# Climate and Snowfall

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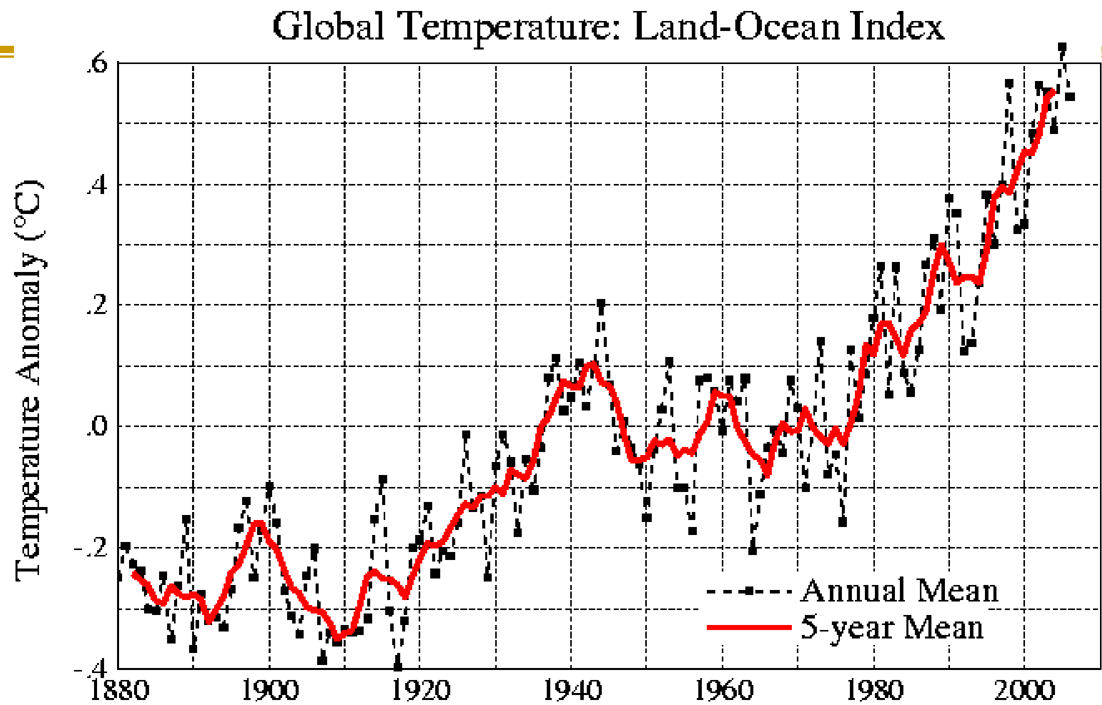
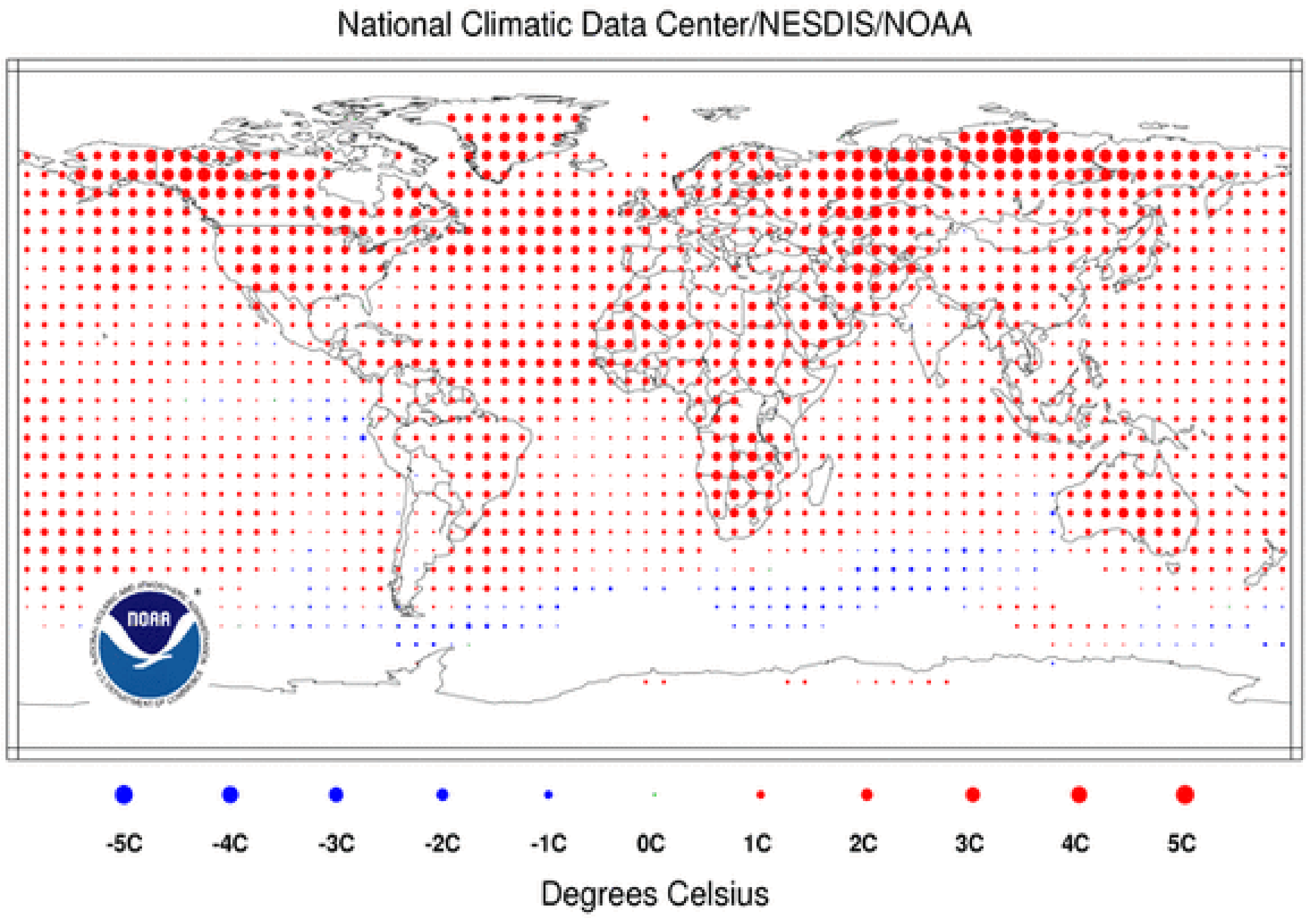
# Global Average Temperature Changes




**(Compared to 1951 – 1980 mean)**

2005 is the warmest year on record
1998 is the second warmest year on record
2002 and 2003 are tied for the third warmest years on record; 2006 was the fifth warmest year on record; 2004 was the sixth warmest …

# Annual 2005 Temperature Anomalies



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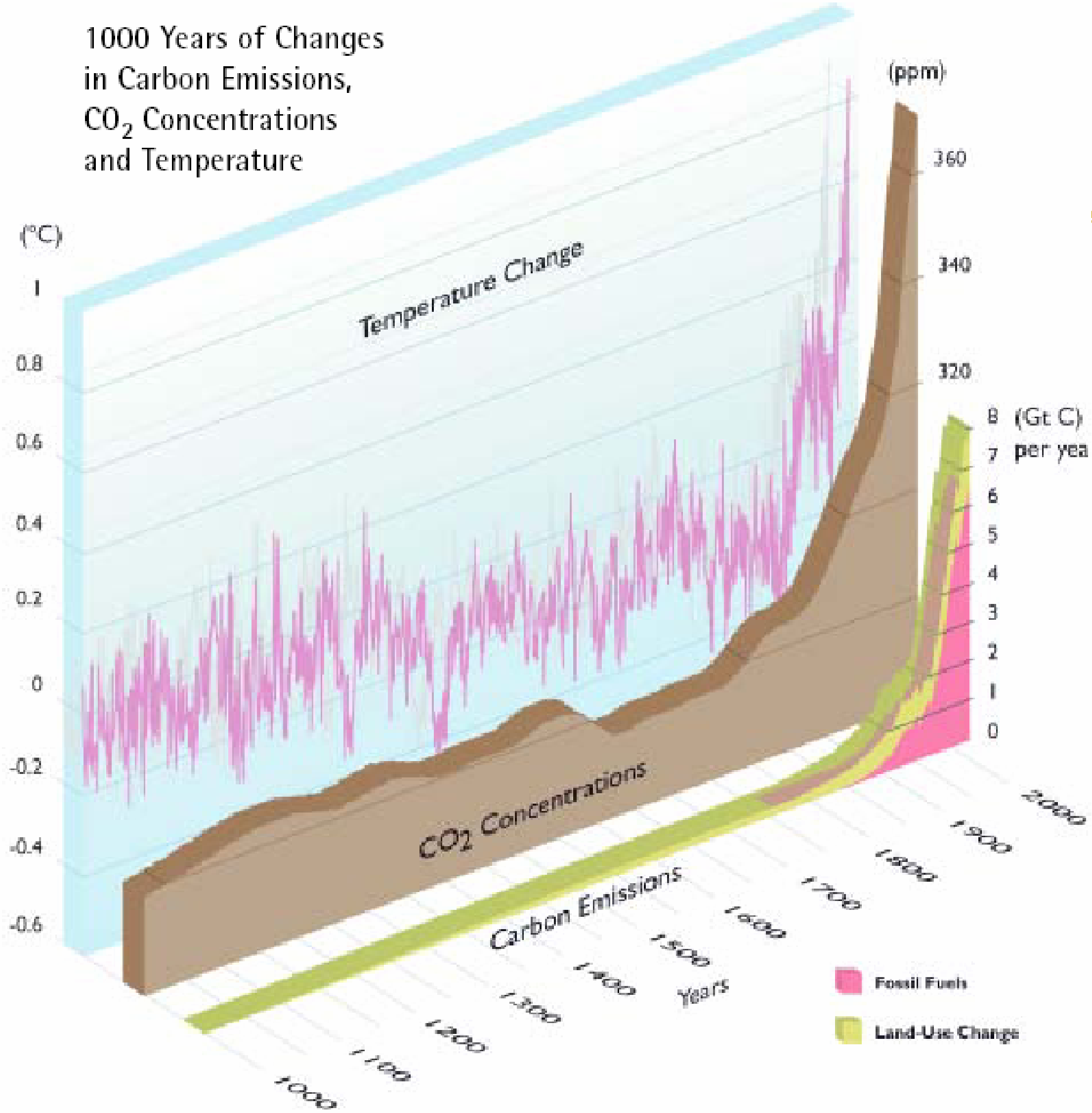


