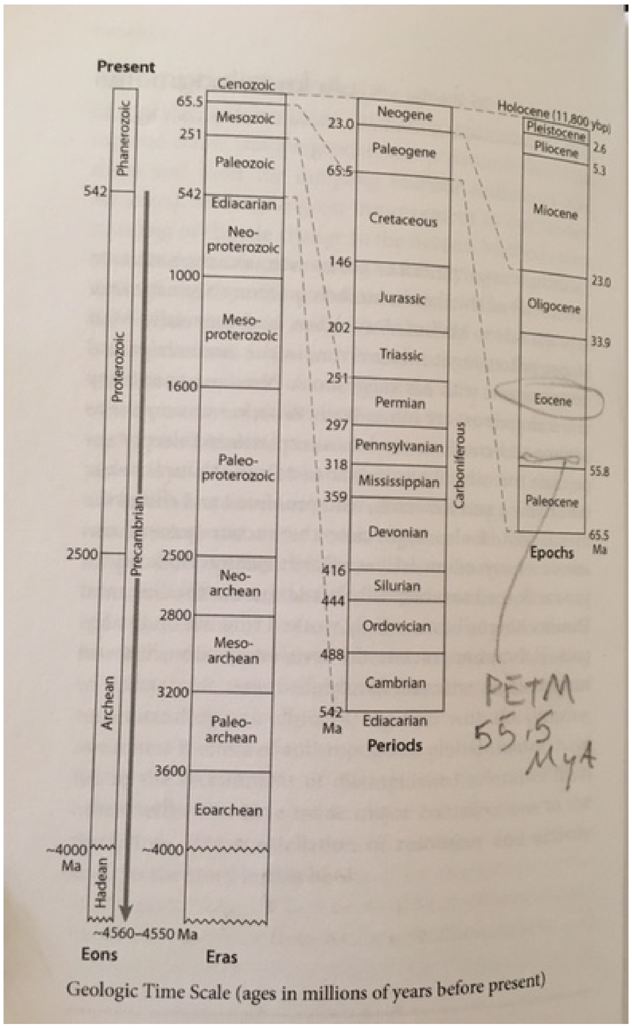
PALEOCLIMATE by Michael Bender (2013)

NOTES

GEOLOGIC TIME



Geologic Time Scale (ages in millions of years before present)

CHAPTER 1 EARTH'S CLIMATE SYSTEM

Page 1. Earth's climate system includes all the realms of the planet that interact to produce the seasonal march of temperature, wind, and precipitation. Most important are the atmosphere; the oceans, including their linked chemical and biological processes; and the solid Earth insofar as it influences CO2 concentration in air. Atmospheric processes govern climate over time scales of a few years or less. The oceans influence climate change over periods of decades to tens of millennia. Over periods of a hundred thousand years or more, interactions between the solid Earth and the surface environment fix the CO2 concentrations of air and Earth's average temperature.

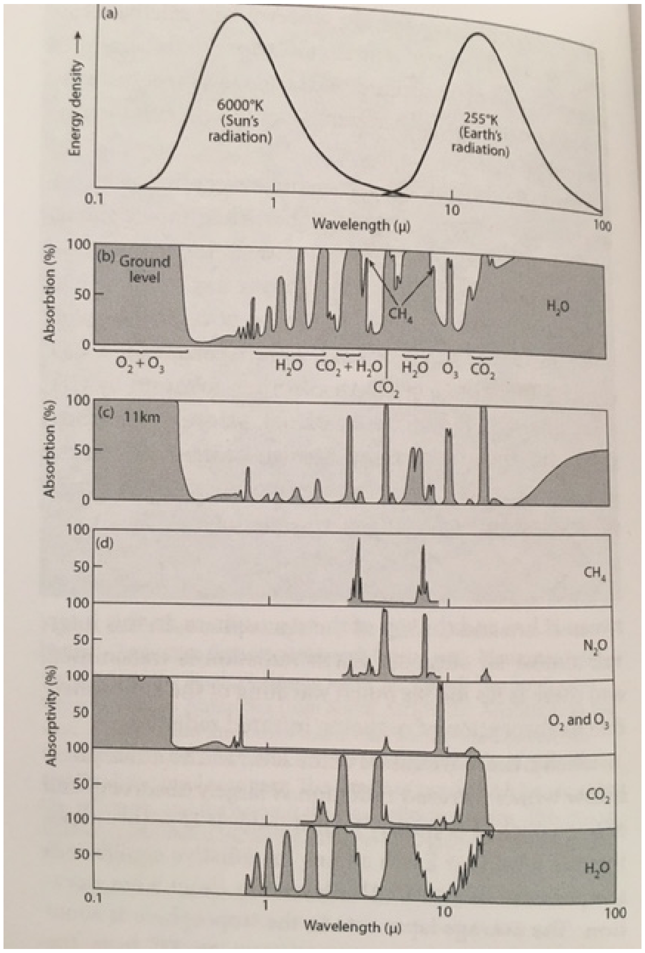
Page 2. ATMOSPHERIC PROPERTIES AND CLIMATE

Pressure and Temperature as a function of altitude.

Earth is heated by sunlight predominantly at ground level, which in turn warms the lower atmosphere (troposphere). Temperatures are cold at higher altitudes because of the decrease of pressure with elevation. This decrease with temperature reverses at an altitude of about 11 km (where the troposphere ends and the stratosphere begins), caused by the absorption of high energy (UV) light from the sun due to reactions of the ozone cycle, where O2 and O3 absorbs UV and warms the surrounding air.

Solar heating and radiative equilibrium.

Page 4. Average insolation is 342 W per sm, and most sunlight is in the visible range of the electromagnetic spectrum. Earth's average albedo (reflectance) is 0.31 caused mostly by clouds, snow, ice and deserts. Radiation from Earth is in the lower energy infrared region. Most solar radiation passes through the atmosphere while most Earth radiation is absorbed as it passes through the atmosphere; which warms the air.



Page 7. The "ideal" radiative equilibrium temperature is -19C (-2F) which is achieved at elevation 5 km, which equates to a sea level temperature of 14C (57F), which is the global average.

Page 8. See figure. Panel (a) indicates energy density of sun and Earth as a function of wavelength. Panels (b), (c) and (d) show the fate of radiation as it passes through the atmosphere, where gray indicates that it is absorbed by interactions with molecules of the gases in the air. Panel (b) shows absorption from ground to top of atmosphere, Panel (c) shows the fraction of radiation absorbed between 11 km and the top of atmosphere. Panel (d) illustrates the absorption of radiation by different gases between the surface and top of the atmosphere. It illuminates the role of ozone as the UV shield, and that most absorption of infrared is due to water, followed by CO2, methane, and nitrous oxide.

Page 10. ATMOSPHERIC CIRCULATION.

Sunlight warms the Earth's surface which in turn warms the atmosphere. Air rising at the equator flows to a latitude of about 30 degrees, sinks to ground level, and flows back to the equator ("Hadley cells"). In "Polar cells" air rises at 60 degrees latitude, flows toward higher latitudes, sinks at the poles, and closes the loop by equatorial flow at the surface. Because of the "Coriolis force" winds are westerly in the upper, poleward flow of the Hadley cell. In the middle latitudes (30-60 degrees) the circulation is more chaotic, dominated by large air masses rotating counterclockwise in the Northern hemisphere and clockwise in the Southern. Heat is transferred from the tropics to the poles.

Page 14. THE OCEANS

Ocean Circulation

Like the atmosphere, the oceans are dynamic, although it mixes on much longer times scales (about one millennial vs one year). Three factors cause the ocean to mix. First, waters that are more dense than their surroundings tend to sink, and more buoyant waters will rise. Second, winds transfer momentum to the sea surface, inducing lateral flow and in some cases vertical motions. Third, ocean tides and currents induce vertical mixing of waters in the ocean interior, especially over mountainous areas of the sea floor.

Page 18. Ocean Biogeochemistry

The interaction between ocean chemistry and biology reflects five generalizations. First, all photosynthesis takes place in the sunlit upper ~100 meter layer of the oceans. Second, almost all metabolism in the oceans is by prokaryotes (primitive single celled organisms) and single celled eukaryotes (genetic material is DNA). Third, most organic matter is heavier than water and tends to sink. Fourth, almost all organic matter is eventually respired or remineralized rather than preserved in deep-sea sediments. Fifth, ocean currents transport dissolved chemicals in the direction of flow, while turbulence mixes waters with higher and lower concentrations.

