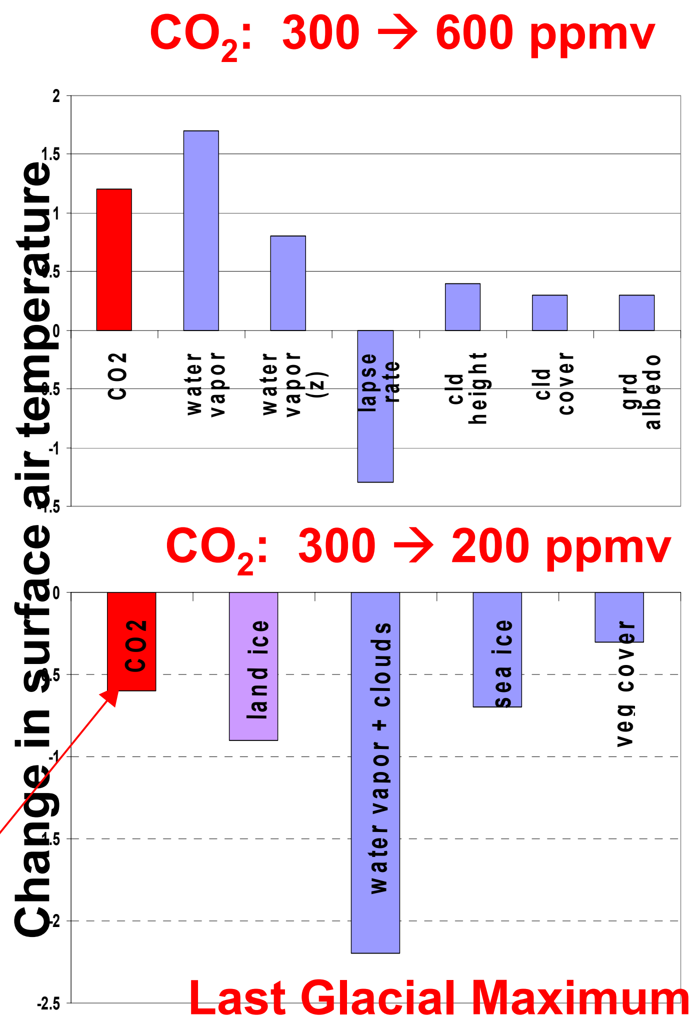
$$\Delta T\_realized = \textit{feedback factor} \times \Delta T\_forcing$$

Climate Forcing and Climate Feedbacks:
ΔT_realized = *feedback factor* x ΔT_forcing

