BCS 100: Introduction to the Circumpolar North
University of the Arctic

MODULE 7 Climate Change (Part 1)

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Overview

This module will give students an overview of the factors that cause climate change, the short-term and longer-term records for global and Arctic air temperature, and forecasted temperatures for the next century. As well, some of the observed and predicted biophysical impacts of climate change are discussed.

Learning Objectives & Outcomes

Upon completion of this module you should be able to:

1. Differentiate between weather and climate.
2. Describe the major causes of climate change.
3. Compare the general patterns of Arctic and global temperatures during the 20th century with those in the more distant past.
4. Identify the sources and limitations of temperature and precipitation data.
5. Project the biophysical and societal impacts of climate change.

Required Readings

Gregoire, L. 2008. "Cold Warriors," *Canadian Geographic*, October 2008, pp. 34-50.

Module Appendix A: Sources for High Quality Information on Climate Change / How to Evaluate the Quality of Climate Change Information.

Key Terms and Concepts

- Aerosols
- Albedo
- Climate
- Earth's orbital cycles
- Energy balance
- Feedback loops
- Greenhouse gases
- Proxy data
- Radiative forcing factor
- Reflectivity

- Residence time
- Specific heat
- Weather

Learning Materials

Introduction

In the past 100 years mean global air temperature has risen by about 0.74^{o}C with higher temperature increases in the Arctic (IPCC 2007). There is very high scientific confidence that the global temperature rise since the middle of the 20th Century has been due to human-caused increases in greenhouse gases, (carbon dioxide, methane, and nitrous oxide); overall there is very high confidence that warming is the net effect of human activities since 1750 (IPCC 2007). The change underway is abrupt, and the speed of the temperature excursion has not been duplicated in the climate record for at least 11,000 years, a time when humans were still in the Stone Age. Climate models, based on assumptions about human population size (now 6.5 billion) and energy consumption and sources, forecast a global mean annual temperature (MAT) increase of 2-4^{o}C by the year 2100. Warming in the Arctic is expected to be at least 2-3 times greater. In some areas, drought and other temperature-related responses (storms, sea level rise, and sea ice changes) will have greater biophysical and societal impacts than temperature alone. Fundamentally, climate change is transforming the circumpolar North, including its ecosystems, natural resources, governments, economies, and cultures; these transformations will accelerate over the next century.

While climate change is widely recognized as human caused, there are skeptics who do not believe the proposed theories and data. So, how do scientists know with certainty whether their theories are correct? Scientists know what they think they know because their knowledge comes from a scientific approach involving discovery, observations, and hypothesis testing, and because science is a collective process that involves the vetting of ideas and findings with peers. Scientists do not try to prove a hypothesis or prove that their view of the world is correct; rather, scientists try to disprove hypotheses (theirs or others') based on current understanding about the way the world works. A new scientific idea or a modification to an existing scientific idea (the more common practice) gains acceptance only after it withstands repeated and independent attempts to disprove it. Science is a self-correcting discipline. The process of science is to identify wrong ideas and mistakes and to formulate a revised or new scientific view consistent with the evidence.

Knowledge about climate change has developed over many centuries and has continually evolved with new findings. Ultimately the non-scientist must largely depend on climate change information and interpretations from scientists. Acceptance, rejection, and the degree of skepticism or trust will depend largely on whether sources (scientists and their institutions) are trustworthy. Here I use scientific sources that climate change scientists endorse as having high reliability. I have also referenced several academic books and a few articles from the popular media.

7.1 Climate versus Weather

People frequently misunderstand the difference between weather and climate. When talking about climate change, people often refer to whether a particular winter or summer is cold or warm, compared to their perception of normal conditions. You might hear a person say, "I can't understand why people believe there is global warming. This winter was one of the coldest I can remember." Such a statement illustrates the confusion about weather and climate. An unusual season (e.g., an especially cold winter in England or an unusually warm winter in Finland) or even an unusual year or two do not indicate a change of climate.

Weather is the combination of atmospheric conditions "in the moment" or over the course of a day or several days. Weather includes all the elements of the atmosphere that are typically included in a weather report or forecast — air temperature (high and low), humidity, wind speed and direction, atmospheric pressure, precipitation, and amount of cloudiness. **Climate** is the average of weather conditions (including ranges) over many years (usually several decades) and for a given location or region. Weather changes quickly from hour-to-hour and day-to-day. Climate generally varies little in a human lifetime, though there is strong evidence from ice cores and other sources that abrupt climate change is common at local, regional, and global scales. A common phrase that captures the difference between weather and climate is "Climate is what you can expect, and weather is what you get."

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Weather forecasts and current weather conditions are readily available via the Internet and via the media (radio, television, and newspapers). Climate information is typically presented in tables and graphs that give long-term monthly and annual averages and ranges for various weather conditions (temperature and moisture commonly) and via climate classification maps. The Köppen or Köppen-Geiger system, developed by Köppen in 1900 and updated by Geiger in the 1950s, is still the most commonly used climate classification scheme. Following are three maps: the Köppen-Geiger system (updated by Kottek et al. 2006) for the globe (Figure 1) and, to illustrate a larger spatial scale, a climate map (Figure 2) and weather map (Figure 3) for Australia. The Köppen-Geiger map is based on precipitation and temperature and reflects the spatial patterns of vegetation types or biomes.

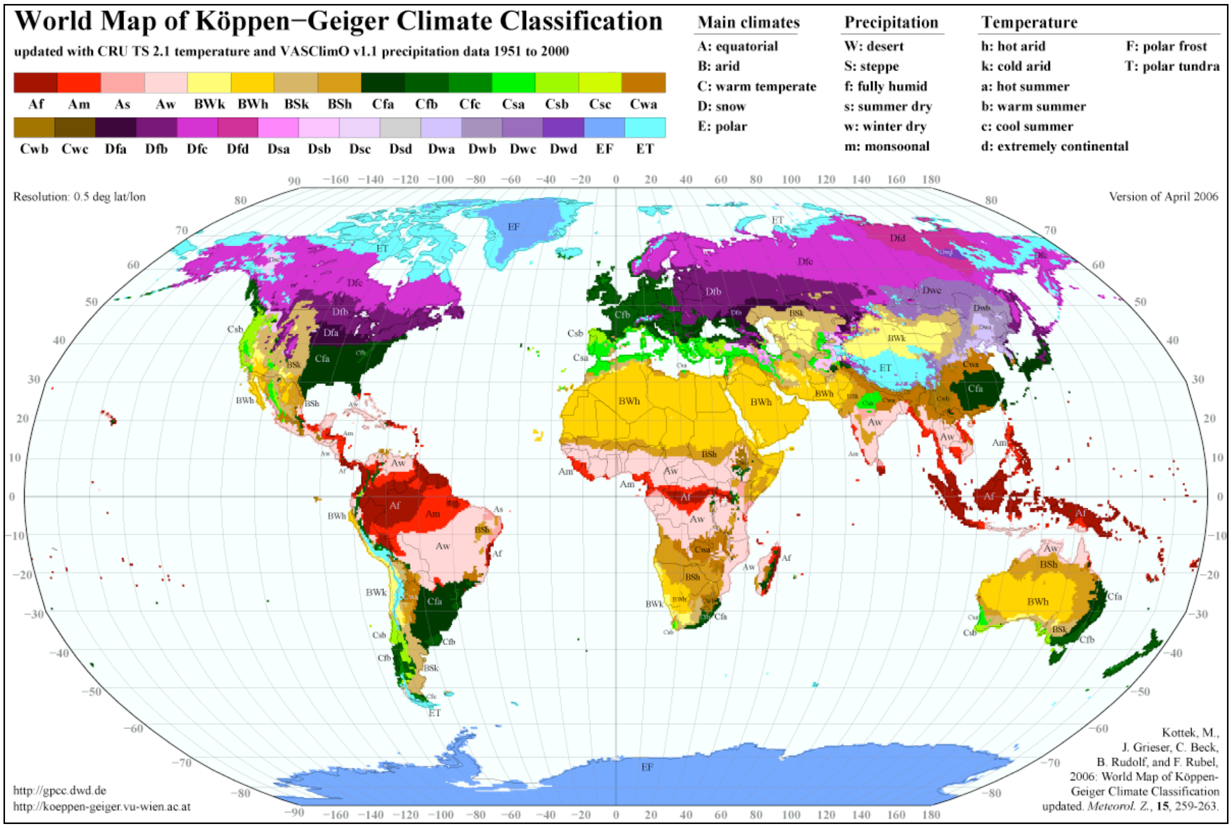

Figure 1: Köppen-Geiger climate classification for the world updated by Kottek et al. (2006).