In the upper ocean, single-celled plants assimilate carbon, nitrogen, phosphorous, trace metals to make tissue. Most tissue is rapidly remineralized by respiration with the consumption of O_2 and the release of dissolved inorganic carbon (DIC), nutrients and metals. A fraction survives to sink toward the sea-floor, and even this component is mostly remineralized as it sinks. The process depletes shallow waters and enriches subsurface waters. If the oceans were stagnant nutrients would be completely drained from the sunlit zone and life on the surface would cease, but upwelling and mixing return nutrients to the surface.

Page 20. Dissolved inorganic carbon (DIC) is used in the biological activity to some degree, and has important consequences for atmospheric CO_2. The partial pressure of CO_2 (pCO_2) in surface seawater sets the concentration of CO_2 in the atmosphere. The interplay of three processes can cause changes in the pCO_2 in the sea and the air over timescales of 100's to 10's of thousands of years. First is biological utilization of DIC which lowers pCO_2, second is production of skeletal calcium carbonate which raises pCO_2, third is riverine input of HCO_3 and the burial of skeletal calcium carbonate in deep-sea sediments. These processes play the fundamental role in glacial-interglacial CO_2 variations.

P21. REGULATION OF ATMOSPHERIC CO2 AND EARTH'S TEMPERATURE OVER MILLIONS OF YEARS

There is a fairly simple hypothesis for the regulating of Earth's average temperature. It invokes our understanding that volcanism, and other degassing processes associated with Earth's hot interior, steadily add CO_2 to the atmosphere. At the same time, weathering removes CO_2 to balance this input. Weathering is the attack of carbonic acid on rock-forming minerals of the solid Earth. In this process, rock-forming minerals are degraded to clay minerals, and CO_2 is converted to HCO_3^-. The dissolved carbon-containing products go into groundwater and eventually to the oceans.

If Earth's climate is stable, CO_2 input to the atmosphere by volcanism must be nearly in balance with CO_2 removal by weathering. A simple feedback maintains this balance. If CO_2 input is faster than consumption by weathering, the CO_2 concentration of air rises, and temperature warms. Under these conditions weathering will accelerate, mainly because chemical reactions accelerate as temperature rises. If volcanic input slows, CO_2 will fall, temperatures will cool, weathering will slow, and CO_2 input and output will once again come into balance.

IMPLICATIONS FOR PALEOCLIMATE

In summary, there are three reasons the Earth's average temperature might vary. First, the sun might have been shining more or less brightly in the past. Second, the concentration of GHGs might have been higher or lower. Third, Earth's albedo may have changed.

P24 CHAPTER 2 THE FAINT YOUNG SUN

Early in Earth's history, the sun's energy output was 30% less than at present, and Earth's surface should have been frozen over, but it wasn't.

P25 THE FAINT YOUNG SUN PROBLEM

The solar system accreted (over a period of 20-100 million years) by the gravitational collapse of a mass of dust and gas in our region of space, starting around 4.6 billion years ago. Earth was heavily bombarded by large bodies until about 3.9 billion years ago. There is evidence of water as far back as 4.3 billion years ago, and evidence of photosynthesis at 3.8 billion years ago. And evidence of glaciers at 2.8 billion years ago. Thus, it would appear that a climate similar to today's, or warmer, was common even when Earth was young, and the sun shone 30% less than now.

P35 KEEPING EARTH WARM DESPITE A DARKER SUN

The overall consensus is that young Earth's albedo was lower (no plants) and methane concentrations were highly elevated, resulting in a non-frozen planet that had oceans.

P38 CHAPTER 3 PRECAMBRIAN (prior to 542 million years ago) GLACIATIONS

Ice sheets were mostly absent, though glaciations did occur, including 4 "snowball Earth" glaciations where glaciations extended to the tropics.

P43 CAUSES OF SNOWBALL GLACIATIONS AND DEGLACIATIONS

P45 Earth would tend to stay in a snowball condition due to high albedo. Volcanos would, however, continue to emit CO_2 to the oceans and atmosphere, raise CO_2 levels, causing melting, causing lower albedo, more warming on and on. In snowball events, much of the oceans were ice covered, deglaciation was rapid, and there were large changes in the global carbon cycles.

P46 ENTERING INTO SNOWBALL GLACIATIONS

Basically, GHGs were drastically reduced, but why? One mechanism is that photosynthesis produced oxygen, which combined with GHGs and reduced their concentration in the atmosphere. Another mechanism is the extent and location of continents. There were times when the continents were massed in the tropics and weathering was rapid enough to drawdown CO_2 concentrations quickly. Another mechanism could have been extra-terrestrial in which the Earth passed through a giant molecular cloud.

P54 CHAPTER 5 REGULATION OF THE EARTH SYSTEM AND GLOBAL TEMPERATURE

Since land plants evolved 400 million years ago and Earth then became biogeochemically modern, atmospheric CO_2 concentrations have varied by perhaps a factor of 10 or so. Concentrations fell to about 180 ppm during recent ice ages, and most indicators are that they did not exceed 1500 ppm during the last 400 million years (though some research suggests 3000 ppm as the maximum). <u>Modeling studies suggest that temperatures rise by about 2.5C for every doubling of CO_2.</u> Interestingly though, CO_2 concentrations and global temperatures variability has not been as extreme in the last 543 million years, as they were prior to that. <u>What mechanisms limit the magnitude of the CO_2 variations and keep the system in check?</u>

During the Phanerozoic Eon (the last 543 million years) plants and animals were mostly present, atmospheric O_2 was at around the present level, and Earth was in many ways geochemically modern.

P55 BACKGROUND

CO_2 concentrations in the air are very small, but they can't be easily changed because atmospheric CO_2 is in equilibrium with the oceans which have a much larger buffering reservoir. Changes in ocean circulation and the ocean carbon cycle will induce changes in atmospheric CO_2 by transferring this gas between the atmosphere and the very large deep ocean reservoir. The timescale for these changes is several ocean mixing times, or thousands of years. Also relevant is the land biosphere which contains carbon in plants and soil, but that mechanism is not nearly as large as the atmospheric CO_2 changes induced by the oceans.

Glacial/interglacial CO_2 changes have been mostly modest in magnitude during the Phanerozoic (between 180 and 300 ppm, which would lead to a deglacial warming of about 2C). Processes that can lead to higher CO_2 ppm involve the carbon cycle: CO_2 is continually being added to the oceans and atmosphere by degassing from Earth's interior mainly through volcanism and metamorphism of carbonic ocean sediments.

When transferred to the atmosphere, CO_2 does not accumulate, it is continuously consumed to weather crystalline rocks at the surface.

The time required for volcanism to replace all the CO_2 in the surface reservoirs (atmosphere, ocean, biosphere) is hundreds of thousands to millions of years. Over this time period the atmospheric CO_2 level is stabilized and regulated by a simple feedback mechanism: atmospheric CO_2 adjusts to the level where the temperature is such that weathering removes CO_2 as fast as it is supplied by volcanism.

P62 Prior to the evolution of land plants at about 400Mya, the atmospheric CO_2 concentrations and temperatures were higher than after, because plants were not there to facilitate weathering. (CO_2 concentrations and temperatures are generally lower since the evolution of land plants.)

P67 CARBON DIOXIDE CHANGES IN THE CONTEXT OF LARGE-SCALE CHANGES IN THE EARTH SYSTEM DURING THE PHANEROZOIC (LAST 542 MILLION YEARS)

The oscillation between "aragonite seas" and "calcite seas" form the context in which to place specific climate changes. Calcite seas correspond to warm climate, high atmospheric CO_2, low sea water Mg/Ca, precipitation of $CaCO_3$ cements, and high sea levels. Aragonite seas correspond to a cool climate and glaciation, low CO_2, high Mg/Ca, precipitation of aragonite cements, and low sea levels. <u>We are currently in a strong aragonite seas cycle based on the Mg/Ca ratio</u>.

P97 CHAPTER 6 EQUABLE CLIMATES OF THE MESOZOIC AND PALEOGENE

Earth was substantially unglaciated from 260Ma to 34Ma, the tropics were somewhat warmer than today and the higher latitudes were far warmer. These very warm conditions are referred to as "equable climates" (equable climates are periods of roughly equal temperatures throughout the world). A more detailed description focuses on the equator to pole temperature difference (EPTD) and the seasonality in the high-latitudes, or regions that are above 60°N or below 60°S. The striking differences between equable and modern climates are accompanied by evidence that changing GHGs may not explain the dramatic warming of the high latitudes with respect to the tropics.

