FIGURE 10-1. Since 1700, carbon dioxide levels have risen dramatically. Pre-1960 values derived from air samples trapped in the Antarctic ice sheet. Values since ~1960 were directly measured from the atmosphere on the top of Mauna Kea, Hawaii.

FIGURE 10-2. Changes in temperature from the years 1000 to 2000 have been determined from tree rings and glacial ice. Note the distinct increase in temperature since 1900.

FIGURE 10-3. Seasons: Earth’s axis inclined at 23.5 degrees to Earth’s orbit around the Sun. Northern hemisphere day on summer solstice (usually June 21) is longest. Shortest northern hemisphere day is winter solstice (usually December 21).

Earth’s orbit & climate
Milankovitch cycles
• gravitational interactions among planets & sun
• cyclic changes in Earth’s orbit
• cycles in the amount of solar energy arriving at Earth’s surface
• intensity of seasons

UCAR graphic

Fig. 10-4a, p.250
Milankovitch cycles

Plus tilt varies between ~21.5 and 24.5 deg every 41,000 years.

Earth Moisture Inventory

- Oceans: 97.2%
- Streams, atmospheric, and biological water: 0.01%
- Saline lakes: 0.1%
- Freshwater lakes: 0.1%
- Soil water: 0.94%
- Underground water: 0.5%
- Glaciers: 2.05%
- 2.8%

Figure 9-4

Lapse rate

- Wet adiabatic rate: 5°C/1,000 m
- Dry adiabatic rate: 10°C/1,000 m

Figure 10-8, p.253

Saturated

Unsaturated
Moist air expands in upslope—**orographic lifting**

FIGURE 10-10. Schematic diagram of the orographic effect shows how warm moist air rises, expands, cools, and dumps precipitation. Descending on other side of mountains, it contracts, warms, and dries out.

FIGURE 10-11. Differences in atmospheric pressure drive air movements and winds. High pressure => cold dry air descends & compresses; skies clear. Low pressure => air rises, expands, and condenses to form clouds and rain. In N hemisphere, descending air in high pressure cells rotates clockwise (viewed downward); rising air in low pressure cells rotates counterclockwise (cyclones).

Typical global air circulation for January.

Typical global air circulation for July.

FIGURE 10-15. The region of the subtropical high pressure area near 30 degrees N latitude where warm tropical air meets colder polar air is the area with the greatest contrast in air temperature. Their interaction forms the subtropical jet stream shown in this vertical cross section from the North Pole to the equator.
FIGURE 10-16. The weather forecast for December 16, 2003, shows the meandering jet stream with a huge polar low in the Pacific off western Canada that funnels rain into coastal California. Another Arctic low over the Great Lakes funnels rain into the Ohio River Valley.
Fig. 10-19. (a) A low pressure cell initiated by interaction of warm front and cold fronts. Warm air moving east against cold air causes shear rotation counterclockwise. The warm air pushes northeast over the front to the east, causing development of a warm front. Cold air moving southeast under the front to the west similarly forms a cold front. More rapid counterclockwise rotation strengthens the low.

(b) The same process of convergence of cold and warm fronts around a low pressure cell can lead to a cutoff low that detaches to spin off on its own.

Fig. 10-20. A weather map for June 26, 2003, shows a prominent cold front (blue) intersecting a warm front (red in upper right of map), with a cutoff low in Canada north of Lake Superior.

Fig. 10-21. Wind and ocean temperature conditions are shown during (a) normal conditions with strong trade winds and (b) El Niño conditions with weak trade winds. El Niño leads to warm temperatures off the west coast of South America.

(a) El Niño promotes greater winter precipitation in some areas, less in others. During El Niño, SW US is wet, in contrast to its normally dry weather, while the SE states are cooler than normal. Western and eastern Canada are warmer.

(b) During normal, or the opposite extreme, La Niña conditions, southwestern BC and WA are wet, as are areas immediately south of the Great Lakes. Western Canada,
**FIGURE 10-23.** Sea-surface temperatures for the Pacific Ocean are shown for the major 1997–1998 El Niño. The highest sea level in warm water over the eastern equatorial Pacific Ocean is shown in white and red. Darker shades to the west are the coldest temperatures.

**FIGURE 10-24.** Sea-surface temperature anomalies in the mid-Pacific Ocean are shown from 1900 to 1950 and 1950 to 2003. El Niño shows abnormally high sea-surface temperatures.

**North Atlantic Oscillation**

+ NAO = H pressure over the E Atlantic (white) & L pressure sits near Iceland (black). Warm weather develops in the W Atlantic and NW Europe. The westerly and trade winds are strong. – NAO, both pressure systems shift to the southwest (bold arrows).

**FIGURE 7.30** Typical winter sea surface temperature departure from normal in °C during the Pacific Decadal Oscillation’s warm phase (a) and cool phase (b). (Source: JISAO, University of Washington, obtained via the [http://www.jisao.washington.edu/pdo/](http://www.jisao.washington.edu/pdo/). Used with permission of N. Mantua.)

