(lecture on 4/22/08)

Climate Change During the Last 1000 Years and Since the 1800s

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Chapter 16 - Climate Change During the Last 1000 years
the entire chapter except section 16-4 and Box 16-2 on El Niño

Chapter 17 - Climate Changes Since the 1800s
the entire chapter except the last section, Shorter-Term Oscillations

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Climate Change During the Last 1000 Years

Medieval Warm Period: During the Middle Ages around a thousand years ago the climate was mild in Europe and the North Atlantic. The Vikings were able to colonize Iceland and Greenland.

Little Ice Age: Beginning in the 15th century winters in Europe and the North Atlantic grew colder. The Vikings were forced out of Greenland, the canals in Holland froze over, mountain glaciers in Switzerland and Norway advanced down their valleys, and Washington's army shivered at Valley Forge.

Sea ice formed around Iceland.

"Halos" of dead lichens on bare bedrock surround permanent snowfields in arctic Canada. These lichens were of a size indicating that they had been growing for hundreds of years before dying. A few ^{14}C dates indicate they died near the beginning of the Little Ice Age. Small living lichens are large enough to have been growing only since the turn of the twentieth century. Therefore, the older lichens were killed by expansion of the permanent snowfields during the little ice age. The snowfields didn't retreat until the turn of the twentieth century.

20th Century Warming: A warming trend began in the late 19th century and continues today.

Climate Proxy Records for the Last 1000 Years

Mountain Glacier Ice Cores:

$\delta^{18}O$ from Greenland and Antarctica are excellent sources of climate information. But they tell us principally what is happening at high latitude. We need proxies from low latitude as well. Mountain glaciers in the tropics and subtropics give us an important record.

Quelccaya ice cap, Peru: $\delta^{18}O$ indicates a cold period the 16th through 19th centuries with warming in the 20th century. A return expedition found that the ice cap is now melting.

Dundee ice cap, Tibet: $\delta^{18}O$ similarly shows post-medieval cooling and late warming.

Although these mid-latitude glaciers agree on a Little Ice Age cooling, it is not recorded in either Greenland or Antarctic ice. So the Little Ice Age does not appear to be a global event.

Tree Rings:

Trees have annual growth rings. Their width/density depends on temperature and rainfall, especially in spring/early summer.

Trees near the edge of their geographic range are most susceptible to variation in climate.

Arctic & Central Asian studies: Tree ring studies from around the arctic and also tree ring studies from Mongolia indicate generally cooler temperatures but with intervals of warm during the 17th through 19th centuries.

Southern hemisphere studies: Tree ring studies in Tasmania show no sign of a Little Ice Age.

So again, the Little Ice Age appears not to be a global event.

Coral Records:

Corals grow annual layers and live in tropical to subtropical climates. So $\delta^{18}O$ from corals complement the mid and high latitude tree ring and ice data.

An average tropical sea surface record using $\delta^{18}O$ from corals in the tropical Pacific and Indian Ocean indicates cooler tropical sea surface temperatures in the 19th century and rising to much warmer temperatures through the 20th century.

El Niño - Southern Oscillation (ENSO): Multi-year oscillations in ocean and atmosphere circulation in the Pacific region overprint the temperature record from tropical corals and also influences short term climate in wider areas of the globe.

Overview of Northern Hemisphere Temperature Trends the Last 1000 Years

Multi-proxy Studies: By combining proxy records for the past 1000 years or so enables a synthesis that may overcome biases using a single technique or using data concentrated in one region of the globe. The uncertainties estimated for each study are combined into an overall uncertainty envelope about a calculated mean. The uncertainty envelope is large for times before the 17th century. However, there is a suggestion of an overall cooling from the middle ages into the 19th century. The rapid warming beginning in the later 19th century is clear.

The IPCC 2007 report concluded from multi-proxy studeies that average northern hemisphere temperature for 1950-2000 was very likely (>90% likelihood) warmer than any 50 years in last 500 and likely (>66% likelihood) warmer than any 50 in last 1300 years.

Such data are much more sparse in the southern hemisphere and it is not yet possible to do a similar temperature reconstruction.

Proposed Causes of Climate Change A.D. 1000 - 1850

Orbital Forcing: Northern hemisphere summer insolation has been declining during the past 10,000 years. But based on the small estimated cooling of the arctic and the fact that high latitudes are much more sensitive to temperature change, the average northern hemisphere cooling due to reduced summer insolation could only account for half of the observed cooling. So this isn't the cause, or at least not the whole cause.

Bipolar Seasaw: If the northern hemisphere cooled due to a change in ocean currents and re-balancing of heat between northern and southern Atlantic, then the South Atlantic and Antarctic region should have warmed. There is not enough data to test that hypothesis.

