Global Warming

Mechanical Engineering 694C

Seminar in Energy Resources, Technology and Policy

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October 23, 2002

California State University Northridge

Remind students to turn in homework.

Reminder that midterm is next week.

Global warming is covered in pages 267-295 of Fay and Golomb.

Read the National Academy of Sciences 2001 report on climate change; you can download this form the course web site. See the second column of the schedule page for October 23.

For November 6 do problems 10.4, 10.5 and 10.7 in Fay and Golomb. In addition locate two different web sites (not just two pages on the same home site) regarding global warming that you find particularly interesting or informative. Write a one page summary of what you learned from each site.

Outline

- Weather and climate
  - Solar radiation spectrum
  - Radiation heat balance on earth
- Effect of greenhouse gases
- Observed temperature changes
- Climate models and forecasts
- Emission trends and controls

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2

References

- EPA – http://yosemite.epa.gov/oar/globalwarming.nsf/content/index.html
- IPCC – http://www.ipcc.ch/
- USGCRP – http://www.usgcrp.gov/
- NASA – http://earthobservatory.nasa.gov/Library/GlobalWarming/
- DOE – miscellaneous sites (see notes)

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3

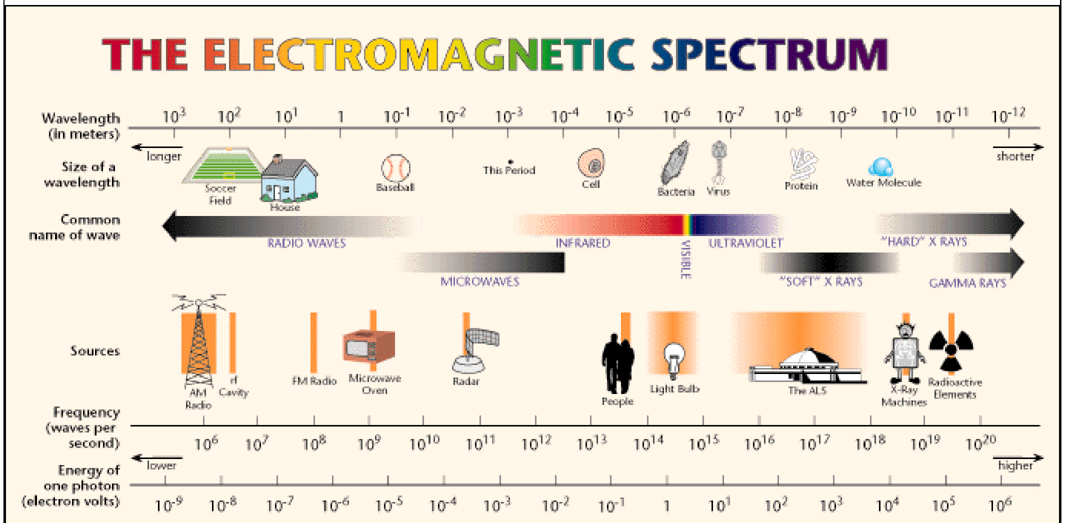
In the slide EPA is the US Environmental Protection Agency; IPCC is the International Panel on Climate Change; USGCRP is the US global climate change research program. The NASA web site is a general information site; additional information is available at web sites for specific NASA facilities. DOE represents the US department of energy; some of their web sites related to global warming are in the list below.

Carbon sequestration: http://www.fe.doe.gov/coal_power/sequestration/

Additional references via web sites are shown below.

Global warming coalition: http://www.globalwarming.org/ (critics of global warming)

NOAA: http://lwf.ncdc.noaa.gov/oa/climate/globalwarming.html



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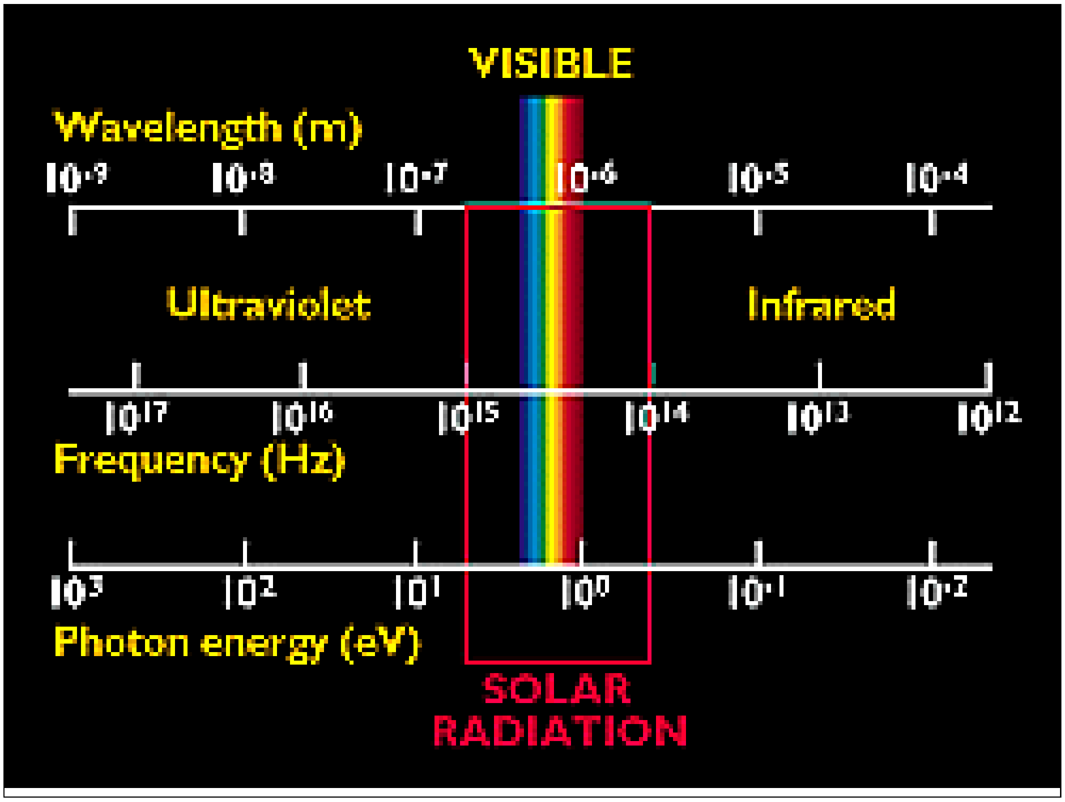
4

Reference: http://www.lbl.gov/MicroWorlds/ALSTool/EMSpec/EMSpec2.html

This is just a reminder of the various regions of the electromagnetic spectrum ranging from very long to very short. Recall the Planck hypothesis that the energy is proportional to the frequency, $E = h\nu$. Thus short wavelength (high frequency) waves have the highest energies.

The visible, infrared and ultraviolet portions of the spectrum are shown, in larger scale, on the next slide.



Reference: http://www.eren.doe.gov/pv/lightsun.html

The sun emits virtually all of its radiation energy in a spectrum of wavelengths that range from about $2x10^{-7}$ to $4x10^{-6}$ m. The majority of this energy is in the visible region. Each wavelength corresponds to a frequency and an energy; the shorter the wavelength, the higher the frequency and the greater the energy (expressed in eV, or electron volts).

Each portion of the solar spectrum is associated with a different level of energy. Within the visible portion of the spectrum, for example, red light is at the low-energy end and violet light is at the high-energy end (having half again as much energy as red light). In the invisible portions of the spectrum, photons in the ultraviolet region, which cause the skin to tan, have more energy than those in the visible region. Likewise, photons in the infrared region, which we feel as heat, have less energy than the photons in the visible region.

Solar Energy

- Solar “constant” outside atmosphere varies from 1,330 to 1,422 W/m^2 normal to solar beam
- Eleven year cycle causes variations in the “solar constant”
- Annual average for earth is 342 W/m^2 (over all regions and seasons)

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6

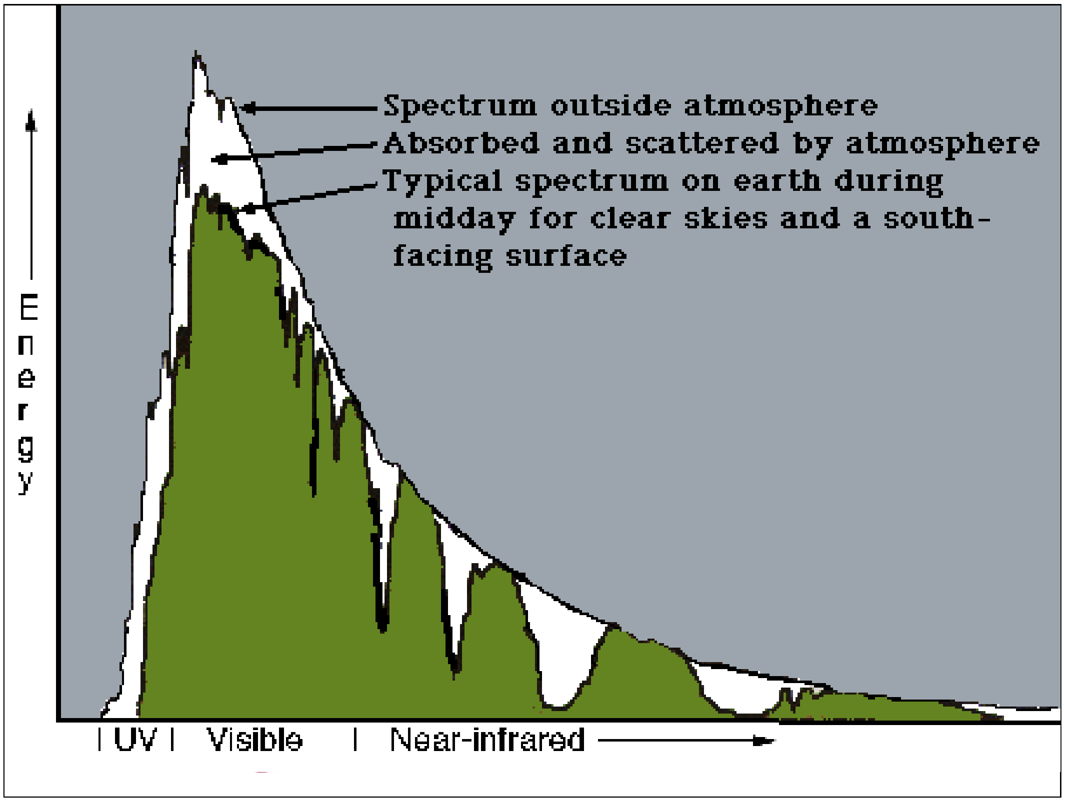
Reference: http://earthobservatory.nasa.gov/Library/Oven/

Averaged over an entire year and the entire Earth, the Sun deposits 342 Watts of energy into every square meter of the Earth. This is a very large amount of heat—1.7 x 10^{17} watts of power that the Sun sends to the Earth/atmosphere system.

Most of the Sun's heat is deposited into the tropics of the Earth. Solar heating of the Earth and its atmosphere drives the large-scale atmospheric circulation patterns, and even the seasons. The difference in solar heating between day and night also drives the strong diurnal (or daily) cycle of surface temperature over land.

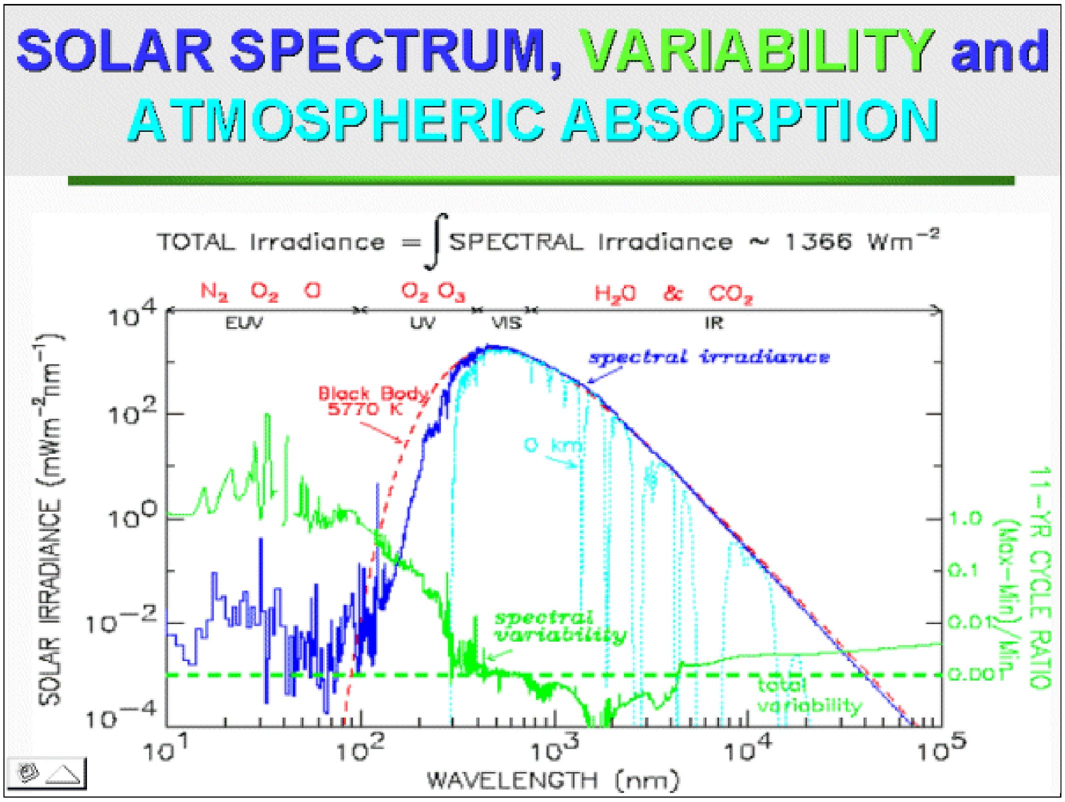
From the Planck distribution we know that the solar radiation from a high temperature heat source is mainly in the visible and ultraviolet while the earth radiation is mainly in the infrared. If the earth were a ball of rock with no atmosphere, a simple calculation that equates the solar energy absorbed by the Earth to the heat emitted by the Earth would predict the global average Earth temperature to be 0 degrees Fahrenheit, or 255 Kelvin-very cold, and not the Earth as we know it (this scenario assumes that an average rock reflects 30 percent of all light that hits it).

Atmospheric gases such as water vapor and carbon dioxide absorb the heat emitted from the surface, capturing it in the atmosphere. Because atmospheric temperature decreases with altitude, the heat emission of the atmosphere is at a much lower temperature than the surface. So the Earth and atmosphere keep heating up until the heat emitted roughly balances with the amount of sunlight absorbed. This trapping of heat by carbon dioxide and water vapor is typically called the "greenhouse effect," and these gases are referred to as "greenhouse gases.“ The natural greenhouse is an important one in keeping our planet at a comfortable temperature.



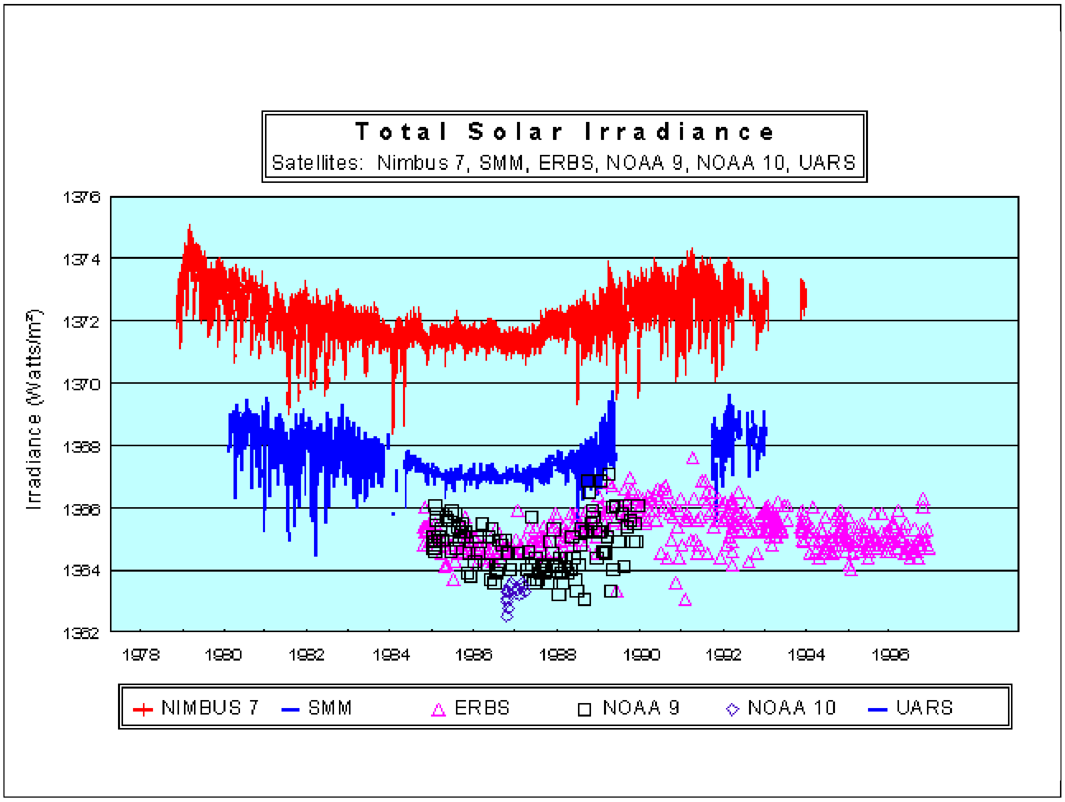
Reference: http://rredc.nrel.gov/solar/pubs/shining/page7a_fig.html

Fig. 2: Because of absorption and scattering by the atmosphere, the spectral distribution of solar radiation outside the atmosphere differs significantly from that on earth. Also, the spectral distribution on earth changes throughout the day and year and is influenced by location, climate, and atmospheric conditions. Consequently, the percentage of energy that is composed of UV, visible, or near-infrared radiation, or portions thereof, also varies by location, time of day, and year.