In: Hassol, S.J., 2004

Carbon emissions
$CO_2$ concentrations
Temperature change



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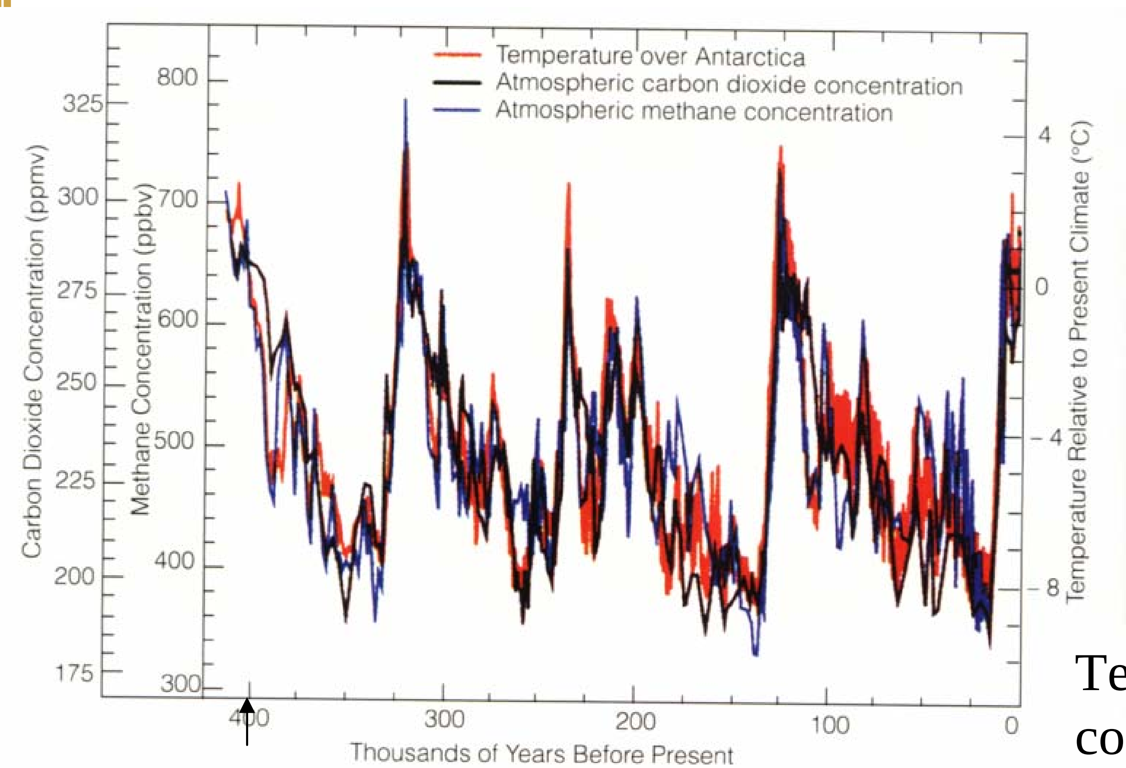
# Gases trapped in ice cores also tell us about changes in greenhouse gases in the past

Present day $CO_2$




400,000 years ago

Bubbles in ice hold samples of ancient atmospheres

Temperature $\propto$ $^{18}O$ / $^{16}O$

Temperature and greenhouse gas concentration go hand-in-hand.



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# European Project for Ice Coring in Antarctica (Epica)

Dome C, Antarctica

Drilled 2,774 m into the ice that is about 900,000 years old.

Results to 650,000 years ago published in December 2005 in the journal Science

The story is the same: temperature and greenhouse gas concentration go hand-in-hand.

# Thermal Balance of Planet Earth - Radiative Equilibrium

$$T_e = \left[ \frac{F_s \left(1 - A_e\right)}{4 \varepsilon_e \sigma_B} \right]^{1/4}$$

$F_s$ – Solar Flux
$A_e$ – Earth's Albedo
$\varepsilon_e$ - emissivity
$\sigma_B$ – Boltzmann Const.

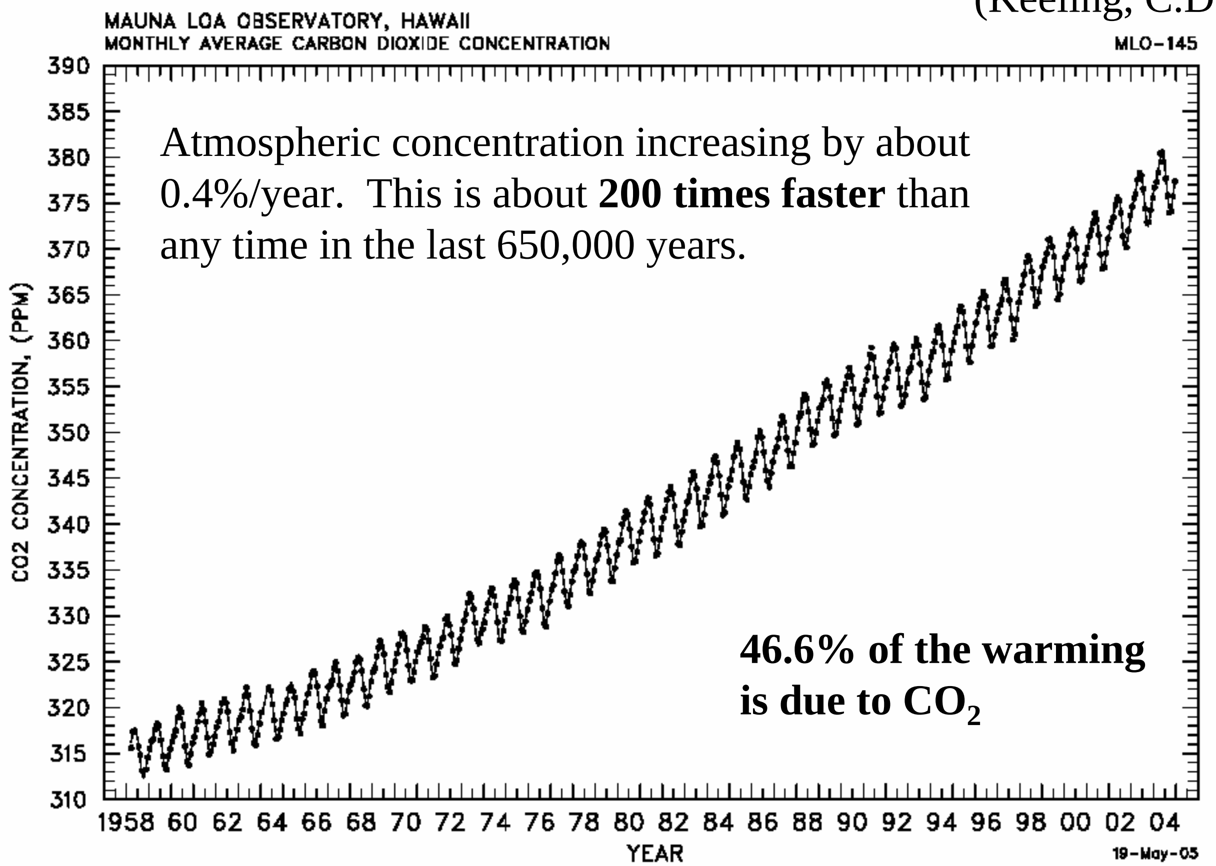
$T_e$ = 255 °K        Actual = 288.5 °K

Outgoing radiation controlled by "greenhouse gases."

- Carbon Dioxide (increasing 0.4%/yr)
  - Recent results +0.68%/yr
- Methane (increasing 0.5%/yr)
- Nitrous Oxide (increasing 0.25%/yr)
- CFC's and HFC's
- Water vapor

# Carbon Dioxide ($CO_2$)

(Keeling, C.D. and T.P. Whorf, 2005)




Atmospheric concentration increasing by about 0.4%/year. This is about **200 times faster** than any time in the last 650,000 years.

