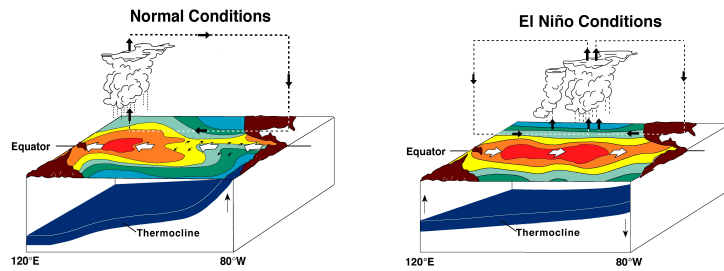


2. Examples of Natural Variability

El Niño/Southern Oscillation (ENSO)

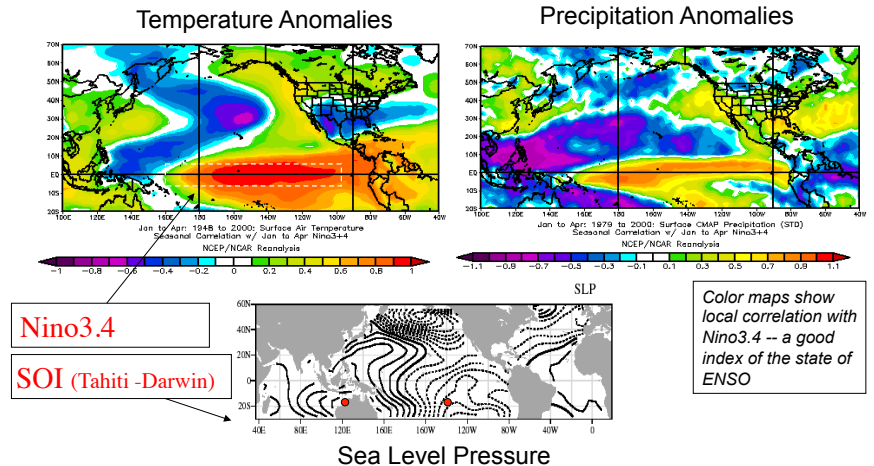
- El Niño/Southern Oscillation (ENSO) is the dominant pattern of climate variability on year-to-year time scales



- The physics responsible for ENSO are localized in the tropical Pacific, but ENSO causes global climate anomalies

ENSO

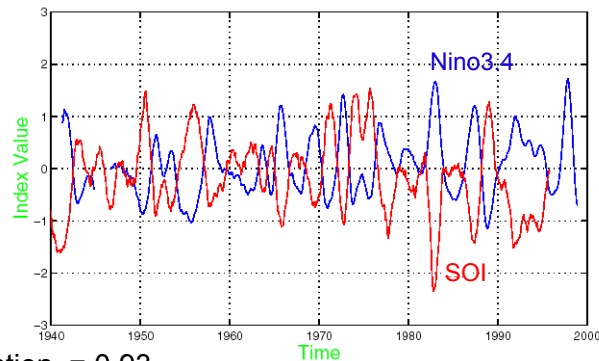
Changes in the distribution of sea surface temperature are coordinated with changes in atmospheric circulation and rainfall patterns