Reference: http://science.nasa.gov/headlines/images/sunbathing/sunspectrum.htm

This image, courtesy of Dr. Judith Lean at the US Naval Research Laboratory, shows the spectrum of solar radiation from 10 to 100,000 nm (dark blue), its variability betwen Solar Maximum and Solar Minimum (green) and the relative transparency of Earth's atmosphere at sea level (light blue). At wavelengths shorter than about 300 nm, there is a relatively large variation in the Sun's extreme UV and x-ray output (greater than 1%), but the Earth's atmosphere is nearly opaque at those wavelengths. For Earth-dwelling beach-goers there is no significant difference between Solar Max and solar minimum.



Reference: http://www.ngdc.noaa.gov/stp/SOLAR/IRRADIANCE/irrad.html

These data shows the variability in the solar constant.

http://lwf.ncdc.noaa.gov/oa/climate/globalwarming.html#Q10: Since the advent of space-borne measurements in the late 1970s, solar output has indeed been shown to vary. There appears to be confirmation of earlier suggestions of an 11 (and 22) year cycle of irradiance. With only 20 years of reliable measurements however, it is difficult to deduce a trend. But, from the short record we have so far, the trend in solar irradiance is estimated at ~0.09 W/m2 compared to 0.4 W/m2 from well-mixed greenhouse gases. There are many indications that the sun also has a longer-term variation which has potentially contributed to the century-scale forcing to a greater degree. There is though, a great deal of uncertainty in estimates of solar irradiance beyond what can be measured by satellites, and still the contribution of direct solar irradiance forcing is small compared to the greenhouse gas component. However, our understanding of the indirect effects of changes in solar output and feedbacks in the climate system is minimal. There is much need to refine our understanding of key natural forcing mechanisms of the climate, including solar irradiance changes, in order to reduce uncertainty in our projections of future climate change.

In addition to changes in energy from the sun itself, the Earth's position and orientation relative to the sun (our orbit) also varies slightly, thereby bringing us closer and further away from the sun in predictable cycles (called Milankovitch cycles). Variations in these cycles are believed to be the cause of Earth's ice-ages (glacials). Particularly important for the development of glacials is the radiation receipt at high northern latitudes. Diminishing radiation at these latitudes during the summer months would have enabled winter snow and ice cover to persist throughout the year, eventually leading to a permanent snow- or icepack. While Milankovitch cycles have tremendous value as a theory to explain ice-ages and long-term changes in the climate, they are unlikely to have very much impact on the decade-century timescale. Over several centuries, it may be possible to observe the effect of these orbital parameters, however for the prediction of climate change in the 21st century, these changes will be far less important than radiative forcing from greenhouse gases.

Climate and Weather

- Climate refers to long term measures, typically 30 years
  - temperature
  - precipitation
  - wind
- Climate change and variability
  - change due to human activities versus
  - natural variability

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10

Climate in a narrow sense is usually defined as the “average weather”, or more rigorously, as the statistical description in terms of the mean and variability of relevant quantities over a period of time ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO). These quantities are most often surface variables such as temperature, precipitation, and wind. Climate in a wider sense is the state, including a statistical description, of the climate system.

Climate change refers to a statistically significant variation in either the mean state of the climate or in its variability, persisting for an extended period (typically decades or longer). Climate change may be due to natural internal processes or external forcings, or to persistent anthropogenic changes in the composition of the atmosphere or in land use. The Framework Convention on Climate Change (UNFCCC), in its Article 1, defines “climate change” as: “a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods”. The UNFCCC thus makes a distinction between “climate change” attributable to human activities altering the atmospheric composition, and “climate variability” attributable to natural causes.

Climate variability

Climate variability refers to variations in the mean state and other statistics (such as standard deviations, the occurrence of extremes, etc.) of the climate on all temporal and spatial scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability). See also: Climate change.

Climate System and Models

- Components
  - Atmosphere
  - Hydroshpere: rain, rivers, oceans, etc.
  - Cryoshpere: glaciers, polar regions, etc.
  - Land surface
  - Biosphere
- Have to model phenomena in each component and their interactions

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11

Climate feedback is an interaction mechanism between processes in the climate system is called a climate feedback, when the result of an initial process triggers changes in a second process that in turn influences the initial one. A positive feedback intensifies the original process, and a negative feedback reduces it.

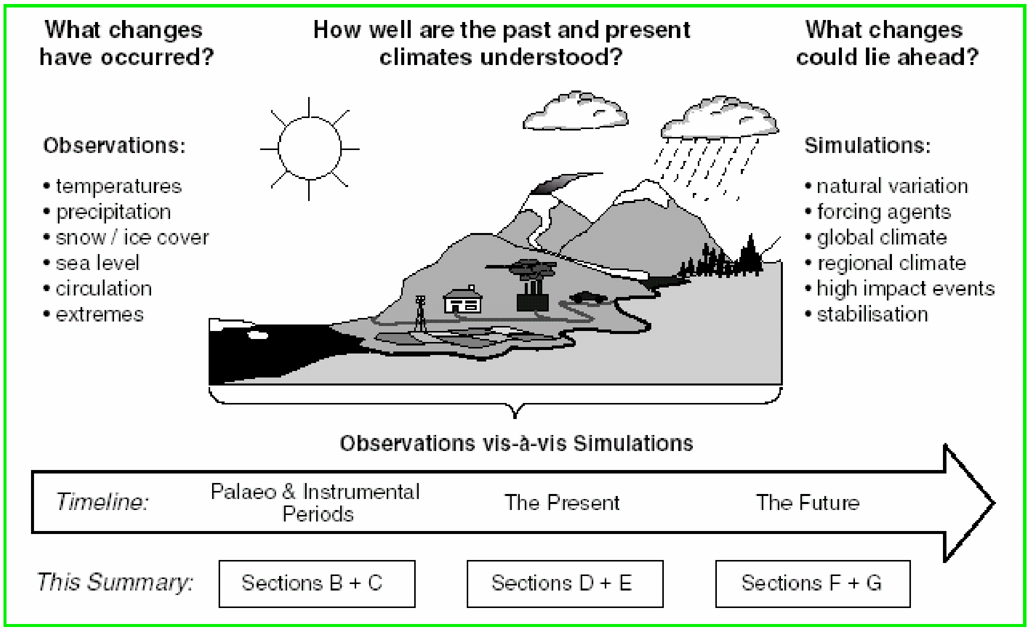
Climate models differ in such aspects as the number of spatial dimensions, the extent to which physical, chemical or biological processes are explicitly represented, or the level at which empirical parametrizations are involved. Coupled atmosphere/ ocean/sea-ice General Circulation Models (AOGCMs) provide a comprehensive representation of the climate system.

Climate prediction is an attempt to produce a most likely description or estimate of the actual evolution of the climate in the future.

Climate projection projection of the response of the climate system to emission or concentration scenarios of greenhouse gases and aerosols, or radiative forcing scenarios, which are based on assumptions, concerning, e.g., future socio-economic and technological developments, that may or may not be realized,.

Climate scenarios are plausible and often simplified representation of the future climate, based on an internally consistent set of climatological relationships.

Climate sensitivity refers to the equilibrium change in global mean surface temperature following a doubling of the atmospheric (equivalent) CO_2 concentration. **Climate system** The climate system is the highly complex system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, and the interactions between them. The climate system evolves in time under the influence of its own internal dynamics and because of external forcings such as volcanic eruptions, solar variations and human-induced forcings such as the changing composition of the atmosphere and land-use change.



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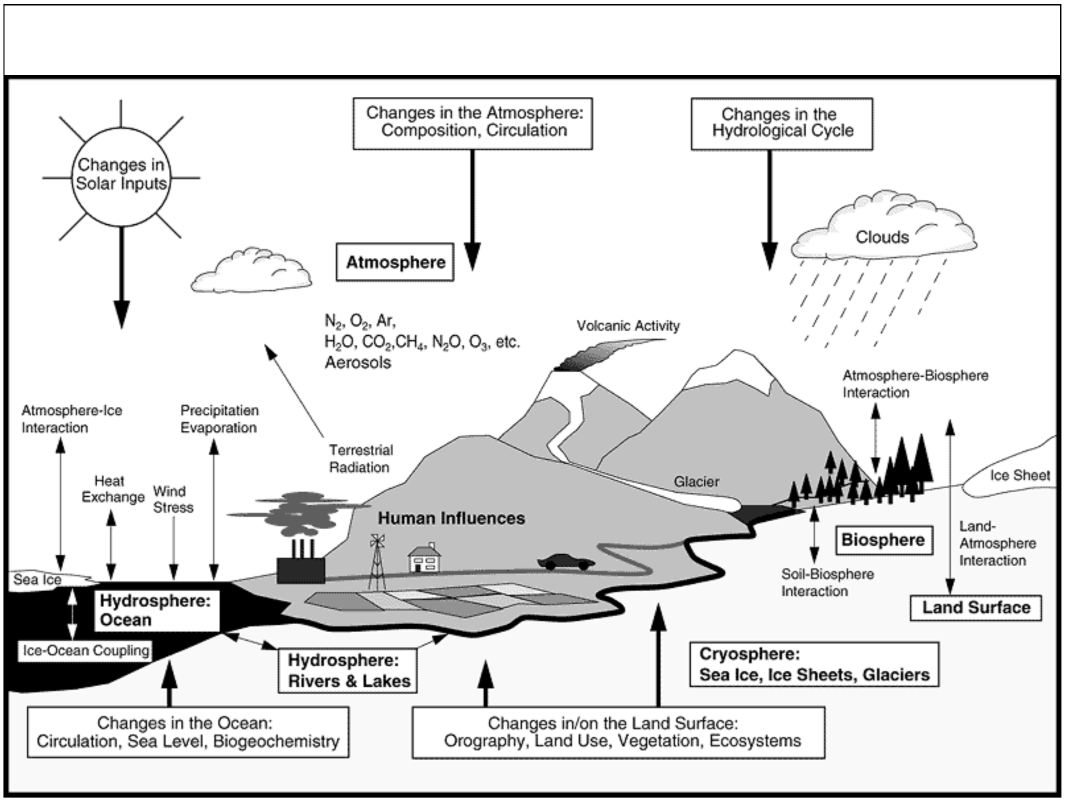
12

Reference: Ingergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Sciencific Basis*, IPCC, 2001. Figure taken from technical summary available at http://www.ipcc.ch/pub/wg1TARtechsum.pdf.

The sections shown in the figure refer to particular sections of the report cited here. This provides a basic summary of climate research. We examine past results from any possible evidence ranging from observations of tree rings and ice bores to modern instrumentation. This research provides us an understanding of what affects climate so that we can try to predict the future and examine the results of changes in conditions (such as the production of greenhouse gases) on the future.



Reference: http://www.grida.no/climate/ipcc_tar/wg1/fig1-1.htm

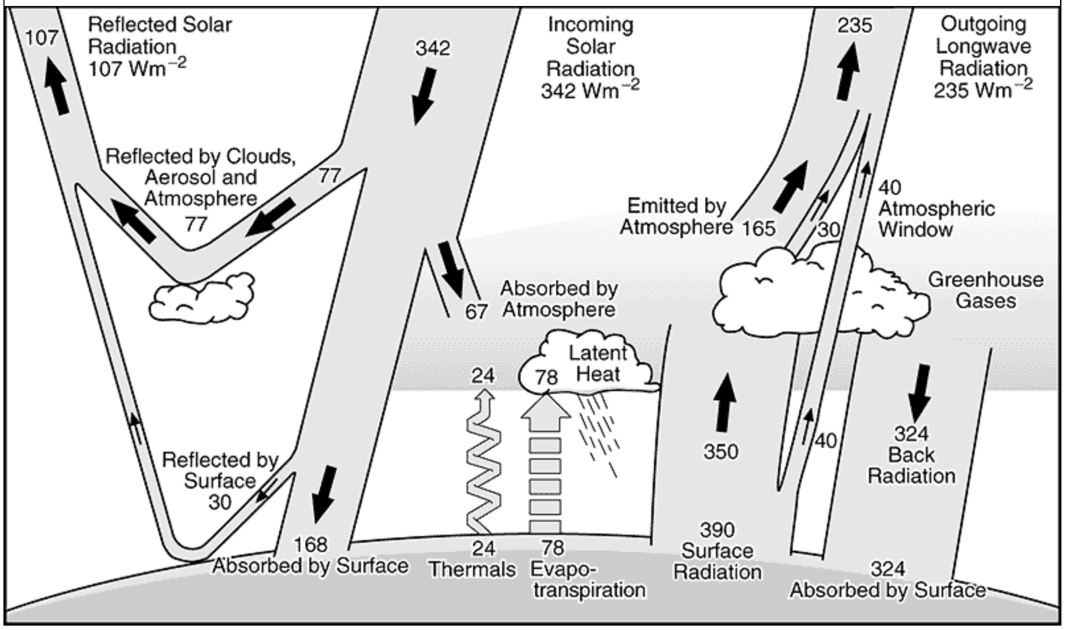
The climate system is an interactive system consisting of five major components: the atmosphere, the hydrosphere, the cryosphere, the land surface and the biosphere, forced or influenced by various external forcing mechanisms. The atmosphere is the most unstable and rapidly changing part of the system. Trace gases, such as carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O) and ozone (O_3), which do absorb and emit infrared radiation. Water vapor (H_2O), which is also a natural greenhouse gas has a highly variable composition, 1%. Because these greenhouse gases absorb the infrared radiation emitted by the Earth and emit infrared radiation up- and downward, they tend to raise the temperature near the Earth's surface. Water vapour, CO_2 and O_3 also absorb solar short-wave radiation.

Ozone in the lower part of the atmosphere, the troposphere and lower stratosphere, acts as a greenhouse gas. Higher up in the stratosphere there is a natural layer of high ozone concentration, which absorbs solar ultra-violet radiation.

Solid and liquid particles (aerosols) and clouds, which interact with the incoming and outgoing radiation in a complex and spatially very variable manner. Water vapor is central to the climate and its variability and change. The hydrosphere is the component comprising all liquid surface and subterranean water, both fresh water, including rivers, lakes and aquifers, and saline water of the oceans and seas. Oceans damp vast and strong temperature changes and function as a regulator of the Earth's climate on the longer time-scales.

The cryosphere, including the ice sheets of Greenland and Antarctica, continental glaciers and snow fields, sea ice and permafrost, derives its importance to the climate system from its high reflectivity (albedo) for solar radiation, its low thermal conductivity, its large thermal inertia and, especially, its critical role in driving deep ocean water circulation. Because the ice sheets store a large amount of water, variations in their volume are a potential source of sea level variation.

Radiation Balance



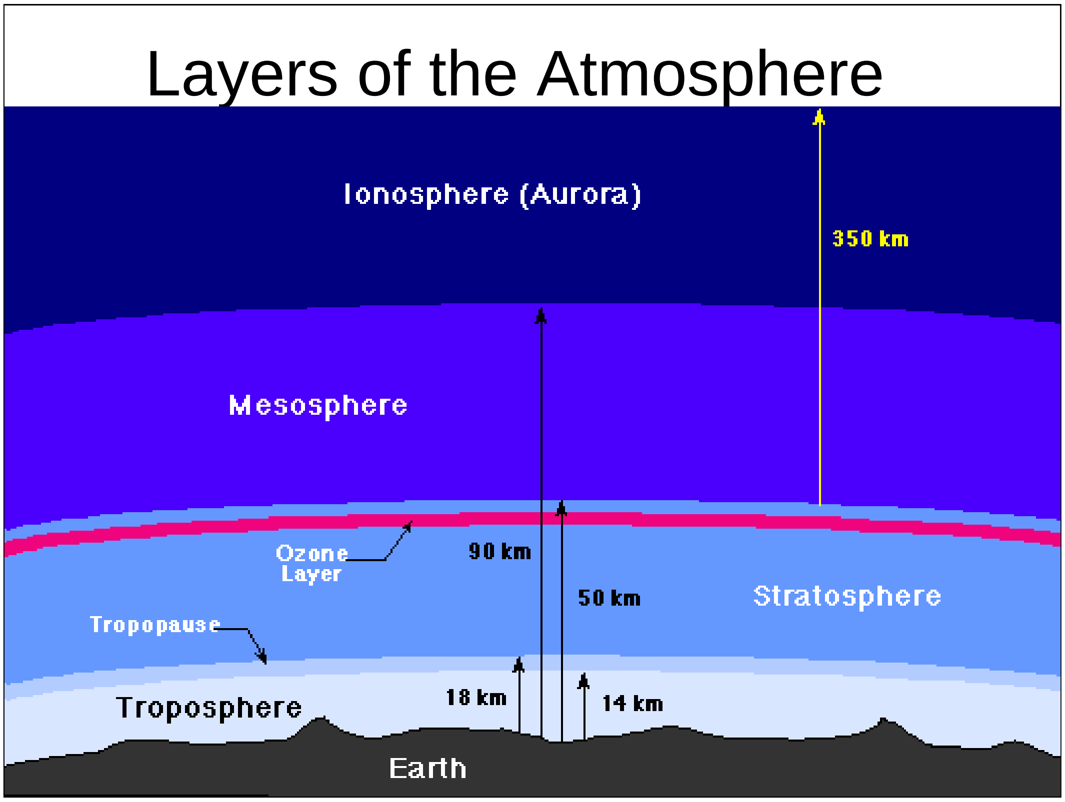
Reference: http://www.grida.no/climate/ipcc_tar/wg1/041.htm

Figure 1.2: *The Earth's annual and global mean energy balance. Of the incoming solar radiation, 49% (168 Wm^{-2}) is absorbed by the surface. That heat is returned to the atmosphere as sensible heat, as evapotranspiration (latent heat) and as thermal infrared radiation. Most of this radiation is absorbed by the atmosphere, which in turn emits radiation both up and down. The radiation lost to space comes from cloud tops and atmospheric regions much colder than the surface. This causes a greenhouse effect. Source: Kiehl and Trenberth, 1997: Earth's Annual Global Mean Energy Budget, Bull. Am. Met. Soc. 78, 197-208*

Vegetation and soils at the land surface control how energy received from the Sun is returned to the atmosphere: as long-wave (infrared) radiation, or evaporating water, which consumes energy and brings water back into the atmosphere. The marine and terrestrial biospheres have a major impact influence the uptake and release of greenhouse gases. Through the photosynthetic process, both marine and terrestrial plants (especially forests) store significant amounts of carbon from carbon dioxide.