**46.6% of the warming is due to $CO_2$**



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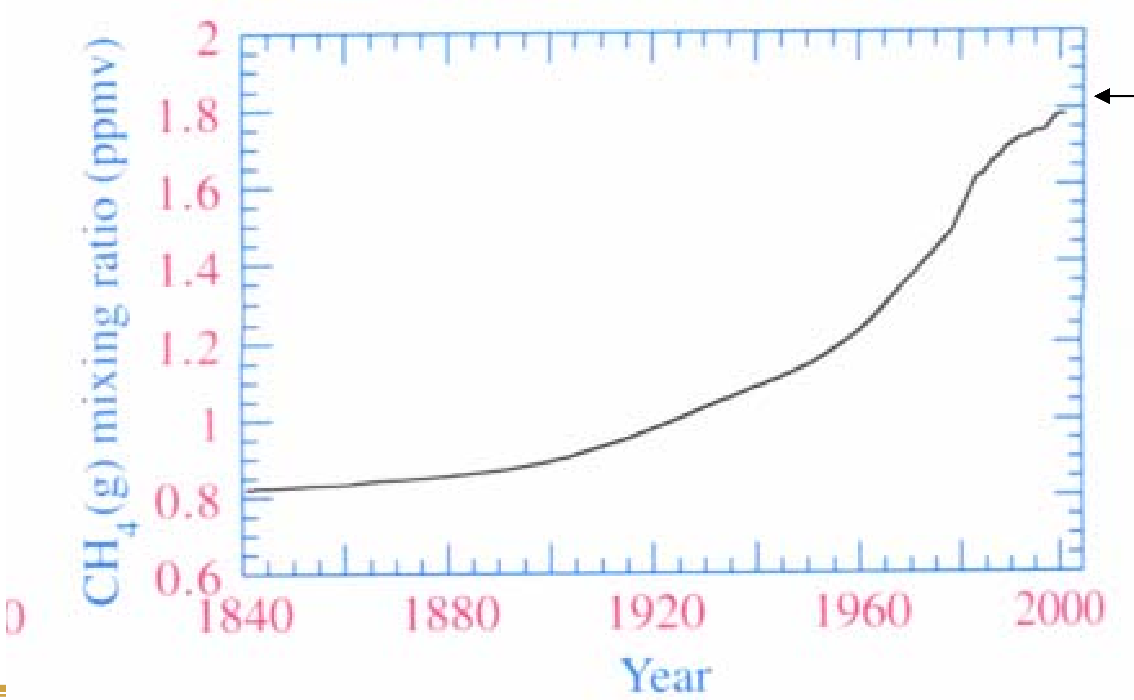
# Methane ($CH_4$)

- Atmospheric concentration increasing by about 0.5% per year.
- Methane is 25 times more effective in absorbing IR than $CO_2$.
- **14% of the warming is due to methane.**




About 130% higher than at any time during the last 650,000 yrs



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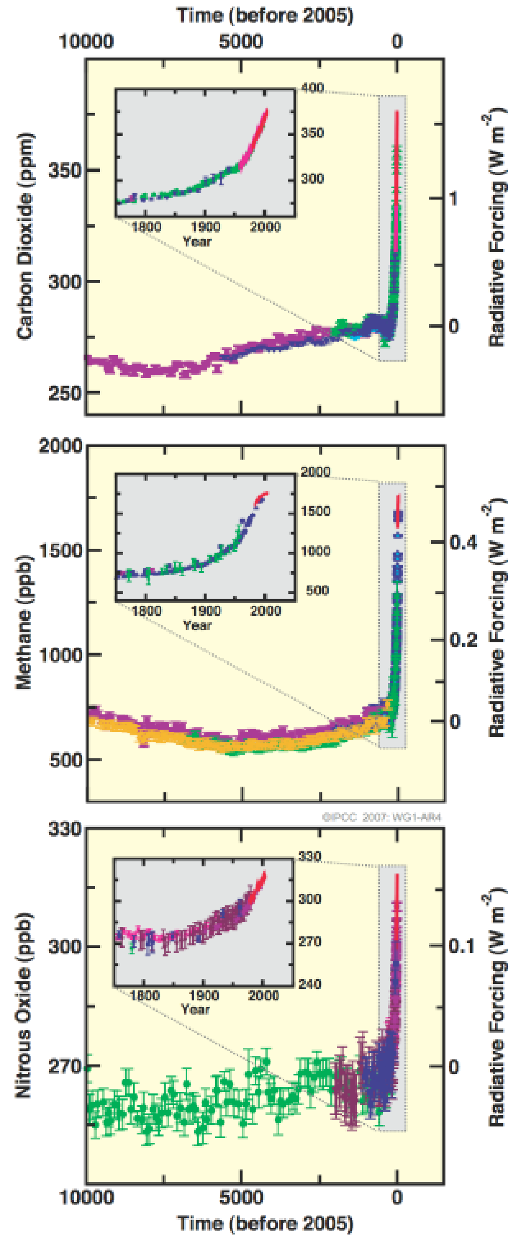
Changes in Greenhouse Gases
from ice-Core and Modern Data

# The past 10,000 years

$CO_2$

$CH_4$

$N_2O$



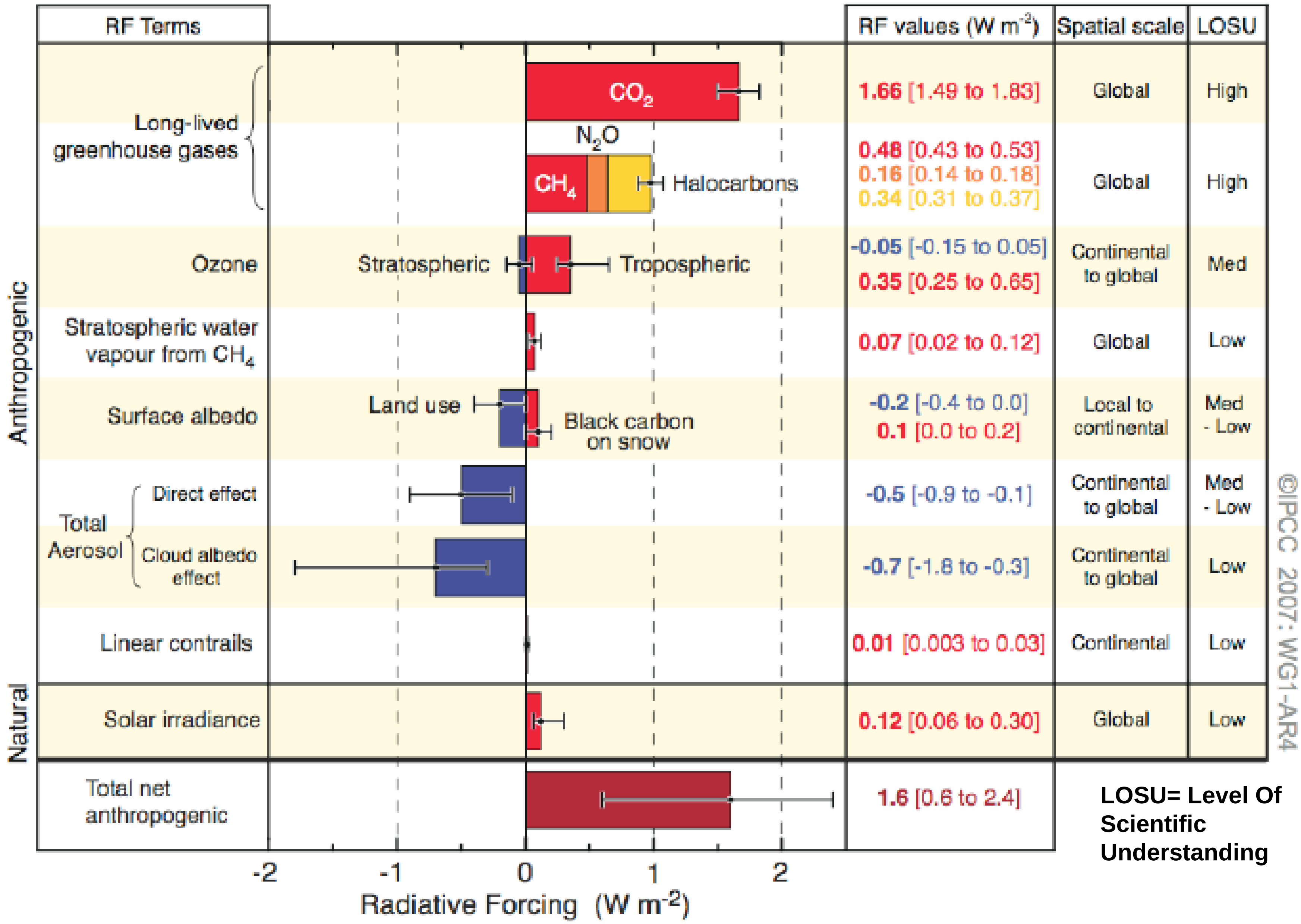
# Other Factors in the Energy Balance of the Earth

- Oceans – Can store vast amounts of energy and $CO_2$.