feedback factor ~ 1 - 4

- Smaller feedback factor cannot explain cooling during the Last Glacial Maximum

- Without CO_2 decrease, cannot explain cooling during the Last Glacial Maximum



Climate and Climate Change

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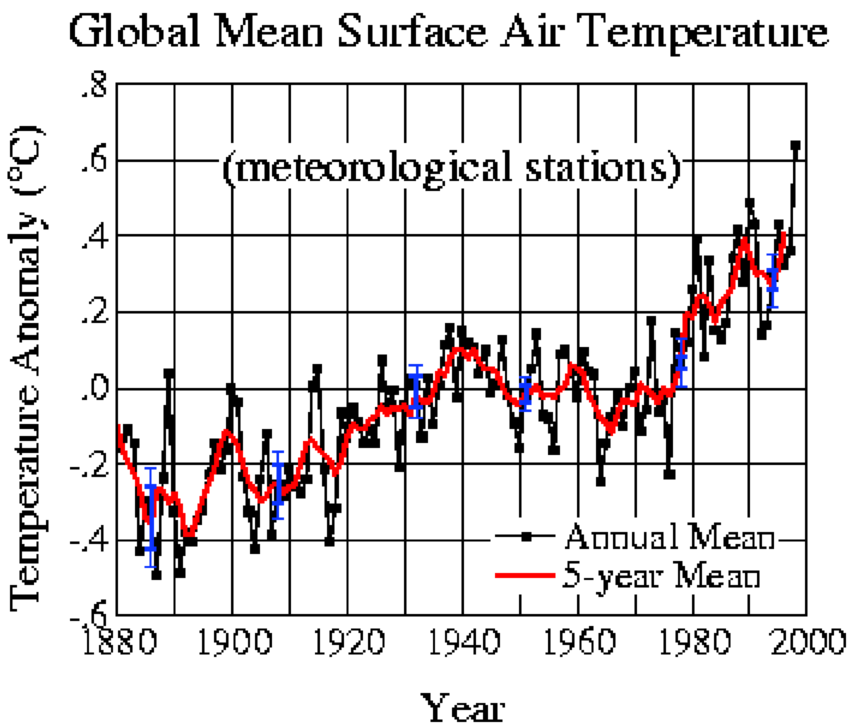
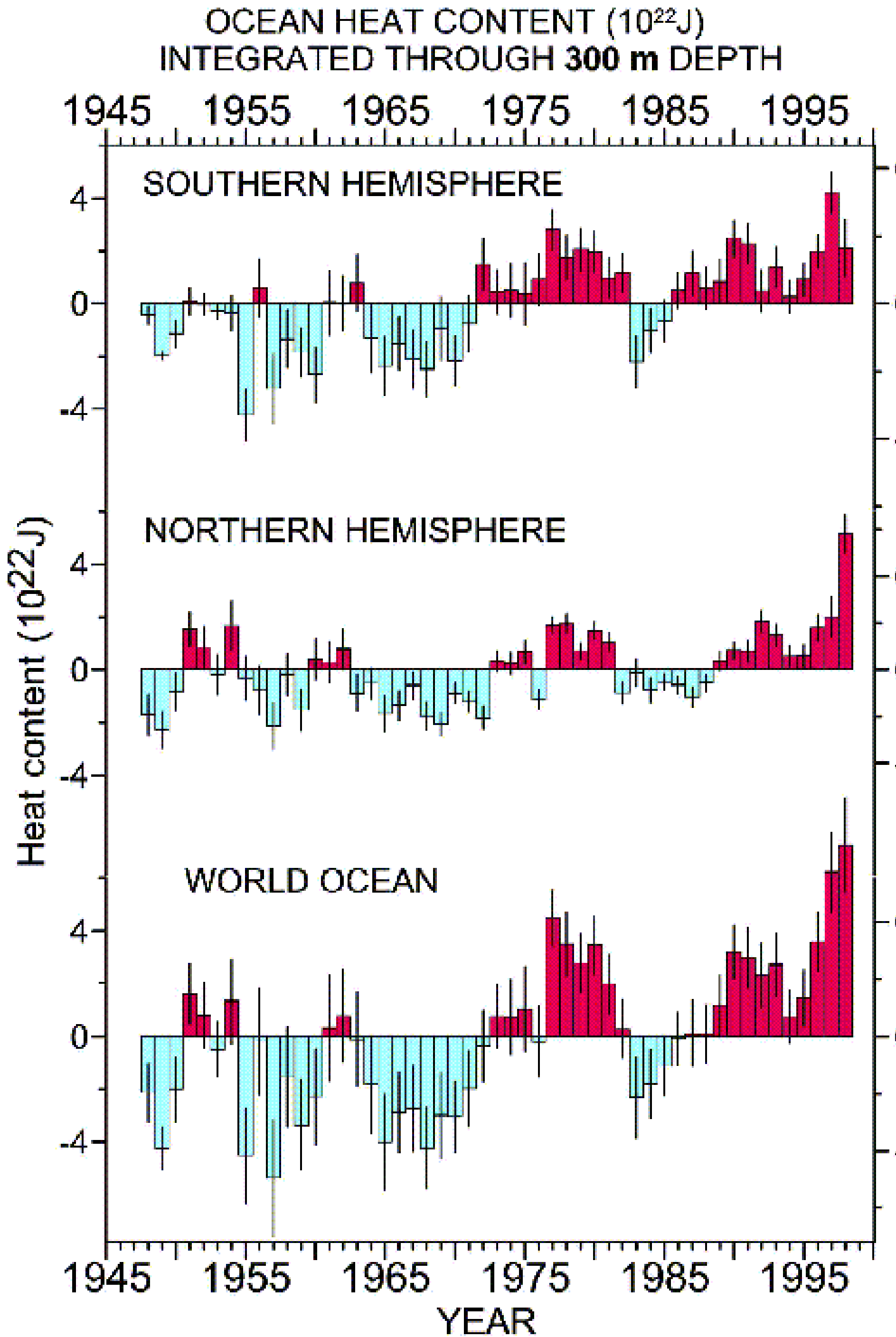
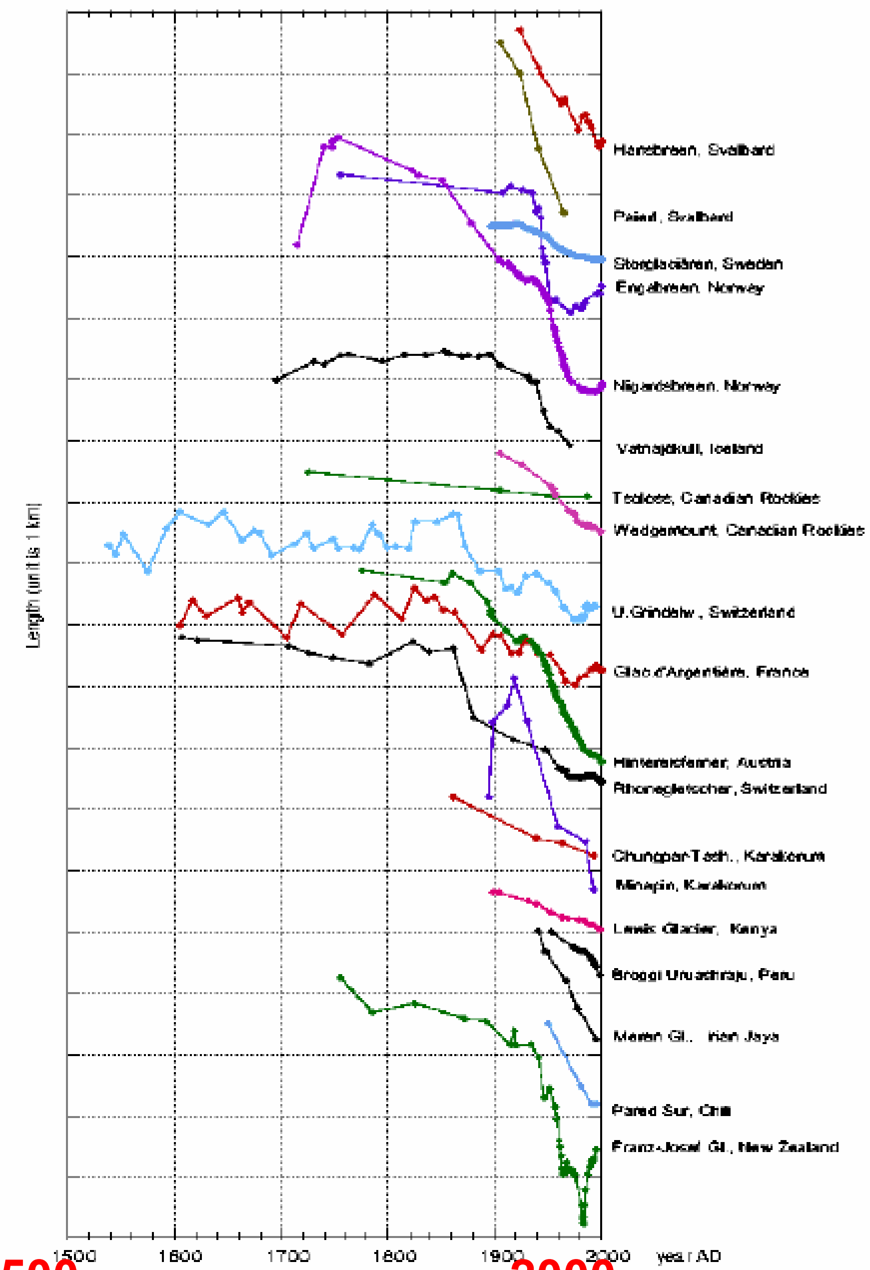
Increase in both atm and ocean heat content since 1945: unlikely caused by natural variability and redistribution of heat