Source: *Meterologische Zeitschrift* 15:3, p. 261. http://www.ingentaconnect.com/content/schweiz/mz/2006 Public Domain.

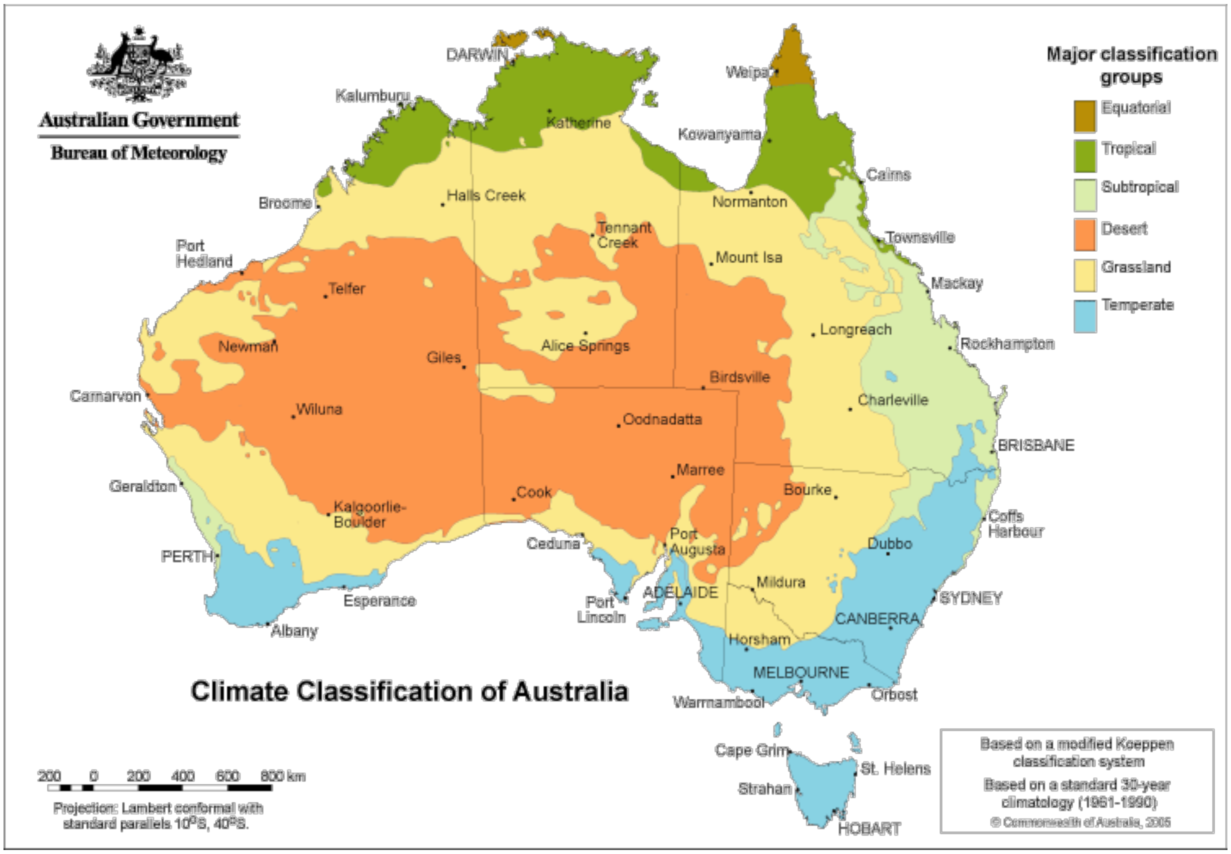

Figure 2: Climate map of Australia based on the Köppen classification scheme.

Source: Australian Bureau of Meteorology
www.bom.gov.au/climate/envion/other/kpn_group.shtml Posted with permission.

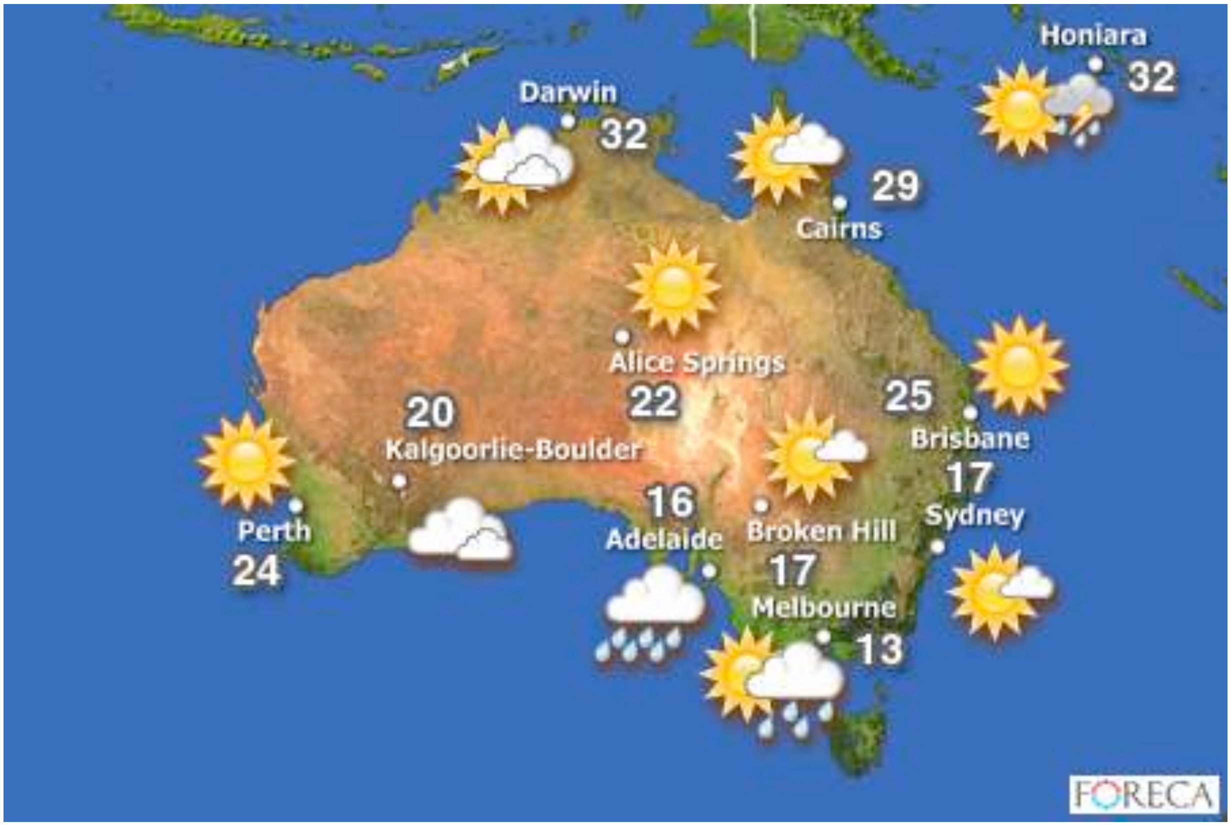

Figure 3: Australia's weather forecast map for April 27, 2008.
Temperatures are in degrees Centigrade.

Source: MSN Weather http://weather.msn.com/region.aspx?&wealocations=Australia_1&map=0 Posted with permission.

Often there is little similarity between a climate zone map and a daily weather map for any region because climate zone maps show the average annual conditions for several decades (usually 20–30 years). Nonetheless climate zone maps provide good information on the expected range of weather conditions and are very useful for inferring patterns for different vegetation groups or biomes. Up-to-date weather information and forecasts for any region worldwide can be found at the World Weather Information Service of the World Meteorological Organization. In the Arctic, government agencies and research organizations are a good source of weather and climate data (e.g., Alaska Climate Research Center) and nearly always provide information about how weather data have been collected and analyzed.

7.2 Causes of Climate Change

Changes in greenhouse gases, water vapor, **albedo** (reflectivity), and solar radiation alter the Earth's **energy balance** (solar radiation received relative to longwave radiation released to space) and cause climate change (Figure 4). These factors are defined as radiative forcing factors: positive forcing factors promote warming, and negative forcing factors promote cooling (Figure 5). By convention, **radiative forcing factors** are expressed in watts per square meter ($W\ m^{-2}$ or W/m^2) relative to pre-industrial conditions defined at 1750 (IPCC 2007). The mean net changes (including the range) in the Earth's energy balance from anthropogenic contributions and total contributions (including solar radiation), respectively, from 1750 to 2005 are +1.6 (0.6–2.4) $W\ m^{-2}$ and 1.72 $W\ m^{-2}$ (IPCC 2007). That means the Earth is receiving slightly more radiation than it is releasing to outer space. Because climate is highly sensitive to changes in the Earth's energy balance (Hansen et al. 2007), this small change in the Earth's energy balance has caused a significant increase in mean global temperature (+0.74^{o}C) over the past 100 years (IPCC 2007).