- Clouds – Both a cooling and warming effect:
  - High clouds: net warming
  - Low clouds: net cooling

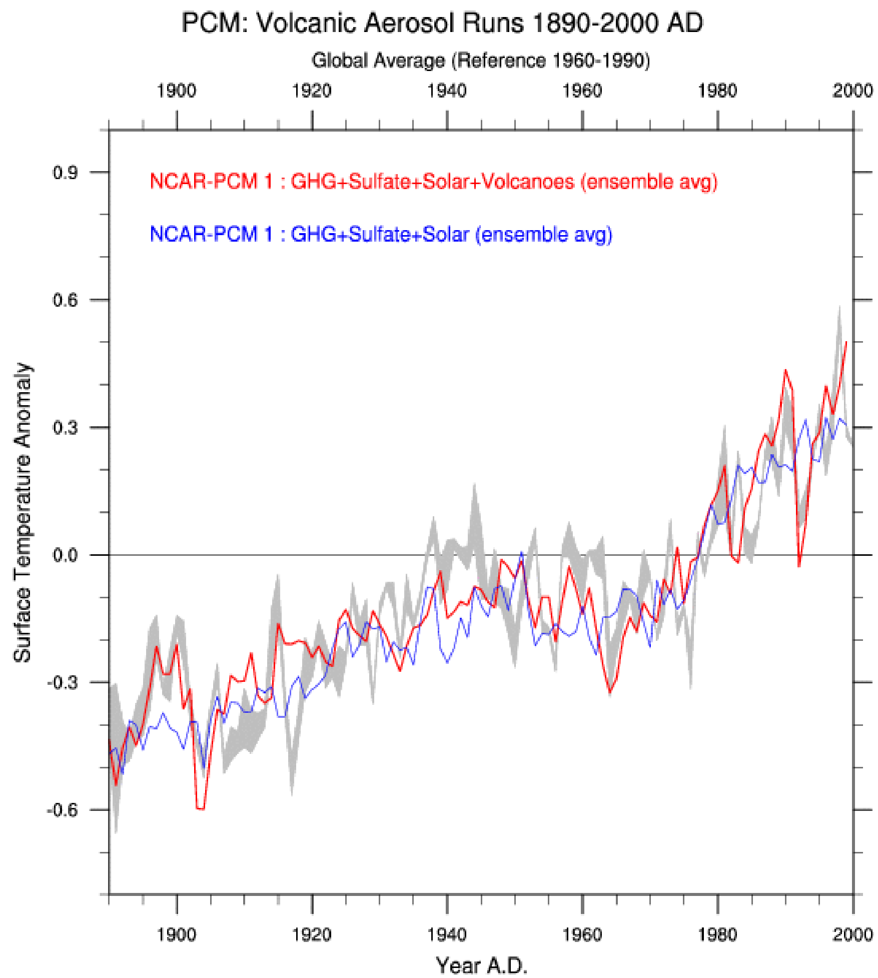
- Pollutants
  - Sulfate aerosols (light colored particles): cooling
  - Soot aerosols (black carbon): warming

# Radiative Forcing Components




**LOSU= Level Of Scientific Understanding**

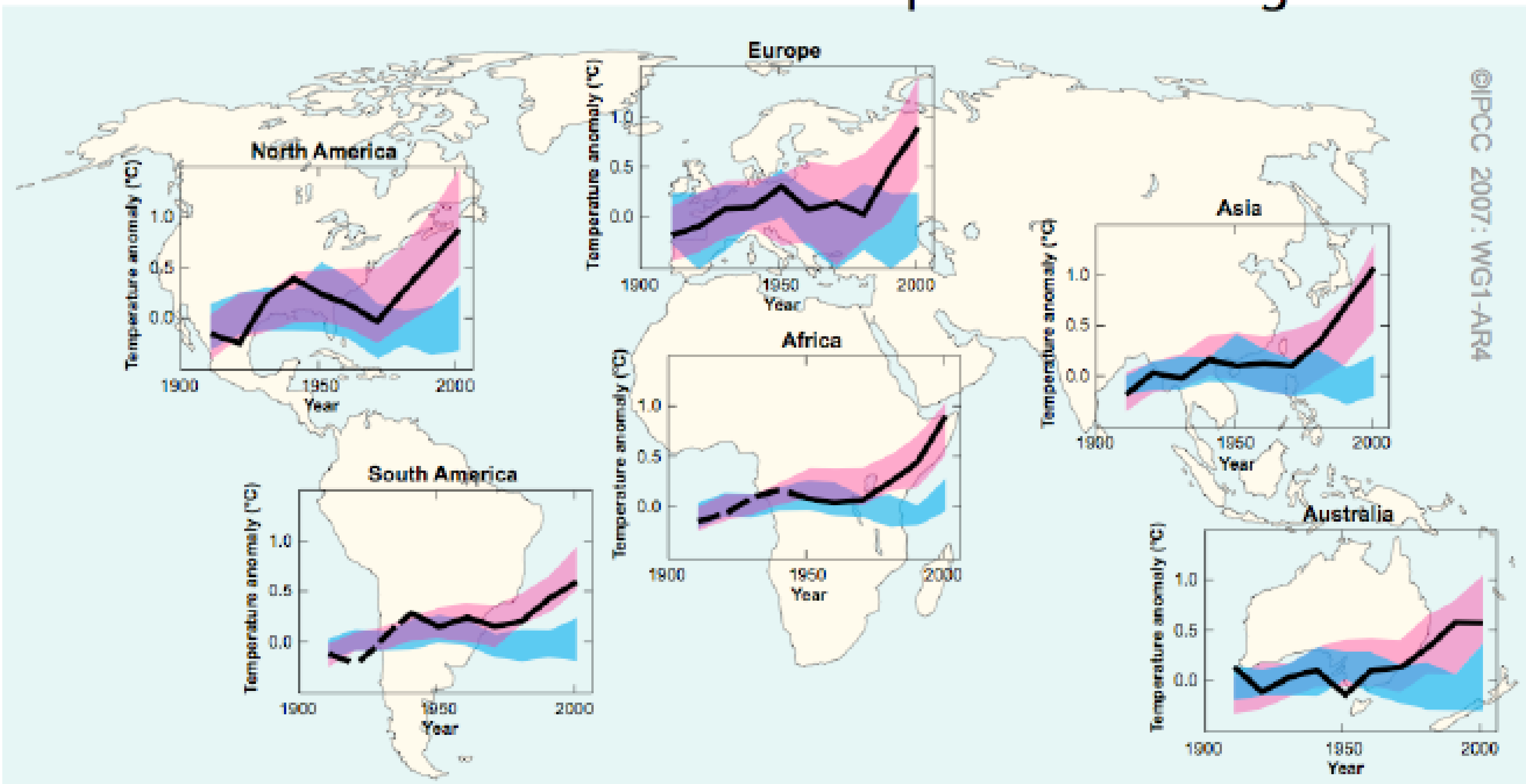
# Numerical climate models are essential in considering all the complexities




## Observations versus the Models

By considering greenhouse gases, aerosols, and solar fluctuations, climate models do a pretty good job showing past temperature trends.

# Global and Continental Temperature Change

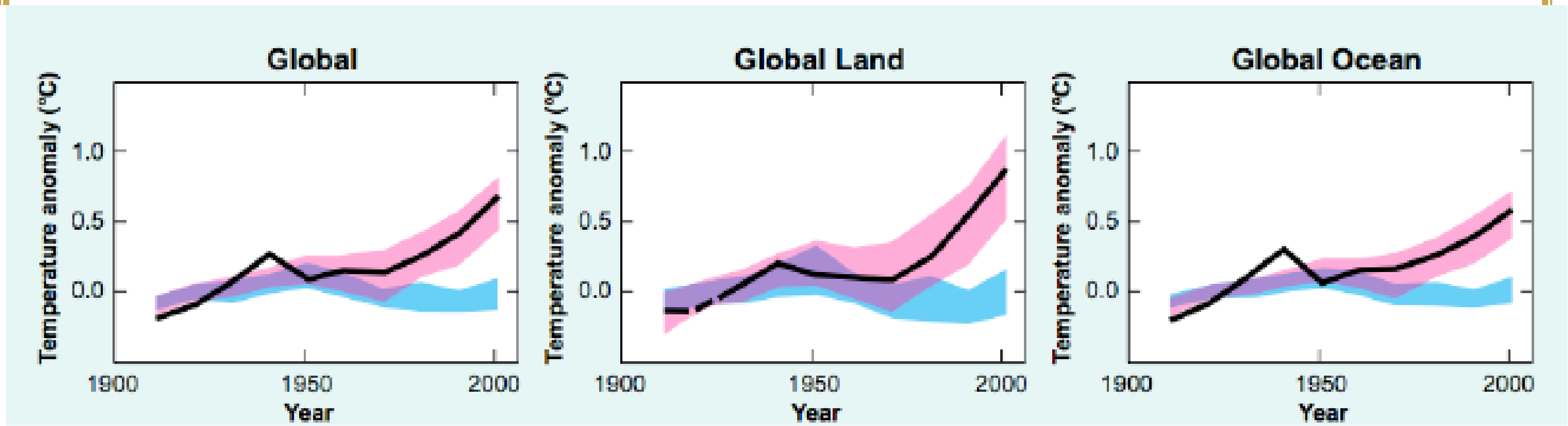



**Blue shaded bands** show the 5–95% range for 19 simulations from 5 climate models using only the natural forcings due to solar activity and volcanoes.