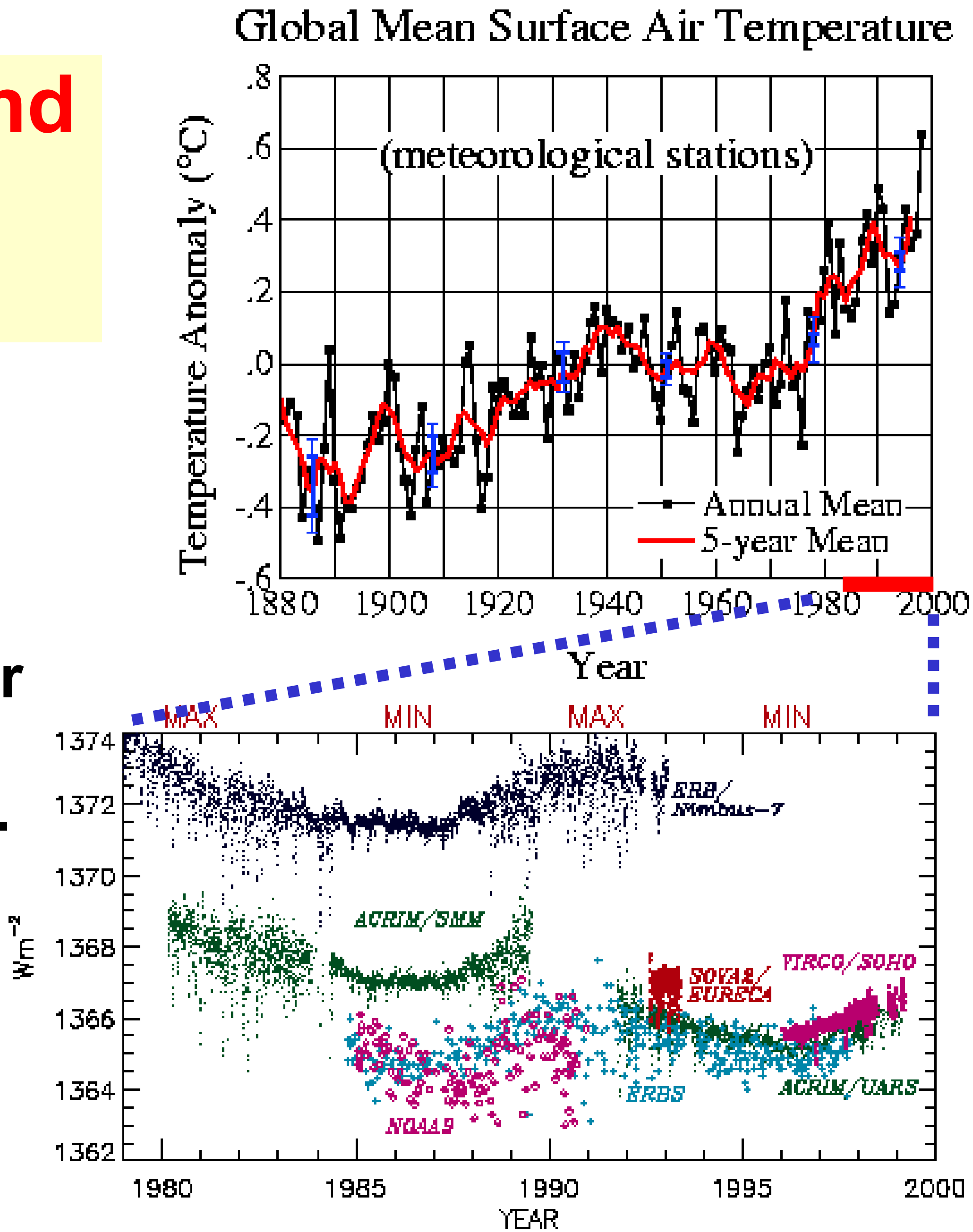


Area of Glaciers



1500 2000

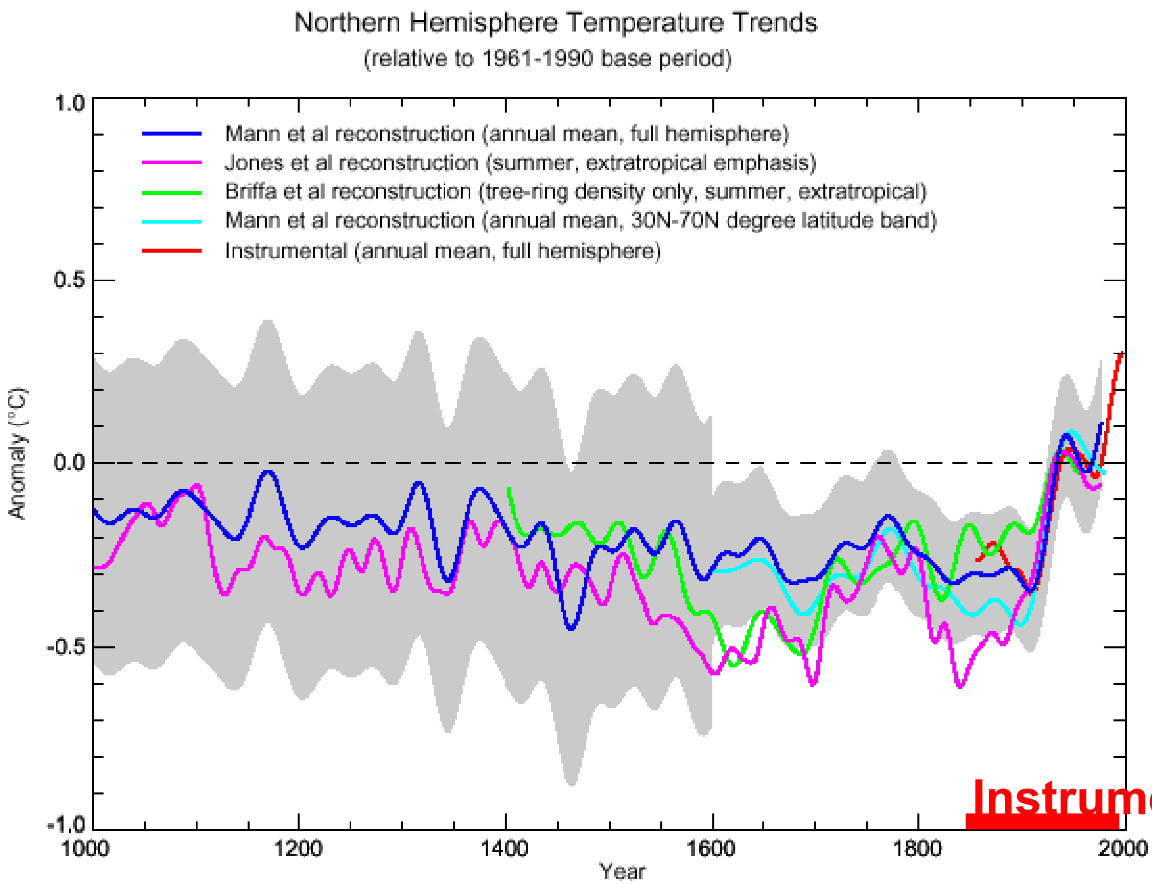
Temperature trend not caused by solar variability



Measurements of solar irradiance:

- **Clear solar-min solar-max cycle**
- **Offsets among instruments**
- **No trend**

“Forced” vs “Natural” climate change



<u>**Temperature Trends**</u>

<u>**Glacial-interglacial**</u>

10 K /10,000 yr
= 1 K/1,000 yr

<u>**AD 1000-1600:**</u>

0.9K / 600 yr
= 0.15K /100 yr
Cannot be ruled out

<u>**AD 1980-2000:**</u>

0.5 K / 20 years
No evidence of abrupt “natural” climate change

Uncertainty: natural climate variability on 10^2 - 10^3 years; abrupt climate change

<u>For the next 100 years</u>, natural variability <u>*unlikely*</u> to exceed 0.5K

Anthropogenically-forced climate change is real

Climate and Climate Change

- Physics of Climate
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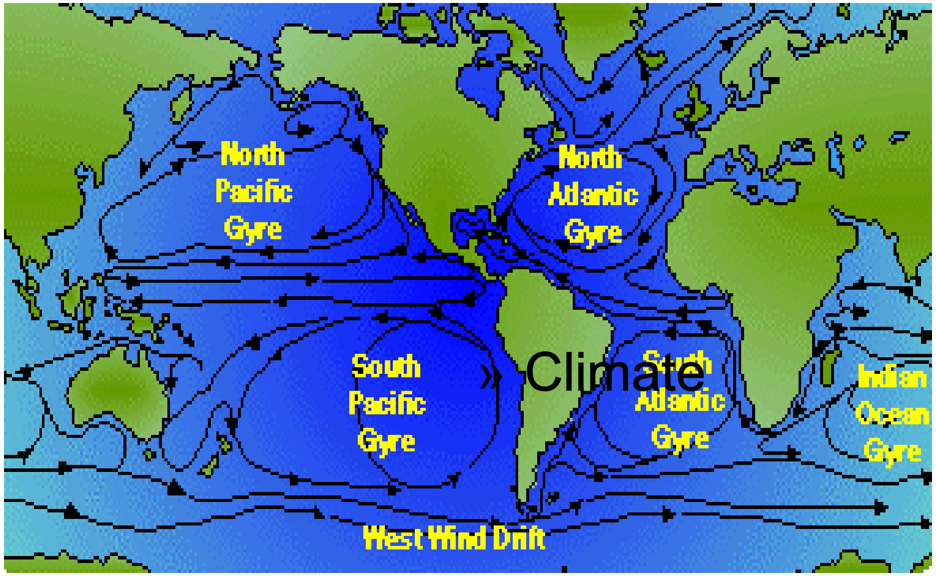
- Climate Change Response
- **Climate Projections & Uncertainties**

Ocean Circulation

Ocn currents ~ cm/s

Redistribute heat and salt



Wind-driven Gyres (x,y, sfc)

Time scale ~ 10^1 yr

Thermohaline (y,z):

