The so-called "Keeling Curve" is a plot of the atmospheric CO_2 concentration measured daily at the Mauna Loa Observatory on the island of Hawaii since 1958. The observatory is at an altitude of 3,400 metres, and measurements are made using a non-dispersive infrared photometer. Figure 19 is the plot from 1958 to September 7th, 2023 [17].

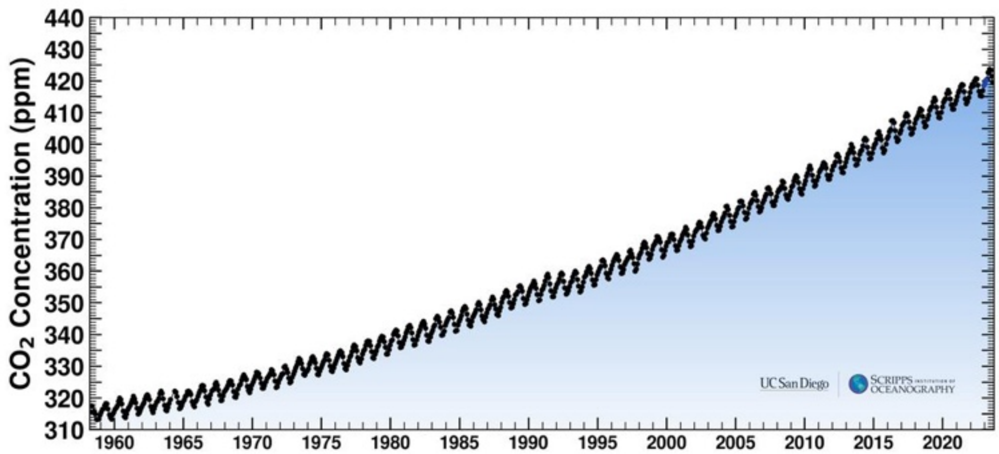

FIGURE 19 – The Keeling Curve. This chart plots the concentration of atmospheric CO_2 measured daily at the Mauna Loa Observatory in Hawaii.

Figure 19 shows a steady rise of CO_2 concentration during the measurement period. It also shows a cyclical variation of approximately 6 ppm every year due to the seasonal change in uptake of CO_2 by the world's land vegetation. The atmospheric level is highest in May, and then it decreases during the northern spring and summer as new plant growth takes CO_2 out of the atmosphere due to photosynthesis. The atmospheric level is lowest in September, and then it rises again through the northern fall and winter as plants and leaves die off and decay.

Many people believe that the continuous rise in atmospheric CO_2 is primarily due to human activities, but the Keeling plot does not show any reduction in slope during 2020 and 2021, when the Covid pandemic caused a major reduction in industrial operations.

There is controversy over the lifetime of CO_2 in the atmosphere. Estimates have varied from 5 to over 1,000 years, but the 1963 treaty banning atomic tests allowed scientists to track the fall in CO_2 concentration containing the ^{14}C isotope from the time of the cessation of testing. This decay followed an exponential decline, falling to 1/e of the initial value within about 20 years. If placed in a sealed container, CO_2 has a very long life. As described above, the "carbon cycle" involves CO_2 being released into the atmosphere at the same time that it is being taken out through the various "sink" processes. The concentration of any "new" CO_2 in the atmosphere will appear to decay exponentially as it is slowly cycled through the various sink and emission mechanisms. Approximately every 20 years, the detectable concentration of any "new CO_2" in the atmosphere will be reduced to a factor of 1/e (approximately 37%). To better understand this, consider the following analogy:

Imagine a swimming pool that has a system which is adding fresh water at the rate of one "pool's worth" of water every 10 days, and a system that is draining out water at the same rate. The casual observer would state that the water is completely exchanged every 10 days, but that is not actually the case! Now let's dump in a container of red dye that represents 1 ppm of the volume in the pool. The pool water would take on a red hue, but our casual observer would say that it *will have completely cleared up in 10 days. However, when we measure the dye concentration 10 days later, it is not zero, it is 0.37 ppm!*

Every 2.4 hours, 1% of the water is "exchanged". Therefore, after 2.4 hours, the red dye concentration will have been reduced to 0.99 ppm. After a further 2.4 hours, it will be reduced to 99% of 0.99 ppm, etc. If you add up the series, you will find that after 100 of these time periods (totalling up to 10 days), you have approximately 1/e times the original 1 ppm concentration. [Note: e is 2.71828 ....., which is the base for natural logarithms]

Many observers will look at the initial rate of red dye depletion, and extend it using a straight line to declare when "all the bad stuff will be gone". This is incorrect, because the curve is exponential, not linear.