ENSO

There is a tight coupling between the atmosphere & ocean

Sea Surface Temperature and Sea Level Pressure



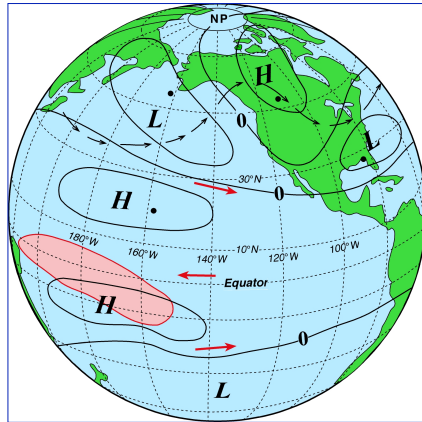
Correlation = 0.93

ENSO

- El Niño is the warm phase of ENSO
 - The tropical Pacific ocean is warmer than usual; rainfall moves from the western Pacific to the central Pacific
- La Niña is the cold phase of ENSO
- El Niños
 - occur every 3-7 years or so and last about one year
 - El Niño is usually followed by one year of La Niña conditions
- The state of the tropical Pacific (ENSO) is predictable up to one year in advance
 - For example, the average skill for a six month forecast is about 0.85 (perfect forecast = 1, no skill = 0)
- ENSO causes the global average temperature to change by $\pm 0.15^\circ\text{C}$

ENSO affects the global climate through atmosphere and ocean teleconnections

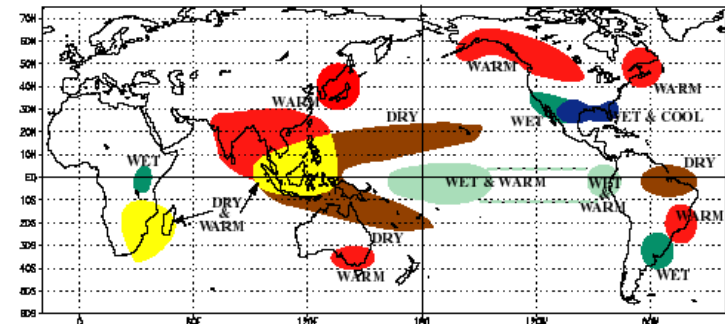
Anomalies during El Nino: the “warm phase” of ENSO



Upper level circulation changes

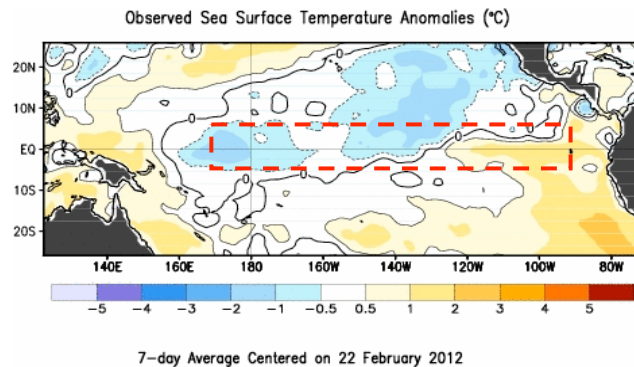
The impacts of ENSO

WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY

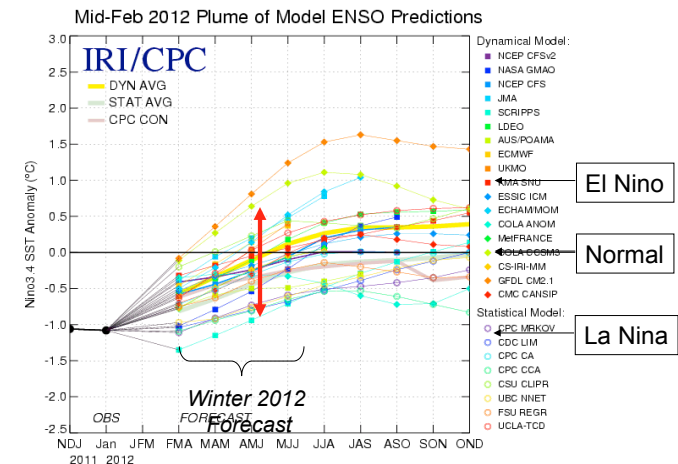


- ENSO alters the climate on a global scale. For example, ENSO impacts
 - Rainfall in Indonesia (correlation 0.7)
 - about 1/4 of the variability in wintertime temperature and storminess in the western US
 - the probabilities of extreme weather events on a global scale