Convective overturning in Greenland- Iceland- Norwegian Seas

Upwelling in N. Pacific

Global time scale ~ 10^3 yr

Ocean for decadal & millennial climate models

Wind-driven + Thermohaline Circulation

- Momentum Equation (Navier Stokes) +
- Energy Equation

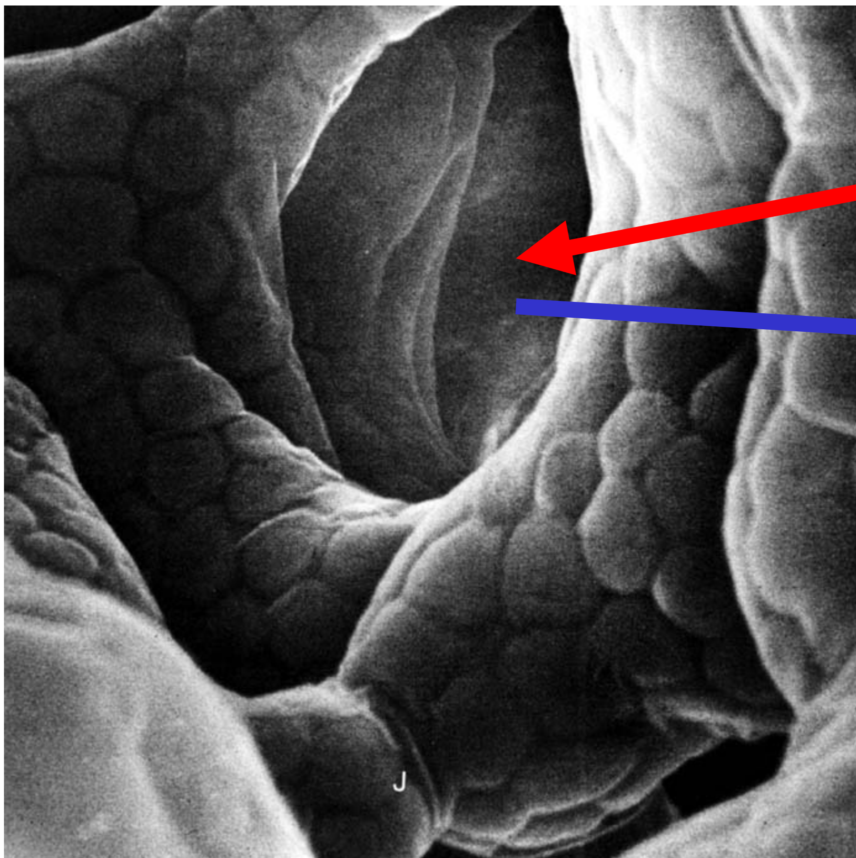
  heat exchange at the ocean surface
- Salinity Equation

  Freshwater fluxes at the ocean surface:
  evaporation + precipitation

Δ temperature and salinity → Δ density →
Δ pressure gradient forces & buoyancy →
Δ ocean circulation → Δ SST → Δ atm circ → ...

Leaf Photosynthesis

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$



Bean leaf x4200

Stomates

CO_2 in

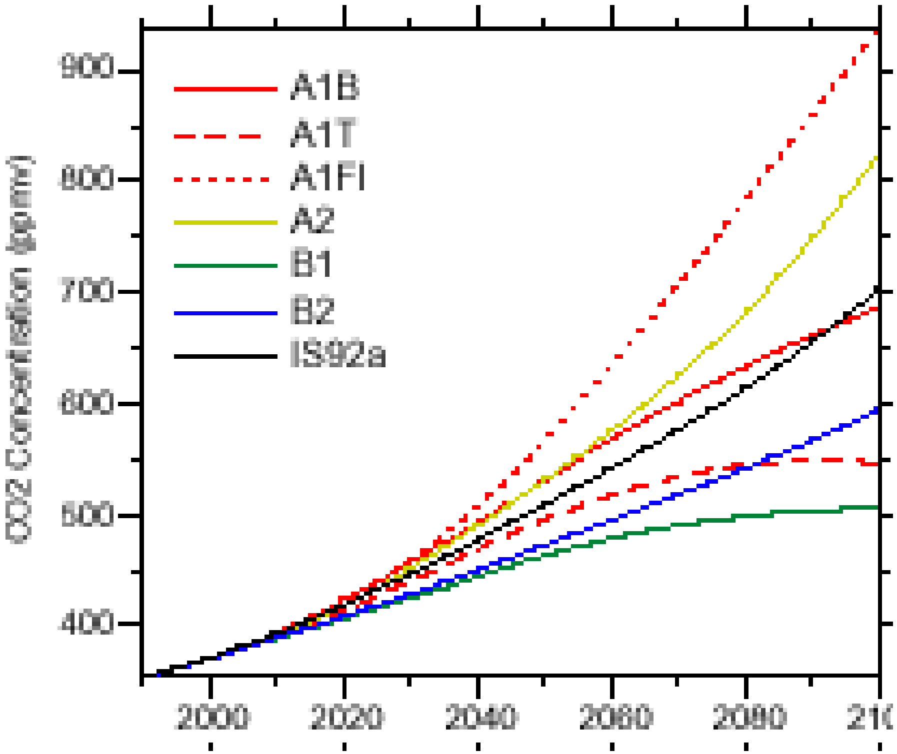
H_2O out (transpiration)

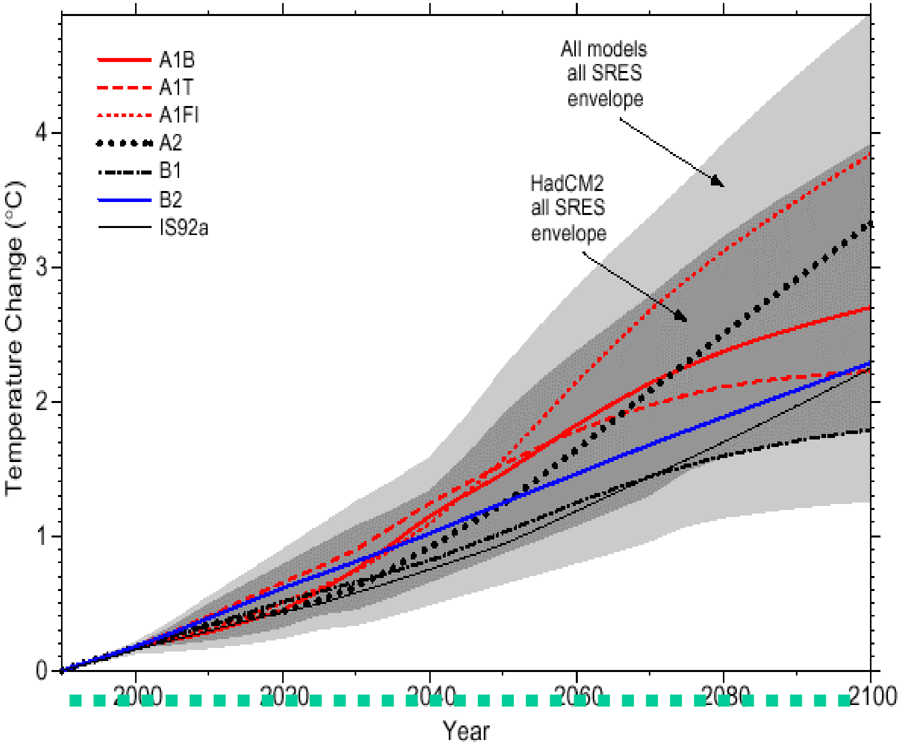
Stomatal Conductance

-function of ambient Temperature, humidity and $C_i - C_a$ = partial pressure diff between ambient (Ca) and cellular (C_i)

By how much will temperatures change over the next 100 years?