Another good analogy is to look at the shape of the voltage discharge curve of a 1 microfarad capacitor in parallel with a 1 megohm resistor. Imagine that the capacitor is initially charged to 1 volt. The so-called "Time Constant" is 1 second (R x C), and the initial rate of discharge suggests that the capacitor will be completely discharged after 1 second, but the measured voltage after 1 second is actually 370 millivolts, which is 1/e times the initial voltage. A plot of the actual voltage as a function of time will follow the classical exponential discharge curve, which never reaches zero, but is asymptotic to it.

If we look at the shape of the $^{14}CO_2$ *concentration after the cessation of open air atomic bomb testing, the curve is exponential, and the concentration had fallen to about 1/e of its starting value after about 20 years. We therefore infer that the "residence time" of* CO_2 *in the atmosphere is 20 years!*

The oceans absorb CO_2. The amount that is absorbed varies with temperature, in accordance with Henry's Law. An equilibrium is established across the air-water interface, depending on the partial pressure of atmospheric CO_2.

ORBITAL MECHANICS

As described earlier, the power density of the solar energy arriving at the top of the atmosphere varies inversely as the square of the distance to the sun. Variations in the sun-to-earth distance will definitely affect the energy arriving at the earth. The average distance is 147 million Km, but the earth's orbit around the sun is not a perfect circle, it is actually an ellipse. The eccentricity of the orbit varies cyclically with a period of about 405,000 years due to the gravitational effects of Saturn and Jupiter. This changing eccentricity is just one of several different changes in orbital mechanics that are known as Milankovitch Cycles[18].

The three main Milankovitch Cycles are: orbital Eccentricity, Obliquity (Tilt), and Precession. These are illustrated in Figure 20.

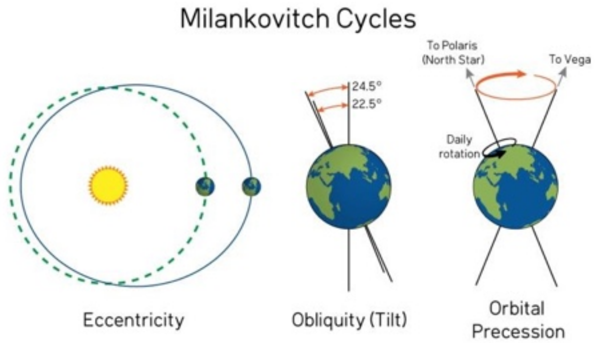

FIGURE 20 – MILANKOVITCH CYCLES. These are cyclical changes to the Earth's orbital parameters as it spins and travels around the Sun.

If the earth's surface was completely covered with land of a constant albedo (reflectivity), the fact that the Obliquity and Precession change over time would have no effect at all on the global temperature. However, the earth's surface can be either land, water, or ice, and these all have very different albedos. In addition, the land proportion is much higher in the Northern hemisphere than in the Southern hemisphere, so the amount of heat absorbed in either the local summer or winter by the two hemispheres will vary depending on the orientation changes due to Tilt and Precession. The three different orbital parameters vary with different periods:

Eccentricity	405 K years and 100 K years
Obliquity	41 K years
Precession	25.7 K years

In addition to these three Milankovitch Cycles, there are also cyclic orbital variations due to Apsidal Precession, and Orbital Inclination. All of these cyclical variations combine to cause a repetitive variation that has several different frequency components, as shown in Figure 21.