P98 OCEAN TEMPERATURES DURING THE TIME OF EQUABLE CLIMATES

P104 The deep ocean was about 10C warmer than today, and the ocean and atmosphere has steadily cooled since 52Ma. Temps in the tropical North Atlantic were around 30C (86F) at around 90-100 Ma. Temps at Tanzania high latitude (55 S) were ~32C. Even the Antarctic Peninsula registered 10-20C as measured in wood structure and fossil trees. Stunningly, lizards, turtles and alligators lived 33-54 Ma west of Northern Greenland (78 degrees N)!

P107 LAND TEMPERATURES DURING THE CRETACEOUS AND PALEOGENE (23-146 Ma)

As indicated by land flora and fauna, the midlatitude and temperate regions were much warmer. Forests were present on the North Slope of Alaska. Dinosaurs lived in the Arctic and Antarctic. Crocodiles were present in the US mountain states up to 55 degrees N (as opposed to 35 N today). Patagonia was ~4C warmer than today.

P110 DYNAMICS OF EQUABLE CLIMATES

One can account for the global warming by invoking some combination of higher GHG concentrations and lower albedo. Three ideas are advanced: More heat was transported from the tropics toward the poles. Second, increased vegetation lowered the albedo of high latitude continents. Third, wintertime clouds at high latitudes may have exerted strong GHG warming.

During the Eocene (34-56 Ma) the Earth was ~5C warmer in the tropics and 30C warmer at high-latitude locations; the global average temp was ~7-14 C warmer than today. CO2 levels were 3-6x higher than today. There was additional warming because the albedo was lower; Earth was ice-free and deserts largely replaced by forests.

Cyclones in the tropics would have been greater due to higher temps, and would have caused deep ocean mixing, with warmer waters transported to higher latitudes.

P117 WAS EARTH EVER GLACIATED DURING THE PERIOD OF EQUABLE CLIMATES?

Probably not; evidence is lacking.

P125 THE PALEOCENE-EOCENE THERMAL MAXIMUM (PETM) (starting around 55 Ma)

The PETM lasted about 200k yr. During the event a massive amount of CO2 was rapidly released to the oceans and atmosphere (origins are unclear). The consequences were predictable and dramatic. Global temps rose ~6C, the oceans became acidified (resulting in extinctions of many deep water calcareous organisms), caustic seawater dissolved CaCO3 shells that normally accumulate on the seafloor. On land, warming led to changes in the distribution of precipitation, an increase of weathering rates, and changes in flora and fauna.

The magnitude of the CO2 release is estimated to be between 2000 and 6000 Giga tons, which is comparable to the anthropogenic CO2 release if we burn all available coal, oil, and natural gas. PETM response involved neutralization of CO2 by CaCO3 sediments, changes in the hydrological cycle, and the responses of land and ocean ecosystems to climate change, all of which are of interest in the context of anthropogenic global change. As a remarkable event in nature that is also something of an analog for the impending high-CO_2 world, the PETM has sparked great interest.

P127 THE PETM EVENT; TIMING, DURATION, AND MAGNITUDE OF THE TEMPERATURE CHANGE

The onset was very abrupt, estimated at 10,000 years (or less). The temperature rise was ~5C in the tropics and ~ 8C at high latitudes. Warming in the deep sea was ~5C. The duration of the PETM (~200k years) was determined by the time required for weathering to take up the huge CO_2 pulse.

P131 THE MAGNITUDE OF CO2 INJECTION AND GLOBAL WARMING

The initial CO_2 ppm was ~1000-1700 which is why the estimated CO_2 injection varies between 3000 and 6000 Gt. (each doubling of CO_2 ppm results in 2.5C warming).

P134 OCEAN ACIDIFICATION AND CACO3 ACCUMULATION IN SEDIMENTS

A complex relationship exists between CO_2 in the atmosphere and the magnitude of sequestration in ocean sediments.

P137 POSSIBLE SOURCES OF CARBON DIOXIDE OR METHANE

Four possibilities have been given for the source of the PETM CO_2 pulse. 1. A warming of unknown cause initiated the release of CH_4 hydrates from deep-sea sediments. These hydrates are formed when large quantities of CH_4 are produced from the decomposition of organic matter in the mud. It is estimated that the modern CH_4 reservoir (8,000 – 15,000 Gt of C) is larger than the PETM reservoir. 2. The CO_2 came from oxidation of organic carbon in sediments of shallow water seas that dried up at the onset of PETM. The sea floor may have uplifted in areas of low rainfall and the carbon converted to CO_2 through respiration or fires. 3. An intriguing coincidence of a massive carbon release, and massive volcanism in the North Atlantic associated with continental drift. 4. The CO_2 was derived from the decay of organic matter in permafrost, which contains high levels of organic carbon derived from organic matter in the "active layer" (the layer that defrosts in the summertime). Warming leads to deepening of the active layer. Slow warming would have warmed large regions of permafrost, then when Earth's orbit favored warm summers, significant areas of permafrost would melt and release large amounts of CO_2. This release would lead to more warming, further releases of CO_2, etc.

P140 The PETM was not unique. There are two events around 2Myr after the PETM that are similar but smaller in magnitude.

P144 CHAPTER 8 THE LONG COOLING OF THE CENOZOIC (65.5 Ma ago to present)

The dominant feature of this recent climate record is the long cooling (though punctuated by dramatic stepwise changes), starting 50Ma that led to the ice age cycles and to our current place in an interglacial period. The story begins with a largely ice-free Earth. The long cooling was accompanied by a series of climate and biotic events that came to shape many features of the modern world. 1. Major coolings at 34 Ma and 14 Ma, 2. The glaciation of Antarctica at 34 Ma and 14 Ma, 3. The origin of the monsoons, 4. The development of C4 grasses around 10Ma.

P146 THE COOLING AT THE EOCENE-OLIGOCENE BOUNDARY (34 MA)

P149 The growth of ice sheets in Antarctica and the cooling of the oceans (at least at high latitudes) were accompanied by major changes in continental temperatures, and cool ecosystems representing open forest and grassland gradually replaced denser, warmer temperature forests. The change in flora drove a change in the mammalian fauna so extensive that it has been named the "Mongolian Remodeling" in Asia and the "Grande Coupure" in France (extinctions). The temperature decreased 5-8C.

P150 Smaller animals became more important and larger animals declined. Milankovitch cycles pervade the climate record.

P151/2 THE MIDDLE MIOCENE COOLING 13.8 MA

This was a major cooling that marks a point of no return, leading to further cooling and eventual intense glaciations. Milankovitch cycles (100kyr, 41ky, 21ky) were strong forcings [see Box 4 p155]

P154 CAUSES OF OLIGOCENE (34Ma-23Ma) AND MIOCENE (23Ma-5.3 Ma) COOLINGS

Falling CO_2 is an obvious culprit, leading to cooling and ice growth.

P161 CHANGING CLIMATES AND THE RISE OF C4 GRASSES DURING THE CENOZOIC (65.5 Ma to present)

The distribution of vegetation on the planet 65.6Ma differed from modern Earth in three ways. 1. High-latitude areas that are currently covered by ice sheets or tundra were then forested, reflecting equable climates. 2. Some arid regions where deserts prevail today were then also forested, reflecting a wetter planet. 3. The vegetation fixed CO_2 into organic carbon by what is known as the C3 pathway, whereas today about 75% of photosynthesis is by the C3 pathway (trees accompanied by browsers) and 25% is by the C4 pathway (grasses accompanied by grazers). These changes in vegetation are in turn linked to a profound change in the nature of animals, with which plants evolved. The development of seasonally arid climates resulted in forests thinning out and grasslands becoming more common.

P163 Photorespiration is more rapid at higher temperatures and lower CO_2 concentrations. Falling CO_2 therefore favors C4 plants (grasses). On the other hand, cooling temperatures and wet climates favor C3 (trees). [what about higher CO_2 (favors trees) and warmer temperatures (favors grasses) – is this a negative feedback loop]?

In Asia, Africa, and the Americas abundant data show that there was a shift from C3 to C4 starting at 8-9 Ma and completed over the next few million years. Many browsers and fruit-eating animals died out across the transition.

P165 The cause(s) of the transition from C3 to C4 are controversial. Photosynthesis in C4 grasses is an adaptation that evolved independently – beginning as early as 34 Ma. C4 plants may have expanded because of increasingly arid conditions and/or because they developed modes of resistance to grazers.