Many physical, chemical and biological interaction processes occur among the various components of the climate system on a wide range of space and time scales, making the system extremely complex. Although the components of the climate system are very different in their composition, physical and chemical properties, structure and behavior, they are all linked by fluxes of mass, heat and momentum: all subsystems are open and interrelated.

As an example, the atmosphere and the oceans are strongly coupled and exchange, among others, water vapor and heat through evaporation. This is part of the hydrological cycle and leads to condensation, cloud formation, precipitation and runoff, and supplies energy to weather systems. On the other hand, precipitation has an influence on salinity, its distribution and the thermohaline circulation. Atmosphere and oceans also exchange, among other gases, carbon dioxide, maintaining a balance by dissolving it in cold polar water which sinks into the deep ocean and by outgassing in relatively warm upwelling water near the equator.



Reference: http://www.onlineastronomy.com/astr161/lect/earth/atmosphere.html

The ***troposphere*** is where all weather takes place; it is the region of rising and falling packets of air. The air pressure at the top of the troposphere is only 10% of that at sea level (0.1 atmospheres). There is a thin buffer zone between the troposphere and the next layer called the ***tropopause***.

Above the troposphere is the ***stratosphere***, where air flow is mostly horizontal. The thin ozone layer in the upper stratosphere has a high concentration of ozone. This layer is primarily responsible for absorbing the ultraviolet radiation from the Sun. The formation of this layer is a delicate matter, since only when oxygen is produced in the atmosphere can an ozone layer form and prevent an intense flux of ultraviolet radiation from reaching the surface, where it is quite hazardous to the evolution of life.

Above the stratosphere is the mesosphere and above that is the ionosphere (or ***thermosphere***), where many atoms are ionized (have gained or lost electrons so they have a net electrical charge). The ionosphere is very thin, but it is where aurora take place, and is also responsible for absorbing the most energetic photons from the Sun, and for reflecting radio waves, thereby making long-distance radio communication possible. The structure of the ionosphere is strongly influenced by the charged particle wind from the Sun (solar wind), which is in turn governed by the level of Solar activity. One measure of the structure of the ionosphere is the free electron density, which is an indicator of the degree of ionization.

Temperature

Profile of atmosphere

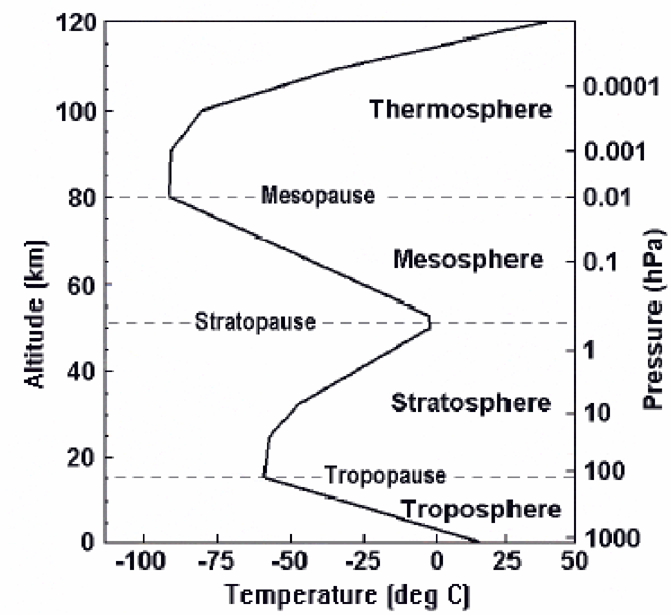


Fig. 2.4 Vertical temperature profile of the atmosphere *(from Bryant, Fig. 2.6).*

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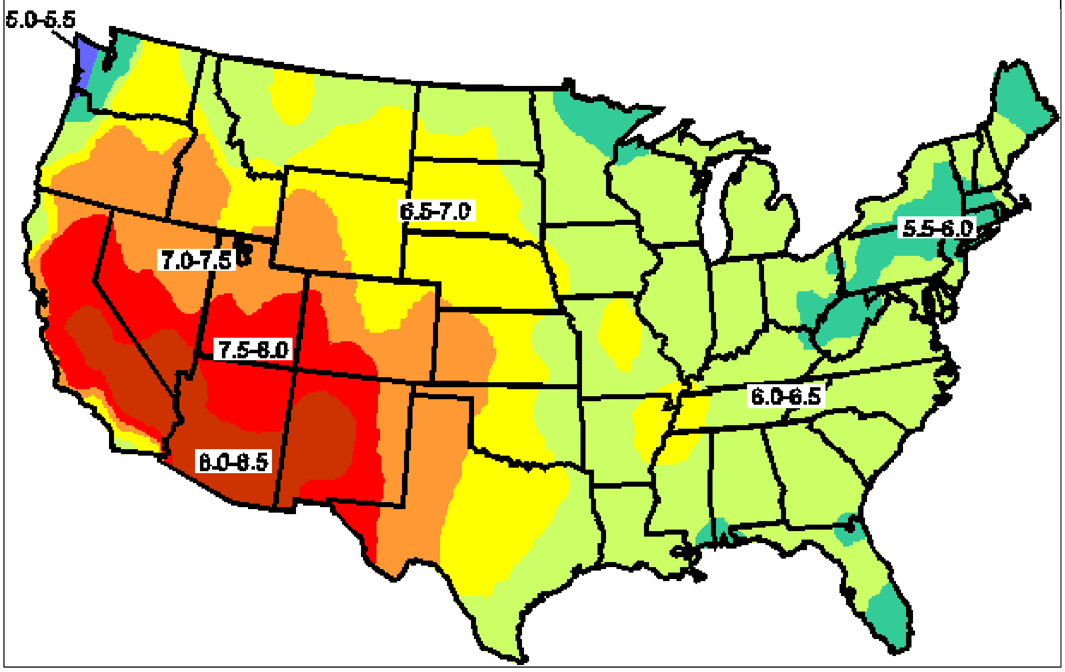
Reference: http://www.ecwa.asn.au/ClimateEngine.pdf

The temperature and pressure profiles of the earth are shown here. The units for pressure are hectapascals (hPa) where 1012.35 hPA is the standard atmospheric pressure. (This give units similar to the millibar traditionally used by atmospheric scientists.) Note that the pressure at 100 km is only 10^{-7} of a standard atmosphere.

According to http://ssd.jpl.nasa.gov/phys_props_earth.html, the mean radius of the earth is 6371 km. This gives an area of $4\pi(6371\text{ km})^2 = 5.3\text{x}10^8\text{ km}^2$. When we consider the area at the outer edge of the atmosphere, 100 km above the earth surface, the area is $4\pi(6471\text{ km})^2 = 5.1\text{x}10^8\text{ km}^2$. Thus there is not much difference in the area on the earth surface and that at the edge of the atmosphere.

June Solar Energy kWh/m^2/day

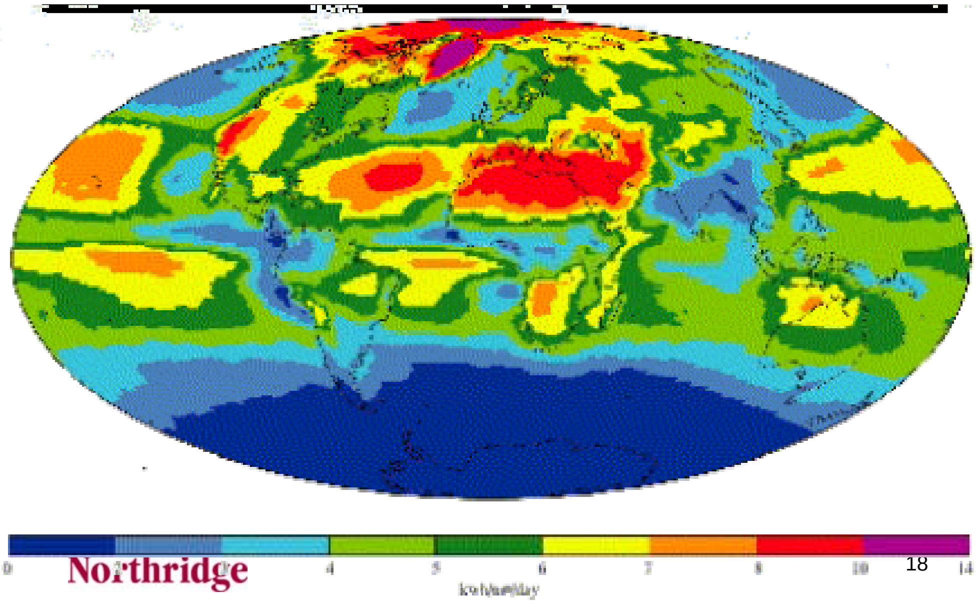


Reference: http://www.eren.doe.gov/pv/solarresource.html

Quoted from the web page: “Although the quantity of solar radiation striking the Earth varies by region, season, time of day, climate, and air pollution, the yearly amount of energy striking almost any part of the Earth is vast. Shown is the average radiation received on a horizontal surface across the continental United States in the month of June. Units are in kWh/m^2[/day]”

This represents the maximum month of solar energy as it includes the summer solstice. Note that the differences are due to both latitude and cloud cover. During June, northern latitudes would have longer days and should receive more solar radiation. However, they would also have more cloud cover.

July Solar Energy 1983-93

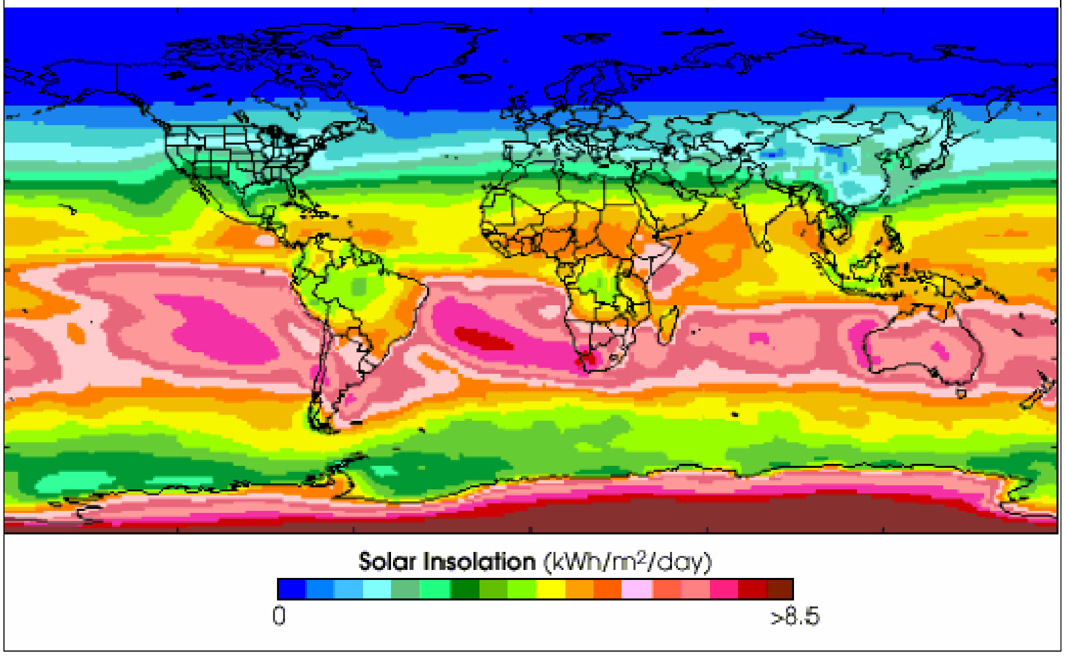


Northridge 18

Reference: http://asd-www.larc.nasa.gov/ceres/brochure/land_cover.html

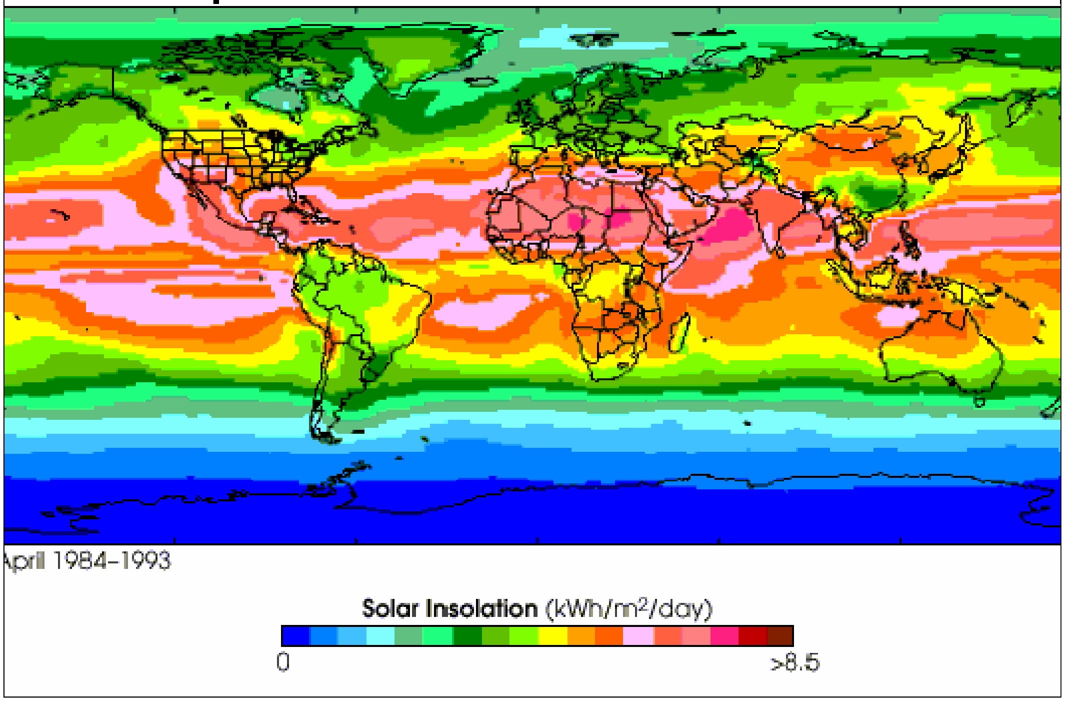
While satellites measure radiative flux at the top of the atmosphere, most people are more concerned about conditions on the surface where we live, grow our crops, heat and cool our homes, and enjoy our skiing or beach vacations. Consequently, one of the objectives of the CERES investigation is to better estimate radiative fluxes within the atmosphere and at the surface. CERES surface radiation budget (SRB) data help us understand the trends and patterns of changes in regional land cover, biodiversity, and agricultural production. In particular, CERES can detect variations in surface albedo and longwave emission that signal potential changes in the nature of the land, such as desertification. The SRB provides data on solar energy available at the surface (as shown in the figure below from the Global Energy and Water-cycle Experiment SRB project), useful for locating sites for solar power facilities and for architectural design applications.

January Insolation 1984-1993



http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=4803

April Insolation 1984-1993



http://earthobservatory.nasa.gov/Newsroom/NewImages/images.php3?img_id=4803

These false-color images show the average solar insolation, or rate of incoming sunlight at the Earth's surface, over the entire globe for the months of January and April. The colors correspond to values (kilowatt hours per square meter per day) measured every day by a variety of Earth-observing satellites and integrated by the International Satellite Cloud Climatology Project (ISCCP). NASA's Surface Meteorology and Solar Energy (SSE) Project compiled these data--collected from July 1983 to June 1993--into a 10-year average for that period.