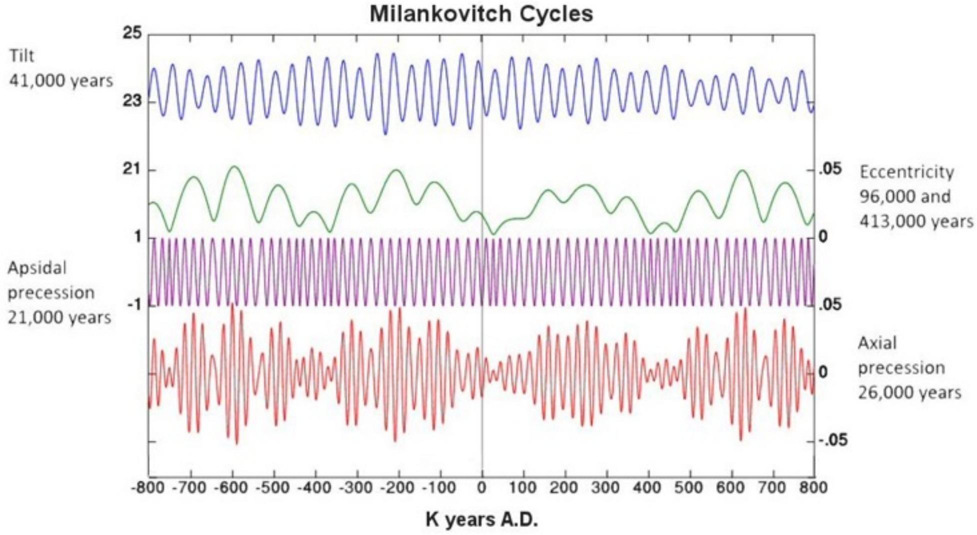

FIGURE 21 – Milankovitch Cycle Periodicity

These Milankovitch Cycles combine, to cause an overall "modulation" of the solar energy density arriving at the top of the earth's atmosphere. This thermal energy is referred to as "Insolation", and is shown in Figure 22 for a Latitude of 65 N at the summer solstice.

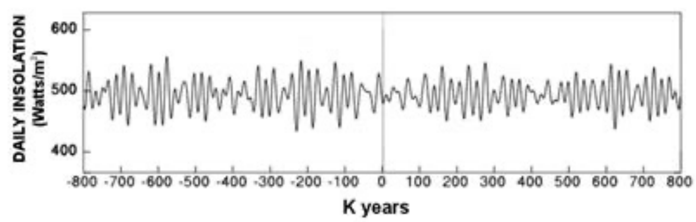

FIGURE 22 – Summer Solstice Insolation at 65N. This is the net effect of the combination of all the individual Milankovitch cyclic frequency components.

The effect of these insolation changes can be clearly seen in the core sample thermal data shown in Figure 3 earlier in this document. The effect of obliquity by itself can clearly be seen in the Holocene temperature record, as shown in Figure 23.

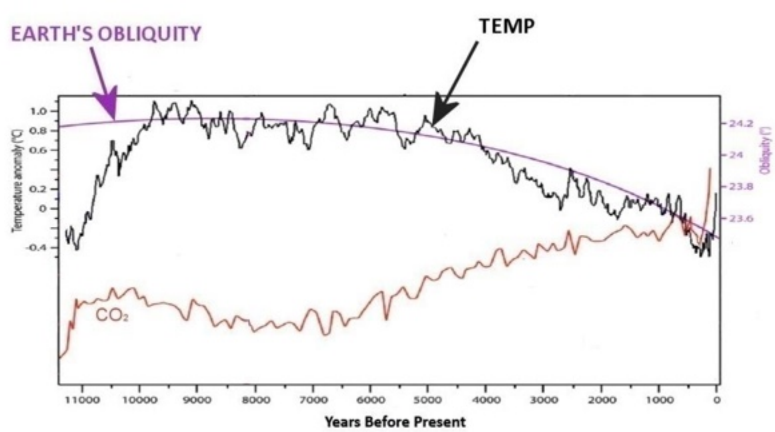

FIGURE 23 – Correlation Between Temperature and Obliquity During the Holocene

CONTINENTAL DRIFT, OCEANS & CURRENTS

Oceans play an important part in controlling or changing the earth's climate. They store energy, transport energy, and absorb and/or release CO_2. Water's Specific Heat is much greater than that of the rocks or soil commonly found on land. The average albedo of land is about 0.3, but the albedo of the oceans is about 0.06. This means that the oceans absorb much more (per unit surface area) of the sun's energy than the land[19]. The best way to interpret this is to consider that the solar energy which warms the land is actually primarily collected by the oceans, and then distributed by oceanic currents.