P165 ORIGIN OF THE INDIAN AND EAST ASIAN MONSOONS

Strong summer monsoons derive from heating over land during the summer months. The oceans warm also, but less so, because vertical mixing distributes the heat increase. Heating over land leads to rising air, which in turn leads to precipitation. Uplift also sucks in wet air from the adjacent ocean, maintaining the moisture supply. Airflow is reversed in winter, with air sinking over land. The land is arid, and becomes a source of dusts.

The climates of India and East Asia are strongly influenced by monsoons. These events have an ancient origin, extending back to at least 34Ma. The nature of precipitation since that time has been strongly affected by the uplift of the Himalayas and the formation of the Tibetan Plateau.

Thus by 5.3 Ma Earth had been transformed from a wetter planet with equable climates throughout, including extensive forests and moderate climates at high latitudes, to a cooler, drier planet with a massive permanent ice sheet on the Antarctic continent. Large continental landmasses were covered by desert or grasslands, and recently evolved C4 plants dominated the landscape in warmer areas. Fauna coevolved with flora, leading to the extinction of many browsers and the appearance of diverse assemblages of grazing animals. The Himalayas had resin, deserts covered much of central Asia, and highly seasonal monsoonal climates were in place in India and East Asia. These aggregate changes set the stage for increasingly intense cyclic glaciations on the Northern Hemisphere continents, the hallmark of recent climates.

P172 THE ORIGIN OF NORTHERN HEMISPHERE GLACIATION AND THE PLEISTOCENE ICE AGES (past 2.6 million years)

The ice ages of the past 2.6 million years are among the most compelling events in the history of Earth's climate. These were periods in which Earth was remarkably transformed. During the peaks of the ice ages, glaciers covered the northern part of Eurasia and the northern and central parts of North America. In the Eastern United States, their southern extent reached almost to central New Jersey. Away from the ice, most continental areas were significantly colder and much drier, and the vegetation was correspondingly impoverished. The oceans cooled as well, wintertime sea ice extended further equatorward, and there were important changes in patterns of ocean circulation. Two key factors maintained these colder climates. 1. The ice sheets reflected more of the sun's heat back to space, and 2. Greenhouse gas concentrations were lower. These two factors provided each other positive feedbacks.

P173 The origin of the glacial climates extends back at least 34 Ma when a large ice sheet grew on Antarctica. At about 3 Ma Earth crossed a climate threshold as ice sheets began to grow and decay on the Northern Hemisphere continents. Climate has varied since that time in a manner forced by Milankovitch cycles. While climate has responded to orbital forcing during much or most of Earth history, the amplitude of the responses and the detail in which they are recorded are unique to this period. Over the past Ma and beyond, the warmest periods of each cycle have tended to be slightly cooler, the coldest times have become much colder, the amplitudes of the cycles have increased, and their period has switched from 41ky to about 100 ky. We are presently living in the warm phase of the current 100ky glacial cycle.

P173 EARTH'S SURFACE DURING THE LAST ICE AGE

Nine continental ice sheets formed the hallmark feature of the glacial Earth.

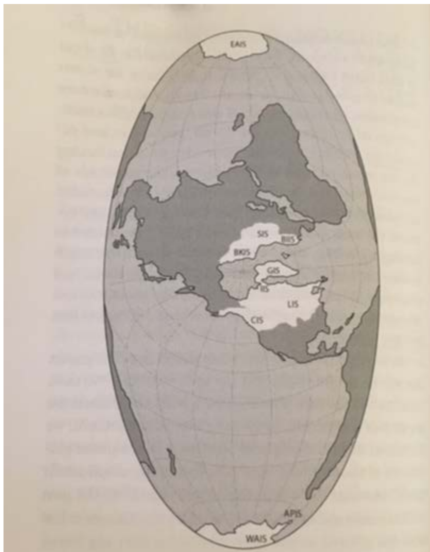


Fig. 9.1. Boundaries of the major ice sheets of the last glacial maximum, or LGM. EAIS, East Antarctic ice sheet; SIS, Scandinavian ice sheet; BIIS, British Isles ice sheet; BKIS, Barents-Kara ice sheet; GIS, Greenland ice sheet; ILS, Inuitian ice sheet; LIS, Laurentide ice sheet; CIS, Cordilleran ice sheet; APIS, Antarctic Peninsula ice sheet; WAIS, West Antarctic ice sheet. From Clark et al. (2009).

Boundaries of the major ice sheets of the last glacial maximum (LGM). In the tropics and mid-latitudes snowlines of mountain glaciers descended by about 1000 m, which corresponds to a cooling of about 6C or more. Antarctic sea ice extended 5-10 degrees north of where it is today.

P177 Almost the world over, vegetation was sparser; desert areas expanded, some forests were replaced by grasslands, closed forests replaced by open forests. These changes were due to three environmental shifts: cooler temperatures, lower precipitation, decreased CO_2 concentrations. Oddly, a southern movement of the jet stream resulted in a wetter Great Basin of the US.

P179 GLACIAL-INTERGLACIAL CHANGES IN ATMOSPHERIC GREENHOUSE GAS CONCENTRATIONS

According to ice core data, glacial CO_2 levels were significantly lower than preindustrial. Deglaciation is related with CO_2 levels moving from 80 ppm to 280 ppm; and CH_4 levels changed from 350 ppb to 700 ppb. These relate to a global temperature increase of about 2C.

P182 The ice core CO_2 records relate to the long-term feedbacks in which Earth's temperature adjust to the level where CO_2 uptake by weathering balances the input to the oceans and atmosphere from outgassing. These processes fixed the average atmospheric CO_2 concentration at about 230 ppm over the past 800kyr.

P184 Over shorter timescales CO_2 will vary as it is transferred between Earth's mobile reservoirs (air, ocean, and plants/soils). Of all the CO_2 in the Earth's mobile reservoirs, 1-2% is in the atmosphere, 5% in plants and soils, and ~94% in the oceans; so atmospheric variations depend primarily on changes in the oceans. There are six factors that contribute to the glacial-interglacial difference in atmospheric CO_2: 1. Ocean temperature. The lower temps of the ice age oceans caused an increase in the solubility of CO_2 in sea water and contributed to <u>lowering</u> the CO_2 ppm in the air. 2. Ocean Salinity. Ocean salinity increased during the ice ages as water was removed from the oceans to make ice sheets. With less water in the oceans the concentration of DIC rose, leading to an <u>increase</u> in atmospheric CO_2 ppm. 3. Mass of carbon in the land biosphere and soil carbon reservoirs. During the ice ages, glaciers covered areas currently occupied by forests and taiga. The biomass carbon and soil carbon were oxidized to CO_2, raising the CO_2 inventory of the air and ocean, thus <u>increasing</u> the CO_2 concentration in the atmosphere. 4. Strength of the biological pump. The biological pump: the fixation of organic matter in the sunlit surface ocean, its sinking, and its oxidation at depth. This process does not change the total inventory of bioactive elements (C, N, P) in the oceans, but influences the distribution. It causes the concentrations of bioactive elements to be low in the surface ocean and high in the deep ocean, which lowers the partial pressure of CO_2 at the surface ocean. The stronger biological pump during the ice ages contributed to <u>decreasing</u> CO_2 in the glacial atmosphere. 5. Residence time of water in the deep ocean. Mixing was more sluggish in glacial times, contributing to more DIC sequestration in the deep sea. Thus, the surface water partial CO_2 and atmospheric CO_2 would <u>decrease</u>. 6. Changes in deep-sea calcium carbonate saturation. Ice age oceans were more acidic, which led to dissolution of $CACO_3$ in the form organic forms, which reacts with dissolved CO2. This decreases the CO2 concentration of surface waters.

P186 Of the 80 ppm CO2 difference between glacial and interglacial; factor 1 decreases 30 ppm, factor 2 adds 7-12 ppm, factor 3 adds 15-34 ppm which suggests that these three cancel each other out; leaving factors 4, 5, 6 (stronger biological pump, sluggish mixing, decreasing alkalinity) to account for the 80 ppm difference in atmospheric CO2.

P 189 WHY WAS EARTH COLDER DURING THE ICE AGES?

Earth's temperature is controlled by the radiative balance (Chapter 1). Our planet's orbit around the sun is changing continuously, and these changes influence times at which different latitudes receive their sunlight. However, the total amount of sunlight Earth receives in one trip around the sun is nearly constant. Instead, three other factors accounted for the cooling of the ice age Earth. 1. The presence of large ice sheets increased the planetary albedo, accounting for a cooling of about 3C. 2. The switch to less abundant vegetation also increased the planetary albedo (deserts reflect more than forests), contributing to a cooling of about 1C. 3. The lower concentration of greenhouse gases led to a further 2C cooling, for a total cooling of about 6C during the ice ages relative to interglacial times.