**Red shaded bands** show the 5–95% range for 58 simulations from 14 climate models using both natural and anthropogenic forcings.

**Black line:** decadal averages of observations for the period 1906–2005 plotted against the center of the decade and relative to the corresponding average for 1901–1950.

# Global Temperature Change



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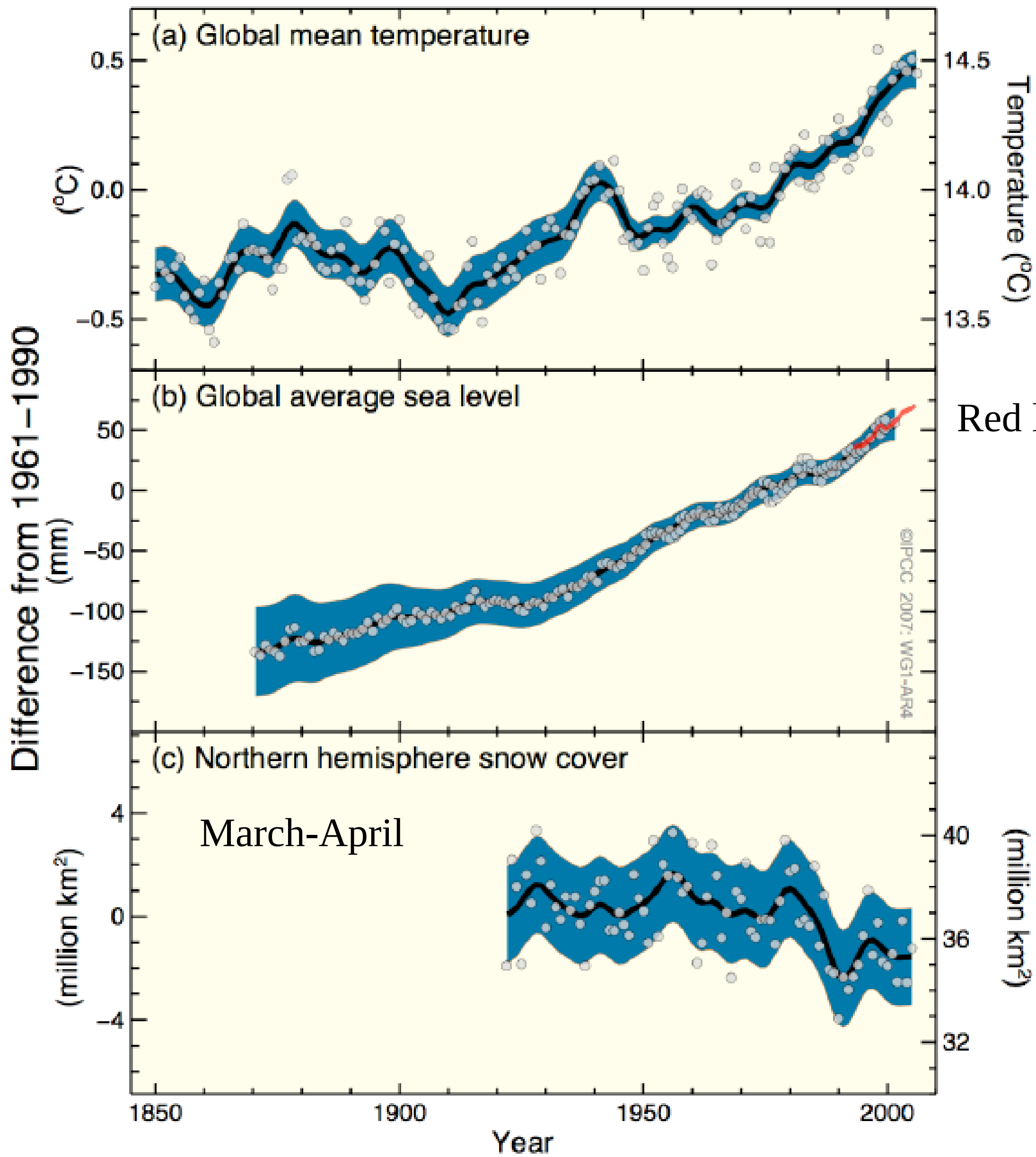
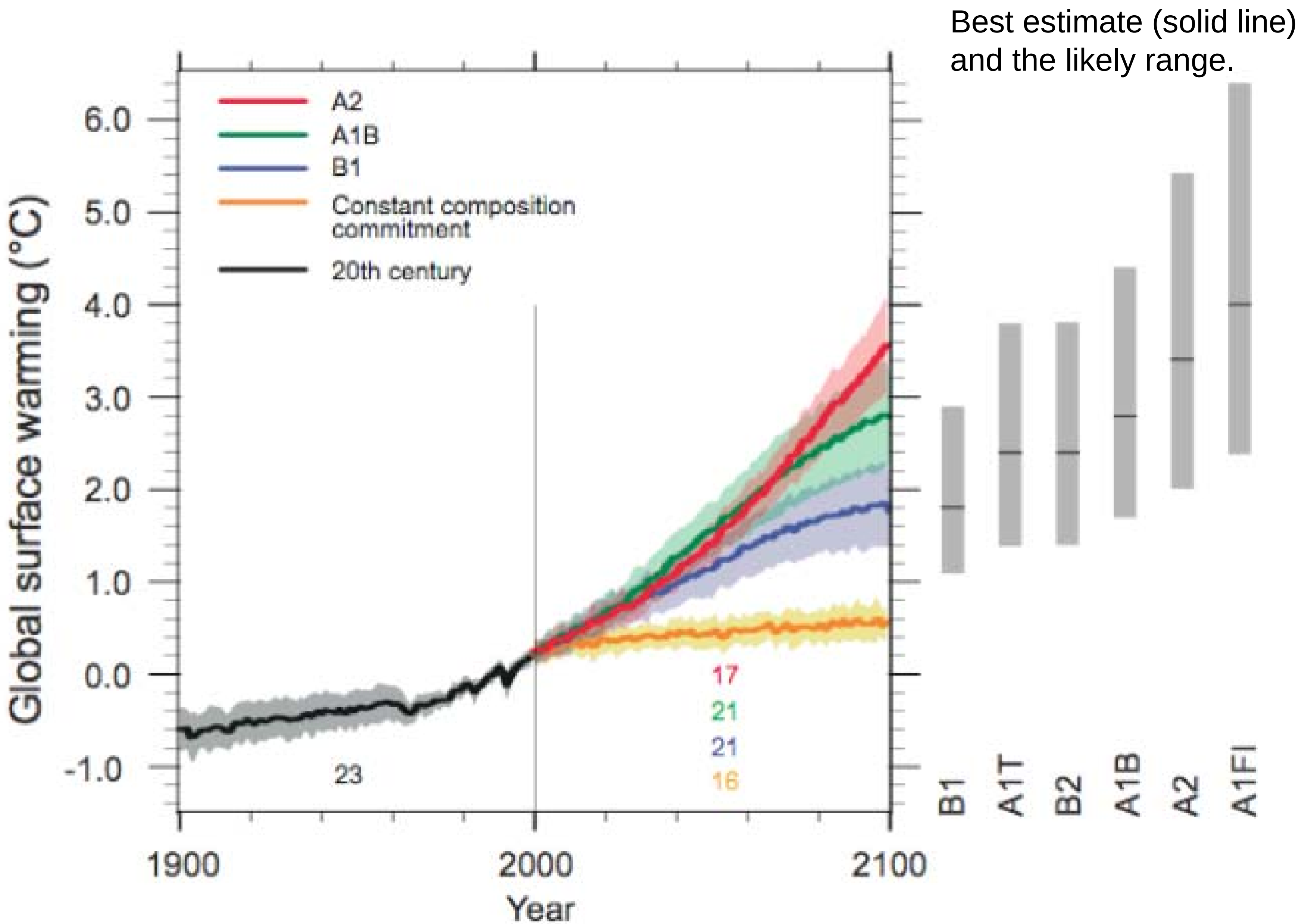
All changes are relative to corresponding averages for the period 1961-1990.

Shaded areas are uncertainty intervals.