Oceans have a thermocline that separates the warmer, well-mixed surface waters from the deeper cold waters. The thermocline depth is usually in the range of 200 to 1,000 metres. The colder water underneath the thermocline stores large amounts of CO_2 as well as other minerals.

Ocean currents are the dominant mechanism for heat transfer on the earth, and these currents have changed radically over the long term as the continents have moved due to plate tectonics. The earth used to have just a single, large continent known as "Pangea", and it was surrounded by the Tethys Sea. About 195 Mya, during the Jurassic Period, the super-continent of Pangea started to break up, as shown in Figure 24. The fault lines between tectonic plates are shown, and the arrows indicate the direction of motion.

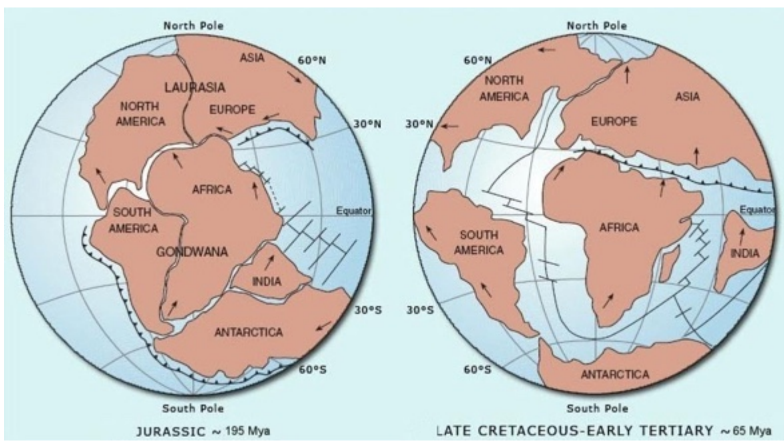

FIGURE 24 – The Break Up of Pangea Due to Continental Drift

As the continents have drifted, ocean passages have opened and closed over time. As a result, there have been major changes in ocean currents, and this has affected energy collection and transportation, and hence climate. We will examine this more closely, starting 66 Mya, right after the K-T event. We will be using a series of images created by C. R. Scotese as part of his Paleomap Project, which researched and illustrated the plate tectonic development of the ocean basins and continents, as well as the changing distribution of land and sea during the past 1.1 billion years. Figure 25 shows the situation just after the asteroid hit the earth at Chicxulub.

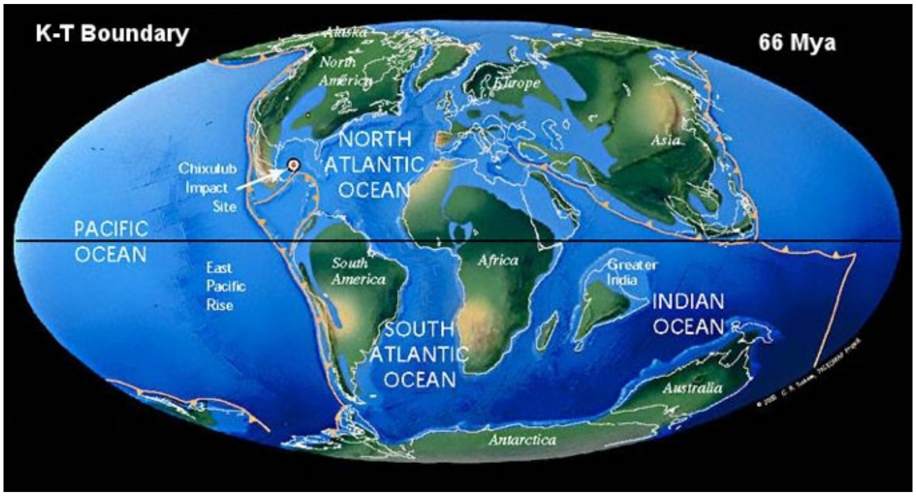

FIGURE 25 – Continental Positions Right After the K-T Event

At this point of time, there is no sea passage between Antarctica and South America or Australia. The Panama Isthmus is wide open, and there are open passages North of Africa and South America that allowed an equatorial current to circulate around the warmest part of the globe, distributing heat. There were no ice caps, and life was abundant. Figure 26 illustrates the Equatorial Current that existed at the start of the Eocene.