P190 EVOLUTION OF EARTH'S CLIMATE SYSTEM OVER THE PAST FIVE MILLION YEARS

At 5Ma Earth was about 3C warmer than today, the amplitude of glacial-interglacial cycles was modest, and the ice volume was about half that of today. Then, beginning at around 3.5 Ma the glacials became colder and the amplitudes increased, and large glaciers formed in the Northern Hemisphere. From 2.8 Ma to 1.0 Ma the large climate cycles were of about 40kyr duration ("the 40k world"). At 1 Ma there was a transition to 100kyr cycles with twice the amplitude of the 40kyr cycles. The termination of last glacial maximum (LGM) marks the beginning of the Holocene – a relatively long period of warm climate that hosted the evolution of civilization.

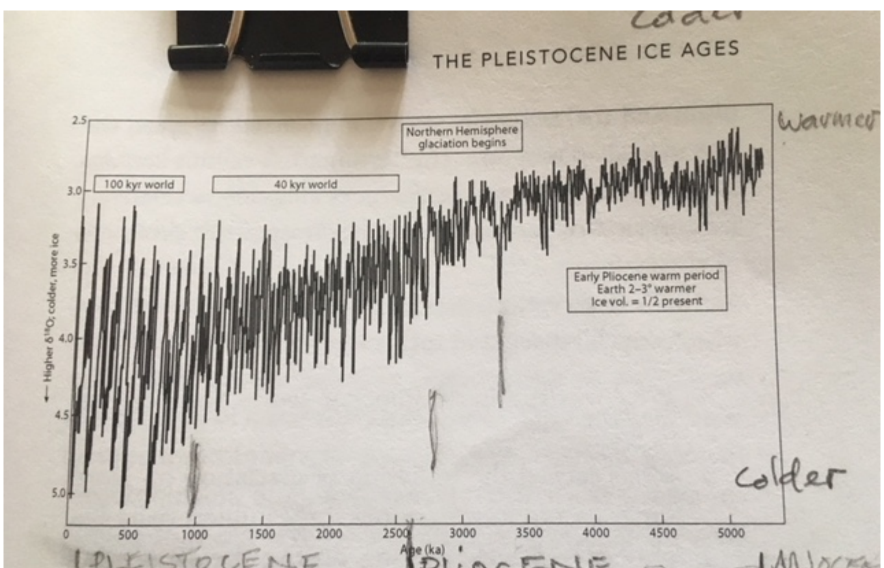


Fig. 9.3. The $\delta^{18}O$ of benthic Foraminifera versus time, 0–5.4 Ma. This curve was derived by "stacking," or averaging, records from 57 deep-sea sediment cores (Lisiecki and Raymo 2005).

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P192 The warmer world of the Early Pliocene (5.3Ma-2.6Ma)

Sea level was 15-35m higher than today. Ocean temps were 2-3C warmer, with North Atlantic temps 5C or more higher. Climates were warmer and wetter. Deserts smaller, more vegetation at higher latitudes.

P194 The atmospheric CO2 was higher (around 400 ppm) and the warmer polar regions resulted in warmer temperate and polar zones.

P197 Origin of Northern Hemisphere Glaciation

There are four groups of explanations: tectonic changes, the permanent El Nino ended, CO2 concentrations fell, hydrography of the North Pacific changed in a way that elevated snowfall rates of North America.

P201 The “40k World” 2.7-1Ma

P204 The Transition to the 100k World, ~1Ma

By 800kyr the dominant cycle is 100kyr.

P206 THE NATURE AND DYNAMICS OF THE 100KYR WORLD, 0.9 MA TO PRESENT

Sawtooth Climate Cycles.

P208 Ice sheets can melt a lot faster than they can grow. The present interglacial has maintained peak temperatures longer than most. The last interglacial (at about 125kyr) was considerably warmer than the present, and sea level was about 7m higher due to a further retreat of the ice sheets on Greenland and West Antarctica.

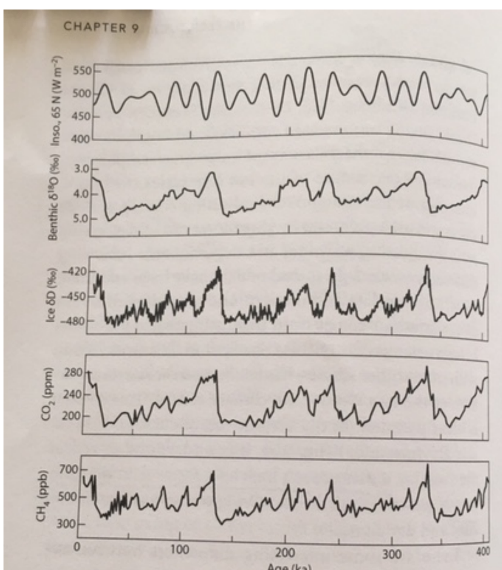

Fig. 9.4. Ice core and related records of climate change, 410 Ka to the present. *Top graph*, average June insolation at 65° N; *next*, the δ^{18}O of benthic Foraminifera according to the stack of Lisiecki and Raymo (2005); *next*, hydrogen isotopic temperature of ice, (trending warmer toward top of graph); *next*, CO_2; and *bottom*, CH_4; all plotted versus time. Lower benthic δ^{18}O values (upward on graph) imply warmer deep waters and less ice; and heavier δD values (upward on the graph) imply warmer East Antarctic temperatures.

Over the past 420kyr there have been four complete glacial-interglacial cycles.

P210 Greenhouse gas concentration changes during the ice ages

GHG concentration changes are closely aligned with changes in global glacial conditions. Concentrations are low during glacial, high during interglacials, and intermediate during periods of intermediate climate. Concentrations of CH4 is an important secondary greenhouse gas and actually track the 100kyr and 20-40kyr variability in temperature more faithfully than CO2. CH4 is produced by fermentation. Under natural conditions CH4 is mostly produced in continental bogs and swamps where oxygen cannot penetrate through the waterlogged soils. These conditions are more prominent in warm times than cold.

P210 Regional temperature histories recorded in the isotopic composition of ice from ice cores.

P212 The general pattern of ice age climate change suggests that Earth's climate generally drifts toward the glacial condition. Upon achieving it, however, some threshold is crossed and the conditions become unstable, leading to deglaciation.

P212 Ice age terminations

The greatest extent of the ice sheets during the last glacial maximum, based on both the distribution of glacial deposits and direct evidence for sea level lowering, lasted from ~ 26 to 19 ka. Lowest sea level coincided with maximum ice extent. There is a close connection between sea level and solar insolation. June insolation at 65 degrees N was a minimum at 23 Ka, when ice sheets were at or very close to their greatest extent. Melting began as insolation started to rise, was about halfway complete by the time insolation reached its maximum (~11.5 Ka), and continued into the early Holocene as summertime insolation slowly decreased. At the glacial maximum, sea level was about 125m below the modern level; it rose to within about 10m of the modern level by 8 Ka. The lag in sea level with respect to insolation reflects the response time of the ice sheets to changing insolation, greenhouse forcing, and other influences.

P214 Three important factors drove the transition from a glacial to interglacial climate. First, rising summertime insolation at 65 degrees N promoted melting of the ice sheets. Second, melting of the ice sheets lowered albedo, which introduced more warming, etc. Third, concentrations of CO_2 and CH_4 rose, promoting additional warming. Thus, a series of positive feedback loops sustained deglaciation until large ice sheets remained only on Greenland and Antarctica. At that point, a stable climate was reached that has now lasted about 7Kyr.

P214 The warming was a complex event punctuated by acceleration, stasis or even climate reversals. East Antarctica began warming at about 17.5 Ka and Greenland about 3 Kyr later. The dramatic Greenland warming at 14.6 Ka was followed by the climate deterioration of the Younger Dryas, a cold period from 12.8 Ka to 11.6 Ka. The Younger Dryas was followed by another episode of rapid warming.

P215 Meanwhile, warming with deglaciation in Antarctica was, to some extent, opposite to that of Greenland; East Antarctica warmed precisely during those intervals when Greenland was cold. These episodes represent deglaciation punctuated by rapid climate change events, in which sudden variations in ocean circulation influenced regional climates in different ways. (See next chapter).

Higher CH_4 concentrations indicate warmer and wetter climates in the Northern Hemisphere. Methane rose during the early stages of deglaciation and jumped when CO_2 concentrations and East Antarctic temperatures reached maxima.