Such images are particularly useful to engineers and entrepreneurs who develop new technologies for converting solar energy into electricity. To attain best results, most devices for harvesting sunlight require an insolation of greater than 3 to 4 kilowatt hours per square meter per day. Luckily, insolation is quite high year round near the equator, where roughly a billion people around the world must spend more money on fuel for cooking than they have to spend on food itself. Natural renewable energy resources is a particularly relevant topic in the United States today as there are rolling blackouts across the state of California while other U.S. city and state governments grapple with energy deregulation issues.

To facilitate development of new technologies for harvesting natural renewable energy sources, the SSE Project at NASA's Langley Research Center has made available a wealth of global-scale data on a variety of meteorological topics, including insolation, cloud cover, air temperature, and wind speed and direction.

Image courtesy Roberta DiPasquale, Surface Meteorology and Solar Energy Project, NASA Langley Research Center, and the ISCCP Project

Radiation

- Solar radiation reflected and emitted in January 2002 (NASA)

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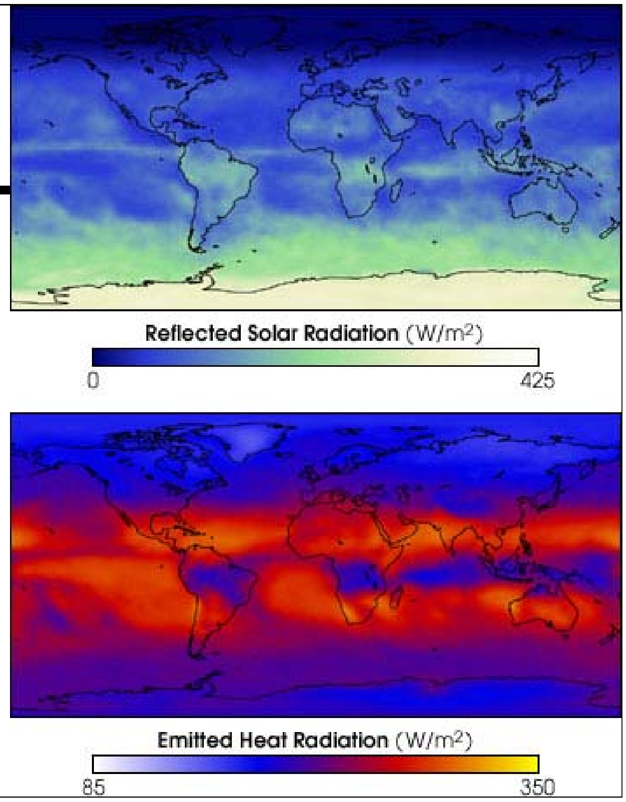

Reference: http://earthobservatory.nasa.gov/Library/GlobalWarming/warming2.html

These two maps show measurements from the Clouds and the Earth's Radiant Energy System (CERES) instrument in January 2002. The top map shows solar radiation reflected from the Earth by clouds, ice, and bright surfaces like desert. Dark, absorbing areas are colored dark blue, while bright, highly reflective areas are light green, yellow, and white. The bottom map shows heat radiated from the Earth. More energy is emitted by warmer surfaces, so tropical regions are radiating strongly except where there are high, cold clouds. The areas emitting the least energy are represented by white, while blue, purple, red, and yellow represent areas where more heat escapes. (Images by Robert Simmon, based on data provided by the CERES science team.)

Some of this outgoing longwave infrared radiation, however, is re-absorbed by water vapor, carbon dioxide, and other greenhouse gases in the atmosphere and is then re-radiated back toward the Earth's surface. On the whole this re-absorption process is good. If there were no greenhouse gases or clouds in the atmosphere, the Earth's average surface temperature would be a very chilly -18°C (-0.4°F) instead of the comfortable 15°C (59°F) that it is today.

According to the IPCC, the surface temperature could rise by between 1.4°C and 5.8°C by the end of the century. Scientists at the Goddard Institute for Space Studies, NASA's division spearheading climate modeling efforts, report that we should expect between 0.5°C and 1°C over the next 50 years.

Rarely in the Earth's history has the average surface temperature changed as dramatically as the changes that scientists are predicting for the next century. During the last ice age 20,000 years ago, for instance, the Earth was roughly 5°C cooler than it is today. Since then it has warmed up, although not steadily, to present levels. That's an increase of roughly 1°C every 4,000 years. Current global warming scenarios predict, at the bare minimum, a 1°C increase over the next century.

Radiation Forcing

- Measure of impact of species on climate
- Compare to solar energy fluxes
  - 1,330 to 1,422 W/m^2 at earth's atmosphere
  - 342 W/m^2 annual average over entire earth
- Radiation forcing is basis for global warming potential defined later

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22

Reference: Web page for University of Reading (UK) Meteorology Department: http://www.met.rdg.ac.uk/~radiation/forcing2.html#definition

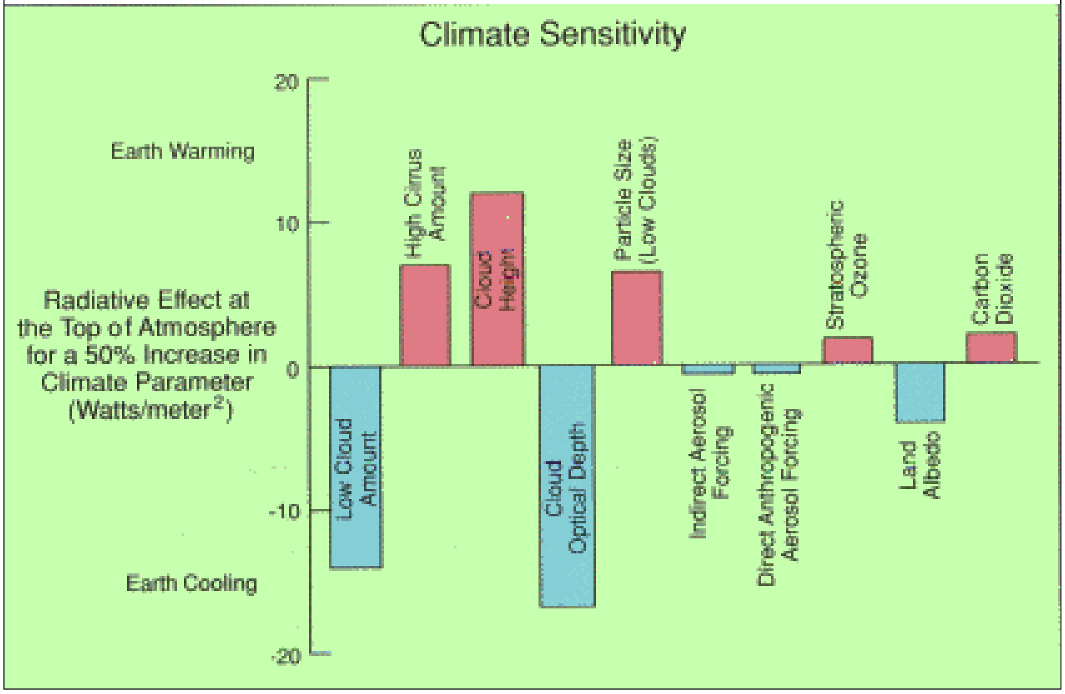
Radiative forcing (or RF) is the change in **net radiative flux** at the tropopause after the climate has been perturbed, **after allowing the stratosphere to come into equilibrium with the perturbation**. The perturbation can from a gas such as carbon dioxide, or particulate matter, such as aerosols.

The RF is calculated after the stratosphere has come into equilibrium with the perturbation because the timescale for stratospheric adjustment is **a few months**, as opposed to **decades** for the troposphere and surface. Temperature changes in the stratosphere are therefore counted as part of the forcing, and not the response. This is the reason for choosing the tropopause as the region where RF is calculated.

A positive radiative forcing implies a warming of the surface, while a negative radiative forcing implies a cooling of the surface. Most species force the climate by a magnitude of about 1 W m^2 or less.

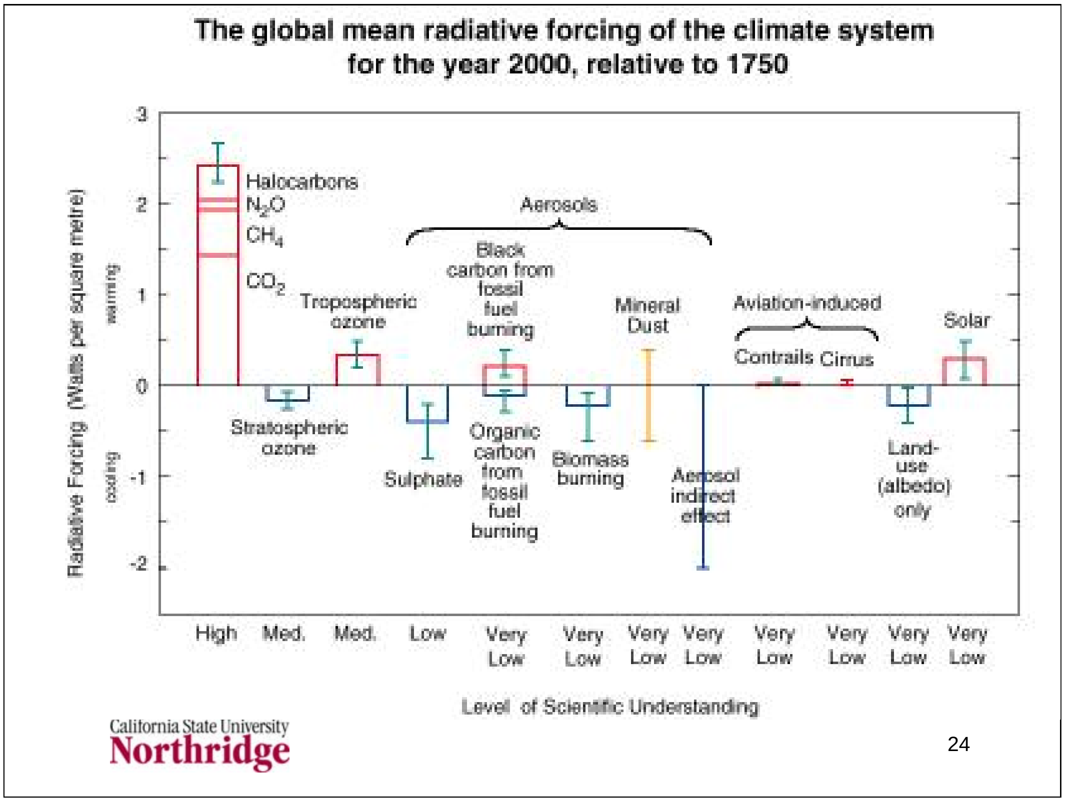
Radiative forcing definition from http://www.grida.no/climate/ipcc_tar/wg1/518.htm
Radiative forcing is the change in the net vertical irradiance (expressed in Watts per square metre: Wm^{-2}) at the tropopause due to an internal change or a change in the external forcing of the climate system, such as, for example, a change in the concentration of carbon dioxide or the output of the Sun. Usually radiative forcing is computed after allowing for stratospheric temperatures to readjust to radiative equilibrium, but with all tropospheric properties held fixed at their unperturbed values. Radiative forcing is called instantaneous if no change in stratospheric temperature is accounted for. Practical problems with this definition, in particular with respect to radiative forcing associated with changes, by aerosols, of the precipitation formation by clouds, are discussed in the IPCC Report.

Natural “Forcing”



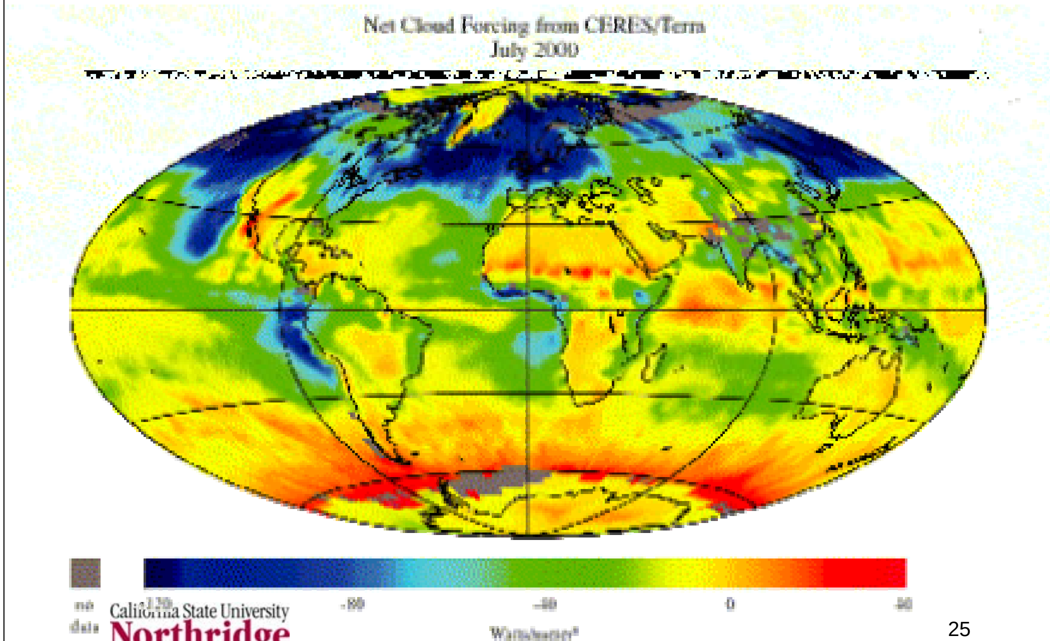
Reference: http://asd-www.larc.nasa.gov/ceres/brochure/climate_change.html

The so-called natural forcings are a measure of the impact that various change in the natural climate can have on the overall planetary energy balance.



Reference: Web page for University of Reading (UK) Meteorology Department: http://www.met.rdg.ac.uk/~radiation/forcing/forc1.jpg

Cloud “Forcing”



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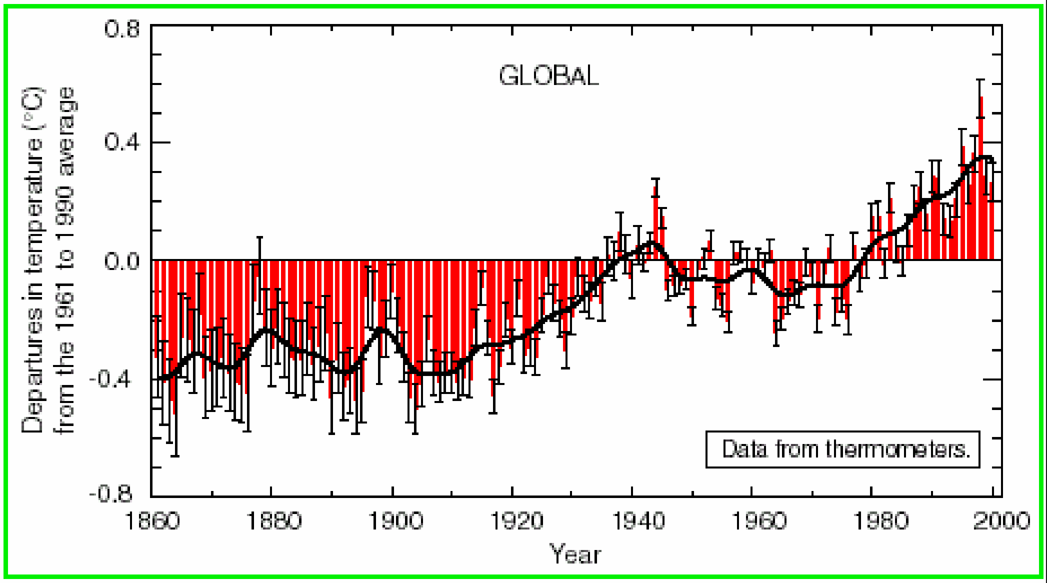
25

Reference: http://asd-www.larc.nasa.gov/ceres/brochure/sci_priorities.html

Radiation and clouds strongly influence our weather and climate. For example, low, thick clouds reflect incoming solar radiation back to space causing cooling. High clouds trap outgoing infrared radiation and produce greenhouse warming. The Earth Radiation Budget Experiment (ERBE), which was launched on multiple satellite in the mid 1980s, and now the EOS CERES instruments, are providing critical data on the effect of clouds on climate. The data indicate that clouds have an overall net cooling effect on the Earth (i.e., negative net cloud forcing in the figure below). The largest negative cloud forcing is found over the storm tracks at high-to-middle latitudes in the summer hemisphere. The most extreme values occur over marine areas, since the contrast in albedo between clear and cloudy conditions is greatest over oceans. In the tropics, the longwave and shortwave cloud forcings nearly cancel; therefore clouds have neither a heating nor cooling effect in these areas. Much more information is needed about clouds and radiation and their role in climate change. The largest uncertainty in climate prediction models is how to determine the radiative and physical properties of clouds. CERES observations will contribute to improving the scientific understanding of the mechanisms and factors that determine long-term climate variations and trends.