FIGURE 26 – Ocean Currents During the Eocene

In Figure 27, we look at the earth at about 50.2 Mya, in the middle of the Eocene Epoch.

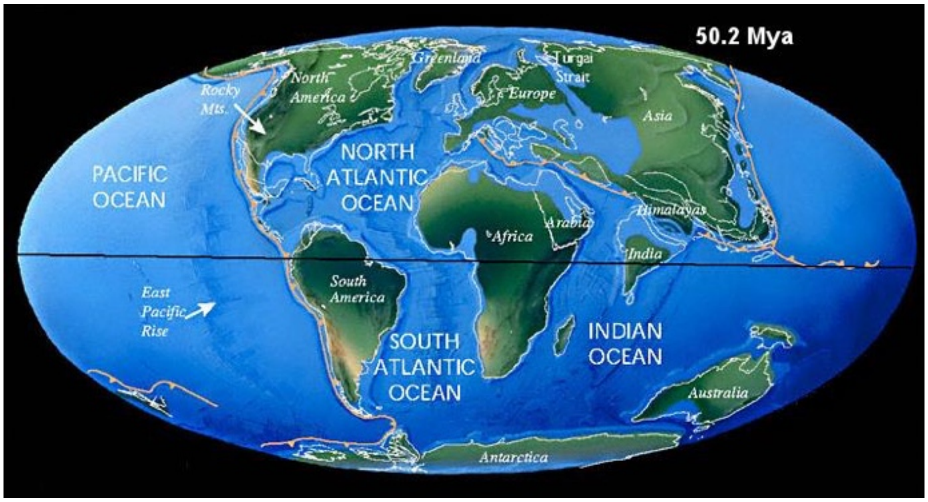

FIGURE 27 – Continental Positions in Mid-Eocene

The dinosaurs have died out, Australia has separated from Antarctica, India is moving rapidly toward Asia, and the Himalayan and Rocky Mountains are forming. The Drake Passage between South America and Antarctica is opening, and the Straits of Gibraltar are narrowing. The equatorial current is getting constricted, resulting in cooling.

Later in geological time, Figure 28 shows the continental positions in the middle of the Miocene, at 14 Mya.

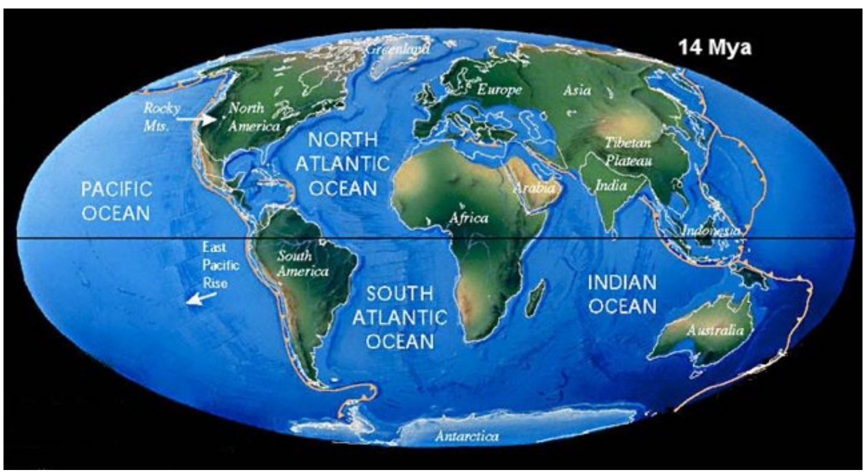

FIGURE 28 – Continental Positions in Mid-Miocene

The cooling has continued, and there is significant ice on Antarctica. India has joined up with Asia, the Gibraltar Strait is quite restricted, and the Panama Isthmus is almost closed. Florida and parts of Asia are under water. The equatorial current is mostly blocked, and the Antarctic Circumpolar Current circles around Antarctica. The Arctic is still ice-free.

