XV. Understanding recent climate variability
• temperature from thermometers, satellites, glacier lengths and boreholes all show significant warming in the 20th C+

• reconstruction of past temperatures from corals, tree rings, and ice cores indicate that the 20th C+ warming is **anomalous** in the last 1000 years
the details of this reconstruction by Penn State climatologist Michael Mann and others (1998) have been questioned by US policy makers and some scientists- a recent comprehensive review finds it to be largely correct within the stated errors (in gray)
recall temperature records compared

from recent review and compilation by the NAS (NRC 2007)
what factors influence climate?

what factors might influence the amount of energy received or retained by the climate system?

- solar variations
- volcanic activity
- change in atmospheric composition
  - GHG’s
  - aerosols
  - clouds (as feedback or “forced” by aerosols)
- change in albedo
  - vegetation (as climate-vegetation feedback or “forced” by land-use change)
  - snow and ice (as feedback)
recall

- **climate forcing** - any mechanism that influences the amount of energy received or retained by the climate system, often expressed as a *radiative forcing* in W/m$^2$

- **climate response** - the response of the climate system to a particular forcing (or forcings), where the response may include climate *feedback* processes *(example: the climate response to CO$_2$ forcing is dominated by water vapor feedback)*

- **climate sensitivity** - the ratio of response to forcing at equilibrium, often therefore expressed as temperature change per W/m$^2$ (or per “CO$_2$ doubling”)*
recall concept of energy balance

• what must happen if the received radiation (or the *radiative forcing*) changes?

• the *temperature* must adjust so that emitted radiation balances received radiation.

• when the *radiative forcing* is changing the system still seeks but will not necessarily achieve equilibrium or radiative balance.
est. radiative forcing of climate 1750-2005

Radiative Forcing Terms

- CO₂
- N₂O
- CH₄
- Halocarbons

Human activities
- Long-lived greenhouse gases
- Ozone
- Stratospheric water vapour
- Surface albedo
- Total Aerosol
- Direct effect
- Cloud albedo effect
- Linear contrails
- Land use
- Black carbon on snow

Natural processes
- Solar irradiance
- Linear contrails
- Total net human activities

Radiative Forcing (watts per square metre)

-2  -1  0  1  2

“balance”

energy deposits and withdrawals

human
sun
net human

radiative forcings are simply additive

IPCC AR4
climate variation of the last 1000 yr

we might expect climate of the last 1000 years to have been influenced by factors that alter the *radiative forcing*, such as:

- solar variability
- volcanoes
- greenhouse gases
- aerosols

*let’s look at them one at a time.....*
Total Solar Irradiance from satellites

- 11-yr solar cycle amplitude ~0.1%
  (so-called sunspot cycle)
- *longer-term variations not yet detectable*

\[ \pm 0.1\% \text{TSI} \frac{(1-0.3)}{4} \]
\[ \pm \sim 0.25 \text{Wm}^{-2} \]

*CLIMATE*

*data: Froehlich & Lean ‘98 & www.pmodwrc.ch*
Sun Spots from telescopes

- Galileo’s telescope, 1611
- Telescopes record periodic changes in sun spot abundance
- Fewer spots, lower irradiance
- Maunder and Dalton Minima (~ Little Ice Age)
- Followed by Modern Maximum

Data: Hoyt & Schatten '98

Approx. size of Earth → •

March 30, 2001
 photons
sunspots (& faculae)
particles and magnetic fields
atmosphere
production of $^{14}$C in atmosphere by cosmic rays
galactic cosmic rays
geomagnetic field
“cosmogenic” isotopes and the sun

• in our discussion of the previous slide, we noted that when the sun is more active, the solar wind (containing particles and magnetic fields) increases, adding to the total magnetic field near Earth

• when this happens fewer galactic cosmic rays penetrate the magnetic field

• “cosmogenic” isotopes are formed by the interaction of cosmic rays with other elements, for example by bombardment of common nitrogen to produce $^{14}$C in the atmosphere

• since $^{14}$C is taken up into plant material along with common carbon, we can use its abundance in tree rings to estimate past solar activity (as shown on the next slide)
sun spot cycle amplitude increased from Maunder Min. to Modern Max.

Longer Term Solar Variability from “cosmogenic isotopes” like $^{14}$C

Wolf Sporer Maunder Dalton

Muscheler, in press

estimated solar strength Mev

yr AD

ionization chamber from tree ring $\Delta^{14}$C

D M Sp W

modeled solar modulation (MeV)
solar variability

- satellites record changes in total solar irradiance since 1978 revealing an 11-yr cycle with an amplitude of ~0.1%
- sunspots and “cosmogenic” isotopes (like $^{14}$C) suggest bigger solar variations in the past (i.e. the Wolf, Sporer, Maunder and Dalton Minima) but these relative changes are difficult to scale to absolute changes in irradiance
- irradiance changes during past solar minima are thought to be in the range of -0.1 to -0.4 %
volcanoes

- inject aerosols into atmosphere (soot, dust, gases)
- can block out sun directly (higher albedo, cools planet)
- but also can change properties of clouds (higher cloud albedo)
atmospheric transmission at MLO

reduced transmission of solar radiation is a negative radiative forcing

Agung 1963, Indonesia
Fuego 1974, Guatemala
El Chichon 1982, Mexico
Pinatubo 1991, Philippines