**PDO-warm phase**—warm surface water off west coast of NA—cooler than normal in central north Pacific

**PDO-cold phase**—cooler than average surface waters off west coast of NA; warmer than aver. in N. Cent. Pacific

Aleutian low strengthens = more Pacific storms into AK and Calif.

Drier in the Great Lakes; cooler and wetter in southern US

Winters cooler and wetter in NW N. Amer.; wetter in Great Lakes; warmer and drier in southern US.
Seasonal boundaries are shown between the warm, moist air of tropics and cooler, drier, higher-latitude air. The limits of warm, tropical air in summer shift northward as shown in the labels at the left.

**FIGURE 10-26.** Seasonal boundaries are shown between the warm, moist air of tropics and cooler, drier, higher-latitude air. The limits of warm, tropical air in summer shift northward as shown in the labels at the left.

**FIGURE 10-27.** Max rainfalls plotted against duration of rainfall. The dotted red lines show expected max value for one-hour period, & solid red lines = expected max rainfall for 10 hr period. Note that on either axis 100 = 1, 101 = 10, 102 = 100, and so on.

**Table 10-1.** Some Extreme Rainfalls

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>Amount</th>
<th>Cause</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cherrapunji, India</td>
<td>July 1861 (month)</td>
<td>9.3 m</td>
<td>Monsoon</td>
</tr>
<tr>
<td></td>
<td>June 24-30, 1931</td>
<td>3.2 m</td>
<td>Monsoon</td>
</tr>
<tr>
<td></td>
<td>June 9-16, 1876</td>
<td>3.39 m</td>
<td>Monsoon</td>
</tr>
<tr>
<td></td>
<td>June 14, 1875</td>
<td>1.03 m</td>
<td>Monsoon</td>
</tr>
<tr>
<td></td>
<td>March 11-16, 1952</td>
<td>4.13 m</td>
<td>Monsoon</td>
</tr>
<tr>
<td>Cilaos, Reunion</td>
<td>March 15-16, 1952</td>
<td>1.87 m</td>
<td>Monsoon</td>
</tr>
<tr>
<td>Albuquerque, New Mexico</td>
<td>July 25-26, 1979</td>
<td>1.09 m</td>
<td>Tropical storm</td>
</tr>
<tr>
<td>Bowden, Pan, Jamaica</td>
<td>Jan 23, 1968 (one day)</td>
<td>1.11 m</td>
<td>Frontal storm</td>
</tr>
<tr>
<td>Rapid City, South Dakota</td>
<td>June 9, 1972 (6 hours)</td>
<td>37 cm</td>
<td></td>
</tr>
<tr>
<td>Curves de Ores, Romania</td>
<td>12 minutes</td>
<td>21 cm</td>
<td></td>
</tr>
<tr>
<td>Barneveld, Western Cape, Canada</td>
<td>1 minute</td>
<td>3.8 cm</td>
<td></td>
</tr>
</tbody>
</table>

**Sidebar 10-1.** The Right-Hand Rule for the Northern Hemisphere

If you point your right thumb in the direction of rising or falling air, your bent fingers point in the direction of air rotation (in the southern hemisphere, use your left hand instead). For example, with low pressure air rising, winds rotate counterclockwise (as viewed looking down on a map).

**Satellite image of water vapor.** This water vapor carries heat to the Arctic from the tropics. Moisture streams (1 Sverdrup...10^6 m^3/sec transport of water carries 2.2 x 10^15 watt thermal energy)

1/3 of the movement poleward of tropical heat in the atmosphere is carried by water vapor...Rhines 07

**Heat Transfer Mechanisms Atmospheric and Oceanic Circulation**
What is paleoclimate?

Where do we get the record?

- Fossils...
- Geologic time...
- Geologic environments...hot/cold and/or dry/wet...paleomagnetic records
- Isotopes preserved in lakes, glacial ice...
- Tree rings, carbonate deposits of corals or in caves...
- Marine, lake, and bog deposits
Major "Ice Ages" in Earth History

"Snowball Earth" Tillite of late pre-Cambrian Windermere: Toby Formation of NE WA & ID

http://www.scotese.com/climate.htm

Climate Change, Plate Tectonics
Mountain-Building, volcanism

(Top) Atmospheric CO2 and continental glaciation 400 Ma to present. Vertical blue bars mark timing and palaeolatitudinal extent of ice sheets (Crowley, 1998). Plotted CO2 records = five-point running averages from each of four major proxies (see Royer, 2006).

(Bottom) Detailed record of CO2 for the last 65 Myr. Individual records of CO2 and associated errors color-coded by proxy method; when possible, records based on replicate samples (see Royer, 2006 for details and data references).

Figure 6.1

Dynamic processes, driven by heat within Earth's interior, that cause the geometry of the continents and ocean basins to change over millennia of years.