At about 3 Mya, the Panama closes, and the Equatorial Current can no longer circulate, causing the start of a general cooling trend at the start of the Pleistocene. (Note – recent research has suggested that the Panama might have closed much earlier: perhaps 18 Mya). For the past 800 thousand years, the earth has gone though a repetitive series of glaciations, as illustrated in Figure 3 earlier in this document.

Figure 29 shows the situation 18 Kya, at the Last Glacial Maximum (LGM).

FIGURE 29 – Continental Positions at the Last Glacial Maximum (LGM)

The continents are in their modern, familiar positions, although the shorelines are considerably seaward due to the lower sea level as a result of the glaciations. Homo Sapiens are well established, and land bridges allow intercontinental migrations. The Mediterranean Sea is completely isolated, and the Indonesian area blocks major current flows between Asia and Australia. Northern Europe and Canada are almost completely covered in ice, and the Antarctic ice sheet extends Northward almost all the way to Tasmania and South America.

The Tectonic Plates are continuing to move, and the continents will slowly drift and form a new "super continent" referred to as Pangaea Proxima in about 250 million years time.

In modern times, energy is distributed via what is known as the "Ocean Conveyor"[20], whose route has been defined by the moving continental land masses. Figure 30 shows the flow.

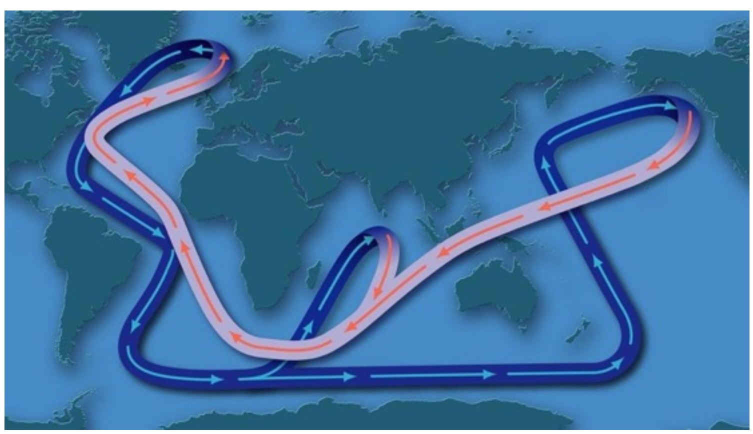

FIGURE 30 – The Ocean Conveyor
(From Woods Hole Oceanographic Institution)

The Ocean Conveyor is a continuously-circulating current that goes by different names in different parts of the world, but it is driven by changes in density due to salinity variations, and it is the major transporter of solar energy throughout the globe. Warm, salty surface water from the Caribbean, the Gulf of Mexico, and Western Africa flows Northward in the Gulf Stream. As it passes through Northern latitudes, it gives up heat and moisture to the atmosphere. By the time it arrives in the North Atlantic, the water has become cool and salty, thereby increasing its density. This dense water sinks to the ocean floor, and flows southward as a current that passes underneath the Gulf Stream, continuing on the

Southern Ocean, then to the Indian and Pacific Oceans, where it eventually mixes with warm water, rises, and returns to the Atlantic to complete the circuit.

A fundamental driver of the Ocean Conveyor is the difference in salinity between the Atlantic and Pacific Oceans. When the Panama was open, waters could freely mix between the Pacific and Atlantic, and there was no salinity difference. After the Panama closed, there was no mixing between the two oceans, and the salinities diverged. Evaporation in the Caribbean and tropical Atlantic caused increases in salinity, and fresh water was put in the atmosphere, where it was carried across to the Pacific by Westerly-flowing Trade Winds, to then fall as precipitation. The net result of this was that the salinity in the Atlantic slowly increased relative to the Pacific. This salinity difference continues to drive the Ocean Conveyor. Contrast the route of the Ocean Conveyor with the Equatorial Current shown earlier in Figure 26.