Solar Variability: Earlier studies proposed that, since the Maunder Minimum during the 17th century occurred during the Little Ice Age and that hotspot intensity has increased since the late 19th century, solar variability might account for a large proportion of the climate variability of the past 1000 years. However, recent astronomical observation of the sun and stars similar to the sun find no variation in radiation beyond the 11-year sunspot cycle. So solar variability probably doesn't contribute more than about 10% of the 20th century temperature rise.

Explosive Volcanic Eruptions: Aerosols produced from SO_2 emissions from explosive eruptions block a small fraction of incoming solar radiation. It appears that increased volcanic activity may have helped the cooling of the Little Ice Age.

Greenhouse-Gas Forcing: Air bubbles in well-dated Antarctic ice cores indicate that CO_2 levels fell during the Little Ice Age. Recall that Ruddiman's ***"early anthropogenic hypothesis"*** correlated the overall rise in greenhouse gases during the past several thousand years to the rise of agriculture (clearing forest for cropland & rice paddy irrigation). Ruddiman notes that due to bubonic plague in Europe 14th century and the pandemics among Native American populations following 1492 caused large declines in human populations in Europe and the Americas and left much cropland to go back to forest. This natural reforestation removed CO_2 from the atmosphere until human populations increased and cleared the land again, followed by much more.

Climate Changes Since the 1800s

Instrumental Record of Temperature (thermometers)

Earth Surface Temperature: Thermometers have been used to regularly measure temperature for 200 years. But few stations have temperature records that far back. A large global network of weather stations developed in the 20th century. The average global (land and ocean) surface temperature rose by about 0.7 °C.

Deep Ocean Temperature: Analysis of direct measurements of temperatures various depths in the oceans collected over the latter half of the 20th century shows the upper 3000 m of the ocean warmed by a global average of 0.06 °C. This seems like a small, insignificant amount. But there is little exchange between the atmosphere and the deep ocean below the wind-mixed upper 100 m. Also, because of the high thermal capacity of water and the great size of the deep ocean, this small temperature rise amounts to 10 times the amount of increased heat as compared to the additional heat stored in the atmosphere due to global warming.

Ground Temperature: As the Earth's surface warms, the heat is gradually transmitted downward through soil and rock. Borehole temperature measurements made around the globe indicate a large warming during the past 125 years.

Observations of Melting Ice and Warming in the Arctic

Mountain Glaciers: Approximately 98-99% of all the mountain glaciers on Earth are retreating. The global average amount of glacial retreat between 1850 and 2000 is over 1.5 km.

Arctic Sea Ice: Based on satellite measurements, the minimum extent of sea ice at the end of the arctic summer has decreased by ~25% since the 1970s. The thickness of multi-year ice in the middle of the Arctic Ocean decreased by ~40% between the 1950s and 1990s based on submarine soundings.

Decreasing Snow Cover: Satellite measurements from recent decades, combined with older ground-based records of snow cover at high latitudes in the northern hemisphere indicate later arrival in the fall and earlier melting in spring.

Alaskan Growing Season: The length of the growing season in central Alaska has increased by about 2 weeks since the 1950s, based on surface temperature measurements. Satellite measurements indicate a week and a half increase in growing season between the early 1980s and late 1990s.

Ice Sheet Volume: Satellite measurements of radar waves reflecting off the ice surface and from the ice-bedrock interface indicate that lower elevation portions of the Greenland ice sheet have been thinning rapidly, while the thicker/high elevation, interior regions are still stable (that can't last for long if the margins keep accelerating their flow to the sea).

Rising Sea Level

Bedrock Complications: Long term records of sea level exist from tide gauges in ports around the world. However, in order to determine sea level from the tide gauges corrections must be made for local/regional uplift or subsidence due to tectonics, sediment loading, and isostatic rebound following the ice ages. For example, uplifted beach ridges surrounding Hudson Bay (central part of the Laurentide Ice Sheet) have risen nearly 150 feet in the past 7000 years and today some areas are still rising ~10 mm/year.

20th Century Sea Level Rise: Accounting for such complications, it has been determined that sea level rose by about 20 cm since the 1880s or about 17 cm during the 20th century. The average rate of sea level rise during thee 20th century was 1.7 mm per year (17 cm / 100 yrs). Satellite measurements of the ocean surface indicate that since 1992 sea level has been rising 3 mm per year, nearly double the 20th century average rate.

Sources of Sea Level Rise: The rise in sea level is caused by a combination of melting ice and expansion of seawater as it warms. Estimates of contributions to sea level rise are in the table below. They don't all add up yet, but we know little about the overall 20th century mass balance of the Greenland and Antarctic ice sheets.

Contributions to 20th Century Sea Level Rise

thermal expansion	4 cm
alpine glaciers	5 cm
Greenland and Antarctica	2 cm
Total:	11 cm
Observed	17 cm