Current Tropical Pacific Ocean Temperature Anomalies



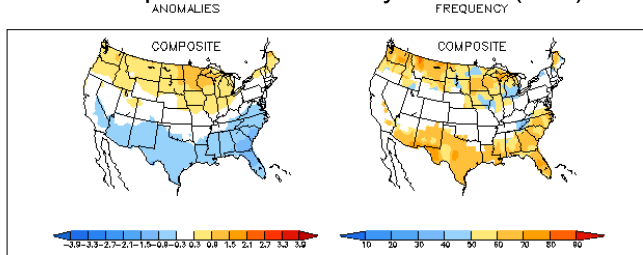
Most recent El Nino Forecasts



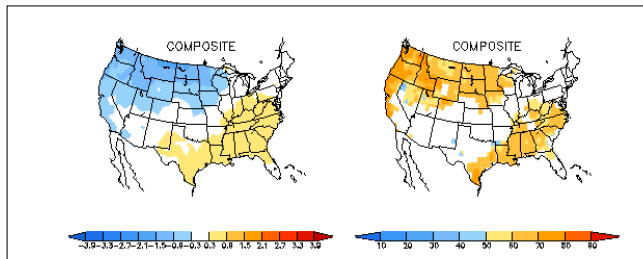
Historical Impact of ENSO on the US

<http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml>

Temperature in January - March (in C)



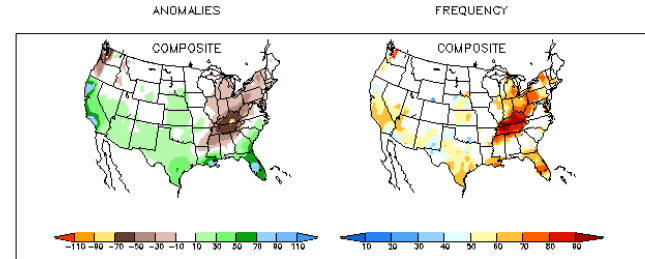
El Nino



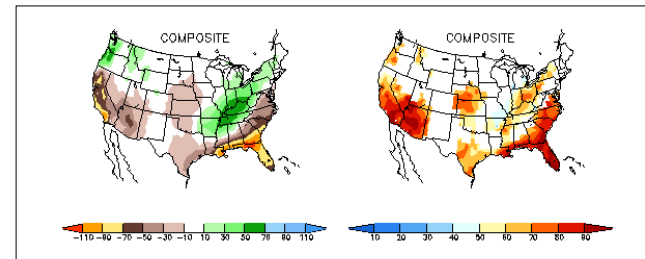
La Nina

Historical Impact of ENSO on the US

Precipitation in January - March (in mm)



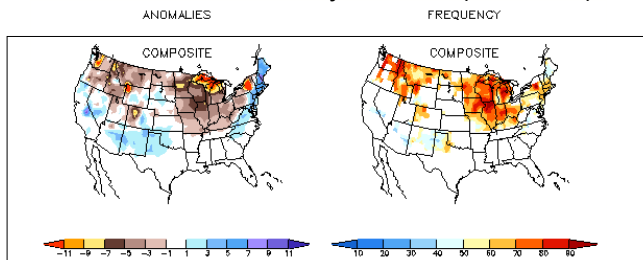
El Nino



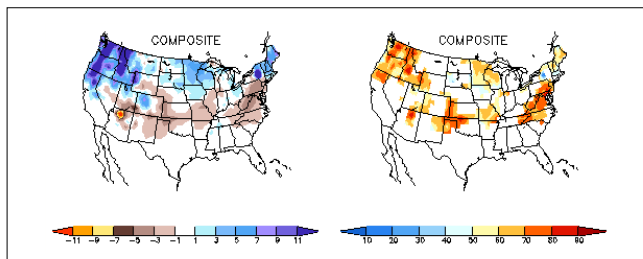
La Nina

Historical Impact of ENSO on the US

Snowfall in January - March (in inches)