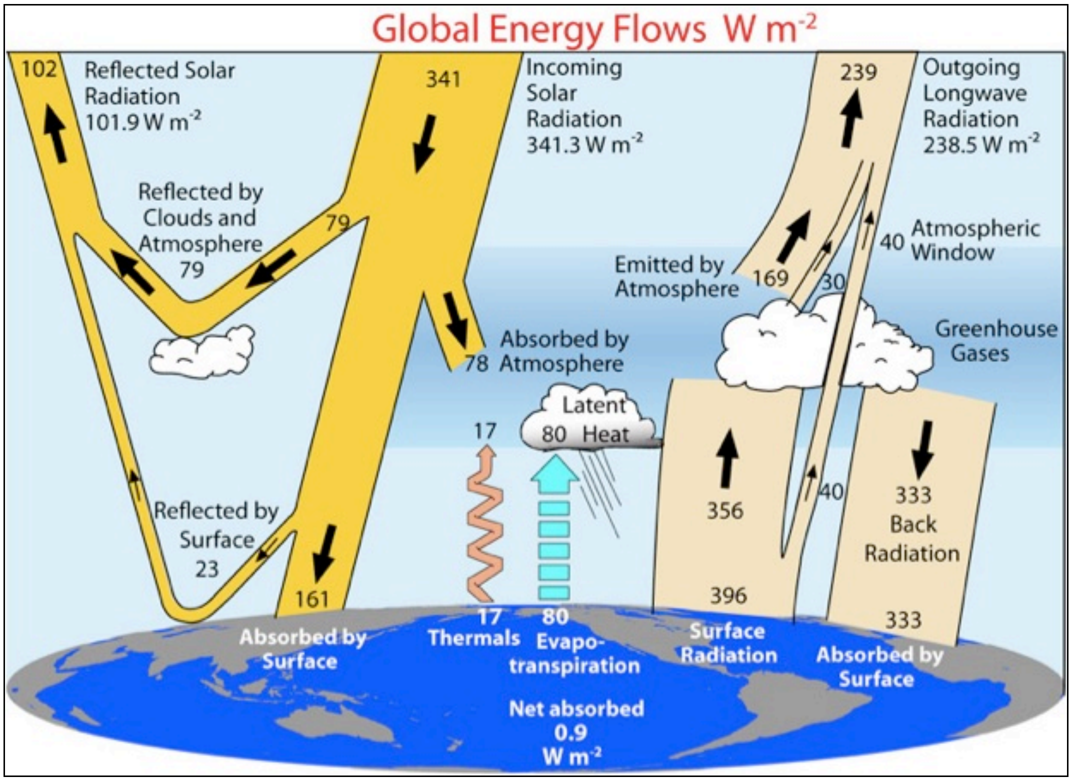

Figure 4: The Earth's global mean annual energy budget (W/m^2) for the period March 2000 to May 2004.

Source: Trenberth, K.E., Fasullo, J.T., and Kiehl, J. 2009. "Earth's global energy budget." *Bulletin of the American Meteorological Society 90*, p. 314. © American Meteorological Society. Posted with permission.

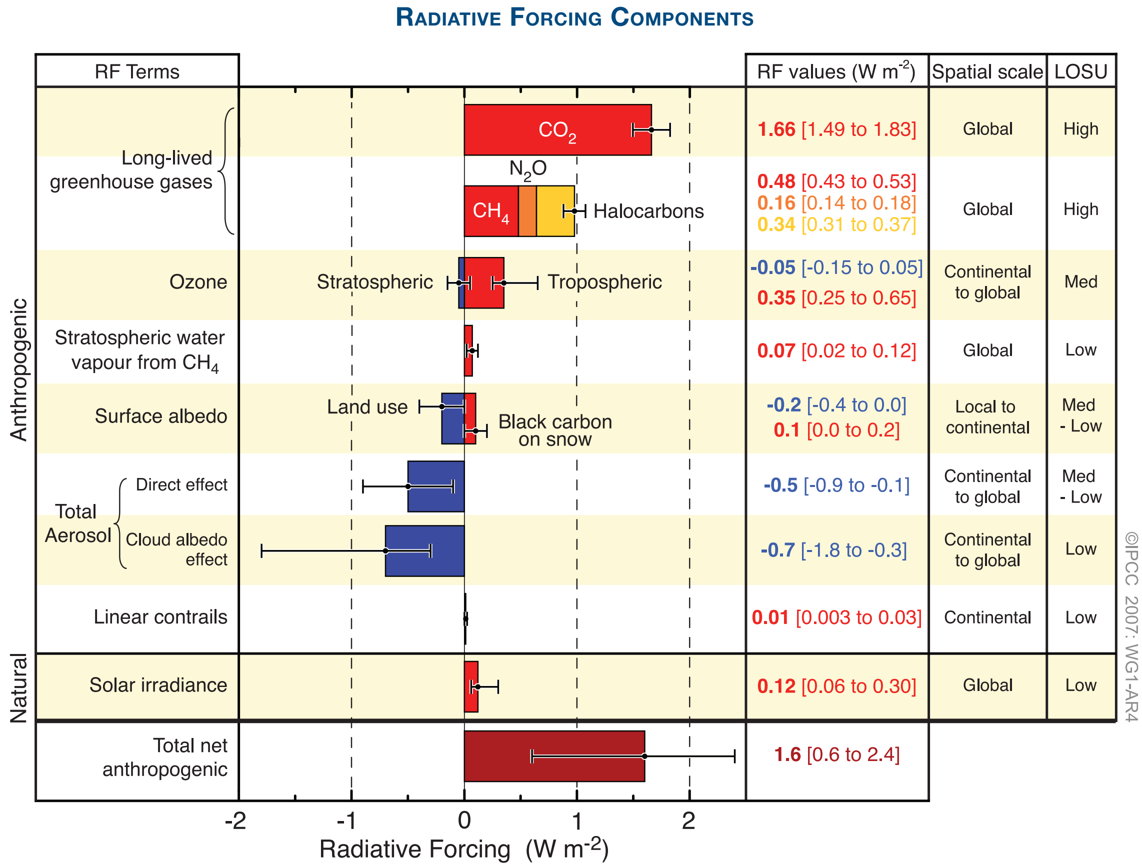

Figure 5: Global mean estimates (and ranges) of radiative forcing in 2005, relative to 1750, for greenhouse gases and other agents that influence the Earth's net energy balance. Included are the spatial scale of effects (local to global) and the assessed level of scientific understanding (LOSU). Volcanic aerosols, which have a cooling effect, are not included because they are episodic. Red bars indicate positive forcing (warming effect); blue bars indicate negative forcing (cooling effect).

Source: IPCC. (2007). *Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* Core Writing Team: Pachauri, R.K and Reisinger, A. (eds.). IPCC, Geneva, Switzerland, p. 39. www.ipcc.ch Open Source.

Human Effect

Humans have caused 93% (+1.6 out of +1.7 W m^{-2}) of the total change in the Earth's net positive radiation balance from 1750 to 2005. Humans are responsible for negative forcing factors (increased albedo due to aerosols, cloud changes, and land conversions) as well as positive forcing factors (increasing greenhouse gas concentrations), but the positive forcing factors predominate.

Greenhouse gases (carbon dioxide, methane, nitrous oxide)

Greenhouse gases (GHGs), defined as atmospheric gases that trap longwave radiation (heat) released from the Earth's surface, occur naturally and are released due to human activity. Some of the heat remains in the atmosphere, some is re-radiated back to the Earth's surface, and some is lost to space (Figure 4). Though not commonly included with the other greenhouse gases, water vapor is the strongest greenhouse gas with respect to total heat absorbed. Prior to the arrival of modern humans, greenhouse gases produced via biogeochemical processes maintained natural greenhouse conditions. In the absence of greenhouse gases the Earth's mean temperature would be 27°C (~49°F) lower than its current temperature of 14.4°C (57.9°F) (National Climatic Data Center 2009; Pew Center on Global Climate Change 2009).

Carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O) have all increased due to human activity since the start of the industrial revolution in the 1700s (Table 1). CO_2 has had the greatest positive forcing (warming effect) of the anthropogenic GHGs and has increased from a pre-industrial value of about 280 ppm (parts per million) to about 386 ppm at the beginning of 2009 (Dr. Pieter Tans, NOAA/ESRL www.esrl.noaa.gov/gmd/ccgg/trends/), representing a net addition of roughly 226 billion metric tons of carbon to the atmosphere. The main sources of anthropogenic CO_2 are combustion of fossil fuels (coal, oil, and natural gas) and the conversion of higher biomass land types (e.g., forests) to lower biomass land types (e.g., pastures), with burning or decomposition of the original vegetation. Methane (CH_4), which is the most important non-CO_2 forcing factor, has more than doubled since 1750 due to increased livestock populations and expansion of rice paddies; methane is produced from incomplete decomposition of organic material. Molecule-for-molecule methane is about 25 times more potent than CO_2 as a greenhouse gas absorber of infrared radiation; however, CO_2 has a greater effect on warming because its concentration is about 200–300 times greater than methane's. Nitrous oxide has risen less sharply than the other two anthropogenic GHGs but still contributes significantly to overall positive radiative forcing; it is produced mainly from fertilizer nitrogen. Nitrous oxide production is likely to rise as agriculture production and nitrogen fertilizer use increase with human population growth.

Table 1: Properties of the major greenhouse gases (except for water vapor.

Data sources: Forster et al. 2007; Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory (USA) 2008. Compiled by module author Richard Boone.

Greenhouse Gas	Radiative Forcing ($W\ m^{-2}$)	Residence Time (yrs)	Pre-Industrial Concentration	Current Concentration	Major Anthropogenic Sources
CO_2 (carbon dioxide)	1.66	Variable (years to millennia)	280 ppm	386 ppm	Fossil fuels, land use change, cement production
CH_4 (methane)	0.48	12 yrs	~715 ppb	1774 ppb	Livestock, rice paddies
N_2O (nitrous oxide)	0.16	114 yrs	270 ppb	320 ppb	Fertilizer nitrogen

[1]Note: ppb = parts per billion

The longevity of CO_2 and other greenhouse gases is reason for significant concern: a large fraction of CO_2, for example, will remain in the atmosphere for centuries in the absence of carbon storage (sequestration or capture) technologies. Computer models indicate that 33% of fossil fuel CO_2 will remain in the atmosphere after a century (Hansen et al. 2007) and 10–15% after 10,000 years (Archer 2005). Even with reduction of current CO_2 emissions, past emissions will promote a warmer climate for centuries to millennia.

Albedo and Aerosols

Humans have increased the net reflectivity (**albedo**) of the planet: the increase in albedo, due primarily to land-type conversions (forest → agricultural land), has exceeded the decrease in albedo due to accumulation of black carbon (the product of fossil fuel combustion, wood burning, and human-caused forest fires) on snow (Figure 5). Humans have also changed the concentration of aerosols, small airborne particles that include dust, black carbon, and sulfate and nitrate crystals. **Aerosols** cause both warming (black carbon) and cooling (sulfate, nitrate, and dust). Overall there has been a cooling effect since 1850 due mainly to increases of sulfate and nitrate aerosols from fossil fuel combustion (sulfate and nitrate) and fertilizer nitrogen (nitrate). Aerosols indirectly have caused additional cooling via their effects on clouds. Aerosols cause increased cloud longevity and promote the formation of smaller water droplets, which are more reflective.

Largely because of increased aerosols the intensity of solar radiation at the Earth's surface declined from 1960 (start of measurements) to about 1990. The trend reversed from about 1990 onward with a decrease in atmospheric aerosol concentrations and an increase in radiation at the Earth's surface (Streets et al. 2006; Wild et al. 2007). The two phenomena have been termed "global dimming" (1960-1990) and "global brightening" (1990 to present). The warming effect of GHGs has more than offset the cooling effect of the increased aerosols (Figure 5). Aerosols have a short **residence time** in the atmosphere – they are removed relatively quickly in precipitation events – whereas GHGs remain in the atmosphere for decades to up to millennia. Consequently and critically, the warming effect of rising greenhouse gases is now less offset by the cooling effect of atmospheric aerosols (Wild et al. 2007). An irony is that reductions in aerosols have improved air quality while progressively strengthening the warming effect of rising greenhouse gases.

Feedback Loops

Forcing factors are connected via a network of positive (amplifying) and negative (reducing) **feedback loops**. A positive feedback relationship is one in which a rise in one factor (A) stimulates an *increase* in another factor (B), which in turn stimulates a further rise in (A). Atmospheric CO_2 provides an example. Rising atmospheric CO_2 (A) promotes higher air temperatures and (via heat conduction) higher soil temperatures (B) that stimulate soil CO_2 flux to the atmosphere from respiration of plant roots and soil microbes, thereby promoting higher atmospheric CO_2 (A). This represents a positive or amplifying feedback loop.

In the case of a negative or reducing feedback, a rise in one factor (A) leads to an increase or decrease in another factor (B), which in turns causes a *reduction* in the first factor (A). Atmospheric CO_2 provides an example of negative feedback as well. Higher atmospheric CO_2, though it promotes higher temperatures, can also stimulate plant uptake of CO_2 via photosynthesis (B); this increased rate of photosynthesis (B) tends to reduce atmospheric CO_2 levels (A), thus counteracting the increased CO_2 release from plant root and soil microbial respiration. Importantly, for the example given, the current net effect of higher atmospheric CO_2 is positive — the positive feedback (increased soil CO_2 efflux) is greater than the negative feedback (increased CO_2 uptake from higher photosynthesis rate). A further element of

Figure 6: True color image of the Earth created by stitching together separate images of the Earth's surface (The Blue Marble). From the Visible Earth project of the NASA Goddard Space Flight Center (http://visibleearth.nasa.gov/view_rec.php?id=24290).

Credits: NASA Goddard Space Flight Center Image by Reto Stöckli (land surface, shallow water, clouds). Enhancements by Robert Simmon (ocean color, compositing, 3D globes, animation). Data and technical support: MODIS Land Group; MODIS Science Data Support Team; MODIS Atmosphere Group; MODIS Ocean Group Additional data: USGS EROS Data Center (topography); USGS Terrestrial Remote Sensing Flagstaff Field Center (Antarctica); Defense Meteorological Satellite Program (city lights). Public Domain

…egative and positive feedbacks between forcing factors are non-linear … over time.

…cal about the overall Earth's energy balance that Figures 4 and 5 do not …kly apparent from a view of the Earth from space (Figure 6) — the importance of oceans. They represent 71% of the world's surface area and absorb most of the Earth's absorbed solar radiation. Unlike the terrestrial surface, which warms up quickly and rapidly transfers heat to the air layer above it, ocean waters (because of their high **specific heat**, i.e., the high amount of heat required to raise their temperature) are a longer-term heat reservoir; over 20% of the heat absorbed by ocean water is stored below 10 m depth (Burroughs 2007). Consequently oceans are a long-term storage sink for the additional heat and energy due to global warming, and ocean currents are major vectors for transfer of energy around the planet.

Longer-Term Causes of Climate Change: Earth's Orbital Cycles

Earth's climate over a long time scale has been profoundly altered by slow, regular, and periodic changes in the **Earth's orbital cycles**: the elliptical pattern (varying diameter) that the Earth circumscribes (traces) as it moves once annually around the Sun, the Earth's tilt (now at 23.5^{o} but that varies from 22.1^{o} to 24.5^{o}) relative to the plane of the Sun, and the direction of the Earth's tilt (which is not constant).

In 1920 Milutin Milankovitch, a Serbian astrophysicist, proposed that slow but periodic changes in these orbital patterns sufficiently raises or lowers summer solar radiation at 65^{o}N latitude roughly every 100,000 years so that polar ice sheets grow, leading to an ice age, or decay, leading to an interglacial period (Figure 7). Although Milankovitch's theory was not broadly endorsed for more than 40 years, the Earth's orbital patterns are now widely accepted as the primary cause of the ice ages and interglacial periods over the past 1 million years and are referred to as the Milankovitch Cycles.

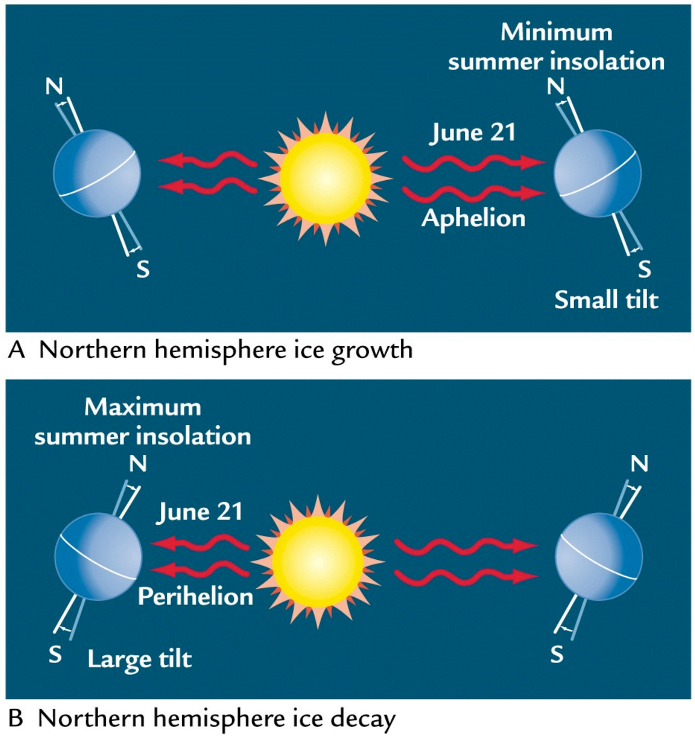

Figure 7: The Milankovitch Theory describes how a change in solar radiation (insolation) at 65°N every 100,000 years promotes growth of ice sheets during glacial periods and decay of ice sheets during interglacial periods. (A) Ice sheets in the northern hemisphere grow when the Earth has a small tilt and when the Earth's farthest position from the sun (the aphelion) is the most distant. (B) Ice sheets in the northern hemisphere decay when the Earth has a large tilt and when the Earth's closest position to the sun (the perihelion) is the shortest.