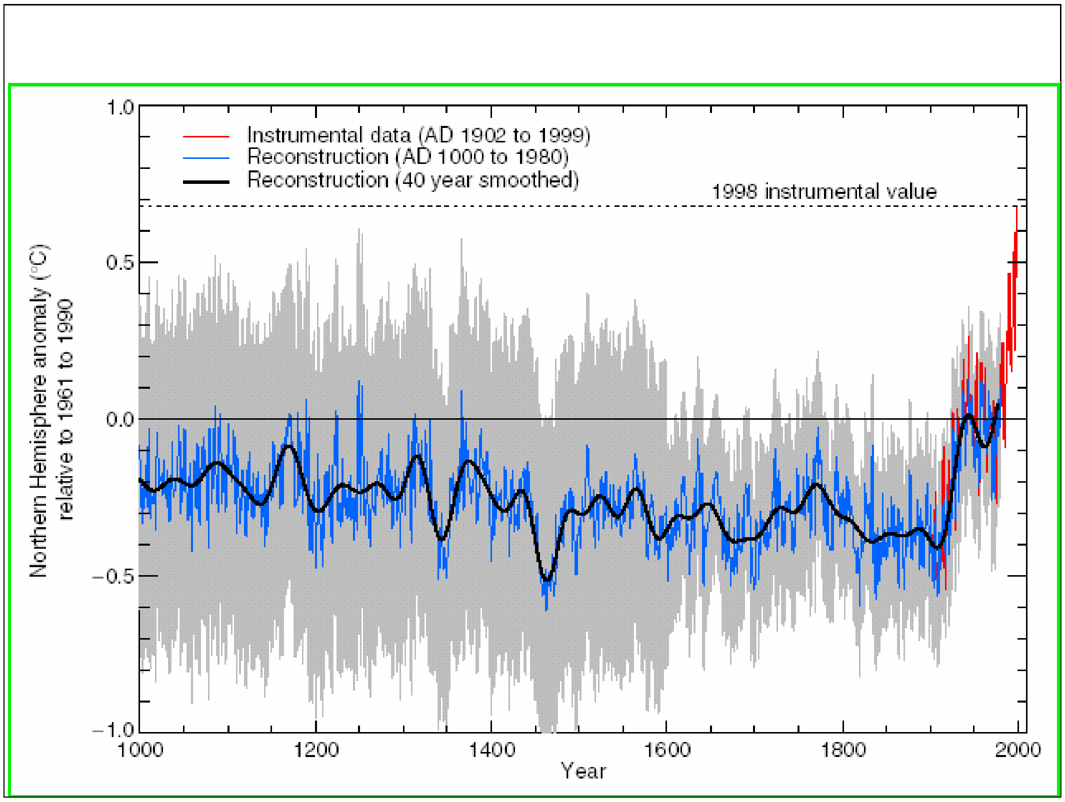
Observed Temperatures



Reference: Ingergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Sciencific Basis*, IPCC, 2001. Figure taken from technical summary available at http://www.ipcc.ch/pub/wg1TARtechsum.pdf.

The global average surface temperature has increased by 0.6 ±0.2°C3 since the late 19th century. It is very likely that the 1990s was the warmest decade and 1998 the warmest year in the instrumental record since 1861. The main cause of the increased estimate of global warming of 0.15°C since the second IPCC analysis report (SAR) is related to the record warmth of the additional six years (1995 to 2000) of data. A secondary reason is related to improved methods of estimating change. The current, slightly larger uncertainty range (±0.2°C, 95% confidence interval) is also more objectively based. Further, the scientific basis for confidence in the estimates of the increase in global temperature since the late 19th century has been strengthened since the SAR. This is due to the improvements derived from several new studies. These include an independent test of the corrections used for time-dependent biases in the sea surface temperature data and new analyses of the effect of urban "heat island" influences on global land-temperature trends. As indicated in the figure, most of the increase in global temperature since the late 19th century has occurred in two distinct periods: 1910 to 1945 and since 1976. The temperature increase for both periods is about 0.15°C/decade. Recent warming has been greater over land compared to oceans; the increase in sea surface temperature over the period 1950 to 1993 is about half that of the mean land-surface air temperature. The high global temperature associated with the 1997 to 1998 El Niño event stands out as an extreme event, even taking into account the recent rate of warming.

The averages shown here do not reflect regional impacts. (See the IPCC report for more details.) The 1910 to 1945 warming was initially concentrated in the North Atlantic. By contrast, the period 1946 to 1975 showed significant cooling in the North Atlantic, as well as much of the Northern Hemisphere, and warming in much of the Southern Hemisphere.



Reference: Ingergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Sciencific Basis*, IPCC, 2001. Figure taken from technical summary available at http://www.ipcc.ch/pub/wg1TARtechsum.pdf.

The data show a relatively warm period associated with the 11th to 14th centuries and a relatively cool period associated with the 15th to 19th centuries in the Northern Hemisphere. However, evidence does not support these "Medieval Warm Period" and "Little Ice Age" periods, respectively, as being globally synchronous. As Figure 5 indicates, the rate and duration of warming of the Northern Hemisphere in the 20th century appears to have been unprecedented during the millennium, and it cannot simply be considered as a recovery from the "Little Ice Age" of the 15th to 19th centuries. These analyses are complemented by sensitivity analysis of the spatial representativeness of available palaeoclimatic data, indicating that the warmth of the recent decade is outside the 95% confidence interval of temperature uncertainty, even during the warmest periods of the last millennium. Moreover, several different analyses have now been completed, each suggesting that the Northern Hemisphere temperatures of the past decade have been warmer than any other time in the past six to ten centuries. This is the time-span over which temperatures with annual resolution can be calculated using hemispheric-wide tree-ring, ice-cores, corals, and and other annually-resolved proxy data. Because less data are available, less is known about annual averages prior to 1,000 years before the present and for conditions prevailing in most of the Southern Hemisphere prior to 1861.

It is likely that large rapid decadal temperature changes occurred during the last glacial and its deglaciation (between about 100,000 and 10,000 years ago), particularly in high latitudes of the Northern Hemisphere. In a few places during the deglaciation, local increases in temperature of 5 to 10°C are likely to have occurred over periods as short as a few decades. During the last 10,000 years, there is emerging evidence of significant rapid regional temperature changes, which are part of the natural variability of climate.

IPCC Conclusion

The variations and trends in the examined indicators imply that it is virtually certain that there has been a generally increasing trend in global surface temperature over the 20th century, although short-term and regional deviations from this trend occur.

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28

Reference: Ingergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Sciencific Basis*, IPCC, 2001. Quote taken from technical summary available at http://www.ipcc.ch/pub/wg1TARtechsum.pdf. Material below is direct quote from the report.

· **Taken together, these trends illustrate a collective picture of a warming world:**

Surface temperature measurements over the land and oceans (with two separate estimates over the latter) have been measured and adjusted independently. All data sets show quite similar upward trends globally, with two major warming periods globally: 1910 to 1945 and since 1976. There is an emerging tendency for global land-surface air temperatures to warm faster than the global ocean-surface temperatures.

· Weather balloon measurements show that lower-tropospheric temperatures have been increasing since 1958, though only slightly since 1979. Since 1979, satellite data are available and show similar trends to balloon data.

· The decrease in the continental diurnal temperature range coincides with increases in cloud amount, precipitation, and increases in total water vapour.

· (continued on next notes page)

Positive Indicators

- Measured surface and atmospheric temperature increases
- Dinural temperature changes coincide with increases in precipitation
- Decreases in snow and ice
- Ocean heat content and level
- More water vapor in troposphere

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29

(continued from previous notes page)

The nearly worldwide decrease in mountain glacier extent and ice mass is consistent with worldwide surface temperature increases. A few recent exceptions in coastal regions are consistent with atmospheric circulation variations and related precipitation increases.

- The decreases in snow cover and the shortening seasons of lake and river ice relate well to increases in Northern Hemispheric land-surface temperatures.
- The systematic decrease in spring and summer sea-ice extent and thickness in the Arctic is consistent with increases in temperature over most of the adjacent land and ocean.
- Ocean heat content has increased, and global average sea level has risen.
- The increases in total tropospheric water vapor in the last 25 years are qualitatively consistent with increases in tropospheric temperatures and an enhanced hydrologic cycle, resulting in more extreme and heavier precipitation events in many areas with increasing precipitation, e.g., middle and high latitudes of the Northern Hemisphere.

Negative Indicators

- Some areas have not warmed (mainly southern hemisphere)
- No trends in Antarctic sea ice extent (measured since 1978)
- No changes in cyclones and severe local storms (limited data)

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30

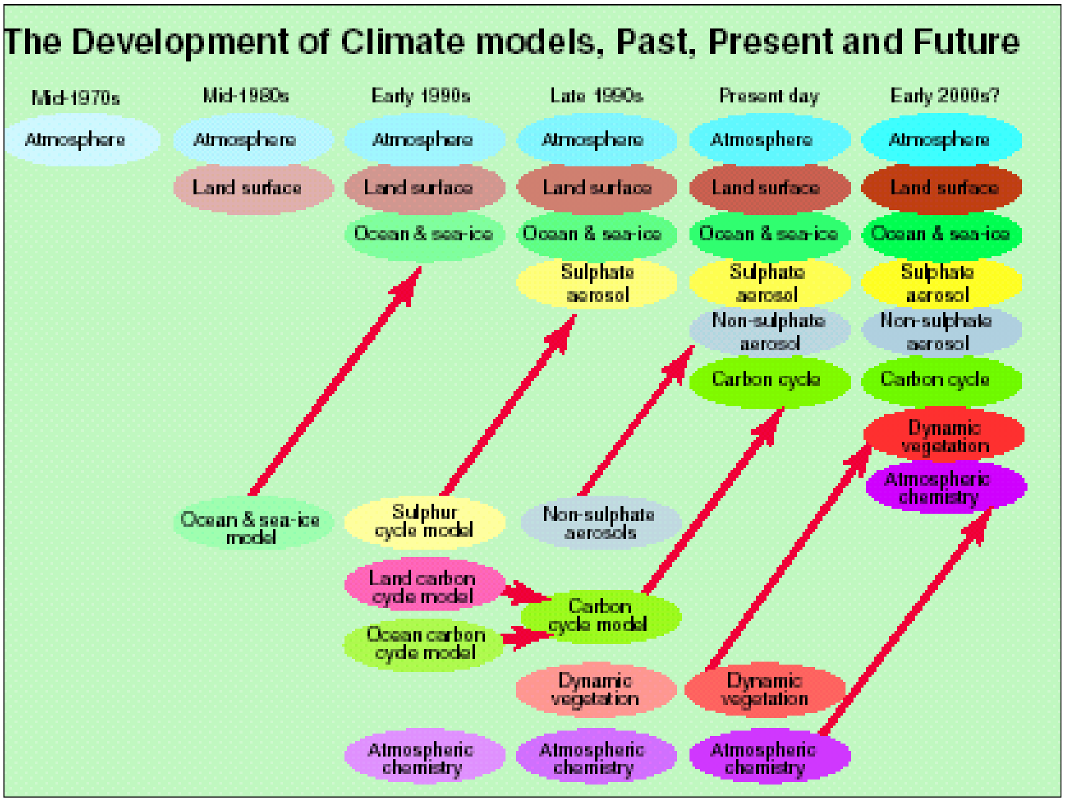
Reference: Ingergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Sciencific Basis*, IPCC, 2001. Quote taken from technical summary available at http://www.ipcc.ch/pub/wg1TARtechsum.pdf. Material below is direct quote from the report.

Some important aspects of climate appear not to have changed.

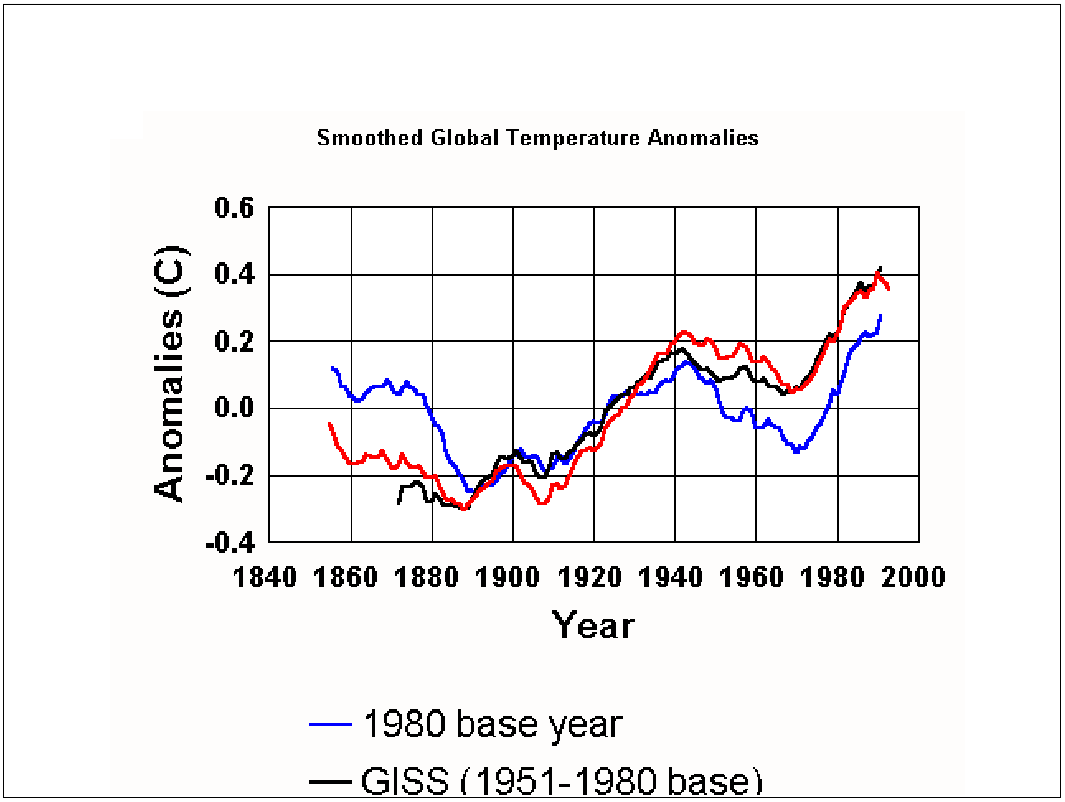
A few areas of the globe have not warmed in recent decades, mainly over some parts of the Southern Hemisphere oceans and parts of Antarctica.

No significant trends in Antarctic sea-ice extent are apparent over the period of systematic satellite measurements (since 1978).

Based on limited data, the observed variations in the intensity and frequency of tropical and extra-tropical cyclones and severe local storms show no clear trends in the last half of the 20th century, although multi-decadal fluctuations are sometimes apparent.



Reference: Ingergovernmental Panel on Climate Change (IPCC), *Climate Change 2001: The Sciencific Basis*, IPCC, 2001. Figure taken from technical summary available at http://www.ipcc.ch/pub/wg1TARtechsum.pdf.

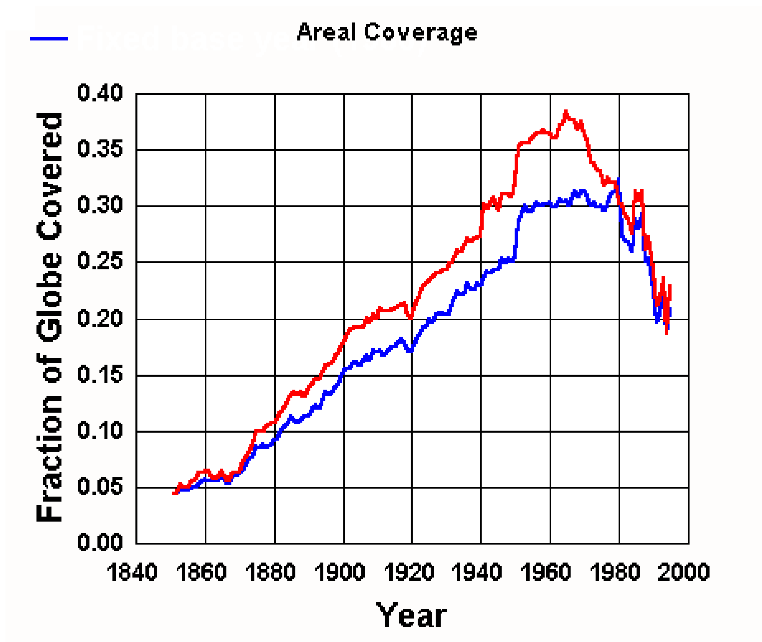


Reference: http://users.erols.com/dhoyt1/home2.gif

In the plot of the time series above, they are smoothed with an 11 year running means so the two derivations of the time series can be compared easily. The red line is our reconstruction and the black line is the GISS reconstruction.

What Happens When the Base Climate Interval is Changed?

Next we changed the base year in our calculations from 1965 to 1980 (blue line in figure above). Otherwise our calculations were identical. Note that using the 1980 base year gives lower temperatures in recent years and higher temperatures in the earlier years. Why are the results such sensitive functions to the choice of base year? The so-called "global" measurements are not really global at all. At best, they sample 40% of the globe. The coverage by land surface thermometers slowly increased from less than 10% of the globe to about 40% in the 1960's, but has decreased rapidly to less than 20% in recent years. Depending upon the base year or interval chosen, a different time history of coverage will result. This different coverage history will lead to different climate reconstructions as shown in the figure above. These differences in trends arise from differences in areal coverage which are a function of baseline interval chosen.