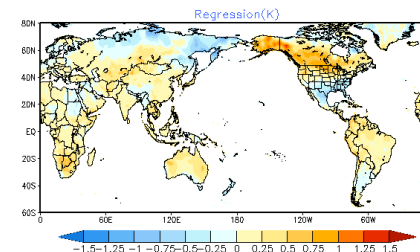
El Nino



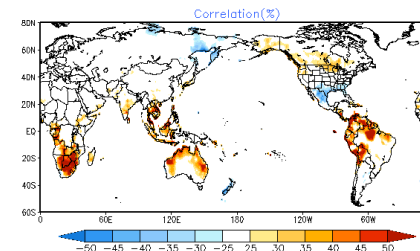
La Nina

Historical Impact of ENSO

Temperature in December – February



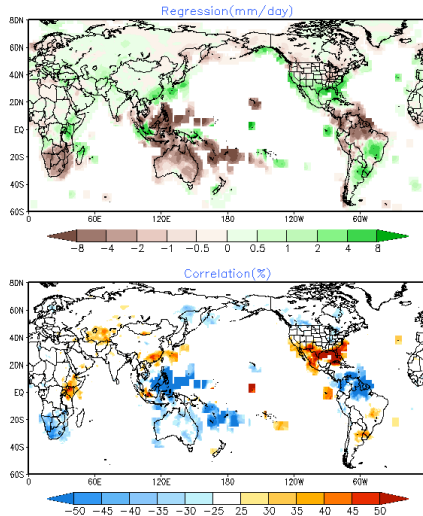
Regression
(how much change
modest El Nino)



Correlation

Historical Impact of ENSO

Precipitation in December – February



Regression
(how much change
modest El Nino)

Correlation

3. Forced Change: Natural

Volcanoes

- Emit sulfur dioxide into atmosphere
- The most explosive eruptions can loft sulfur dioxide 20-30km -- into the stratosphere, where it turns into sulphate particles (aerosols)
- Once in the stratosphere, the winds distribute the sulphate aerosols globally
- The smallest particles fall-out in one or two years
- Climate Impact:
 - Small sulphate particles reflect radiation in the visible band; hence they reduce the insolation arriving at the surface
 - This causes a cooling of the planet -- as much as 0.5C -- that can last for up to two years

Climate Variability and Climate Change

1. Definitions

- The Climate System; Natural and Forced Variability

2. Natural Variability

- North Atlantic Oscillation, El Nino/Southern Oscillation

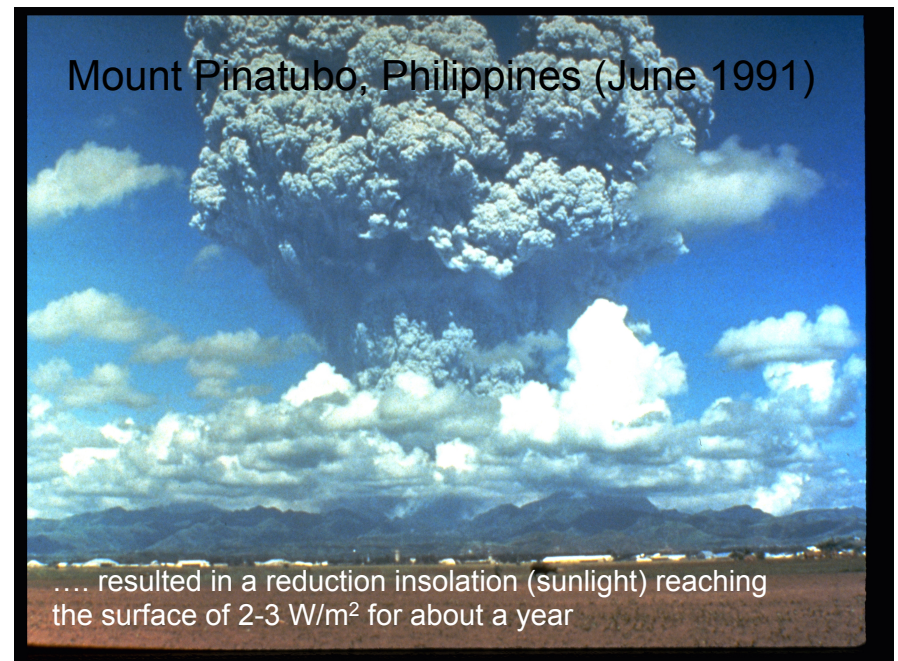
3. Forced Change (natural)