CO_2 (t) → Δ T_surf

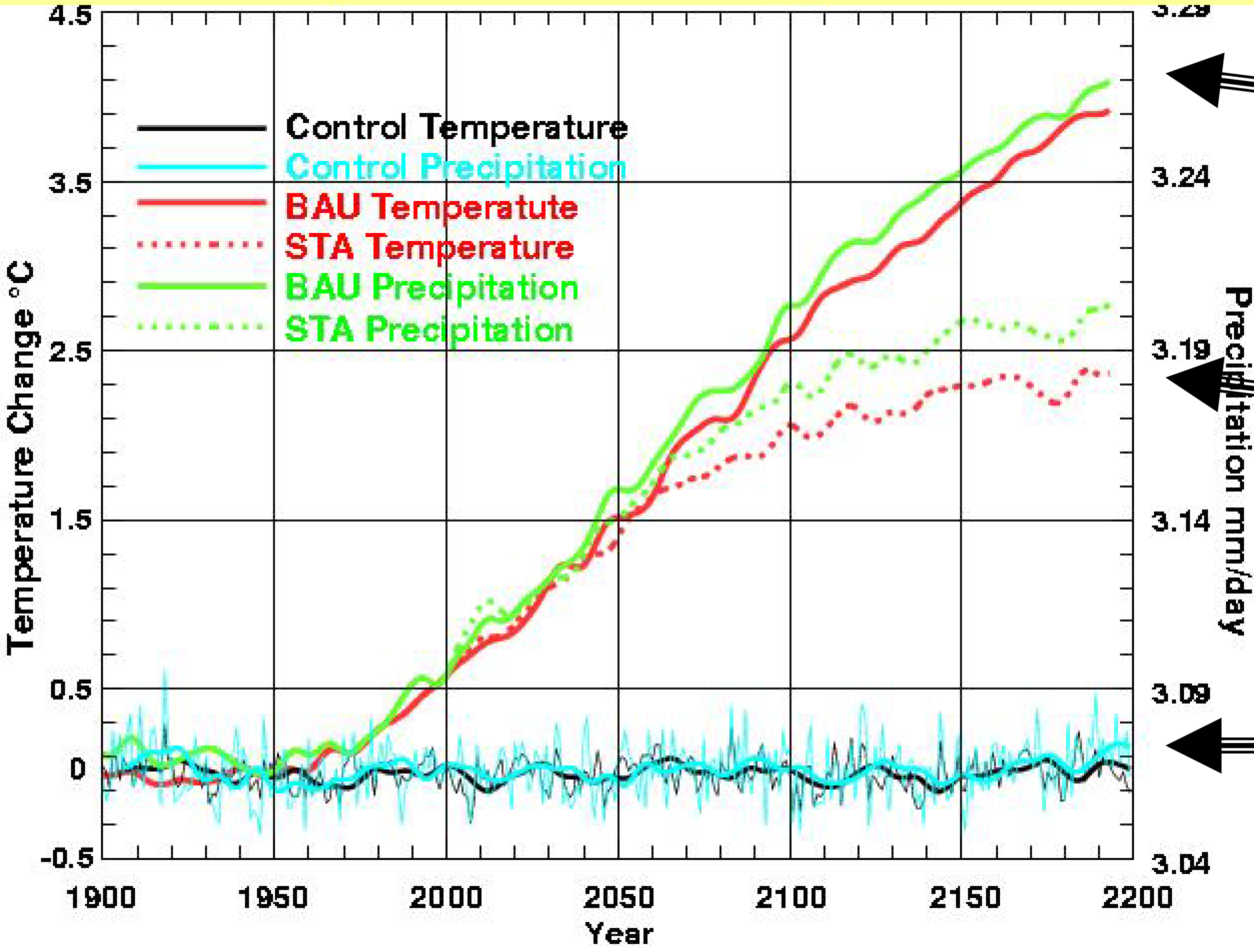




Different emission scenarios

DEPENDS ON MAGNITUDE OF FEEDBACK AND RATE OF INCREASE OF GHG. IN 100 YEARS, FORCED CLIMATE CHANGE WILL MOST LIKELY EXCEED NATURAL VARIABILITY

Global Climate Models used to project climate change from different CO_2 scenarios:



Control run: Annual means (thin lines) and 20 year means
Other runs: 20 year means
Business as Usual (BAU)
Stabilization of Carbon Dioxide concentrations (STA)

Business as usual CO_2 emission

Stabilization of CO_2

Control

Weather versus Climate Models:

- Weather models:
  - Initial value problem
  - Single integration from “observed” initial state
  - Compare instantaneous state of atm
  - Limit to predictability 5-10 days
- Climate models:
  - Boundary value problem
  - Perturb initial conditions → ensemble experiments
  - Analyze circulation statistics
  - [multiple equilibria, chaotic transitions?]
  - Compare circulation statistics between {experiment} and control

Confidence in Models Processes: Model-model intercomparison

http://www-pcmdi.llnl.gov

- Physics: e.g. Radiative transfer under clear sky conditions
- Forced climate change (benchmarks):
  - Paleo-climate: changed irradiance, volcanic forcing, land cover
  - Future: Prescribed dCO_2/dt (e.g. 1%/yr)
- Circulation: Transport of inert tracers (SF_6, CFC, ^{14}C) in the atm, ocean

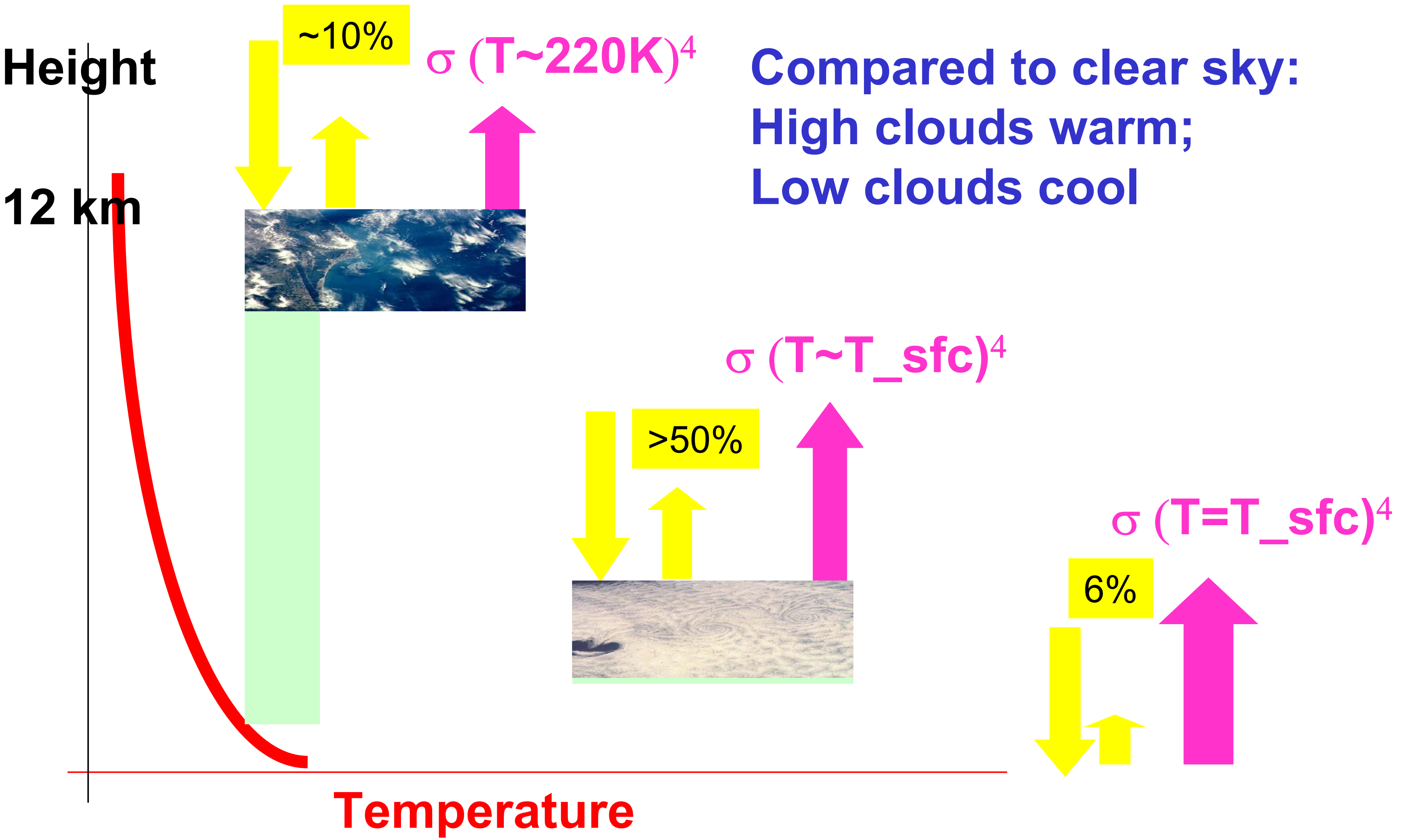
Confidence in Model Projections: Model-Obs Comparison