Source: Ruddiman, W.E. (2008). *Earth's Climate,* 2d Ed. W.H. Freeman and Company, New York, p. 157. Printed/Posted with permission.

Interestingly, in the absence of human-caused climate change or major unexpected biophysical events, the Earth might enter another ice age within the next several thousand years based on its orbital patterns (Hays et al. 1976) though a reliable forecast isn't possible. With the Earth entering a period when solar radiation varies little and given that greenhouse gases are expected to rise at least for a century, the Earth more likely will remain in a prolonged interglacial cycle that could last as long as 50,000 years (Archer 2009).

7.3 Temperature and Precipitation Record

Sources of Temperature Data – Current and Historical

How do we know past and current global mean air temperatures? Calculating a global mean air temperature requires a network of measurement sites that are broadly distributed across the Earth and that include the oceans (71% of the Earth's surface). Scientists calculate a global mean air temperature from air temperatures collected at weather stations and from ships; they also make use of sea surface temperature measurements collected via ship and from fixed buoys and free-floating sensors (e.g., see description of the Argo project at www.argo.ucsd.edu/). Interpolation (area-averaging) is required to calculate temperatures in areas of the globe without temperature measurements by using data from the nearest surrounding temperature points. Current spatial coverage of the globe is quite good though there are still regions with inadequate coverage e.g., the Southern Ocean south of 45^{o} (Burroughs 2007; National Research Council 2006). Though not directly measuring surface air temperatures, satellites have detected the Earth's outgoing thermal radiation from different layers of the troposphere since 1978 and have allowed for calculation of troposphere and ocean temperatures. Current global mean surface temperatures are routinely calculated and reported by NASA, the Hadley Centre in the UK; the University of Alabama in Huntsville (UAH), USA; and Remote Sensing Systems (RSS), a private American company largely supported with NASA funding. NASA and the Hadley Centre use surface air and surface ocean temperature measurements, and the UAH and RSS utilize thermal data for the troposphere collected via satellites (Yale Forum on Climate Change & the Media www.yaleclimatemediaforum.org). Global temperature data are reported by these four groups, the World Meteorological Organization, and the Intergovernmental Panel on Climate Change.

Determining the Earth's less recent global mean air temperatures is certainly more problematic. Although the instrumental record from direct thermometer measurements extends back 250–300 years in some locations (Europe and eastern North America), there have been measurements from sufficiently representative points around the global to calculate global air temperature only since the latter part of the 19th Century (Burroughs 2007; Le Treut et al. 2007; National Research Council 2006). Interestingly one of the first scientists to calculate mean air temperature for a large portion of the globe was the Russian-born German scientist Wladimir Köppen, the same scientist who developed the widely used climate classification scheme described above (Figure 1); in an examination of the effects of sunspots on weather Köppen used data from 100 weather stations to report a near-global value for the tropics plus temperate zone in 1881 (Köppen 1881; Le Treut et al. 2007). Calibration problems (e.g., non-standardized protocols and use of new thermometers), relocations of weather stations, and uneven distributions of instrumental networks are among the challenges to using air temperatures from long-term historical records. Several scientific efforts have addressed these issues and have reported standardized synoptic (i.e., monthly, seasonal, annual) temperature databases. They include the World Weather Records (WWR) initiative,[1] the World Monthly Surface Station Climatology dataset of the U.S. National Center for Atmospheric Research,[2] and the Global Historical Climatology Network database[3] (Peterson and Vose 1997).

Historical temperature records for the Arctic are moderately good for the early part of the 20th century onward but are poor for earlier years. There are only four Arctic stations with a temperature series longer than 20 years prior to 1920; only six records from Arctic sites extend back to the latter half of the 19th Century and those are restricted to Greenland (5 sites) and Russia (1 site) (Przybylak et al. 2009). From 1900-1920 the only operative Arctic stations collecting air temperature data regularly were at Nome and Barrow, Alaska; Green Harbour in Spitzbergen, Norway; and Björnöya Island, Norway (Przybylak et al. 2009). Air temperature was measured at a few sites (e.g., Tornio, Finland and Arkhangelsk, Russia) in the early 18th and 19th Centuries, but the records are non-continuous and relatively brief (McBean et al. 2005). Other Russian data for the 19th century are known to exist but are not publically available. A consistent problem with Arctic temperature data is the absence of long-term measurements for large areas of land and ocean. Systematic measurements of the air temperature in northern Canada, for example, were not established until the 1940s (McBean et al. 2005).

[1] http://gcmd.nasa.gov/records/GCMD_gov.noaa.ncdc.C00160.html

[2] http://gcmd.nasa.gov/records/GCMD_NCAR_DS570.0.html

[3] www.ncdc.noaa.gov/oa/climate/ghcn-monthly/index.php

Prior to the instrumental record and in the absence of historical records, scientists relay upon a variety of **proxy** (indirect) **data** to infer past climate conditions. Proxy data include tree rings, evidence of plant species (e.g., pollen and plant debris in peat and lake sediments); isotope data from glacial ice cores, corals, and fossil plankton in marine sediments; and temperatures from boreholes (holes drilled in the Earth's surface that are used to measure rock temperatures by depth). Meteorological parameters are determined from relationships obtained when both proxy and meteorological data are known and from retrospective climate models. Scientists rely heavily on replication, multi-proxy measures, and cross verification to provide greater confidence in paleoclimate reconstructions (Jansen et al. 2007)

Sources of Precipitation Data

Precipitation on land has been measured for as long as temperature at most sites, but the quality and representativeness of the data are much more limited. The quality is lower because measurement approaches and instruments have been less standardized (e.g., snowfall data for some locations are particularly suspect) and because precipitation is much more variable in space and time. That variability prevents determination of long-term trends for larger spatial scales. Another reality is that there are no long-term precipitation measurements for the oceans, which represent 71% of the Earth's surface; precipitation measurements prior to 1970 were restricted to land (Burroughs 2007). Proxy data (e.g., tree rings) have been used to determine drought events but do not provide information on long-term trends in the annual amount of precipitation at a large scale. Estimates of global precipitation (including oceans) have a considerable degree of uncertainty. A surprising fact is that we don't know with sufficient accuracy or confidence the rate of annual global precipitation. Most recently satellites have begun to provide information on global scale precipitation though there are challenges with converting satellite measurements into surface precipitation rates.

7.4 Global Temperature Records

Past 1 Million Years

Over the past 1 million years the Earth, largely determined by the Milankovitch Cycles, has experienced eight periods of cooling (ice ages) and warming (interglacial periods) with global mean temperatures excursions (increases or decreases) of roughly 2–6^{o}C or 4–11^{o}F (Figure 8).