## Changes in Temperature, Sea Level and Northern Hemisphere Snow Cover




Red line - satellite

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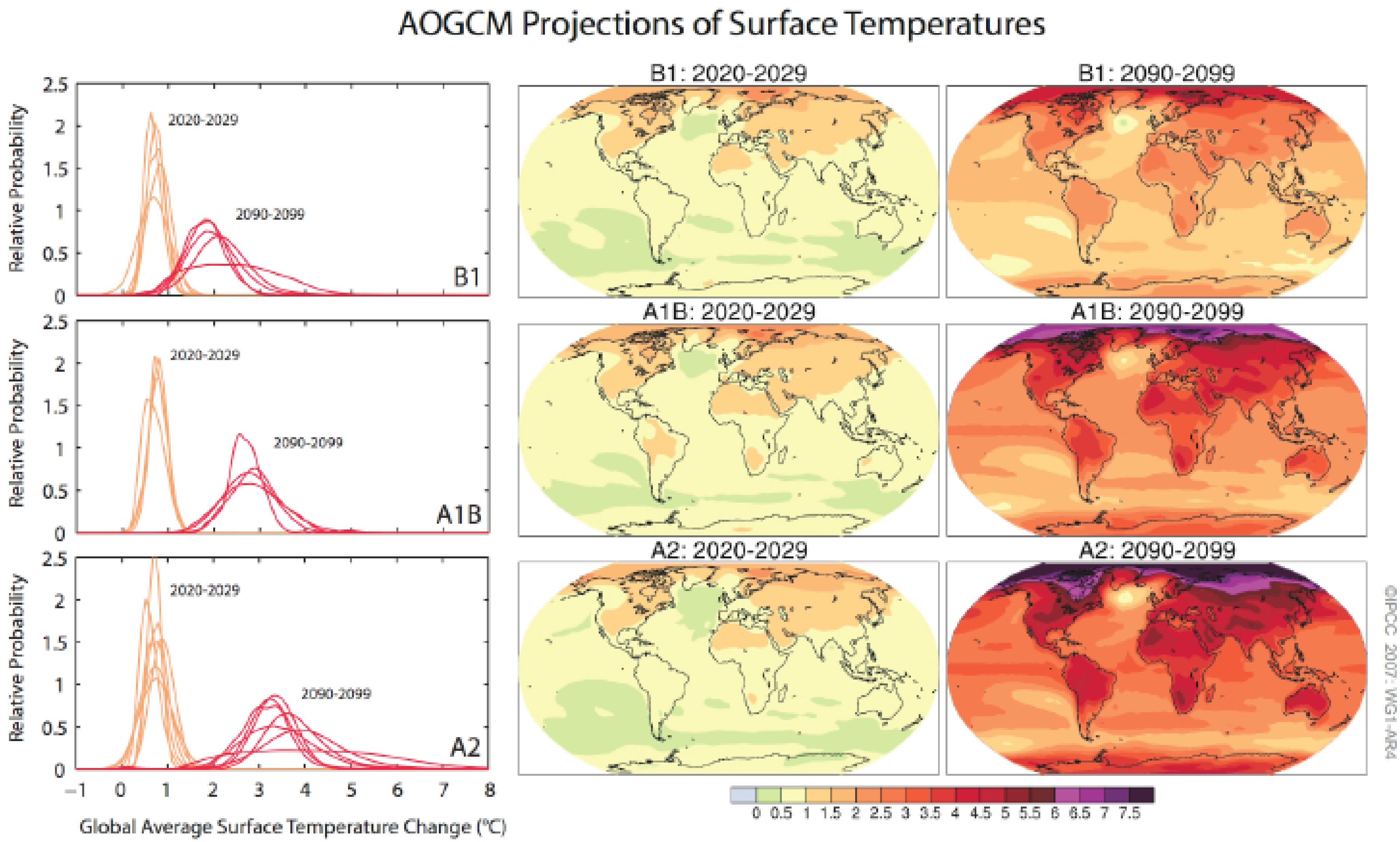
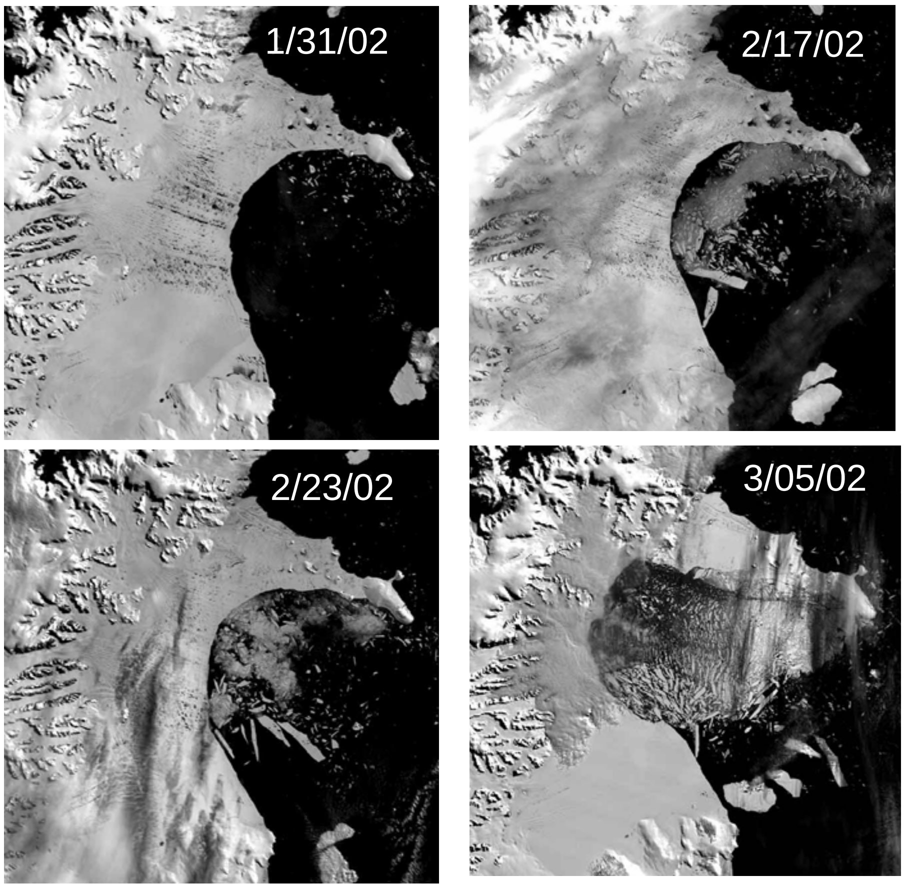
# Surface Temperature changes relative to 1980 – 1999.



# Larsen B Ice Shelf Collapse




Scambos, 2002

Rignot et al, *GRL* October 2004

Thomas et al, *Science* October 2004



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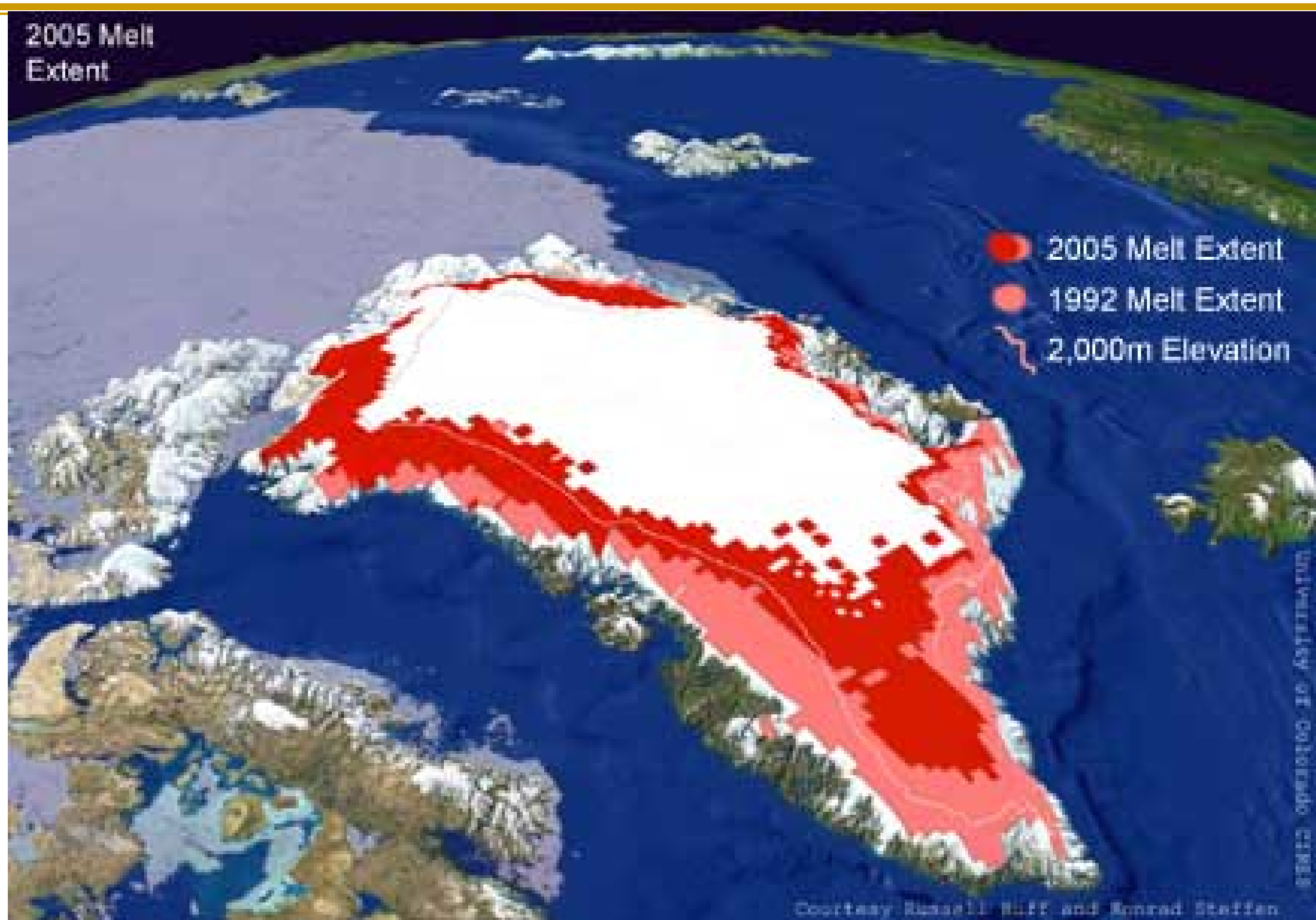
# Increasing Surface Melt Extent