P216 While glacial terminations differ in detail, they follow a basic sequence of events. They begin when summertime boreal insolation begins rising. Melting of ice sheets and warming of the deep ocean are roughly synchronous with the warming of Antarctica and the rise of atmospheric CO_2. Northern Hemisphere climates warm and become wetter toward the end of a glacial termination, when CO_2 has reached its maximum value. This suggests that the Southern Ocean plays a large role in the CO_2 rise during glaciation. The Greenland ice sheets can maintain cold climates in the north until they shrink below a threshold value. The Milankovitch forcing plays a big role in the pacing of glacial-interglacial change.

P216 Interglacial climates are impermanent. Eventually, orbital changes will induce cooling, and the opposite feedback loops will push the planet toward a glacial mode. Whether the Earth is heading toward warmer or cooler climates, the feedbacks run out of steam at some point, limiting the extremes to something like today's world on the warm end, or at the other end, the world of the last glacial maximum.

P217 ORBITALLY DRIVEN CLIMATE CHANGE INDEPENDENT OF THE ICE SHEETS

Superimposed on the 100kyr cycles are two other modes of climate change. The first consists of events lasting hundreds or thousands of years that are global in extent but are most strongly manifested in the North Atlantic region. These events involve very rapid climate change, are prominent during glacial times, but may also have muted expressions during interglacials. (See chapter 10)

The second climate mode is paced primarily by precession and occurs mainly on the lower latitudes. The most dramatic example of this mode is in hydrologic changes associated with the East Asian monsoon. The summer monsoon in East Asia is stronger when summertime insolation is more intense. First, more insolation means hotter continental temperatures during the summertime, leading to stronger monsoons. Second, more insolation means stronger steering of the Intertropical Convergence Zone (ITCZ) to the north during the boreal summer – leading to greater summer precipitation. (We are currently at a dip in the precession cycle Figure 9.6)

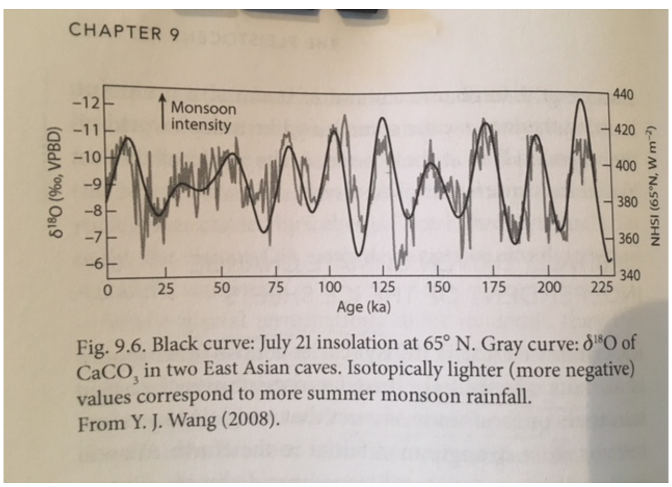

Fig. 9.6. Black curve: July 21 insolation at 65° N. Gray curve: $\delta^{18}O$ of $CaCO_3$ in two East Asian caves. Isotopically lighter (more negative) values correspond to more summer monsoon rainfall. From Y. J. Wang (2008).

WHAT DRIVES THE 100KYR ICE AGE CYCLES?

First, ice sheets respond to Milankovitch climate forcing. When summers are warm, ice sheets tend to retreat, and when cool, they tend to advance. Second, Earth's favored climate mode is toward the colder end of the spectrum. Earth has most often been in the cold mode. Third, ice volume has a high-volume threshold that, when crossed, leads to instability and rapid deglaciation. Fourth, changes in the physical climate system cause the atmospheric CO2 concentration to rise when Earth is warming and fall when Earth is cooling; forming a positive feedback that leads to the full amplitude of the glacial cycles.

P221 In glacial times, slower overturning of the Southern Ocean, greater windblown dust supply of fertilizing iron, cooler ocean temps, and deep-sea CACO3 compensation all tend to lower CO2. Higher ocean salinity and the retreat of the land biosphere during ice ages tend to increase CO2. The processes lowering CO_2 win, CO_2 is lower during ice ages, and there is a positive feedback involving increased ice volume, increased albedo, lower atmospheric CO_2, and colder climates.

The key event linking CO_2 to climate is the one that initiates changes in the rate at which waters of the ocean interior come to the surface in the Southern Ocean, thereby releasing to the atmosphere CO_2 that accumulated from the decay of singing organic matter. This rate seems to be affected by the status of deep water formation in the North Atlantic. During terminations, there may be intervals in which North Atlantic Deep Water does not form, because meltwater runoff lowers the salinity. At these times, Sothern Ocean mixing is enhanced; one possible mechanism is wind belts shifting south with westerly winds becoming stronger of the Southern Ocean. The higher flux of CO@-rich waters to the surface leads to the rise in atmospheric CO_2 that promotes deglaciation.

There seem to be two candidates influencing the ice volume threshold for deglaciation. First, growth of an ice sheet depresses the underlying basement rocks because the weight causes the underlying crust to flow laterally away from the ice. The margins of the ice sheet then tend to sink with respect to sea level, making it easier for the oceans to erode glaciers on the borders of the continents. Second, the bed of the glacier paradoxically warms as the thickness of ice increases; because the ice sheet has the effect of insulating the bed from cold air at the surface – geothermal heating can warm the bed and melt basal ice.

P223 This provides a simple, provisional model of the 100kyr cycle. An interglacial period will end, and ice sheets will start to grow, when a minimum in Northern Hemisphere summer insolation is sufficiently intense. Ice sheets will wax and wane in concert with summer insolation changes, but tend to get larger over time. At the same time, the atmospheric CO_2 concentration will fall as progressive Northern Hemisphere cooling causes increase stratification and slower upwelling in the Southern Ocean. Lower CO_2 further cools the planet and provides a positive feedback to the growth of ice sheets. Eventually ice volume crosses a threshold leading to instability. The next strong maximum in Northern Hemisphere summer insolation will lead to the melting of ice sheets and warming of the planet. Events associated with deglaciation can cause increased mixing of deep waters back to the surface of the Southern Ocean, leading to increased atmospheric CO_2 burdens, rapid deglaciation, and the return to interglacial conditions.

P235 CHAPTER 10 RAPID CLIMATE CHANGE DURING THE LAST GLACIAL PERIOD

The last ice age was marked by a series of climate cycles that, while most intense in the North Atlantic, had manifestations throughout the world. These events have been studied extensively; much is known about the sequence of events, but basic causes remain to be understood.

The aspects of the rapid climate change are illustrated in figure 10.1, which illustrates five different studies. The interval begins shortly after the start of the last ice age, and ends after Greenland warmed to its postglacial value (10ka when deglaciation was largely complete).

Remarkable statements can be made based on this plot. There were more than 12 times when Greenland temperature (NGRIP) warmed VERY rapidly – on the order of decades or less – followed by a slow cooling back to glacial temps, followed shortly by another warming. Each warm event had a counterpart in the Antarctic – however, Antarctica warmed first, then Greenland warmed very abruptly. Also, atmospheric CH_4 concentration rose each time Greenland warmed abruptly.

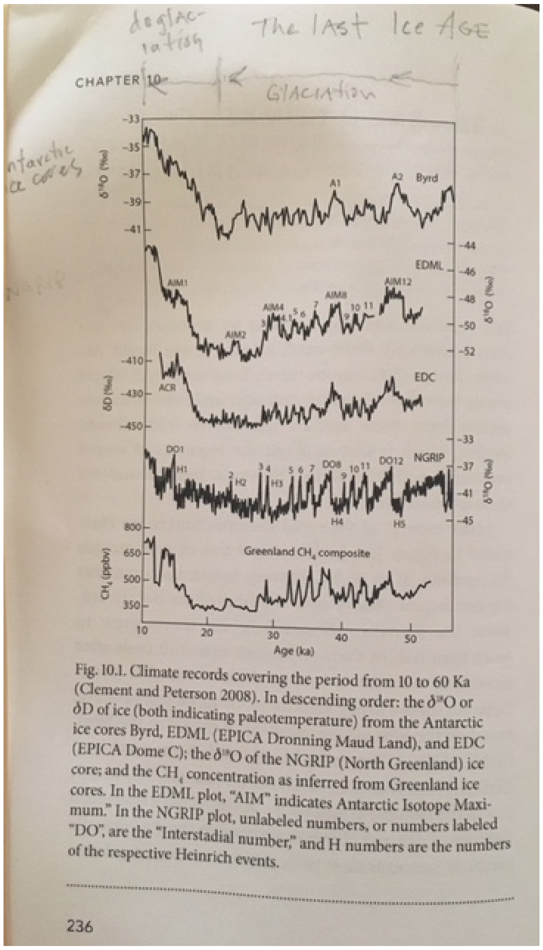

Fig. 10.1. Climate records covering the period from 10 to 60 Ka (Clement and Peterson 2008). In descending order: the $\delta^{18}O$ or δD of ice (both indicating paleotemperature) from the Antarctic ice cores Byrd, EDML (EPICA Dronning Maud Land), and EDC (EPICA Dome C); the $\delta^{18}O$ of the NGRIP (North Greenland) ice core; and the CH_4 concentration as inferred from Greenland ice cores. In the EDML plot, "AIM" indicates Antarctic Isotope Maximum." In the NGRIP plot, unlabeled numbers, or numbers labeled "DO", are the "Interstadial number," and H numbers are the numbers of the respective Heinrich events.