http://www-pcmdi.llnl.gov

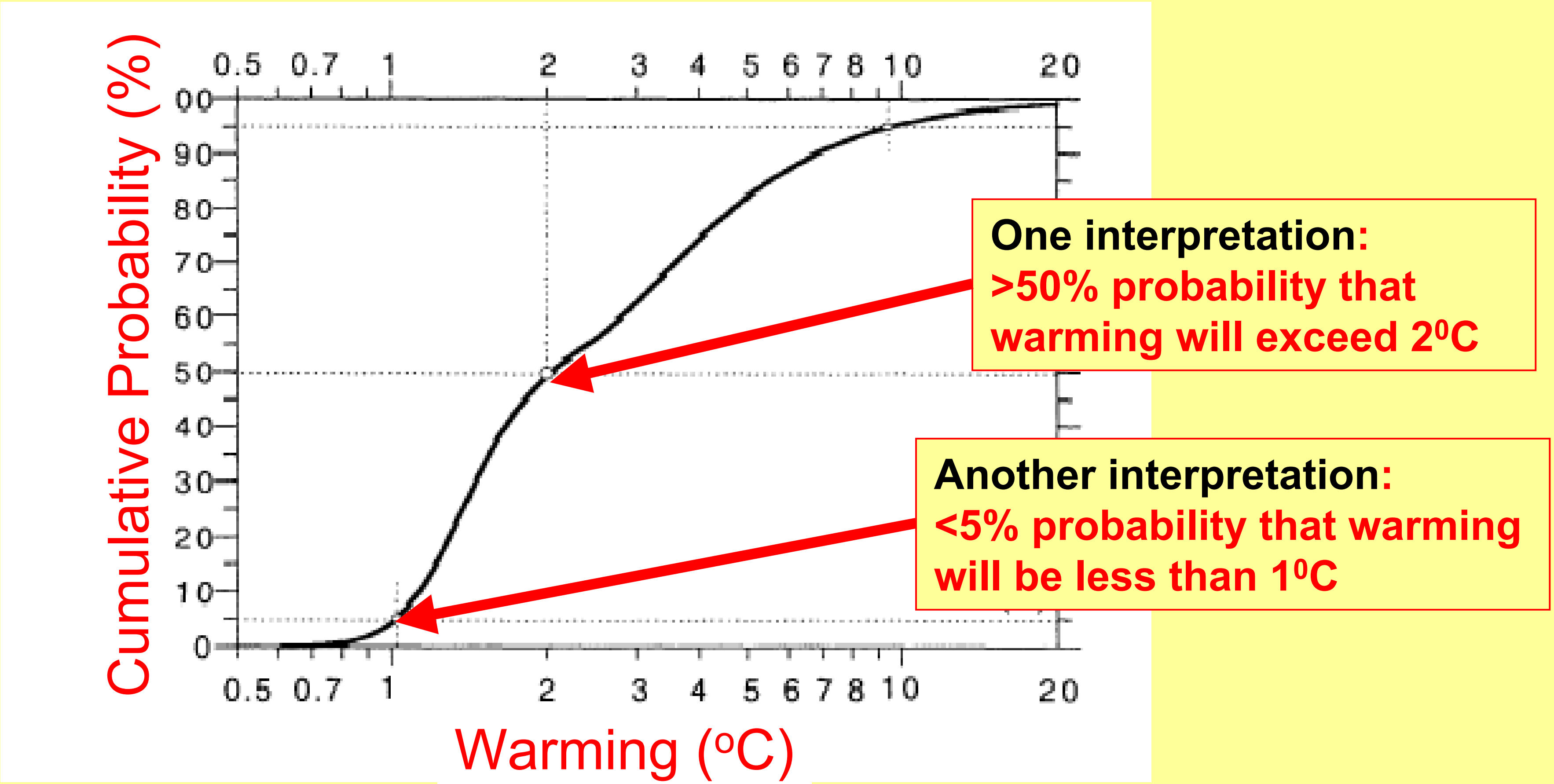
- Internal climate variability: e.g. prescribe interannually varying sea surface temperature since 1980's, compare with satellite records
- Forced Response: Simulation of 20th century climate,with atm composition changes specified from obs

Uncertainty in the climate change:
Will cloud height increase or decrease with warming?
[models: increase; more vigorous convection; +ve feedback

Compared to clear sky:
High clouds warm;
Low clouds cool



Warming Odds for $2xCO_2$ (benchmark):



Timing of warming

- Depends on rate of GHG emissions
- Other emissions

Andronova and Schlesinger, JGR 2001

Uncertainties

- Shallow vs tall clouds $\{\sigma T_{cld\_top}^4$; latent heating (z)$\}$ Turbulent transport in vertical: space and time scales of instabilities < resolved flow
- Cloud albedo: drop size, N_drops, condensation nuclei? Cloud microphysics – coalescence into big drops
- Aerosols and their radiative properties: composition of aerosols? Single scattering albedo?
- Turbulence closure → parameterization

Uncertainties: Biology

- UpScaling: stomatal CO_2-H_2O exchange → canopy → ecosystems; light, water, nutrient, CO_2 competition in determining photosynthetic rates
- No guidelines for biological behavior in future climate – no past analogs

Climate and Climate Change

- Physics of Climate
- Climate Forcing
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- Climate Projections & Uncertainties
- Outlook

Decadal to Millennial Climate *Change*

$\frac{\partial}{\partial t}$(**temperature**) **+ advection = forcing terms**

= solar rad + net IR rad + sensible heat + latent heat

(clouds) (T, humidity)