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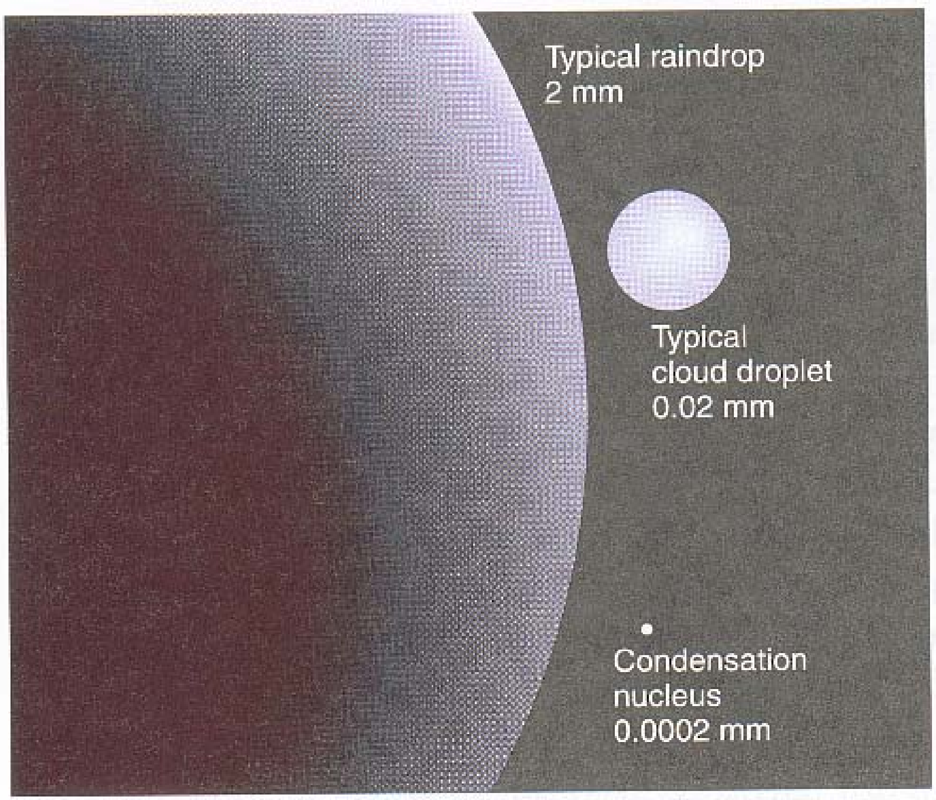
# Snowfall – Input term to mass balance

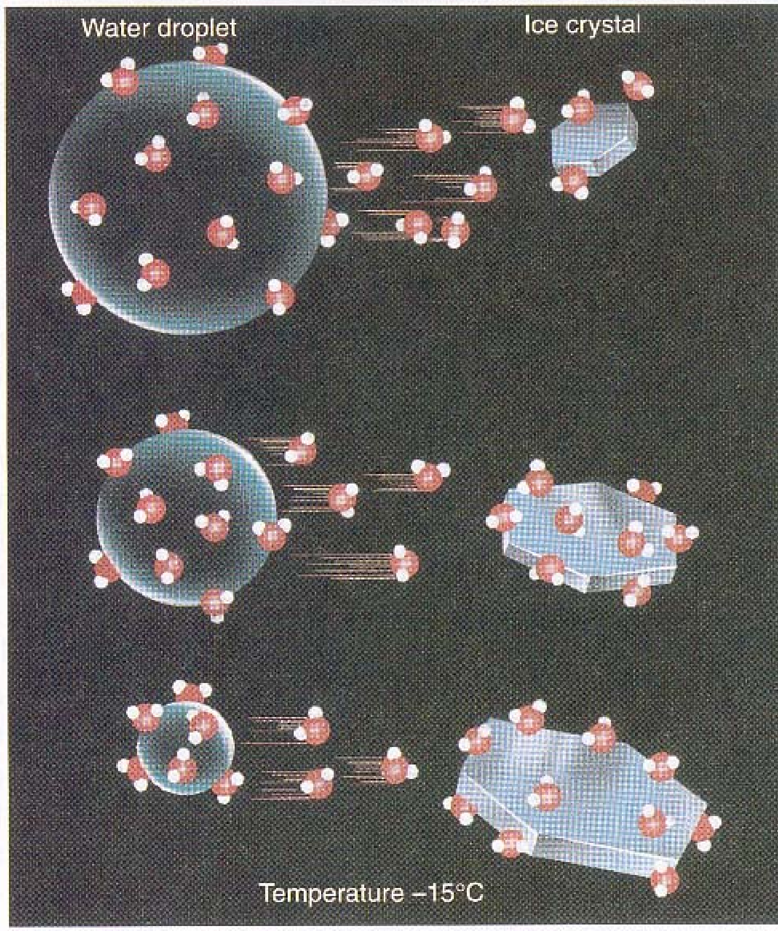



Growth of cloud droplets begin with small particles – condensation nuclei.

Ice Crystal – up to few mm

Snowflake – up to 10 cm.

# Bergeron Precipitation Process




Precipitation process that involves both ice crystals and liquid cloud droplets that co-exist at temperatures below freezing (Cold Clouds).

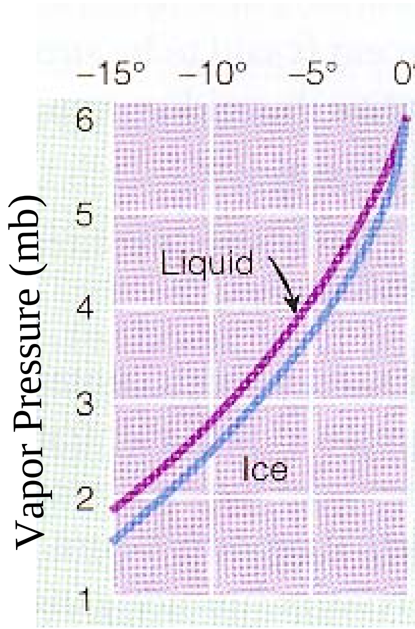
Ice crystals grow by deposition; droplets shrink by evaporation

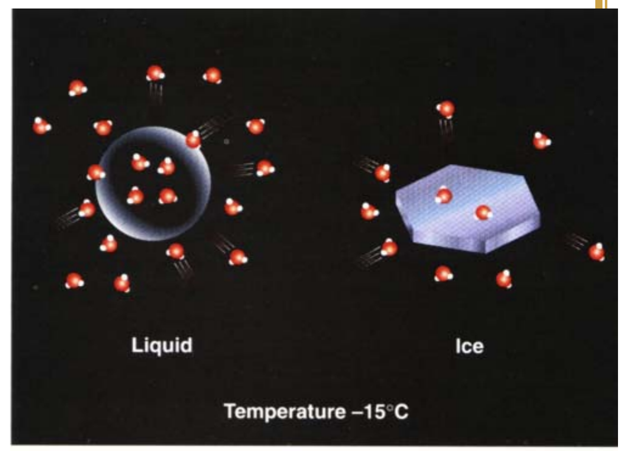
"ice crystals grow at the expense of the surrounding water droplets"

# Why do ice crystals grow and water droplets evaporate?

Saturation Vapor Pressure for water liquid and ice.

For a given temperature, liquid water has a higher saturation vapor pressure than ice.

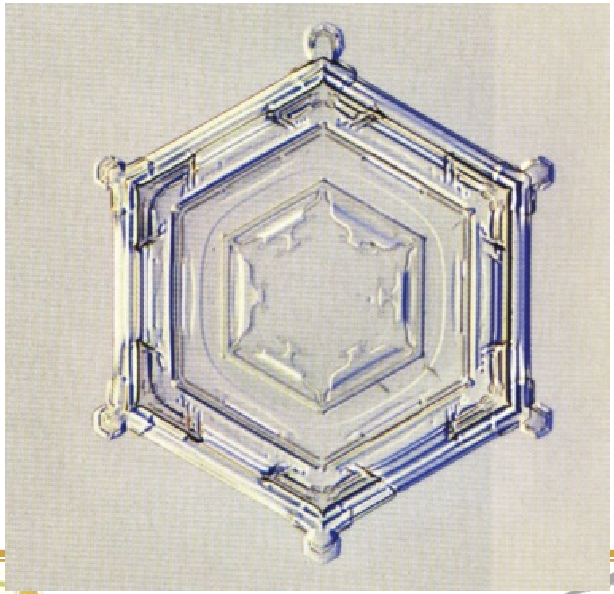



This saturation vapor pressure "imbalance" causes water droplets to shrink, and ice crystals to grow.

## Ice crystals

- Individual, single ice crystals, with hexagonal shapes.
- Grow directly from water vapor in the air.
- Microscopic to a few millimeters.