- Volcanic Eruptions (scattering particles)
- Changes in the Solar Luminosity

4. Forced Change (human)

- Burning of fossil fuels (increasing GH gases)
- Burning of biomass (scattering particles)

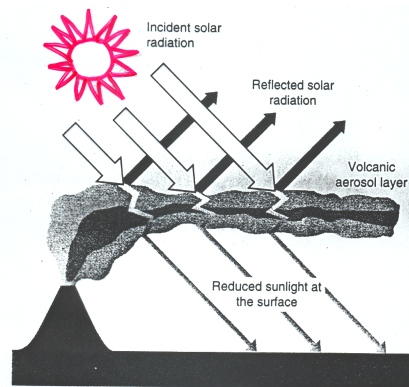
Mount Pinatubo, Philippines (June 1991)



.... resulted in a reduction insolation (sunlight) reaching the surface of 2-3 W/m² for about a year

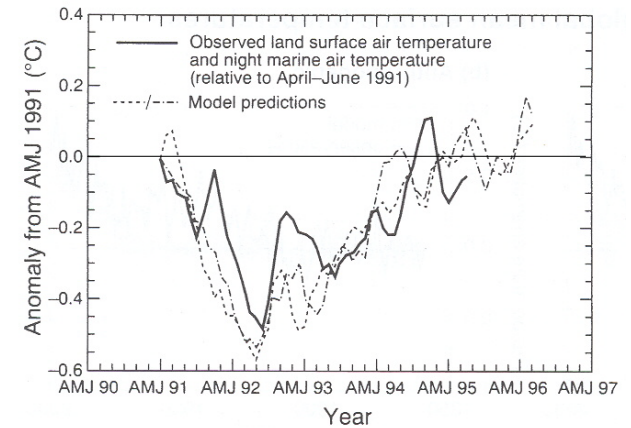
Mechanism of Volcanic Perturbation

- Sulphate particles in the stratosphere reflect sunlight, hence increase the planetary albedo
- Process is well understood but ...
 - Amount of sunlight scattered depends greatly on size and amount of aerosol particles
 - The global monitoring of aerosols began in ~1980
- Hence, the history of the amplitude of the 'forcing' before 1980 is poorly known



The impact of Mount Pinatubo eruption: Model vs Observations

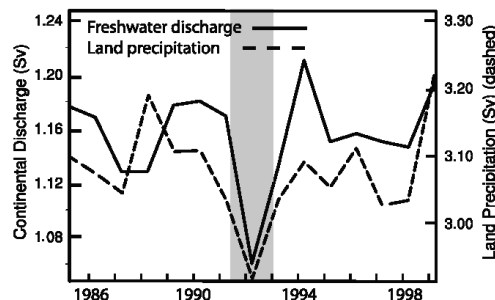
Departure of
Global Average
Temperature
from April-June
1991 average



Pinatubo caused the planet to be about 0.3°C cooler for about 18 months

Houghton Fig. 5.21

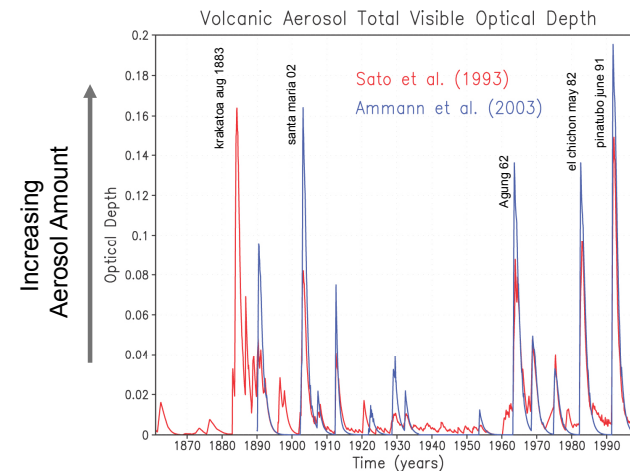
The impact of Mount Pinatubo eruption: Precipitation