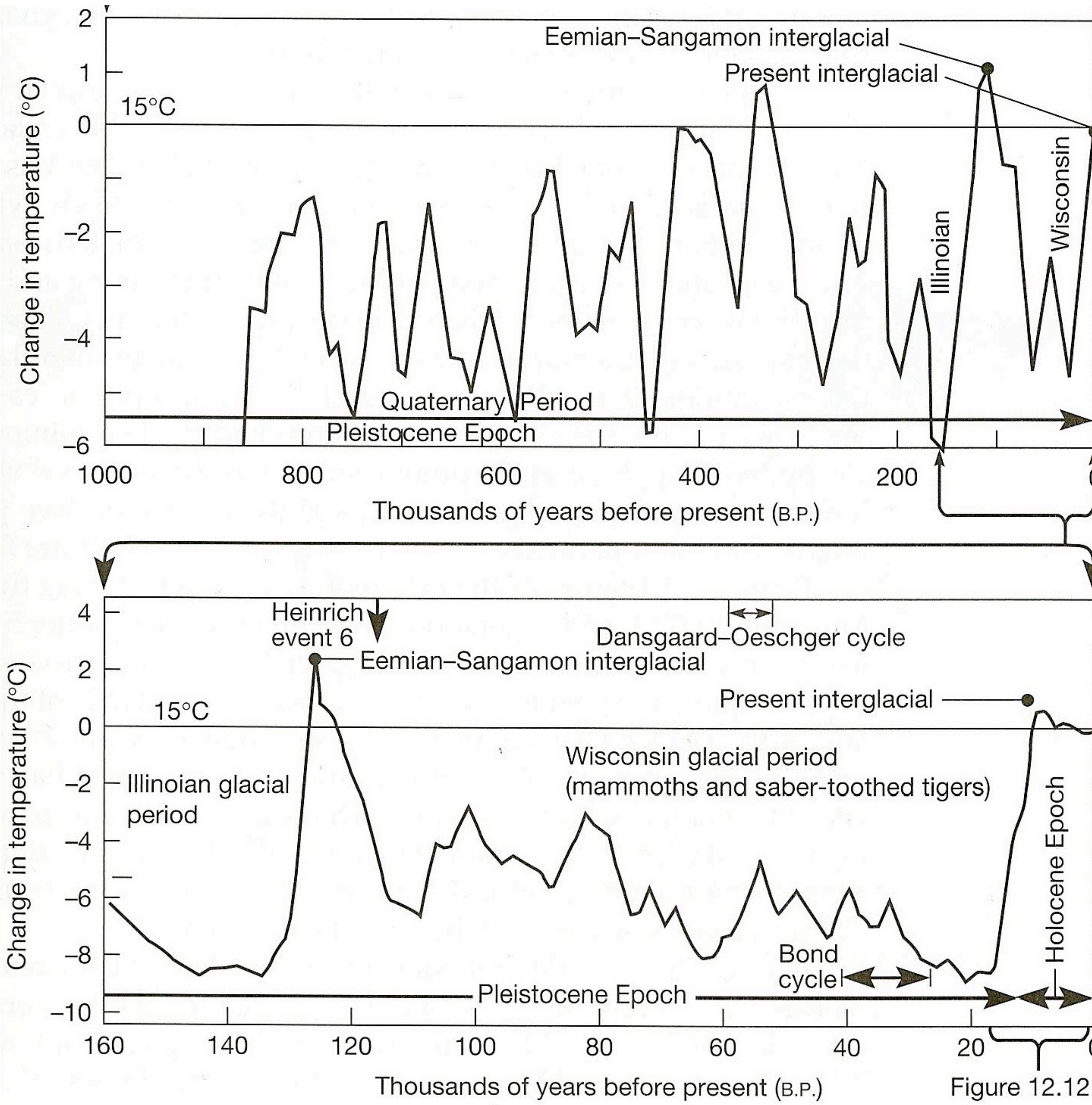

Figure 8: Change in global mean air temperature (relative to a base temperature of 15°C) over the past 1 million years and the past 160,000 years relative to global mean air temperature

Source: MacKenzie, F.T. *Our Changing Planet : An Introduction to Earth System Science and Global Environmental Change,* 3rd Ed. © 2003, p. 399. Reprinted by permission of Pearson Education, Inc., Upper Saddle River, NJ.

During each ice age much of northern Europe and northern North America were covered with glacial ice sheets (Figure 9), and sea levels were lowered by up to several hundred meters (Kearney 2000). Over the past 1 million years global temperatures at times have been higher but predominantly much lower than the current global temperature, which was 14.4°C (57.9°F) in 2008 (National Climatic Data Center, 2009). For example, during the previous interglacial period roughly 125,000 years ago global temperatures were higher than current temperatures. In fact the fossil record shows that the climate in England was sufficiently warm that hippos swam in the Thames River and lions and elephants occupied the land around what is now the city of Cornwall (MacKenzie 2003). Conversely, 18,000 years ago a layer of ice roughly 1 km thick covered what is now Boston, Massachusetts, USA; and North American camels, saber-toothed tigers, and wooly mammoths (all now extinct) roamed the land south of the ice sheets. Keep in mind that modern humans, based on the fossil record, did not emerge in Africa until 154,000–160,000 years ago (White et al. 2003, cited by Burroughs 2005). During most of our history (most of it during the Stone Age) modern humans lived mainly in Africa and other subtropical areas but occupied a world in an ice age.

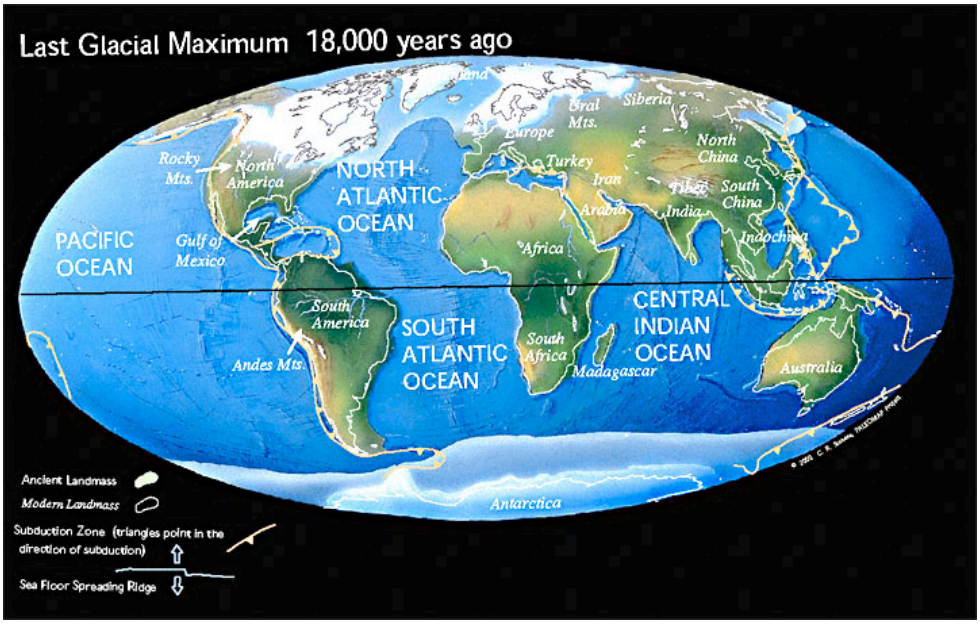

Figure 9: Maximum extent of glacial ice sheets during the most recent ice age (Pleistocene), which ended roughly 10,000 years ago. Ice sheets at both poles expanded during the ice ages and retreated during the interglacial periods.

Source: Plate tectonic maps and Continental drift animations by C. R. Scotese, PALEOMAP Project (www.scotese.com) Posted with permission.

Past 1000-2000 Years

There is considerable debate about temperature reconstructions that extend back more than 1,000 years. Given that the instrumental record is poor and restricted to just a few regions before 1850, climate scientists rely on various proxy data, statistical analyses, and climate models. Because scientists use different proxy data, different statistical relationships, and different models, reconstructions vary from one another (National Research Council 2006). A good example is the compilation of temperature reconstructions for the Northern Hemisphere (Figure 10). However, the bulk of the evidence from prior reconstructions suggests that temperatures at the end of the 20th Century were higher than those for the past 400 years and likely for the past 1300 years (Jansen et al. 2007).

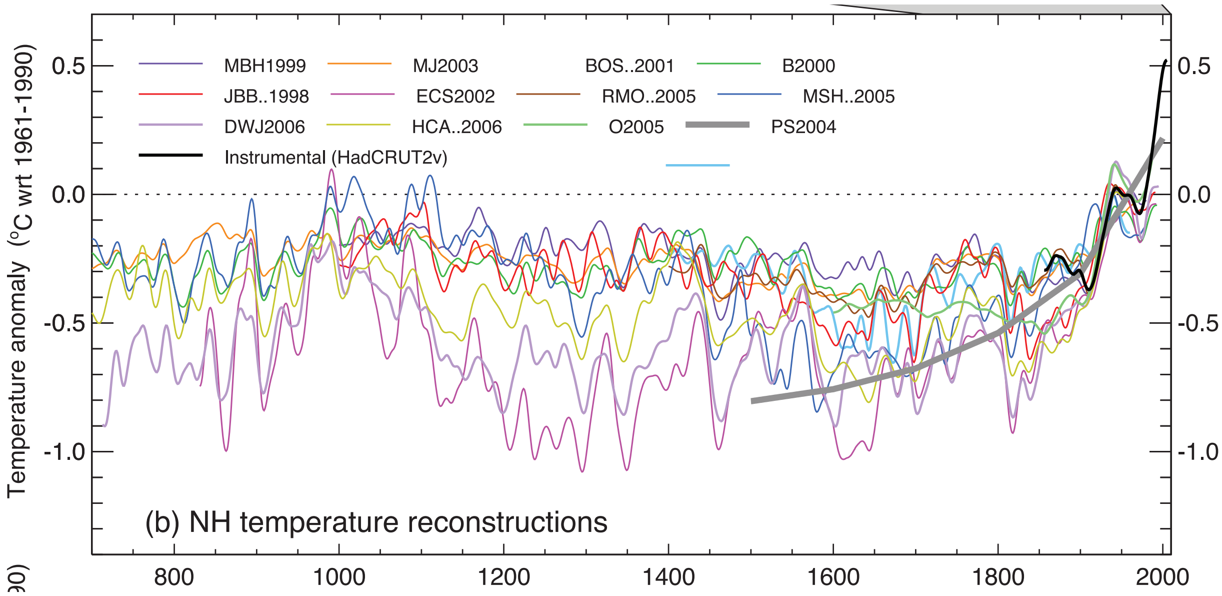

Figure 10: Reconstructions of Northern Hemisphere temperatures using multiple proxy records. Each line represents a forecast from a different scientific group and model. Values are the temperature difference (anomaly) from the mean temperature during the reference period 1961–1990.