Reference: http://users.erols.com/dhoyt1/home3.gif

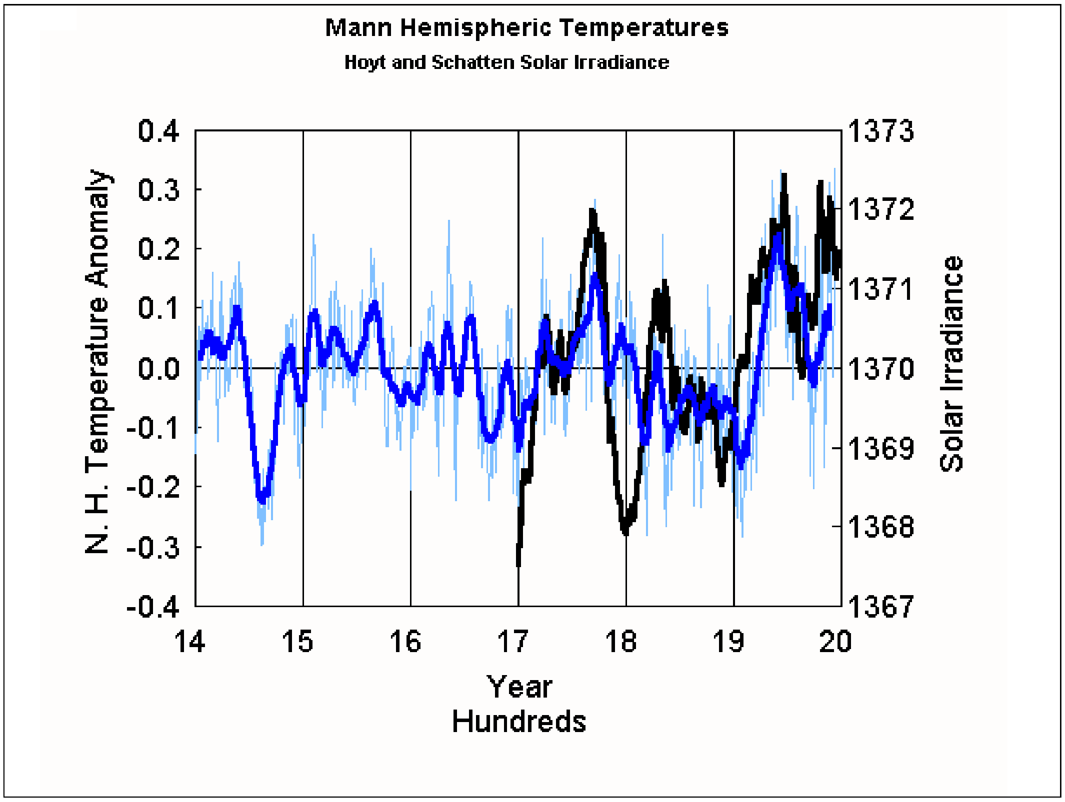
Depending upon the base year or interval chosen, a different time history of coverage will result. This different coverage history will lead to different climate reconstructions as shown in the figure above. These differences in trends arise from differences in areal coverage which are a function of baseline interval chosen.

The Temporal Variations in Areal Coverage

Changes in areal coverage of the land based thermometers are shown in the attached figure. Using either 1965 or 1980 as base years gives increasing coverage to the 1960's with sharply decreasing coverage since. The slight temporal differences in coverage for these two years give rise to different temperature trends. It is important to realize that only 8% of the climate variability can be categorized as global with the remaining 92% being regional variations. Thus, even if the global variations were eliminated, climate fluctuations at the local and regional level will still occur. If the thermometer network is sampling a portion of the globe, as is now the case, the combined regional variations could be interpreted as a global change even if no change is occurring. We will revisit this point in the next section of this essay.

Returning to our climate reconstruction, it is not clear that 1965 is a better base year than 1980. Although it provides more coverage, it has a greater temporal variation in its coverage. However, based upon a climate reconstruction using hundreds of different base periods, we conclude that using 1980 instead of 1965 provides a better reconstruction of climate. Or, in other words, today's climate is much like it was in the 1940's and 1860's. A study by Robeson in Climatic Change in 1995 showed that the CRU temperatures for 1880 were too low by 0.25 C, which is a completely independent confirmation of our results. Also J. Murray Mitchell in 1970 showed that there was a cooling between 1860 and 1880 as we have also found. Finally Wu et al. (1990) found the period around 1850-1880 is warmer than CRU and GISS have. Thus, four independent studies have found that the CRU and GISS temperature reconstructions for 1850 to 1880 are incorrect. This era was slightly warmer than they claim.

Despite our reservations about the temperature reconstructions which have been made so far, it is instructive to look at the recent reconstruction by Mann, Bradley and Hughes (Nature, vol. 392, pp. 779-787), which uses various proxies such as tree rings



Reference: http://users.erols.com/dhoyt1/

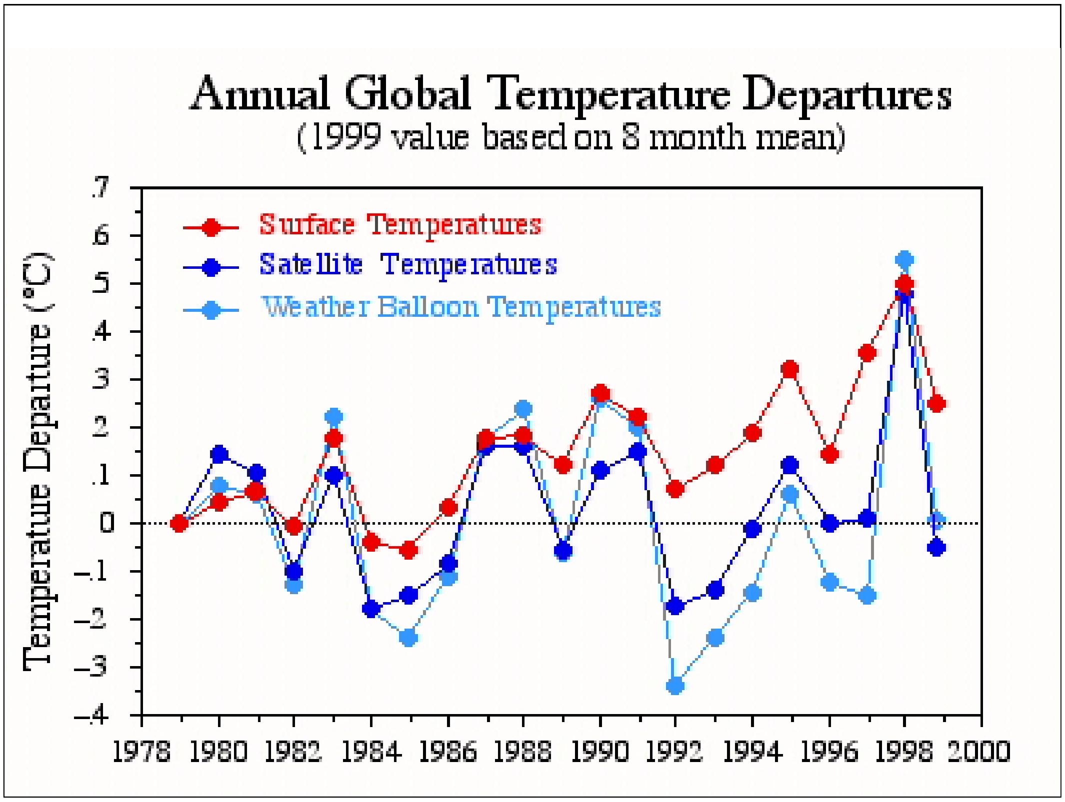
Mann's reconstruction is shown in the figure above as the blue line and bold blue line with a 11 year smoothing. In this version of Mann's temperature reconstruction, the temperatures have been adjusted so that the long-term trends agree with the 6000 borehole measurements of Huang et al. (1997). Note that the modeled solar irradiance (black line), given in our 1993 JGR article (vol. 98A, pp. 18895-18906), has many similarities to the temperature variations with the puzzling exception around 1800 about which Lamb (1977) says "the extent of snow and ice... attained a maximum as great as...any since the last major Ice Age." It is likely both the temperature reconstruction and solar irradiance reconstruction have some uncertainties associated with them. Despite this, the two series correlate well, particularly in recent years where the correlation is as high as 0.7.

This reconstruction uses tree rings to get the short term variations. However, tree rings respond not only to temperature, but also to precipitation, snow cover, snow melt, the concentration of carbon dioxide (i.e., fertilization), nitrogen fertilization, and so forth. The location of treelines can also be expected to respond to these same factors. These spurious effects can effect the tree ring reconstructions, particularly on the longest time scales, and are not easily removed. Briffa et al. (Phil. Trans. B, 1999) comment on these problems saying "this partial non-climatic enhancement of twentieth century tree growth, particularly if acts in tandem with temperature forcing, will bias the coefficients in any regression-based equation estimating tree growth as a function of recent measured temperatures. Hence, the magnitude of the modern warming might be overestimated in the context of earlier reconstructed variability." The various forcing factors might interact in a non-linear fashion which could lead to greater uncertainties in reconstructing climate variations, particularly on the longest time scales, than is commonly assumed.

In contrast, borehole reconstructions respond primarily to temperatures. They are good at getting long-term trends, but have poor temporal resolution. Combining the two reconstructions takes advantage of the strengths of the two techniques and supports the existence of a Medieval Warm Period which is warmer than the present. Oxygen-18 isotope records from the Caribbean also show similar climate variations.

Using Mann's reconstructions, the correlation of temperature and model solar irradiance around 1800 (covering the years 1701-1800) is about 0.4. In recent years it is about 0.6. Yet centered around 1880, the correlation is actually negative and reaches a value of about -0.4. The reason for the negative value is that a large number of volcanic eruptions occurred between 1811 and 1912. These eruptions cooled the climate and masked the solar signal. The volcanic eruptions occurred near solar maxima in nearly every case, so while the solar irradiance model would say the Earth would warm, the volcanic forcing would make it cool.

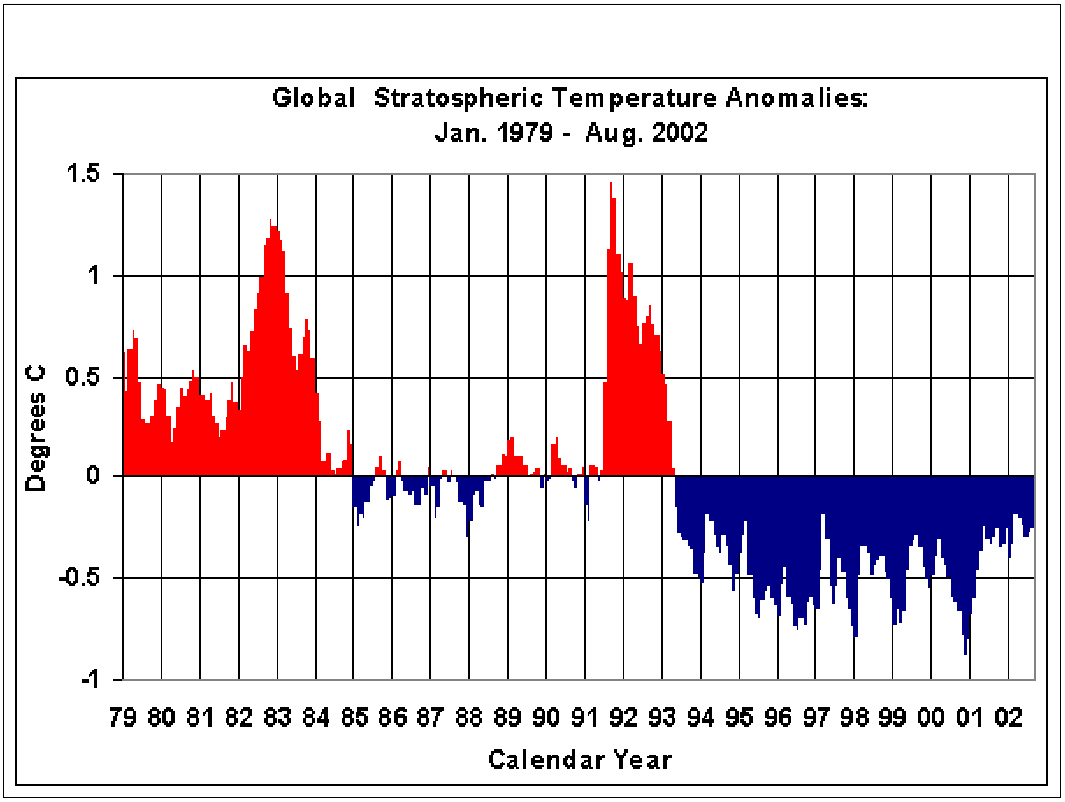
Another important point to make is that the temperature anomaly for the last 30 years of Mann's record equals 0.10 C. For 1400 to 1800, before any anthropogenic influence, the mean anomaly was -0.16 C. Therefore, the net positive temperature anomaly is 0.26 C. Since 1800 the anthropogenic forcing due to greenhouse gases should have reached half the value it will reach for a doubling of the greenhouse gases. Thus, if the recent 0.26 C warming is attributed solely to greenhouse gases, a doubling of greenhouse gases will give a net warming of 0.52 C. This number must be considered an



Reference: http://users.erols.com/dhoyt1/

We sub-sampled the MSU observations so their spatial and temporal sampling was identical to the surface observations. Then we ran our program to calculate temperature anomalies. We found that the anomalies and trends in the MSU data were not quite the same for both full and partial sampling. Careful examination of the trends shows that the spatial-temporal sampling for the land surface stations has substantial uncertainties in the yearly means (of the order 0.070 C). How these yearly uncertainties may effect the long-term trend determinations is not clear, but, from the above attached figure, about 0.12 C of the 0.23 C trend from 1979 to 1994 may be arising from spatial-temporal under-sampling by the surface network. This means that only about 0.11 C warming at the surface may be real.

A few other points are worth adding. Of the 2907 stations in the database, only 161 (or 5.5%) have complete temporal coverage from 1900 to 1990. All but 19 of these stations are in the United States. The US, with the most complete record anywhere, has no trend in temperatures during this century. In 1989 and 1990 about 30% of the stations ceased reporting. This may account for the difference in global temperature trends derived from surface observations when compared to balloon and satellite observations. Support for this idea comes from the fact that 135 stations in the USSR ceased observing at the end of 1989. Subsequently there appeared to be a warming in the USSR but this warming is not supported by pressure observations. Thus, it appears half or more of the reported global warming from ground observations is arising from this change in station coverage. It is possible that as much as 0.2 C of the 0.25 C warming for 1979-1999 can be explained by this change in stations, although more study is required to refine this number. Other locations where the surface network has notable problems include South Africa, Nigeria, Timbuktu, Algeria, Peru, central and coastal Brazil, the Seychelles, Diego Garcia, New Guinea, and several Polynesian islands.



Reference: http://www.ghcc.msfc.nasa.gov/MSU/hl_temp_glbave.html

The figure above shows the monthly temperature deviations from a seasonally adjusted average for the lower stratosphere - Earth's atmosphere from 14 to 22 km (9 to 14 miles). Red is an increase in the temperature from the average, and blue is a decrease in temperature. The large increase in 1982 was caused by the volcanic eruption of El Chichon, and the increase in 1991 was caused by the eruption of Mr. Pinatubo in the Philippines. September 1996 was the coldest month on record for stratospheric temperature.

The chart on the next page shows the monthly temperature changes for the lower troposphere - Earth's atmosphere from the surface to 8 km, or 5 miles up. The temperature in this region is more strongly influenced by oceanic activity, particularly the “El Niño” and “La Niña” phenomena, which originate as changes in oceanic and atmospheric circulations in the tropical Pacific Ocean. Like the upper plot, the overall trend in the data is downward, about 0.06 degrees C per decade. Surface thermometer measurements indicate that the temperature of the Earth is warming, while the satellite data show long-term cooling trends. These differences are the basis for discussions over the existence and magnitude of any global warming the Earth may be experiencing as a result of human activity. This chart shows the monthly temperature changes for the lower troposphere - Earth's atmosphere from the surface to 8 km, or 5 miles up. The temperature in this region is more strongly influenced by oceanic activity, particularly the “El Niño” and “La Niña” phenomena, which originate as changes in oceanic and atmospheric circulations in the tropical Pacific Ocean. Like the plot on this page, the overall trend in the data is downward, about 0.06 degrees C per decade. Surface thermometer measurements indicate that the temperature of the Earth is warming, while the satellite data show long-term cooling trends. These differences are the basis for discussions over the existence and magnitude of any global warming the Earth may be experiencing as a result of human activity.