Mount Pinatubo also caused about 5% less global averaged precipitation

Trenberth and Dai 2007

Major Volcanic Eruptions in the past



Estimates from two different groups

IPCC 2007 Fig 2.18

Volcanic Eruptions and Global Temperature

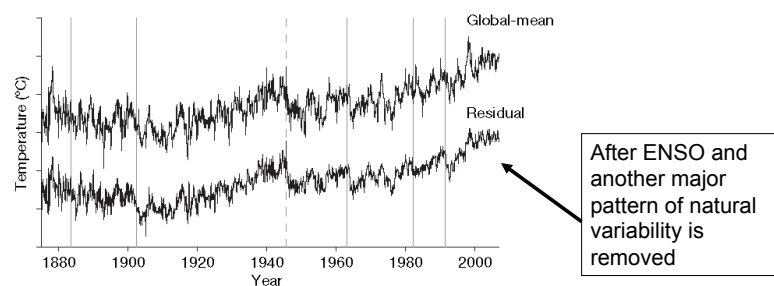
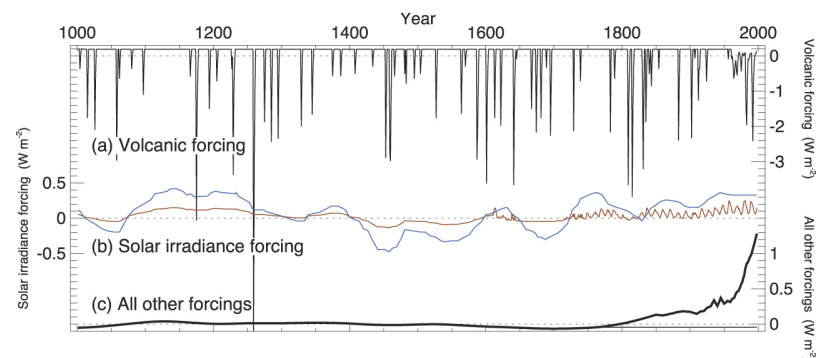


Figure 2 | The original (that is, unfiltered) and residual global-mean temperature time series duplicated from Fig. 1. The solid vertical lines denote volcano eruption dates: from left to right, Mts Krakatoa, Santa Maria, Agung, El Chichón and Pinatubo. The dashed vertical line denotes the month of August 1945. Vertical axis shows temperature anomalies; tickmarks indicate steps of 0.5 °C.

- Suggestion that the typical large volcano can cool the planet by ~0.2°C for about a year or so

Thompson et al 2008

Major Volcanic Eruptions in the past



Estimates of forcing amplitude are highly uncertain because amount and size of aerosol lofted is only crudely estimated

IPCC 2007 Fig 6.14

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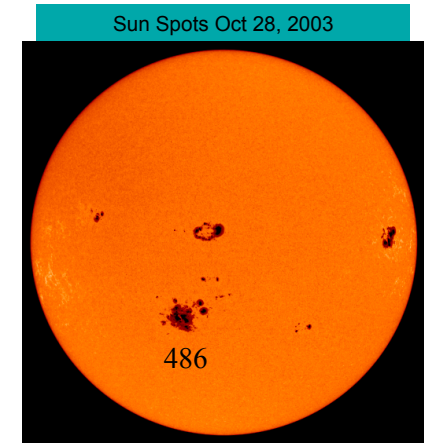
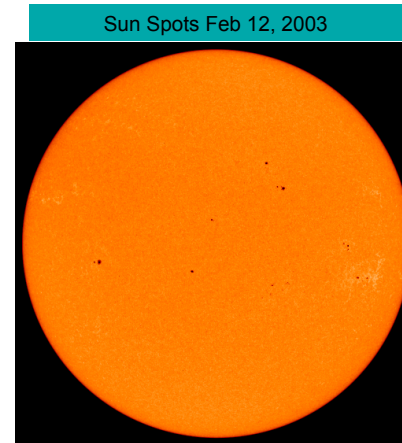
- Volcanic Eruptions (scattering particles)
- Changes in the Solar Luminosity