Source: Jansen, E., Overpeck, J., Briffa, K.R., Duplessy, J.C., Joss, F., Masson-Delmotte, V., Olago, D., Otto-Bliesner, B., Peltier, W.R., Rahmstorf, S., Ramesh, R., Raynaud, D., Rink, D., Solomina, O., Villalba, R., Zhang, D. (2007). "Paleoclimate." In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change.* Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M., and Miller, H.L. (eds.) Cambridge University Press, United Kingdom, p. 467.

Past 150 Years

Global temperature has risen appreciably from the late 19th century to present, with considerable fluctuations, a rapid rise from about 1920 to 1940 followed by a decline, and a second rapid rise from 1980 to the early part of the 21st century (Figure 11). Over the past 100 years global air temperature has risen by 0.74°C (IPCC 2007), with most (~0.6°C) of the increase during 1975–2000 (Hansen et al. 2006). Fourteen of the 15 years during 1995–2009 (1996 being the exception) rank among the 14 warmest years in the instrumental record since 1850. 2005 was the warmest year on record; 2009 was the second warmest globally and the warmest in the southern hemisphere (NASA, www.nasa.gov/topics/earth/features/temp-analysis-2009.html). 2008 (though still one of the 10 warmest years on record) was the coolest since 2000, in part because of the strong La Niña (cooling of eastern Pacific) that developed in late 2007 (Peterson and Baringer 2009). Air temperatures have warmed roughly twice as fast over land as over water. Sea surface temperatures have increased less than marine air temperatures (due to the smaller temperature response of water to heat inputs); since 1961 the oceans have absorbed roughly 80% of the heat added to the climate system (IPCC 2007). In August 2009 the world's ocean surface temperature was the warmest for any August in the historical record, which dates back to 1880 (NOAA 2009). The world's oceans will act as an energy reservoir that will release additional heat to the Earth's surface air for millennia.

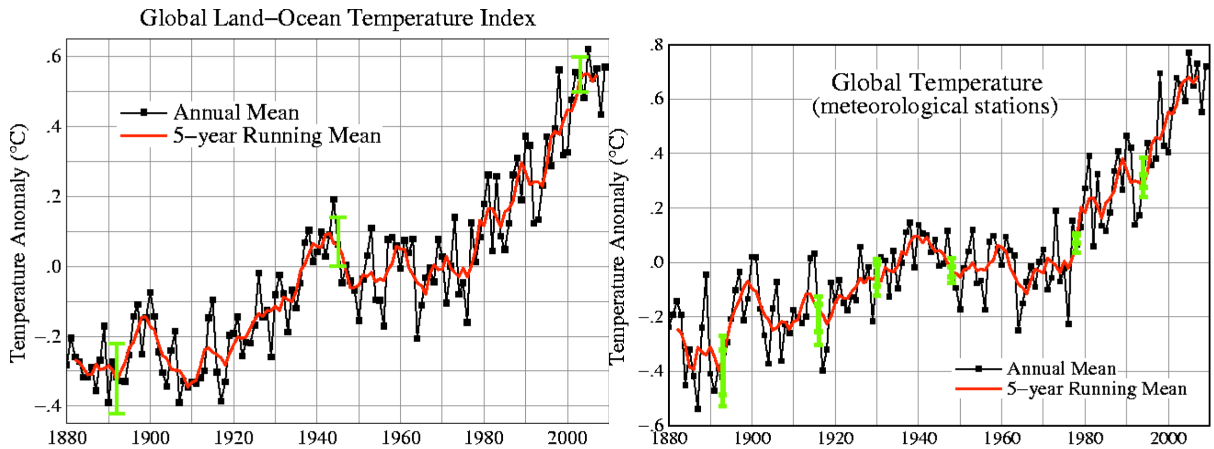

Figure 11: Anomalies (differences) 1880–2009 relative to 1951–1980 for (a) surface air temperatures from meteorological stations and sea surface temperatures from ships and satellites and (b) surface air temperatures from meteorological stations only.

Source: Goddard Institute for Space Studies, NASA. http://data.giss.nasa.gov/gistemp/graphs Open Source.

A map of temperature changes over the past century and a few decades (Figures 12 and 13) shows warming across most of the planet but with some differences in time and space. For the 1901–2005 period warming is greatest in western Canada, Alaska, and central Eurasia and in some places exceeded 2^{o}C. During the same period the area southeast of Greenland cooled; this most likely does not represent the natural variability of climate but rather a reduction in the North Atlantic circulation (Archer and Rahmstorf 2010). The amount of warming has been more spatially uniform during the more recent decades. Interestingly, temperature changes differ more across the planet when examined by season. In the Arctic, for example, a small area in eastern Siberia had unusually cooler temperatures from December to February during 1979 – 2005, whereas the same period in Western Europe and North America was markedly warmer (Trenberth et al. 2007, Figure 3.9).

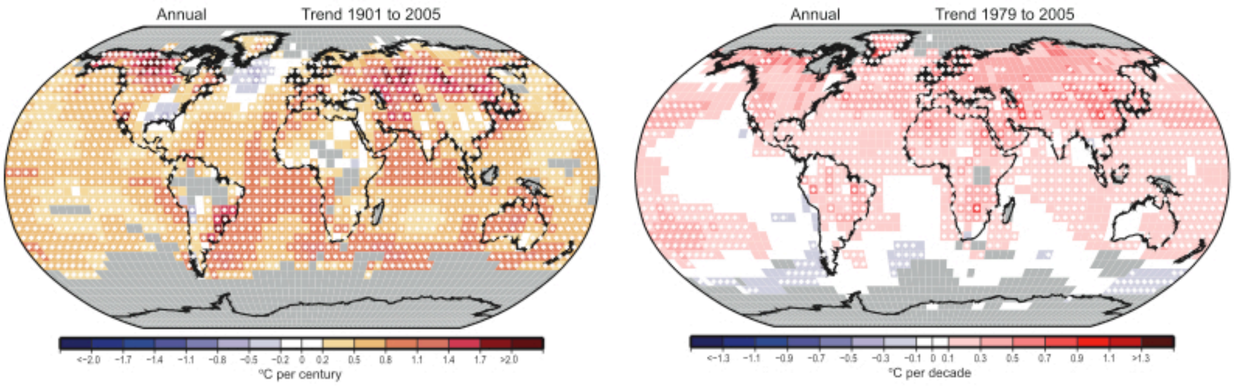

Figure 12: Temperature changes 1901–2005 (left, °C per century) and 1979–2005 (right, °C per decade). Linear trends are shown for each time period. Areas with insufficient data to determine a reliable tend (Arctic Ocean, the Barents Sea, the Southern Ocean, and Antarctica) are depicted in gray.

Source: IPCC. (2007). Trenberth, K.E., P.D. Jones, P. Ambenje, R. Bojariu, D. Easterling, A. Klein Tank, D. Parker, F. Rahimzadeh, J.A. Renwick, M. Rusticucci, B. Soden and P. Zhai, 2007: Observations: Surface and Atmospheric Climate Change. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 250. www.ipcc.ch Open Source.