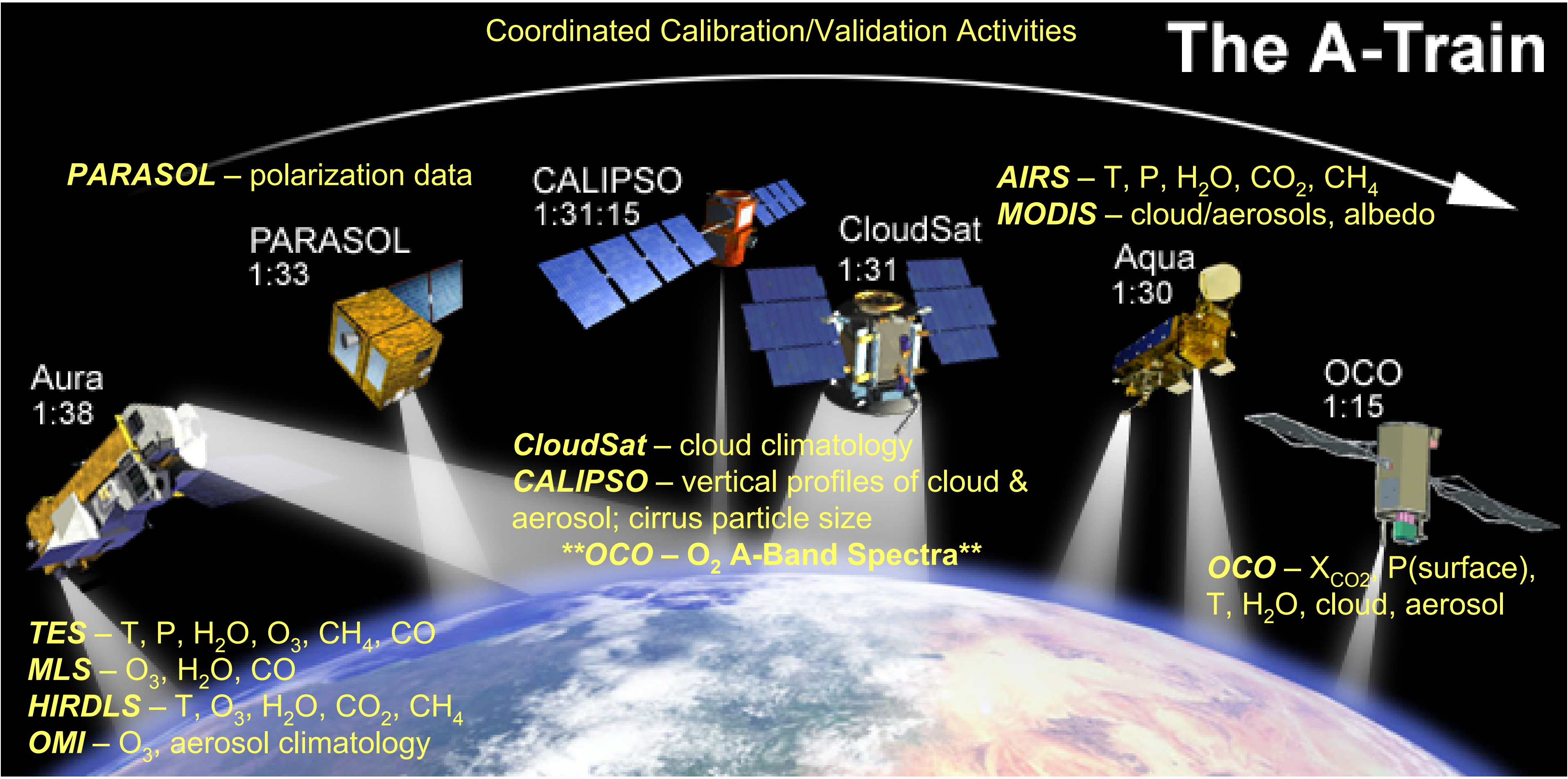
$SO_4^{=}$ CO_2 , CH_4 , CFC

Trop O_3

----- Dust, Carbon Black … --------

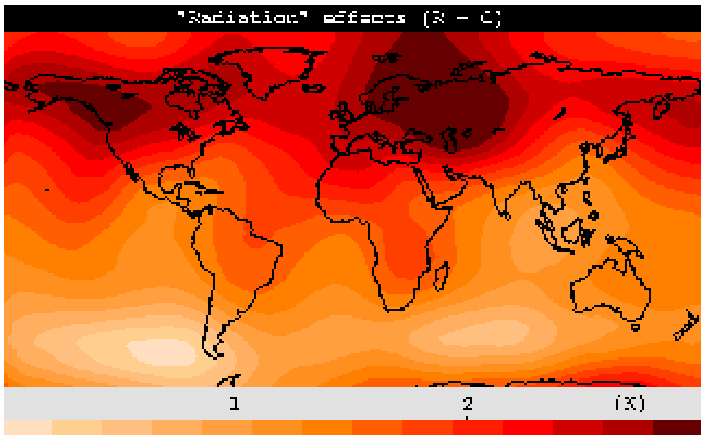
Predict, rather than specify, changes in atm composition {specify emissions}

Science Synergy:
OCO Formation Flying with the A-Train

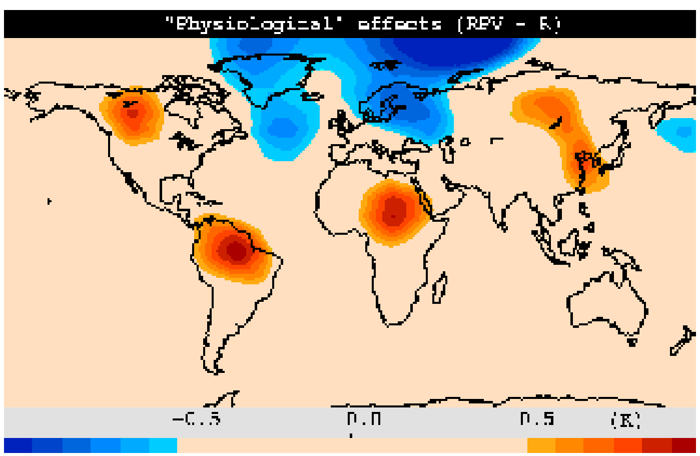


Clouds off Guadalupe, Mexico

Hypothesis: Additional Climate Feedbacks due to Plant Physiology



Warming due to radiation



Additional Warming due to plant physiology

In the tropics:

- Nutrient limitation of photosynthesis
- Stomatal closure at high water stress
- Reduces transpiration and
- Causes net radiation to be balanced by sensible rather than latent heating