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- Burning of biomass (scattering particles)

Forced Change: Changes in the Sun's output

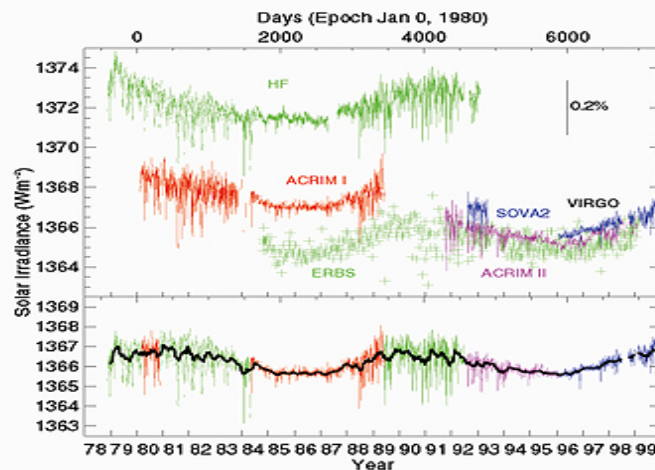
- Sunspots are associated with a small increase in energy coming from the Sun
 - Sunspot numbers vary (11 year cycle, and other poorly understood time scales)
- Direct estimates of the change in insolation since 1978
 - The solar constant varies by $\pm 0.05\%$ over the sunspot cycle, or about $\pm 0.5 \text{ W/m}^2$, or about $\pm 0.125 \text{ W/m}^2$ averaged over the whole Earth
- Changes are too small to explain correlated variability in global temperature (so proponents of solar forcing offer exotic ideas -- often involving cosmic rays and clouds -- to amplify the impact):
 - Expect $\sim 0.05^\circ\text{C}$ changes in global temperature



"one of the most powerful solar flares in years... erupted from sunspot 486."

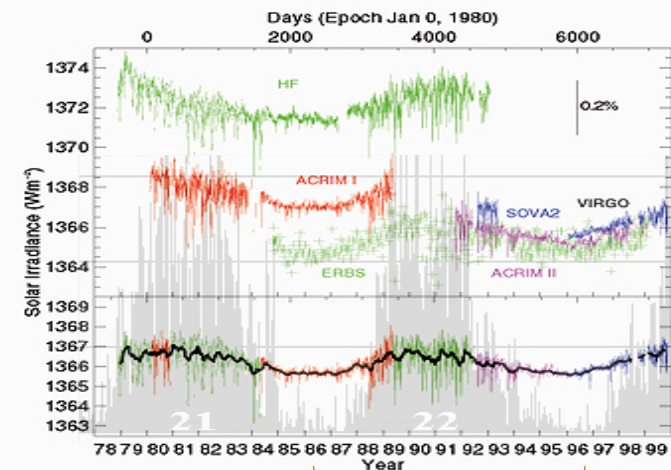
www.spaceweather.com

The Solar Constant



Direct measurements of Solar luminosity since 1978

The Solar Constant



Sunspot cycle #22

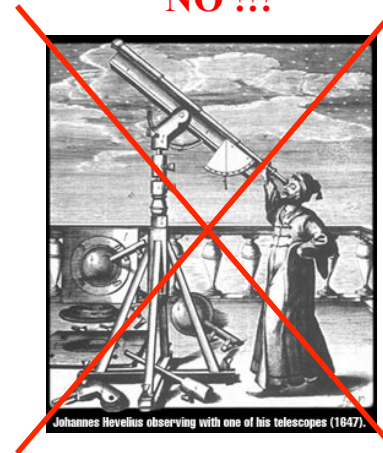
Sunspot observations

25 BC: First sunspot records in China
1611: Sunspots discovered by Europeans (with telescopes)



How to view sunspots

NO !!!