VEI= Volcanic Explosivity Index

comprehensive list of large eruptions last 10 kyr can be found at http://www.volcano.si.edu/world/largeeruptions.cfm
(Global Volcanism Program)
sulfur aerosol in stratosphere following injection by Pinatubo (for layer at 26 km)

large explosive eruptions punch ash and gases into stratosphere

aerosols can spread out before destruction and removal

Read et al., 1993
radiative (and chemical) effects

stratospheric warming (energy incr.) “white house effect”

surface cooling (energy deficit)

adapted (by a Hungarian?) from Robock 2000
volcanoes

history and size of major eruptions from historic records and volcanic ash in ice cores, last 1000 years (expressed here in terms of impact on radiation balance at top of troposphere)

after Crowley ‘00
greenhouse gases 0-2005 AD

- Carbon Dioxide (CO₂)
- Methane (CH₄)
- Nitrous Oxide (N₂O)

IPCC AR4
Estimated forcings, last 1000 yr

Small overall increase since 1750
(range: a few tenths W/m²)

After Crowley ‘00
estimated forcings, last 1000 yr

after Crowley ‘00
estimated forcings, last 1000 yr

after Crowley ‘00
estimated forcings, last 1000 yr

Which forcing is now dominant?

after Crowley '00
a test of our understanding

• how might we use information about *radiative forcing* to evaluate our understanding of past climate change?

• use model (or understanding or *climate sensitivity*) to calculate *climate response* to *radiative forcings*

• compare to observations and reconstructions

• and .....
estimated temperature response from a simple “Energy Balance Model”

estimated temperature response to individual forcings

now let’s compare responses to observed and reconstructed temperatures

after Crowley ‘00
reconstructed temperature vs. response to natural forcings

reconstruction 1 (tree rings etc.)

after Crowley ‘00
reconstructed temperature vs. response to natural forcings

recons v. volc/sol

reconstruction 1 (from tree rings etc.)
reconstruction 2

after Crowley ‘00
reconstructed temperature vs. response to natural forcings

Temperature variability prior to 20th C+ well explained by natural forcings, but not after! (temperatures have now reached ~0.7 on this scale)
extra warming after 1920 must be due to GHGs (minus aerosol effect)

reconstruction 1
reconstruction 2
temp. fr. natural forcings (volc. & solar)

after Crowley ‘00
global temperature change since 1860

climate model “hindcast”: natural forcings only

IPCC TAR (2001)
global temperature change since 1860

(a) Natural forcing only

(b) Anthropogenic forcing only

climate model “hindcast”
man-made forcings only

IPCC TAR (2001)
global temperature change since 1860

climate model “hindcast”: natural and man-made forcings

note strong resemblance of model and obs
58 simulations (fr. 14 models) vs. observations

global temperature change since 1900

IPCC AR4 (2007)
temperature change since 1900

*model* “hindcasts” considering all factors (incl. GHG’s), *natural factors only*, black is *observed temperatures*

source: IPCC ‘07
Hansen’s bold prediction

In 1988 NASA’s Jim Hansen testified to the US Congress. He showed a yearly forecast (and hindcast) of global surface temperature change in the NASA-GISS model due to past and projected GHG emissions (and other forcings). He modeled 3 scenarios, A for fast burning, B for “business as usual”, and C for slow burning. He suggested scenario B was most likely. For realism, he sprinkled volcanoes into the future record at mid-decade. This is what he showed, but with the 20 years of observations since now added........
Hansen’s bold prediction

volcanic eruption occurred in 1991, not mid-decade...
large El Nino in 1998
Hansen’s bold prediction

Most scientists are uneasy making predictions.

Jim Hansen understood the limitations of models, but he also understood that radiative forcing was ever increasing due to GHG’s and would soon dominate all sources of natural variation, giving him confidence in his predictions.

Jim Hansen is a national science hero!
summary points

• natural variation in estimated *radiative forcing* from solar changes and volcanoes explains much of the variability in reconstructed temperature prior to ~1900

• after that, *radiative forcing from increasing GHG’s* is required to explain observed temperatures

• we have already reached the point where radiative forcing from GHGs (minus that from aerosols) is larger than the natural variation in radiative forcing during the past millennium
six easy pieces

• there is a natural greenhouse effect
• radiatively important trace gases contribute to the natural greenhouse effect
• radiatively important trace gases have increased markedly due to human emissions
• radiative forcing is a useful diagnostic and can be easily estimated (and individual radiative forcings are simply additive)
• climate sensitivity is somewhere around 3/4 °C per W/m$^2$ (i.e. ~3 °C for CO$_2$ doubling)
• the product of the altered radiative forcing and the climate sensitivity is a significant number
lecture 16 learning goals

• be able to describe the factors that may have influenced global temperature over the last millennium

• use the concept of radiative forcing and climate response in an attempt to explain the temperature history of the last 1000 yrs as reconstructed from geologic proxies (tree rings, etc.) and thermometers

• consider how well estimated changes in radiative forcing from natural factors explain reconstructed temperatures of the last millennium v. the anomalous warming of the 20th Cent.+

• be familiar with Jim Hansen’s 1988 prediction and the observed outcome
next class:

• sea level change

• reading: Ch. 11

• HMWK due today