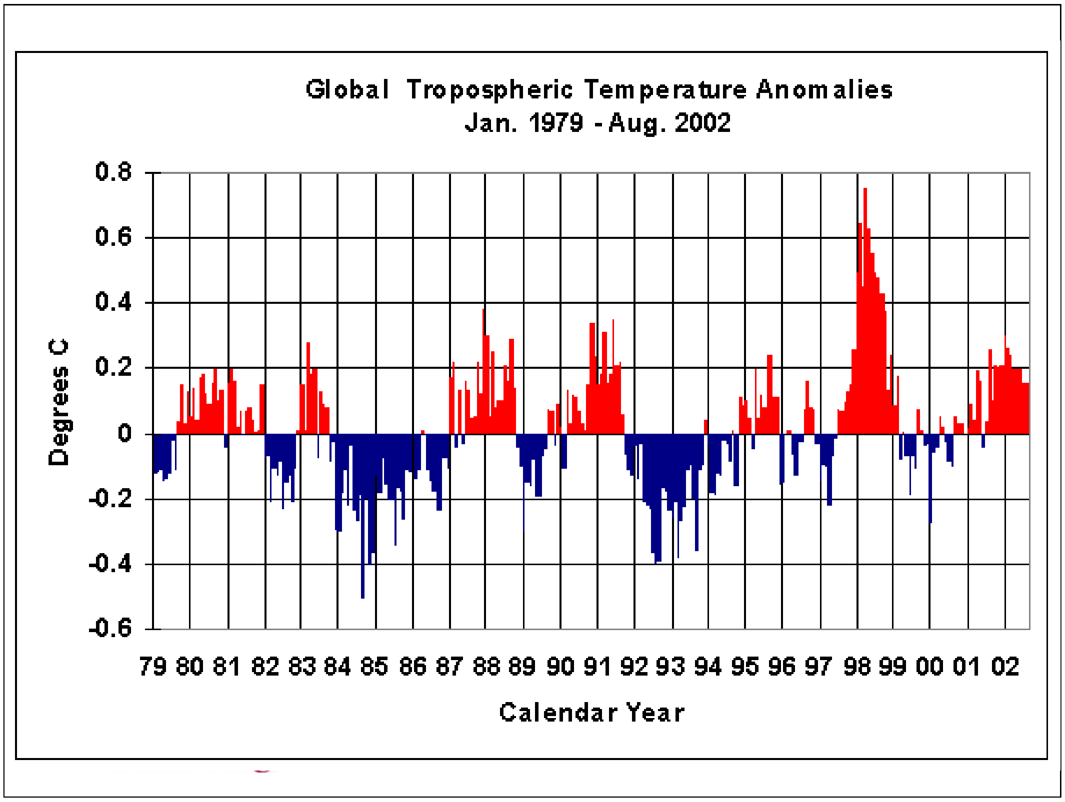


Figure reference: http://www.ghcc.msfc.nasa.gov/MSU/hl_temp_glbave.html

The following is quoted from http://www.ghcc.msfc.nasa.gov/MSU/hl_temp_ud.html: (Originially published July 14, 1997) Over the past century, global measurements of the temperature at the Earth's surface have indicated a warming trend of between 0.3 and 0.6 degrees C. But many - especially the early - computer-based global climate models (GCM's) predict that the rate should be *even higher* if it is due to the man-made "Greenhouse Effect". Furthermore, these computer models also predict that the Earth's lower atmosphere should behave in lock-step with the surface, but with temperature increases that are even more pronounced.

However global temperature measurements obtained from satellites of the Earth's lower atmosphere reveal *no* definitive warming trend over the past two decades. The slight trend that *is* in the data actually appears to be *downward*. These satellite data are verified by *in-situ* measurements of the lower atmosphere made by balloon-borne observations around the world.

Some scientists now believe that this apparent "disagreement" between the predictions by computer models and the measurements may be due to a less-than-accurate modeling of the role of water-vapor in the atmosphere of the GCM's.

In the June 1997 edition of the *Bulletin of the American Meteorological Society*, Dr. Roy Spencer of NASA/Marshall, and Dr. William Braswell of Nichols Research Corporation. have shown that the low humidity of the tropical free troposphere is playing a previously-overlooked central role in the dynamics of the atmosphere. The very low humidity in this region allows a larger portion of the infrared radiation to escape from the Earth, thereby cooling the atmosphere. Current computer models do not accurately handle the processes which control the humidity in this region, which are related to how much cloud material falls out of rainfall systems.

Temperature Trends (^oC/decade)

Weather balloon trend (Angell/NOAA)	**-0.07**
Unadjusted satellite trend:	**-0.04**
Weather balloon trend (UK Met Office):	**-0.02**
Spencer and Christy adjusted satellite trend	**-0.01**
Wentz and Schabel adjusted satellite trend	**+0.08**
Surface Temperatures (UK Met Office)	**+0.15**

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38

Quoted from http://science.nasa.gov/newhome/headlines/notebook/essd13aug98_1.htm

The paper published by Wentz and Schabel in *Nature* on August 14, 1998) is bound to generate controversy about the satellite measurements of global tropospheric temperatures. These measurements, for the period since 1979, have been made with the TIROS-N satellite Microwave Sounding Units (MSUs) by Spencer (NASA) and Christy (The University of Alabama in Huntsville). We are grateful to Wentz and Schabel for discovering the first convincing evidence for needed corrections to our satellite-based global temperatures.

However, we believe that there are a few important points that should be considered when reporting on this paper.

1) 1) The spurious cooling in the satellite record due to the orbital decay ("downward drift") effect was only estimated by Wentz and Schabel as an average adjustment to our processed satellite data. The effect, which will have different values for the eight different satellites in the record, should instead be removed one satellite at a time before the satellites in the record are intercalibrated. Christy and Spencer performed this adjustment, with the result shown.

2) 2) The effect reported by Mr. Wentz had been partly offset by an east-west drift in the satellites' orbits. The valuable discovery of the downward drift effect by Wentz and Schabel allowed us to separately quantify two consequences of the east-west drift (MSU instrument temperature change, and observation time-of-day change).

3) The global decadal temperature trends, for the period 1979-1997, from the various satellite, weather balloon, and surface temperature measurements are shown aboveIt can be seen that the adjustment by Wentz and Schabel does not agree with our (more complete) adjustments, or to the weather balloon data. Instead, their adjustment comes closer to the surface thermometer measurements, and herein lies a temptation to jump to conclusions.

4) The adjusted satellite trends are still not near the expected value of global warming predicted by computer climate models. The Intergovernmental Panel on Climate Change's (IPCC) 1995 estimate of average global warming at the surface until the year 2100 is +0.18 deg. C/decade. Climate models suggest that the deep layer measured by the satellite and weather balloons should be warming about 30% faster than the surface (+0.23 deg. C/decade). None of the satellite or weather balloon estimates are near this value.

5) 1998 UPDATE: The last six months of our adjusted satellite record (February through July 1998) were the warmest in the 20 year record. The updated trend is now +0.04 deg. C/decade (which is still only 1/6th of the IPCC-expected warming rate). The current demise of El Nino, and the possibility of a La Nina forming, will likely cause significant cooling in the coming months.

Is the temperature increasing?

- Surface temperatures are increasing
- Temperatures by balloon and satellite measurements are not
- This is at variance with models
- Only short term trend data for balloon and satellite data
- Questions our understanding

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39

The quote below was taken from the following report:

Committee on the Science of Climate Change, *Climate Change Science An Analysis of Some Key* Questions, National Academy Press, 2001. Prepublication copy available on course web site. (http://www.ecs.csun.edu/~lcaretto/energy/NAS2001.pdf)

"Although warming at the Earth's surface has been quite pronounced during the past few decades, satellite measurements beginning in 1979 indicate relatively little warming of air temperature in the troposphere. The committee concurs with the findings of a recent National Research Council (2000) report, which concluded that the observed difference between surface and tropospheric temperature trends during the past 20 years is probably real, as well as its cautionary statement to the effect that temperature trend based on such short periods of record, with arbitrary start and end points, are not necessarily indicative of the long-term behavior of the climate system. The finding that surface and troposphere temperature trends have been as different as observed over intervals as long as a decade or two is difficult to reconcile with our current understanding of the processes that control the vertical distribution of temperature in the atmosphere."

Effects of Global Warming

- Warmer temperatures over land, oceans and ice
- Warmer environments affect plants
- Sea level changes and effects on fish
- Increase in disease vectors
- Increase in severe stroms
- Effects estimates highly uncertain

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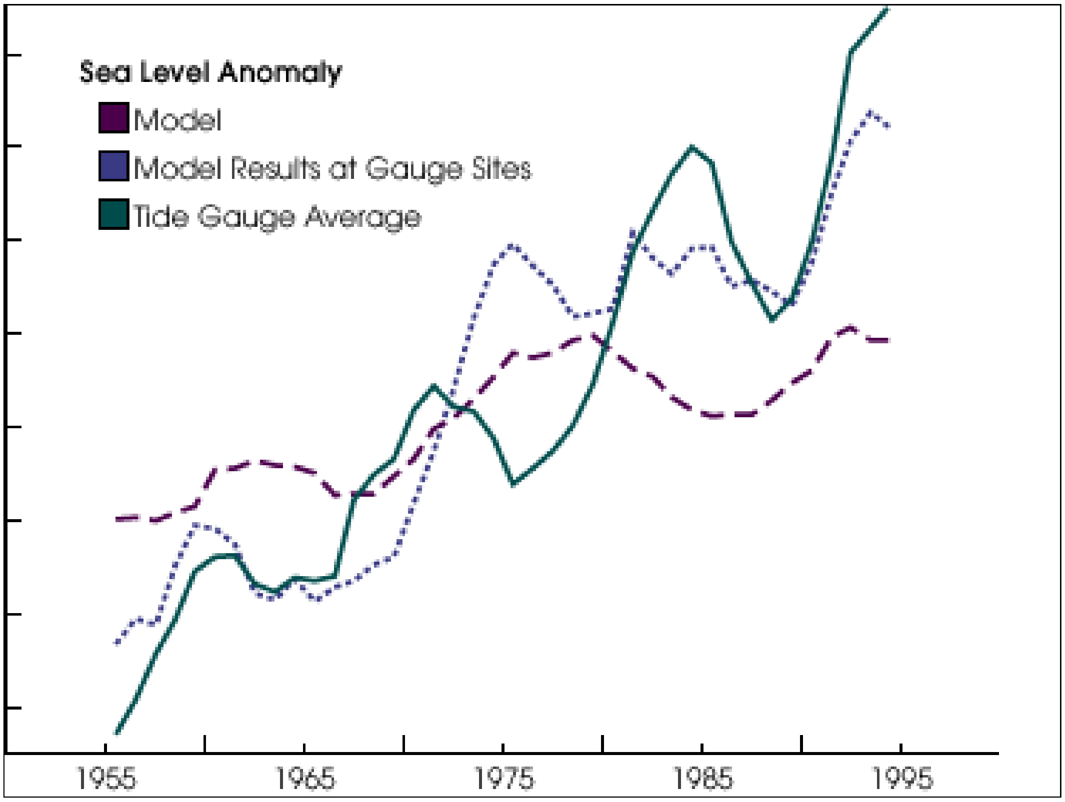
40

Potential Effects of Global Warming Some scientists believe that global warming will continue to have relatively little impact on the day-to-day climate conditions. Others purport that future changes will likely be subtle, and they will spread over large areas of the globe from decade to decade and creep up on us like old age. Still others hypothesize that when the Earth's surface temperature reaches some critical threshold, the heat will trigger relatively drastic changes to the atmosphere and the oceans and transform the Earth's weather patterns in a matter of years.

Not surprisingly, many scientists speculate that such changes in the climate will probably result in more hot days and fewer cool days. According to the IPCC, land surface areas will increase in temperature over the summer months much more than the ocean. The mid-latitude to high-latitude regions in the Northern Hemisphere—areas such as the Continental United States, Canada, and Siberia—will likely warm the most. These regions could exceed mean global warming by as much as 40 percent.

Forecasts for precipitation and weather are cloudier. Right now the IPCC reports that the amount of precipitation, especially in the mid-latitude to high-latitude regions of the Northern Hemisphere, will likely increase. They believe, however, that it will come in the form of bigger, wetter storms, rather than in the form of more rainy days. So it's more probable that the increase in rain will only serve to tax our drainage systems rather than benefit vegetation or replenish natural, underground aquifers. As to larger more destructive weather patterns, hurricanes will likely increase in intensity due to warmer ocean surface temperatures. And researchers speculate that El Niño events may increase in intensity for the same reason. Should global warming continue, many biologists envision the alteration of natural habitats. Some of this change may be for the better. Higher levels of carbon dioxide and warmer temperatures may cause forests to become more lush and vigorous. Warmer ocean waters on the open ocean could be beneficial to fish and algae on the high seas. Unfortunately, most changes will likely be for the worst. Plants and animals in mid-latitude regions, such as nut-bearing oaks in the midwestern United States, may find themselves in warmer environments where they cannot survive. Rising sea levels may inundate delicate coastal wetlands with brackish waters, which could drive out certain types of fish and kill wetland vegetation. Warmer ocean temperatures around the coast could overheat many types of coral, killing them and many of the animals that depend on them.

As far as human health is concerned, those hit hardest will probably be residents of poorer



Reference: http://earthobservatory.nasa.gov/Library/GlobalWarming/warming3.html

The chart shows sea level anomaly in millimeters starting at –35 mm on the abscissa. The first tick mark is –30 mm and the increment between tick marks is 10 mm. The highest tick mark is 40 mm. The text is quoted from the web page.

Sea-level rise is one of the most widely discussed effects of global warming. The graph above shows real-world tidal gauge measurements (green) compared with a model of global average sea level (purple), and model calculations at the locations of the real-world gauges (blue). Models can both help predict future change (so scientists can estimate the effects of global warming) and evaluate the accuracy of instrumental measurements. (Graph adapted from Cabanes, C. et. al., Sea Level Rise During Past 40 Years Determined from Satellite and in Situ Observations, *Science,* October 26, 2001, Vol 294, pp. 840-842.)

The outlook for rising sea levels is nothing like the deluge portrayed in Hollywood. The Statue of Liberty won't be up to her neck in water, and we won't all be living on flotillas on an endless sea. According to the IPCC, over the next century sea levels are likely to rise between 0.09 and 0.88 meters. The rise will mainly be due to seawater expanding from the increased ocean temperatures and run-off from the melting of continental glaciers and a slight melting of the Greenland Ice Sheet. For now, the West Antarctic Ice Sheet, which could raise our sea levels dramatically, will probably stay in place. It may even gain more mass due to an increase in precipitation over the next century. But, if somehow the entire Greenland Ice Sheet melted and the West Antarctic Ice Sheet fell into the sea, the sea level would rise roughly 10 meters. This is probably impossible over the next century, but there is the danger that global warming could initiate ice sheet changes that will continue to develop over future centuries.

CO_2 Sequestration

- Reduction of CO_2 is a two-fold task
  - Removal of CO_2 from combustion gases
  - Disposal of CO_2 removed
- Current cost estimates are $100 to $300 per ton of ***carbon*** emissions avoided
- Research goal is $10/ton
- US emissions of 6.44 billion tons of CO_2 (1.76 billion tons carbon) in 2000

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42

Reference: http://www.fe.doe.gov/coal_power/sequestration/index.shtml

The joint Office of Fossil Energy and Office of Science April 1999 draft report *Carbon Sequestration: State of the Science* subsequently has assessed "...key areas for research and development (R&D) that could lead to an understanding of the potential for future use of carbon sequestration as a major tool for managing carbon emissions."

To be successful, the techniques and practices to sequester carbon must meet the following requirements: (1) be effective and cost-competitive, (2) provide stable, long term storage, and (3) be environmentally benign.

Using present technology, estimates of sequestration costs are in the range of $100 to $300/ton of carbon emissions avoided. The goal of the program is to reduce the cost of carbon sequestration to $10 or less per net ton of carbon emissions avoided by 2015. Achieving this goal would save the U.S. trillions of dollars.

Further, achieving a mid-point stabilization scenario (e.g., 550 parts per million CO2) would not require wholesale introduction of zero emission systems in the near term. This would allow time to develop cost effective technology over the next 10-15 years that could be deployed for new capacity and capital stock replacement capacity.

The near term program will examine and identify a spectrum of science-based sequestration approaches that have the greatest potential to yield the cost-effective technologies that are required. For example, a competitive solicitation was issued in FY 1998 and resulted in the selection of 12 innovative novel concepts for the control of atmospheric emissions of CO2, methane and nitrous oxide. In May 1999 six of the most promising concepts were selected for further study.

Modeling and assessments provide the capabilities to evaluate technology options in a total systems context, considering costs and impacts over the full product cycle. Further, the societal and environmental effects are analyzed to mental effects are analyzed to provide a basis for assessing trade-offs between local environmental impacts and global impacts.

CO_2 Removal Options

- Absorption (chemical and physical)
- Adsorption (physical and chemical)
- Low-temperature distillation
- Gas separation membranes
- Mineralization and biomineralization

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43

Reference: http://www.fe.doe.gov/coal_power/sequestration/sequestration_capture.shtml

Before CO_2 gas can be sequestered from power plants or industrial sources, it must be captured as a relatively pure gas.

CO_2 is routinely separated and captured as a by-product from industrial processes such as synthetic ammonia production, hydrogen production, and limestone calcination. However, existing capture technologies are not cost-effective when considered in the context of CO_2 sequestration.