Yes

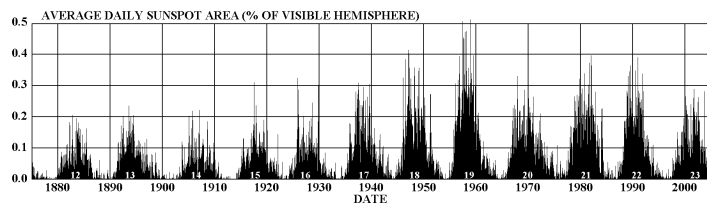
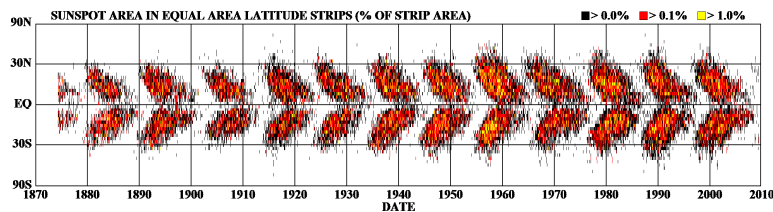


focus solar image onto a screen



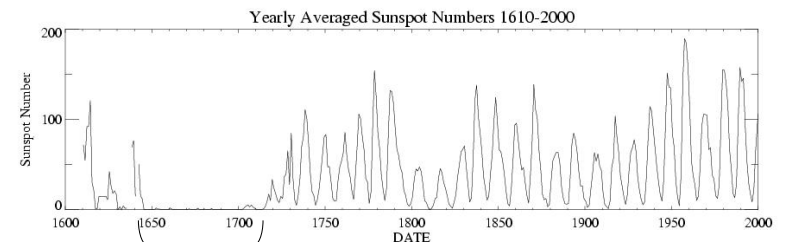
Sunspot Evolution

DAILY SUNSPOT AREA AVERAGED OVER INDIVIDUAL SOLAR ROTATIONS



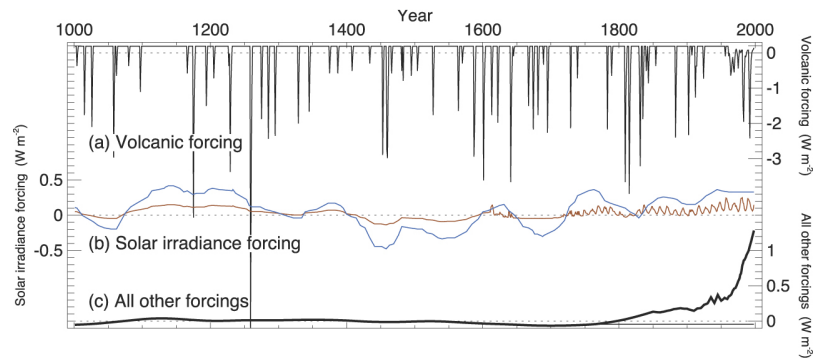
Cycle is on average 10.55 yrs (range is 9 to 14 yr)

Sunspot Numbers



Maunder Minimum in Sunspots
(Also the time of the "Little Ice Age" in Europe)
Coincidence?

The Solar Constant in the past



History of Sun's luminosity is revised downward (to brown curve)

Estimate comes from: (i) extrapolating direct insolation-sunspot number relationship; (ii) modeling of the solar magnetic flux; ^{14}C and ^{10}Be measurements in trees (cosmogenic flux); (iii) observing range of luminosity in other Sun-like stars.

IPCC 2007 Fig 6.14

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