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From these observations we can draw a number conclusions. First, rapid climate change affected both polar regions. Second, rapid climate change events were fast, although more so in the north. Third, continental areas were affected because continental wetlands are the major source of atmospheric CH4; signifying that wetlands were more extensive and precipitation was greater when Greenland was warm. Finally, climate continually changed rapidly over most of the time between 10-60ka and beyond.

We can systematize the 10.1 information by invoking three tightly linked sets of occurrences. First, interstadial events are the warm events that repeately punctuate the ice core records (DO 1-12 in the NGRIP plot). In extrapolar regions during interstadial events, waters were warmer in the North Atlantic and Indian Oceans, East Asian Monsoons were stronger, ocean circulation of the coast of California was less vigorous, and precipitation was greater along the north coast of South America.

The second set of ocurrences is the Heinrich events. They are labeled H 1-5 on the NGRIP curve of 10.1. Heinrich events are periods of 1-2kyr during which Greenland climates were at their coldest levels, sea ice extent dramatically increased in the North Atlantic, and precipitation was elevated in the western United States and southern Brazil. Paradoxically, sea ice increased and sea level rose during Heinrich events as continental ice sheets melted. Massive icebergs were discharged; they carried glacial debris out to the middle of the Atlantic Ocean. Glacial runoff and melting icebergs lowered the salinity of the North Atlantic surface waters, leading to important changes in ocean circulation. Not all interstadial events were separated by Heinrich events – only the longest and coldest periods. Heinrich events were immediately followed by interstadials that were especially warm and long.

P239 Finally, the Antarctic Isotope Maxima (AIM 1-12) were warm periods in Antarctica that are clearly linked to both interstadial and Heinrich events. AIMs began during the cold periods in Greenland. Atmospheric CO2 rose by about 20 ppm during the long AIMs.

P240 CLIMATE CHANGES RECORDED IN THE GREENLAND ICE CORES

During the last ice age rapid climate changes began with warmings that were largely complete within a few decades. Temp changes were big; 20C between glacials and interglacials with rapid warming encompassing half this range. The cause of the rapid temp changes in Greenland seems to have been the extent of wintertime sea ice in the surrounding seas.

P241 The best studied warming occurred at 11.6ka; this warming ended a cold period in the northern Atlantic region (known as the Younger Dryas which had interrupted the overall warming associated with the last glacial termination). The warming reached its full maximum within a couple of decades. The warming was associated with an increase in snowfall. Greenland was 20C colder than present at the height of the last ice age, and warmed ~10C during this 11.6 ka event. How could Greenland get so cold at the LGM? It was surround by ice sheets in the North Atlantic and thus isolated.

P243 MILLENIAL CLIMATE CHANGE IN THE NORTH ATLANTIC DURING THE ICE AGES

Heinrich events mainly occurred when icebergs from the Hudson Straits drained out of the Laurentide Ice Sheet centered on Hudson's Bay, but also from other areas around the North Atlantic. Ocean salinity levels were lowered by 2-3 units out of 35, which is the average ocean value. This lowered the density of ocean waters, which had important consequences for ocean circulation and global climate.

P247 CLIMATE CHANGE IN THE TROPICS AND MIDLATITUDES

P249 Strong Asian monsoons are linked to warm interstatial events in Greenland. Precipitation was enhanced in the western US while Greenland was cold, the northern tropics were dry, and wetlands elsewhere were reduced. Precipitation in the northern tropical North Atlantic was elevated during interstadial events and suppressed during Heinrich events and other cold periods in Greenland.

P251 CLIMATE CHANGE IN ANTARCTICA

There are four salient features of the Antarctic ice core record during the last ice age. First, millenial-duration warm events in Antarctica cooccur with interstadial events in Greenland. Second, particularly long and warm AIMs coincide with Heinrich events and the long Greenland interstadials that follow. Third, AIMs begin before the rapid warming in Greenland. Fourth, CO_2 rise by about 20 ppm at the time of H3-6, and may have been associated wit increased winds over the Southern Ocean and more rapid mixing.

P252 CAUSES OF RAPID CLIMATE CHANGE EVENTS DURING THE ICE AGES

There are many competing ideas about the causes of rapid glacial climate change, but a leading therory is emerging: Heinrich events. Think of it as an analogy to a capacitor: ice or basal meltwater reservoirs fill, and then discharge. Most of this drained into the North Atlantic through Hudson's Straits.

Heinrich events end because, eventually, fresh meltwater is flushed out of the North Atlantic.

P256 It is unlikely that we would experience a Heinrich event in modern times because it is likely that massive ice sheets (more than presently exist) are required to produce that rapid change.

P257 WHAT CONTROLS THE TEMPO OF DANSCAARD-OESCHGER EVENTS?

Interstadial events occur with remarkable fidelity on a 1500 year beat, but the reasons are not understood.

P258 chapter summary.

P264 CHAPTER 11 THE HOLOCENE

The Holocene began 11,700 years ago, at the end of the Younger Dryas cold excursion. It extends to the present, although the era beginning around 1850, when man first undertook activities that would hav ea significant impact on gloal climate, is sometimes called the Anthropocene. Local and regional changes are extensively documented. There are two modes of climate change distinguished by their hemispheric or global imprint.

HOLOCENE CLIMATE CHANGE ASSOCIATED WITH PRECESSION

P265 The orientation of Earth's spin axis has changed over the past 10kyr so that northern summers now occur when Earth is farthest from the sun (a near minimum), whereas at 10ka they occurred when Earth was closest to the sun. This change has had two important effects on climate. First, Northen Hemisphere summers have grown cooler over time. Second, precipitation in the subtropics and tropics has changed progressively; monsoonal precipitation has grown weaker in the Northern Hemisphere, and the ITCZ with its belt of high rainfall, has moved progressively to the south. However, because a remnant of the Laurentide Ice Sheet survived until 7ka, its high elevation and albedo contributed to cooling of Western Europe such that the Holocene climate maximum occurs between 4-7 ka rather than earlier in that region.

P266 Summertime temperatures in northern latitudes at 10ka were higher in the ocean as well as on land. The boundary between forest and taiga was further north in the Northern Hemisphere during the mid-Holocene. Mean annual temps in northern Europe fell by about 2.5C after 6ka, with considerable warming in Europe from 6 to 8 ka, when temps stabilized.

P267 The ITCZ tends to follow the sun, since air will rise where the surface is heated the most, and it has moved southerly. Areas in the northern tropics that get their precipitation from the ITCZ have become drier, and the areas in the souther tropics have become wetter.

P268 The southern monsoons have become stronger. The summer monsoon develops as land is heated more in summertime than the adjacent ocean. Wet air from the ocean flows onto land where it rises, cools, and releases precipitation.

P270 North Africa is the site of a summer monsoon, which was much stronger between 14-5 ka when summer insolation was greater. North Africa had lakes grassland and trees where there are deserts today. Extremely arid central Niger had lakes, savanah, hippos and crocodiles at the beginning of the Holocene. Occupation was sparse by 4.5 ka and ended by 2.4 ka.

P271 Between 10k and 7.4 ka people were occupying all of northeast Africa west of the Nile.

Orbitally driven climate changes during the Holocene have had profound impact on human civilization.

MILLENIAL-DURATION RAPID CLIMATE CHANGE DURING THE HOLOCENE

These changes may be driven by variability in the brightness of the sun.

P275 Solar forcing may have contributed to the two major climate excursions of the last millenium, the Medieval Warm Period (1000 BP when global climate was somewhat warmer than the previous millenium) and the Little Ice Age (1300 to 1850 when global climate was somewhat cooler). Since 1850 Earth has been recovering from the Little Ice Age.