Carbon dioxide capture is generally estimated to represent three-fourths of the total cost of a carbon capture, storage, transport, and sequestration system. The program area will pursue evolutionary improvements in existing CO_2 capture systems and also explore revolutionary new capture and sequestration concepts. The most likely options currently identifiable for CO_2 separation and capture include the following:

Absorption (chemical and physical)

Adsorption (physical and chemical)

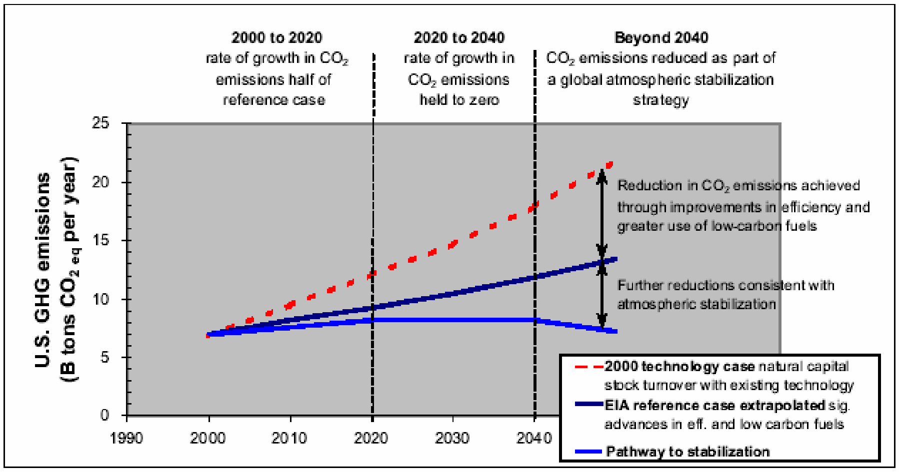
Low-temperature distillation

Gas separation membranes

Mineralization and biomineralization

Opportunities for significant cost reductions exist since very little R&D has been devoted to CO_2 capture and separation technologies. Several innovative schemes have been proposed that could significantly reduce CO_2 capture costs, compared to conventional processes. "One box" concepts that combine CO_2 capture with deduction of criteria-pollutant emissions are concepts to be explored.

Carbon Sequestration Paths



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Reference: U. S. Department of Energy, Office of Fossil Energy, National Energy Technology Laboratory, “Carbon Sequestration Technology Roadmap: Pathways to Sustainable Use of Fossil Energy,” January 7, 2002. Available as http://www.netl.doe.gov/coalpower/sequestration/pubs/CS_roadmap_0115.pdf

Global Warming Potential

- Measure of relative radiative forcing
  - Higher GWP means higher radiative forcing per unit mass of gas
  - Relative to reference gas over time
- Use 100-year time horizon
- Use CO_2 as reference
- Based on direct and indirect effects

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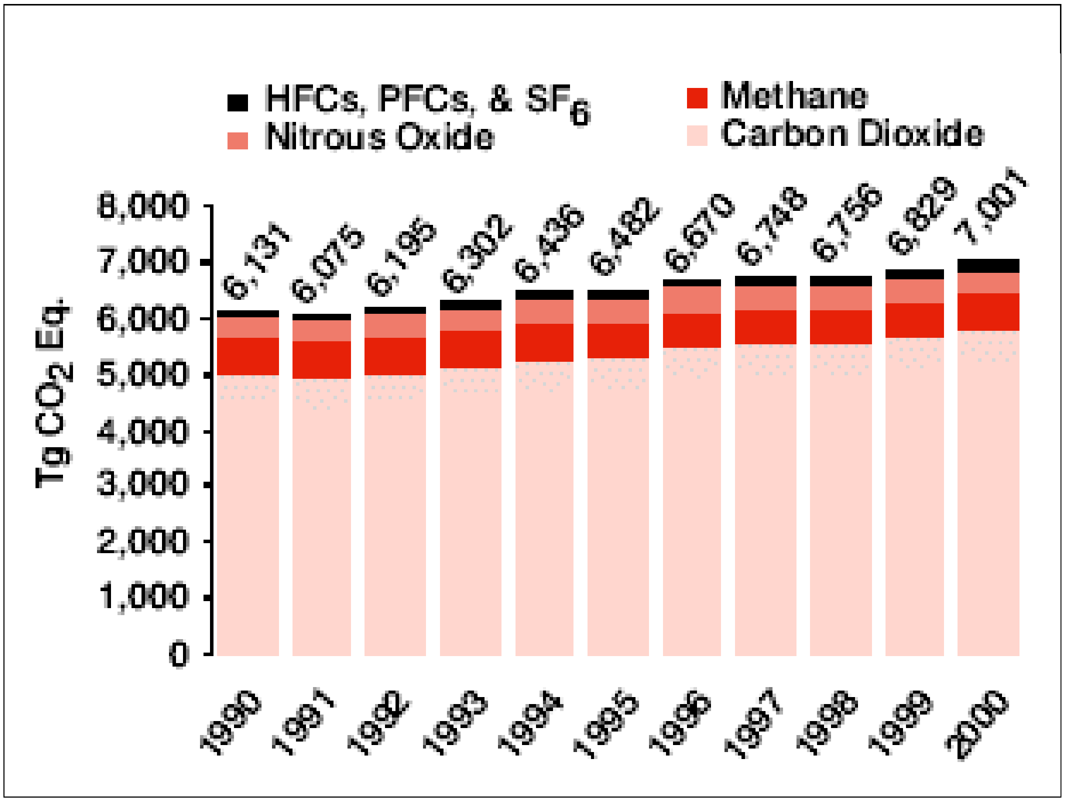
45

Reference: http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsNationalGlobalWarmingPotentials.html (Attributed to IPCC 1996 report)

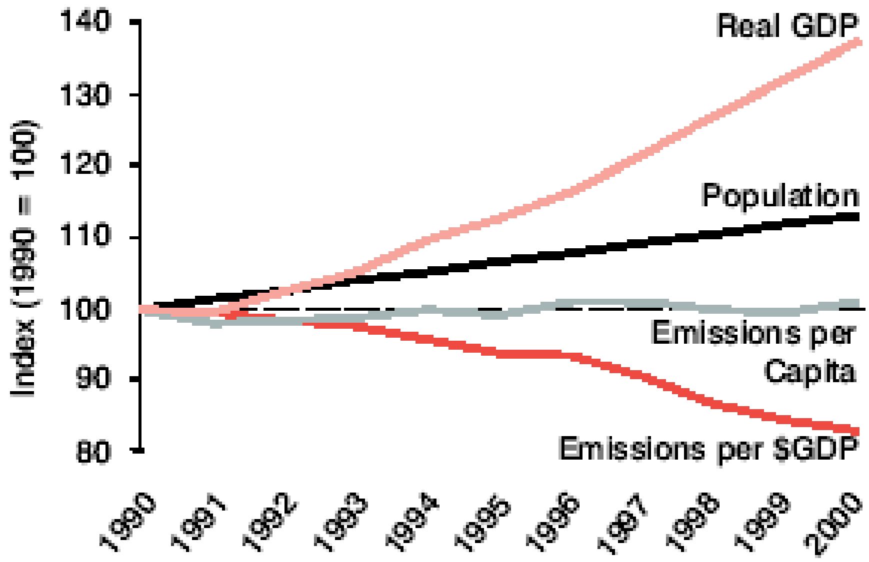
Gas	**GWP**
Carbon dioxide (CO2)	1
Methane (CH4)	21
Nitrous oxide (N2O)	310
HFC-23	11,700
HFC-32	2,800
HFC-125	1,300
HFC-134a	3,800
HFC-143a	140
HFC-152a	2,900
HFC-227ea	2,900
HFC-236fa	6,300
HFC-4310mee	1,300
CF4	6,500
C2F6	9,200
C4F10	7,000
C6F14	7,400
SF6	23,900



http://yosemite.epa.gov/oar/globalwarming.nsf/content/EmissionsNationalRecentTrends.html

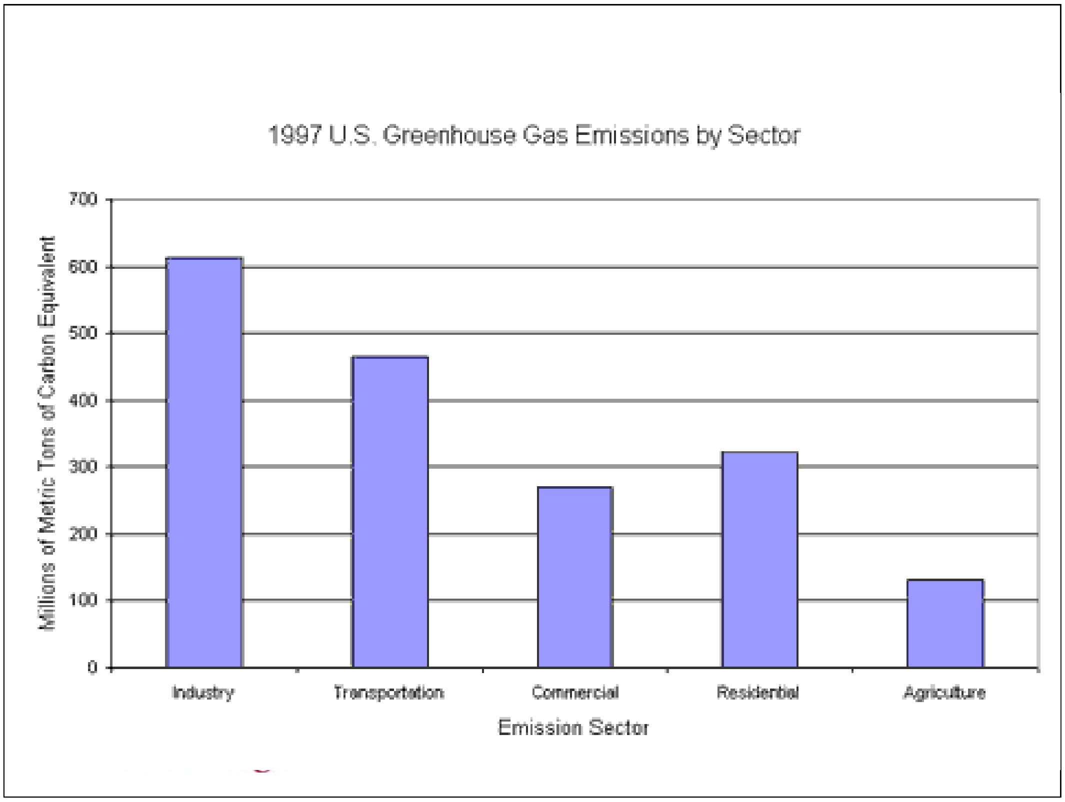
Data in Tg CO_2 equivalents (billion kg or million metric tons equivalent)

Gas / Source Years→	1990	1995	1996	1997	1998	1999	2000
CO2	**4,998.5**	**5,305.9**	**5,483.7**	**5,568.0**	**5,575.1**	**5,665.5**	**5,840.0**
Fuel Combustion	4779.8	5,085.0	5,266.6	5,339.6	5,356.2	5,448.6	5,623.3
Iron and Steel Production	85.4	74.4	68.3	76.1	67.4	64.4	65.7
Cement Manufacture	33.3	36.8	37.1	38.3	39.2	40	41.1
Indirect CO_2 (CH_4 Ox)	30.9	29.5	28.9	28.4	28.2	27	26.3
Waste Combustion	14.1	18.6	19.6	21.3	20.3	21.8	22.5
Ammonia Manufacture	18.5	18.9	19.5	19.5	20.1	18.9	18
Lime Manufacture	11.2	12.8	13.5	13.7	13.9	13.5	13.3
Limestone and Dolomite	5.2	7	7.4	8.4	8.2	9.1	9.2
Natural Gas Flaring	5.5	8.7	8.2	7.6	6.3	6.7	6.1
Ammonia Production	6.3	5.3	5.6	5.6	5.8	5.9	5.4
Soda Ash	4.1	4.3	4.2	4.4	4.3	4.2	4.2
Titanium Dioxide	1.3	1.7	1.7	1.8	1.8	1.9	2
Ferroalloys	2	1.9	2	2	2	2	1.7
Carbon Dioxide Use	0.8	1	1.1	1.3	1.4	1.6	1.4
Land-Use/Forests	-1,097.7	-1,010.0	-1,108.1	-887.5	-885.9	-896.4	-902.5
Bunker Fuels	113.9	101	102.3	109.9	112.9	105.3	100.2



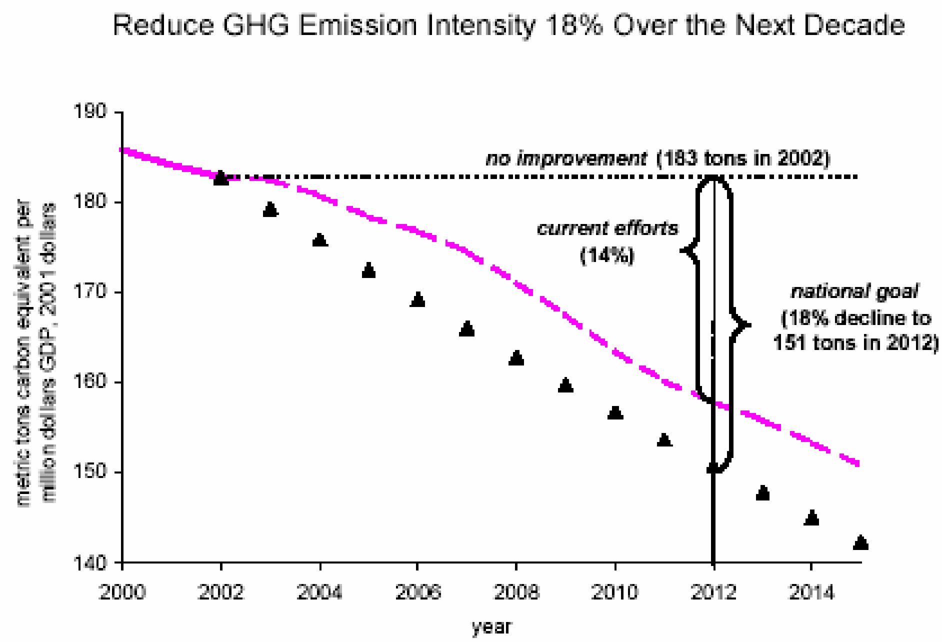
Source: BEA (2001), U.S. Census Bureau (2000), and emission estimates in this report.

Years→	1990	1995	1996	1997	1998	1999	2000 **CH4**
	651.3	**657.6**	**643.7**	**633.3**	**627.1**	**620.5**	**614.5**
Landfills	213.4	216.6	211.5	206.4	201	203.1	203.5
Enteric Fermentation	127.9	133.2	129.6	126.8	124.9	124.5	123.9
Natural Gas Systems	121.2	125.7	126.6	122.7	122.2	118.6	116.4
Coal Mining	87.1	73.5	68.4	68.1	67.9	63.7	61
Manure Management	29.2	34.8	34.2	35.8	38	37.6	37.5
Wastewater Treatment	24.3	26.8	27	27.5	27.8	28.3	28.7
Petroleum Systems	26.4	24.2	24	24	23.4	22.3	21.9
Stationary Combustion	7.9	8.2	8.4	7.5	7	7.3	7.5
Rice Cultivation	7.1	7.6	7	7.5	7.9	8.3	7.5
Mobile Combustion	4.9	4.8	4.7	4.6	4.5	4.4	4.4
Petrochemical Production	1.2	1.5	1.6	1.6	1.6	1.7	1.7
Agricultural Burning	0.7	0.7	0.7	0.8	0.8	0.8	0.8
Silicon Carbide Production	+	+	+	+	+	+	+
Bunker Fuels	0.2	0.1	0.1	0.1	0.1	0.1	0.1



Years→	1990	1995	1996	1997	1998	1999	2000
N2O	**387.3**	**419.8**	**430.5**	**429.8**	**426.3**	**423.5**	**425.3**
Agricultural Soils	267.1	283.4	292.6	297.5	298.4	296.3	297.6
Mobile Sources	50.9	60.4	60.1	59.7	59.1	58.7	58.3
Nitric Acid	17.8	19.9	20.7	21.2	20.9	20.1	19.8
Manure Management	16	16.4	16.8	17.1	17.1	17.1	17.5
Stationary Sources	12.8	13.5	14.1	14.2	14.3	14.6	14.9
Human Sewage	7	7.7	7.8	7.9	8.1	8.4	8.5
Adipic Acid	14.9	17.9	17.8	11.5	7.7	7.7	8.1
Agricultural Burning	0.4	0.4	0.4	0.4	0.5	0.4	0.5
Waste Combustion	0.3	0.3	0.3	0.3	0.2	0.2	0.2
Bunker Fuels	1	0.9	0.9	1	1	0.9	0.9
HFCs, PFCs, and SF6	**93.6**	**98.5**	**111.9**	**116.9**	**127.7**	**120**	**121.3**
ODS Substitution	0.9	21.8	30.6	38	44.9	51.3	57.8
HCFC-22 Production	35	27	31.1	30	40.2	30.4	29.8
Electrical Transmission	31.2	26.5	26.8	24.5	20.1	15.5	14.4
Aluminum Production	18.1	11.8	12.5	11	9	8.9	7.9
Semiconductor Manufacture	2.9	5.9	5.4	6.5	7.3	7.7	7.4
Magnesium Production	5.5	5.5	5.5	6.9	6.2	6.1	4
Total Emissions	**6,130.7**	**6,481.8**	**6,669.8**	**6,748.1**	**6,756.2**	**6,829.5**	**7,001.2**
Net Emissions	**5,033.0**	**5,371.8**	**5,561.7**	**5,860.5**	**5,870.3**	**5,933.1**	**6,098.7**

US Proposals February 2002



Reference: http://yosemite.epa.gov/oar/globalwarming.nsf/UniqueKeyLookup/SHSU5BNMAJ/$File/bush_gccp_021402.pdf