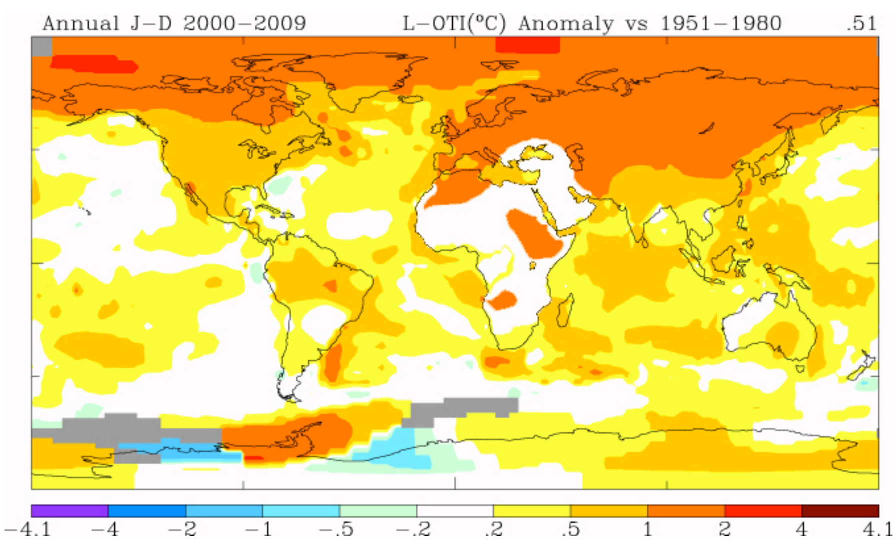

Figure 13: 10-year mean temperature anomaly 2000–2009 relative to 1951–1980 mean temperature.

Source: NASA, **www.nasa.gov/topics/earth/features/temp-analysis-2009.html** Open Source.

A potential controversy is that the rise in global temperature has slowed over the past decade, though temperatures remain elevated (Figure 14) (Knight et al. 2009; Kerr 2009a); in fact, if temperatures are corrected for the effects of El Niño (warming) and La Niña (cooling), the trend from 1999-2008 shows little change (positive or negative) in global temperature. Should this raise significant doubts about forecasts for continued temperature rise during the 21st Century? No. The error associated with any trend increases over shorter time intervals because of random jitters in temperature (Archer and Rahmstorf 2010). Near-zero temperature trends for 10 or more years are not unusual in climate models because of natural variability in ocean-surface air heat fluxes, atmospheric water vapor concentrations, solar radiation, and other factors. Keep in mind that the oceans are the largest sink for heat; a small change in heat gained or released by the oceans can have a large effect on global surface temperature. Although the warming of surface air appears to have paused, temperatures remain elevated. The decade 2000-2009 ranked as the warmest decade on record (NASA, 2010), and climate models continue to forecast an average temperature rise of 2^{o}C in the 21st Century (Kerr 2009a).

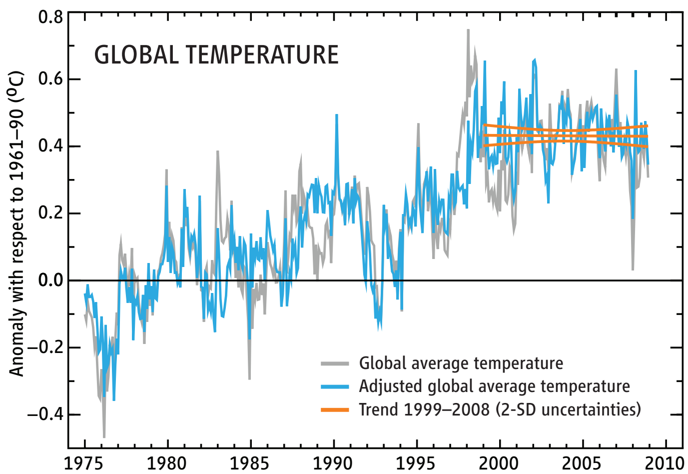

Figure 14: Global mean air temperature (grey line) including temperature adjusted for the effects of El Niño (warming) and La Niña (cooling) cycles (blue line). Graph from Kerr 2009a is adapted from Knight et al. 2009.

Source: Kerr, R.A. (2009a). "What happened to global warming? Scientists say just wait a bit." *Science 326*: 29. www.sciencemag.org

7.5 Arctic Temperatures

Paleoclimate and the Past 100 Years

There are few long-term climate reconstructions for the Arctic because proxy data are lacking. A recent exception (Kaufman et al. 2009) is the reconstruction of Arctic summer temperatures based on a synthesis of proxy records (lake sediments, tree rings, ice cores) for locations north of 60^{o}N latitude, together with modeling simulations. Kaufmann and colleagues reported a cooling across the Arctic for roughly 2000 years (likely caused by orbital cycles) that was reversed in the 20th Century. They found that four of the five warmest decades over the past 2000 years in the Arctic were between 1950 and 2000.

Arctic surface air temperatures have warmed at roughly twice the global rate from the late 19th Century to the 21st century and from the 1960s to present in recent decades; they also are characterized by multi-decadal variations (Polyakov et al. 2002) and high spatial variability (Trenberth et al. 2007; McBean et al. 2005; and Anisimov et al. 2007). During the 20th century annual temperatures from 60° to 90°N latitude increased from 1900 to about 1940 (reaching levels near those today), declined till about 1970, and have risen continuously since (Figure 15) (McBean et al. 2005). From 1970 to present the Arctic north of 60°N has warmed by 1–2°C, with strongest warming in the winter and spring and least warming in the autumn (Anisimov et al. 2007). Precipitation in the Arctic has generally increased during the past few decades with most of the increase in the winter (Hinzman et al. 2005; Kattsov and Walsh 2000). At the regional level temperatures in the Arctic are strongly influenced by atmospheric oscillations (Pacific Decadal Oscillation, PDO; North Atlantic Oscillation, NAO; and the Arctic Oscillation, AO).

Amplification of Arctic Temperatures

There is considerable debate about the causes of what appears to be amplification of warming in the Arctic (Serreze and Francis 2006). There are several reasons to expect Arctic temperature amplification: (1) decreasing sea ice cover reduces surface albedo (reflectivity) and increases heat absorption (2) the loss of ice cover allows for greater heat exchange from water to the atmosphere, (3) the troposphere (the layer of the atmosphere next to the Earth's surface) is thinner in the Arctic (and more temperature responsive) than the troposphere at lower latitudes, and (4) the warming of lower latitudes enhances the poleward flux of heat to the Arctic (ACIA 2004; Langen and Alexeev 2007). Many models that forecast Arctic temperatures take these factors into consideration. In addition atmospheric oscillations strongly contribute to warming and cooling.

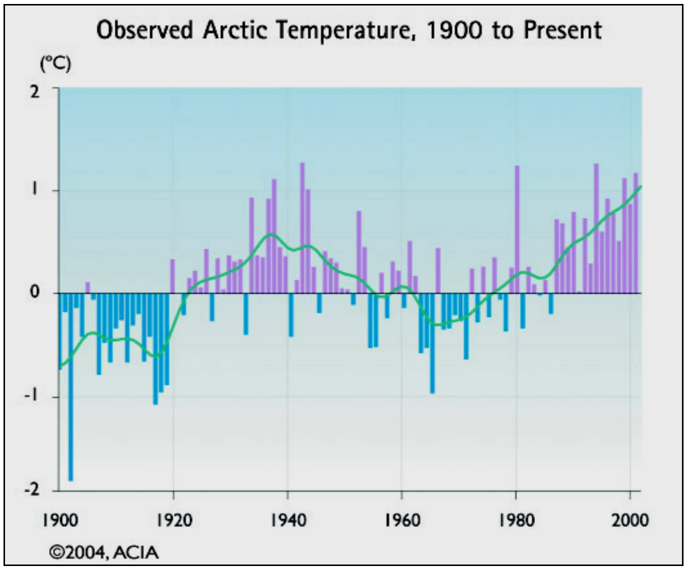

Figure 15: Annual anomalies of land-surface air temperatures in the Arctic (60^{o}N to 90^{o}N) from 1900-2003 relative to the mean temperature during the base period 1961–1990.

Source: McBean, G., Alekseev, G., Chen, D., Førland, E., Fyfe, J., Groisman, P.Y., King, R., Melling, H., Vose, R., and Whitfield, P.H. 2005. In: *Arctic Climate Impact Assessment*. Cambridge University Press, New York, NY, USA, p. 35. Posted with permission of the Copyright Clearance Centre for use in this course only. Resale or further copying or transmission of this material is strictly prohibited.

Global and Arctic Precipitation Records

During the period 1900–2005 global land precipitation showed no significant trend though there were discernible differences by latitude (Trenberth et al. 2007) and considerable spatial patchiness (Archer and Rahmstorf 2010). Precipitation generally increased over land north of 30^{o}N with decreases in the tropics since the 1970s. Though there are exceptions, precipitation in the Arctic generally increased (mostly in winter as snow) during the past century (McBean et al. 2005) with a continuing upward trend over the most recent decades (Hinzman et al. 2005; Kattsov and Walsh 2000).

(End Part I)