Global Tectonics

Mississippian, 340 Ma

Early Cretaceous, 130 Ma

Late Cretaceous, 80 Ma

Opening of Drake Passage ~41 Ma;
Scher & Martin, 2006;
Science, Vol. 312, no. 5772, pp. 428-430

Miocene, 20 Ma

Modern

Plate Tectonics

Ron Blakey Northern Arizona University

Stefan Rahmsdorf

Ron Blakey
long-term global cooling

- Earth has been cooling for ~60 Ma
- changes in continent positions, ocean circulation
- ice in Antarctica by ~30 Ma
  - "big white reflector" helps cool Earth

recent events: Ice Age Earth

- repeated cycles of gradual cooling and rapid warming
- global glaciation and deglaciation
- cyclic changes in Earth's orbit around the Sun
- feedbacks within Earth's climate system

20,000 yr ago, glaciers covered three times more land than they do today. Over portions of North America, ice was thousands of meters thick and extended well into the eastern half of the United States. Today, the ice over North America is gone except for the relatively small valley glaciers that still exist in high mountain valleys.

Ice Age Earth

Earth’s orbit & climate

- gravitational interactions among planets & sun
- cyclic changes in Earth’s orbit
- cycles in the amount of solar energy arriving at Earth’s surface
- intensity of seasons
Records from ice cores

annual layers
backlit face of a snow pit, Siple Dome, Antarctica

Vostok temperature & CO₂

- 4 glacial-to-interglacial cycles
- temperature and CO₂ vary together
- slow cooling & rapid warming

http://cdiac.ornl.gov/trends/temp/vostok/so2_tem.htm

Morrison (1991) marine oxygen isotope stages

Stage numbers = even-numbered peaks (at top) are glacial maxima, and odd-numbered troughs (at bottom) are interglacial minima. Red areas = interglacial episodes.


Fig. 1: (a) The relationship between increased radiative forcing, cooling of the eastern Pacific Ocean, and evidence for widespread drought in western North America during the twelfth century. (b) PDSI map of the twelfth-century drought and (c) the early 21st-century drought (data in Figure 1b are from Cook et al. [2004] and World Data Center for Paleoclimatology, and data in Figure 1c are from National Climatic Data Center). Mann et al, 2003, Oil past temperatures and anomalous late-20th century warmth: EOS, v. 84, no. 27, p. 256-257.

Jamestown; the Lost Colony
Reconstructed Palmer Drought Severity Index for Columbia River Basin (gray), and the reconstructed Columbia River Flow for The Dalles, Oregon (black)—five-year running average filter. From Gedalov, Peterson, & Mantua, 2004.

Time series of tree rings over 3000 yrs in Pacific NW, including individual subfossil trees (unfiltered data). Compiled by Pat Pringle.

Spider Lake, SE Olympic Mountains -- 1992 drought
landslide deposit
Subfossil trees
~ 1000 ybp

Land areas will warm more than oceans -- greatest warming at high latitudes

FIGURE 14.1 If all the ice locked up in glaciers and ice sheets were to melt, estimates are that this coastal area of south Florida would be under 65 m (213 ft) of water. Even a relatively small one-meter rise in sea level would threaten half of the world’s population with rising seas.
Increasing Melt Area on Greenland

- 2002 all-time record melt area
- Melting up to elev. of 2000 m
- 16% increase from 1979 to 2002

Satellite-era record melt of 2002 was exceeded in 2005.
Source: Waleed Abdalati, Goddard Space Flight Center

70 meters thinning in 5 years

West Antarctic Ice Sheet
= 5 m global sea level

IPCC fig. SPM.1

Atmospheric concentrations of carbon dioxide, methane and nitrous oxide over the last 10,000 years (large panels) and since 1750 (insets). Data from ice cores (different colors - different studies) and atmospheric samples (red). Corresponding radiative forcings are on right hand axes of the large panels. (Figure 6.4)

External Causes of Climate Change

- changes in incoming solar radiation (sun, volcanism)
- changes in the composition of the atmosphere (GH gases)
- changes in the Earth’s surface (albedo, tectonics, forests…)

* Emissions of CO₂ and other greenhouse gases are by no means the only way to change the climate.

Climate Change and Feedback Mechanisms

- positive feedback mechanisms
- negative feedback mechanisms
- Ex: water vapor-greenhouse feedback
- Ex: snow-albedo feedback

* Feedbacks cause climate changes to be either amplified or reduced.

25% of U.S. population lives within 10 m of sea level.
Excess heat = warms high latitudes.

If conveyor stopped, lose ocean heat to high latitudes.

Land areas are projected to warm more than the oceans with the greatest warming at high latitudes.

Annual mean temperature change, 2071 to 2100 relative to 1990: Global Average in 2085 = 3.1°C

West Antarctic Ice Sheet = 5 m global sea level
FIGURE 14.16 Clouds play an important role in the earth’s climate system. How they will respond to increasing global temperatures is not totally clear. An increase in global cloudiness could potentially enhance or reduce the warming brought on by increasing greenhouse gases. [p.395]