Sellers et al. Science 1996

Stomatal Suicide

+Δ CO_2

+Δ T

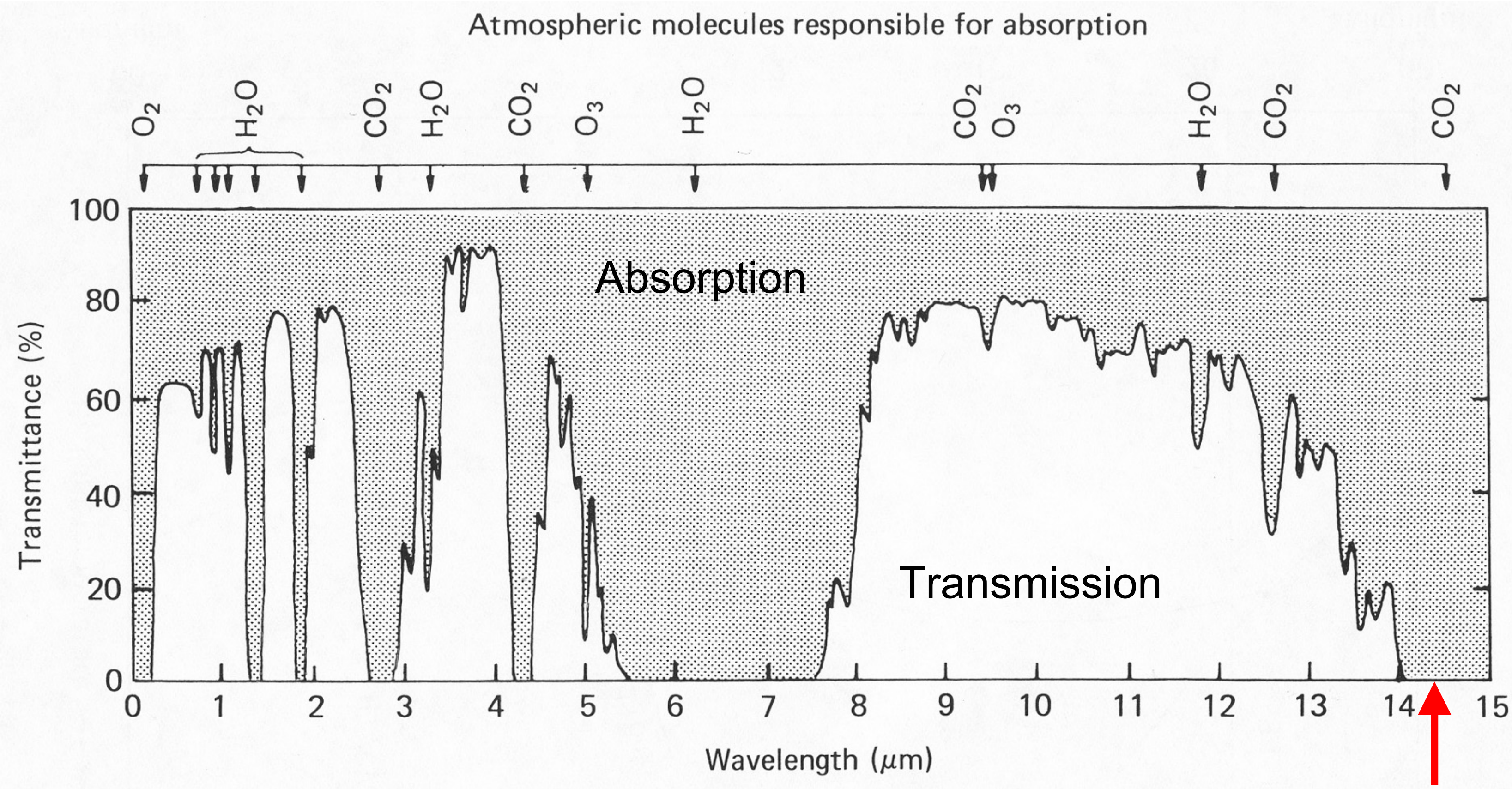
→ **stomatal closure**

→ **less evaporation**

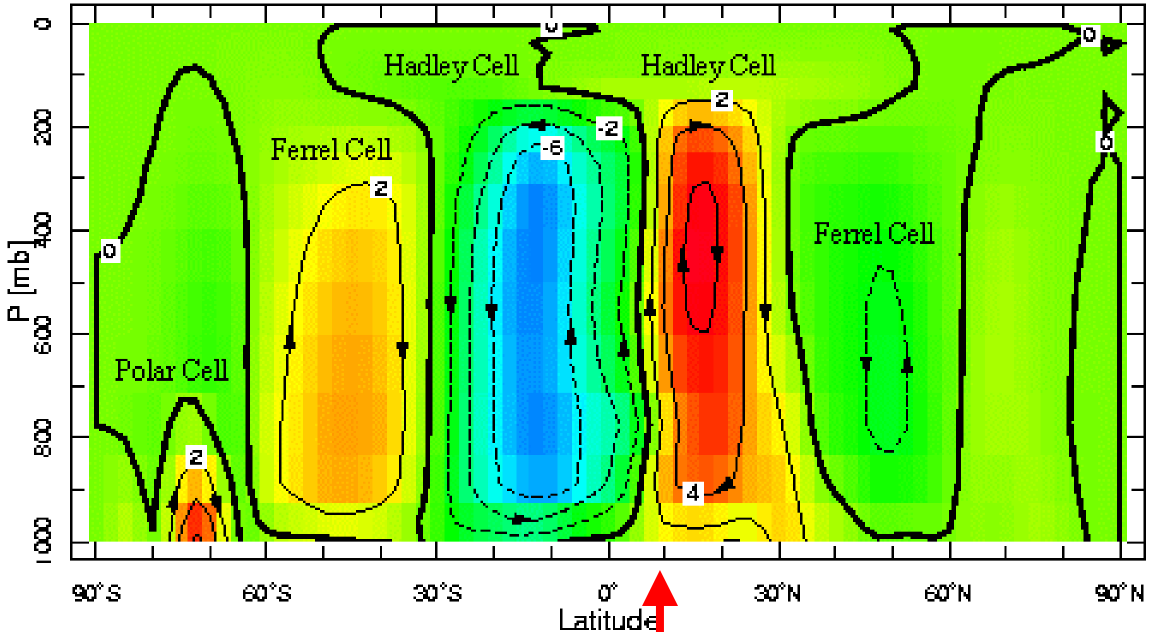
→ **shift to sensible heating to balance net radiation**

How to test the hypothesis?

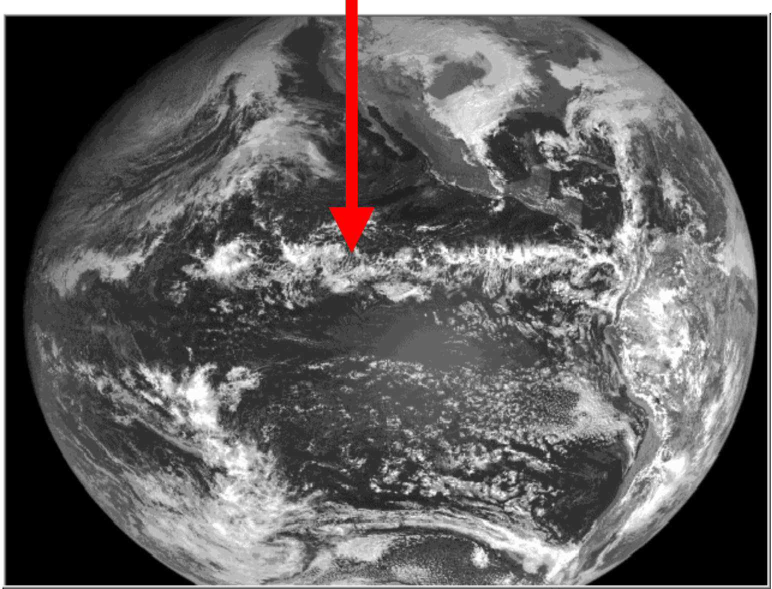
Atmosphere: Characteristic Absorption/Transmission for different atm molecules for λ: 0-15 μm



Peak terrestrial emission at ~300K



Intertropical Convergence Zone



Atm Circulation

- **Winds ~10 m/s**
- **Intrahemispheric mixing ~ 3 months**
- **Cloud formation ~ minutes**
- **ITCZ as barrier to interhemispheric mixing**
- **Interhemispheric mixing ~ 1.5 years**