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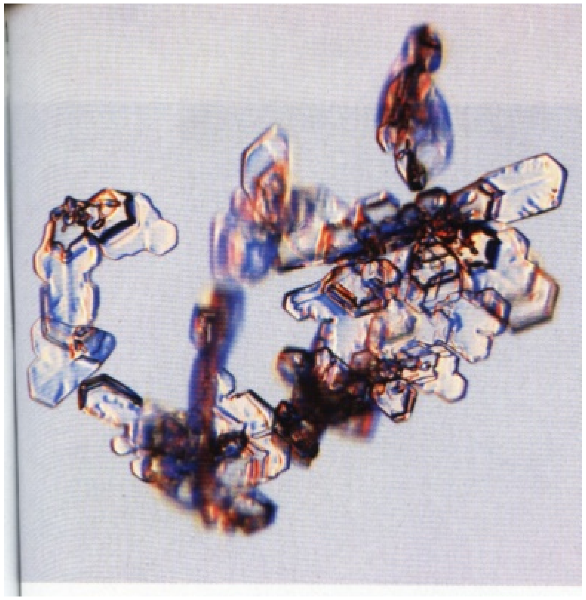
# Snowflakes

Collections of snow crystals, loosely bound together (Aggregation).

• Can grow to large sizes (up to about 10 cm across)

• Largest sizes when the snow is wet and sticky (warm air temperatures).





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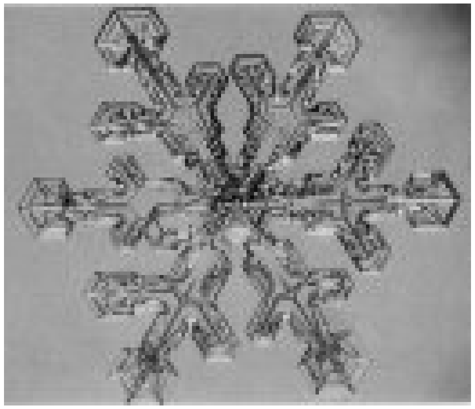
# Snow Crystal Shapes

Sectored plate

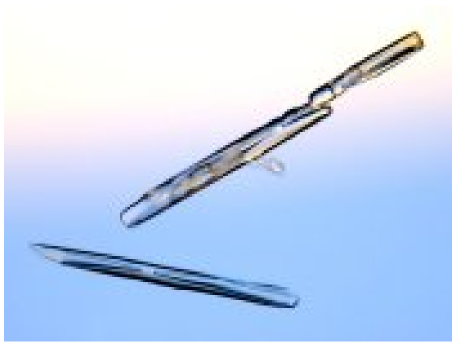
Dendritic sectored plate



Stellar Dendrite

Hollow column

Needle crystal



Columns and needles are often the main snowfall constituents.



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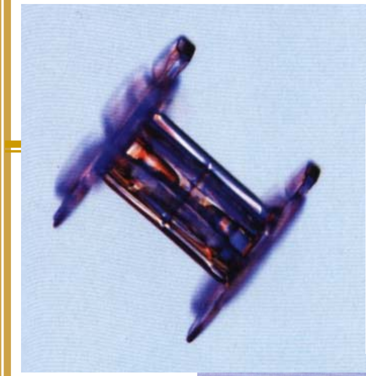
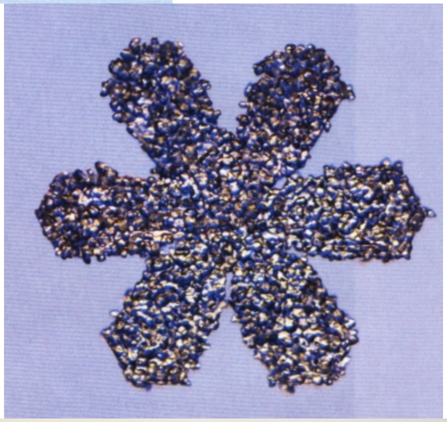
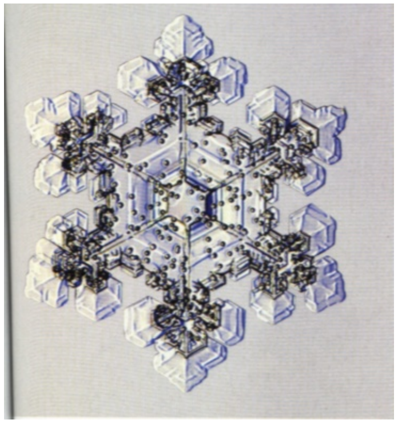
# Strange Snow Crystal Shapes

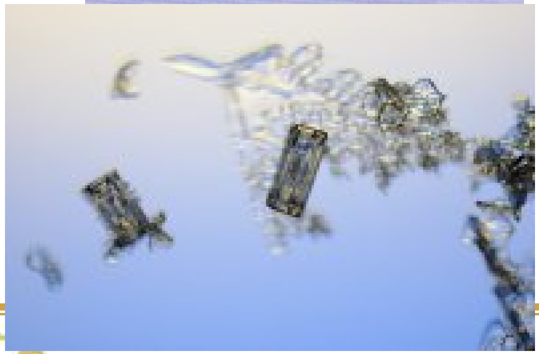


**Capped Columns:** starts growing as a column, then suddenly switches to plate-like growth.



**Rimed Crystal:** supercooled cloud droplets that freeze on a snow crystal.





**Irregulars:** Broken snow crystals from collisions and turbulence.



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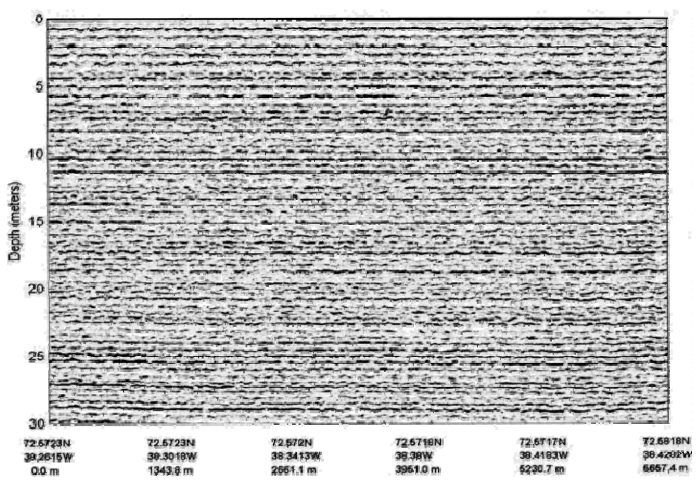
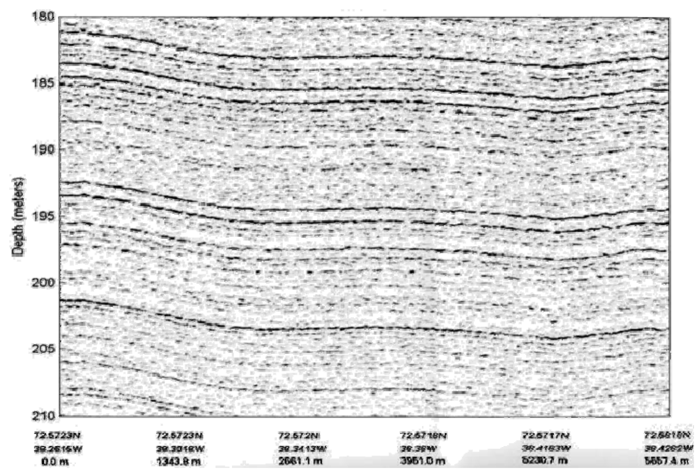
# Accumulation Radar: 0.5 – 2 GHz

Variation in Annual Accumulation – look back 100's of years.

**Accumulation radar data from Summit, Greenland in July 2005**



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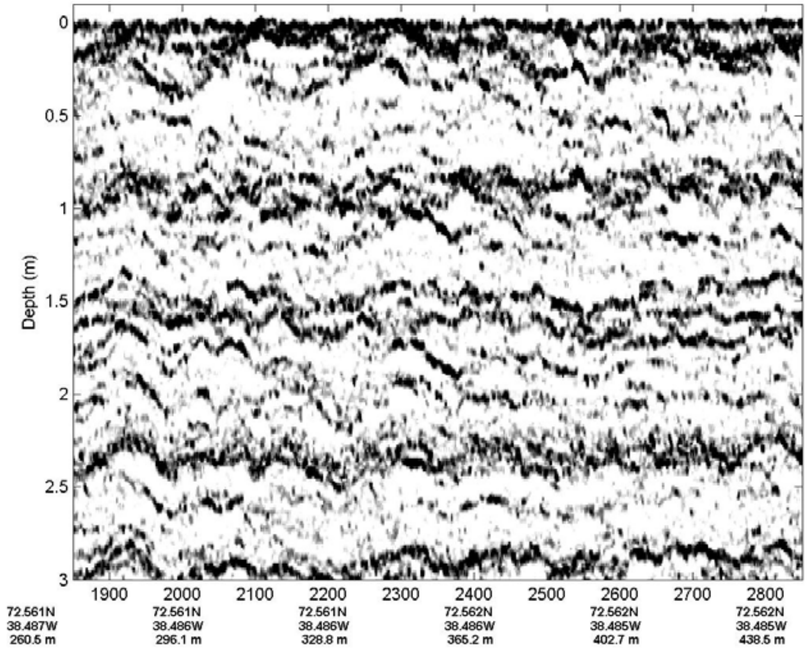
# Planewave Radar: 12 – 18 GHz

Sub-annual accumulation – look back about 10-20 years. 3 cm resolution



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# Questions?



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