WAS SOLAR VARIABILITY AN IMPORTANT CAUSE OF HOLOCENE CLIMATE CHANGE?

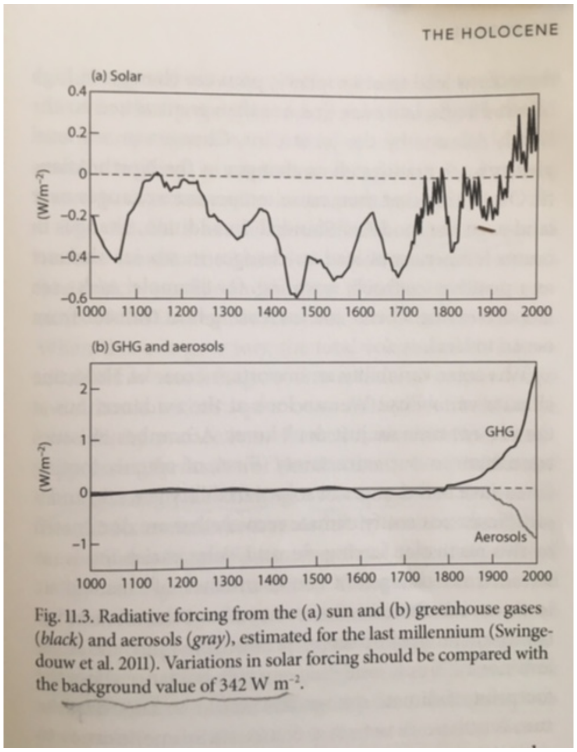

Fig. 11.3. Radiative forcing from the (a) sun and (b) greenhouse gases (*black*) and aerosols (*gray*), estimated for the last millennium (Swingedouw et al. 2011). Variations in solar forcing should be compared with the background value of 342 W m^{-2}.

P276 The great puzzle of solar forcing is how very small changes in solar output can lead to significant changes in climate. The total variation in solar output estimated for the past millenium is slightly less than 1 Watt per meter squared (WM2) out of 342 WM2 (0.3%). Such a small warming can lead to discernable climate change if climate feedbacks focus the warming in a small area of the planet.

To give some idea about why the North Atlantic regions responds so strongly: when solar luminosity increases, the tropospheric circulation comes to resemble that of the positive mode of the North Atlantic Oscillation. The positive mode is characterized in part by stronger westerly winds; in wintertime these winds transport heat from the warm ocean to the cold land, causing warmer continental winters.

In summary, the evidence for solar forcing over the last millenium is rather weak.

OTHER HOLOCENE CLIMATE EVENTS

P278 Many other noteworthy changes in climate ocurred during the Holocene, some having profound impacts on civilizations.

First, at 8.2ka there was a baby Heinrich event that was the last gasp of the dying glacial world. It originated with Lake Agassiz, a massive ice-dammed lake in Canada south of Hudson’s Bay, which was filled from the melting remnants of the Laurentide ice sheet. When this unstable ice dam gave way the total volume of the lake emptied into the Atlantic within a year or so. A low-salinity surface layer formed in the North Atlantic, suppressing formation of North Atlantic Deep Water, causing a regional cooling. Glaciers advanced in northen Europe, temps fell in ice-free areas to the south, areas affected by Asian monsoons became drier, and the ITCZ shifted to the south diminishing precipitation in the low latitudes of the Americas. North American land areas became colder and drier.

P280 Second, the Sahel (a region of North Africa) experienced a very dry period from 1960 to 1980 that led to serious famines. Drought has been connected to warm temps in the tropical Indian and Pacific oceans, which interfered with the summer monsoon.

P281 “Dust Bowl” is the period 1932 to 1938 when there was a widespread drought in the Great Plains region of the US, accompanied by intense dust storms. Low rainfall was due to a combination of cool sea surface temps of the equatorial Pacific, and warm temps in the equatorial Atlantic; which blocked wet Gulf air from passing onto North America. Low precipitation also led to dry soil and the absence of evaporation which could lead to more precipitation.

CHAPTER 12 ANTHROPOGENIC GLOBAL WARMING IN THE CONTEXT OF PALEOCLIMATE

Our current understanding is that, during almost all of Earth's history, interactions between Earth's interior, surface processes, and global climate feedbacks regulated atmospheric GHG concentrations so that temperatures were in the habitable range over most of the planet. Certainly this statement is true for the last 600 Myr, while Earth was inhabited by animals; uncertainty exists for most earlier times because we can't accurately characterize surface temps.

P289 Our ancestors gradually evolved in a world of changing climate. Humans split from apes at around 7 Ma. Over the following millions of years the bodies and brains of our ancestors became large and bipedality developed, with modern humans emerging around 200 Ka.

Climate change had a profound influence on human migrations. E.g. around 14 Ka the region of the Bering Straits became habitable enough that Asians could cross over into North America before sea level rose to cover the land bridge.

Humans (and all animals) evolved physically and culturally in a way that was influenced by climate. Our physiognomy must reflect the long climate deterioration and the evolutionary pressures of the large glacial-interglacial cycles.

Around 10 Ka our ancestors discovered farming, setting the stage for large communities, division of labor, tyranny and the development of powerful political entities. There seem to be two requirements for the development of agriculature. First, the necessary level of intelligence, which was probably anatomically possible at about 30 Ka. Second, was the rise of CO_2 to the preindustrial level, which occurred around 10 Ka. This change was probably essential for agriculture to be competitive with hunting and gathering.

Climate has shaped civilization in many ways. One obvious example is that fertile areas of the planet are more heavily populated than deserts and ice-covered regions. There are many more subtle examples.

P290 Civilization has developed to the point where humankind is now interacting with the cliate rather than merely responding. The primary way we are doing this is by adding CO_2, the leading agent for natural climate change over the past 100's of millions of years. We can assess the effects of this action using models that predict future climate, and by intelligently judging the implications of the paleoclimate record. Our best understanding is that fossil fuel emissions will lead to global warming, sea level rise, and large regional changes in rainfall during the coming centuries. With a high probability, we are already experiencding these effects in our climate. Already the planet has warmed by nearly 1C. Sea level is rising at the rate of about 30 cm/century, and this rate is likely to increase as the planet warms.

How should we view the prospect of anthropogenic climate change? From the perspective of paleoclimate, it might not be particularly troubling, or even seem unwelcome. The present world is good enough for human habitation. However, it would improve if Greenland and Antarctica were unglaciated and habitable, and if there was more rainfall in areas that are currently deserts. For humans, in other words, the world might be more habitable if conditions resembled the high CO_2 equable climates of the Cretaceous, Paleocene, and Eocene (146 – 34 Ma).

The problem of anthropogenic global change, then, is not necessarily that we are heading for a less habitable planet. The problem is that both natural ecosystems and civilizations are aligned to the historic pattern of climate and water resources. Global warming will destroy this alignment in some regions. The most obvious is sea level rise, which will render regions uninhabitable that are now occupied by tens or hundreds of millions of people. Shifting temperatures and rainfall belts will open some northern areas to agriculature while making agriculature impossible in some currently farmed regions. The disappearance of mountain glaciers will make water unavailabe for agriculture in the seasons it is needed, and will supply water at other times when it may not be used efficiently.

P292 The continued burning of fossil fuels will cause the atmospheric CO_2 concentration to rise. If we burn all readily available fossil fuels in the next few hundred years, we are likely to drive the atmospheric CO_2 concentration up to 1500 ppm or so, over five times the preindustrial level. This estimate takes into account that over hundreds of years, a large fraction of CO_2 is taken up rather quickly by the growth of forests and by dissolution in the oceans.

This high CO_2 level would be unsustainable [unstable]. The warm temperature and high CO_2 burden mean that once fossil fuels were exhausted, weathering would consume CO_2 faster than it is added by natural sources. The excess CO_2 would thus be slowly consumed and dissipated by weathering, exactly as for the PETM. CO_2 concentrations would fall, over a period of about 100,000 years, back toward their natural equilibrium level. With such a long horizon, two other factors would come into play. First, orbital change and the natural climate cycle would push Earth back toward a glacial mode at some point. Second, additional transformations of the environment by humans are likely. These transformations are likely to be severe but cannot now be predicted. As for the past 4.5 Gyr, Earth's climate in the near geologic future will be determined by changes in GHG, albedo, Milankovich forcing, and perhaps solar variability. However, we cannot now know the forcings that will dominate climate change hundreds of thousands of years or more in the future, and hence cannot judge how climate will respond. Stay tuned.