This discussion illustrates how the earth's overall climate has changed over time due to long term continental drift and the associated changes in ocean currents. There are other, more localized and shorter term current variations that affect climate in the short term: ENSO, PDO, and AMO. We will examine these in detail, starting with ENSO (El Niño-Southern Oscillation)

The El Niño-Southern Oscillation (ENSO) is a recurring climate pattern involving changes in the temperature of waters in the central and eastern tropical Pacific Ocean. On periods ranging from about three to seven years, the surface waters across a large swath of the tropical Pacific Ocean warm or cool by anywhere from 1°C to 3°C, compared to normal.

This oscillating warming and cooling pattern, referred to as the ENSO cycle, directly affects rainfall distribution in the tropics and can have a strong influence on weather across North America and other parts of the world. El Niño and La Niña are the extreme phases of the ENSO cycle; between these two phases is a third phase called ENSO-neutral. There is much conjecture over the root cause of these cycles, including the possibility that underwater volcanoes and sea vents may be involved. Indeed, there is a whole new field of study that was formally launched in 2004 called "Plate Climatology" that combines input from several branches of science: Geology, Climatology, Meteorology, Oceanography, and Biology.[21]

El Niño is warming of the ocean surface, or above-average sea surface temperatures (SST), in the central and eastern tropical Pacific Ocean. Over Indonesia, rainfall tends to become reduced while rainfall increases over the tropical Pacific Ocean. The low-level surface winds, which normally blow from east to west along the equator instead weaken or, in some cases, start blowing the other direction (from west to east").

La Niña is cooling of the ocean surface, or below-average sea surface temperatures (SST), in the central and eastern tropical Pacific Ocean. Over Indonesia, rainfall tends to increase while rainfall decreases over the central tropical Pacific Ocean. The normal easterly winds along the equator become even stronger.

Figure 31 is provided by NOAA, and it illustrates both a strong La Niña (from December 1988) and an El Niño (December 1997).

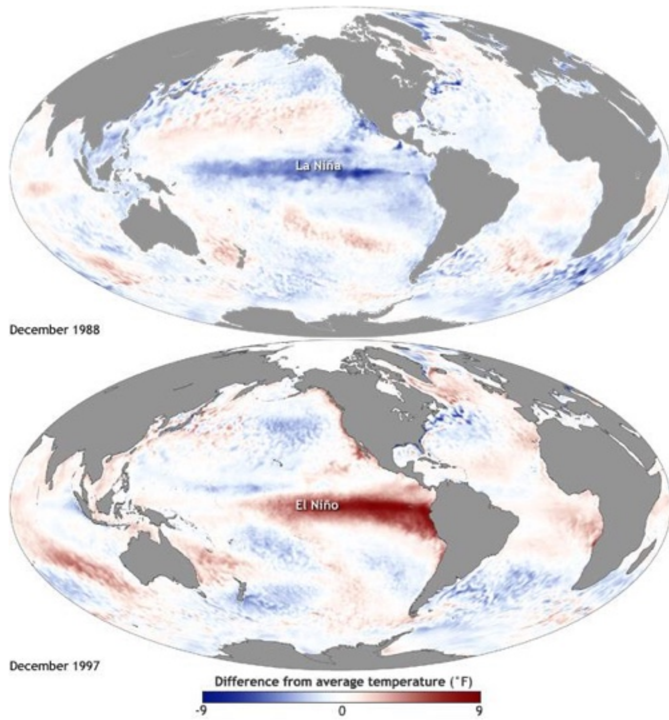

FIGURE 31 - La Niña (top) and El Niño (bottom)

The PDO (Pacific Decadal Oscillation) is more focussed on the Northern Pacific region. The PDO is a long-lived El Niño-like pattern of Pacific climate variability, and extremes in its pattern are marked by widespread variations in the climate of the Pacific Basin and North America. The extreme phases of the PDO have been classified as being either warm or cool, as defined by ocean temperature anomalies in the northeast and tropical Pacific Ocean. The recent historical record of both PDO and ENSO is shown in Figure 32.

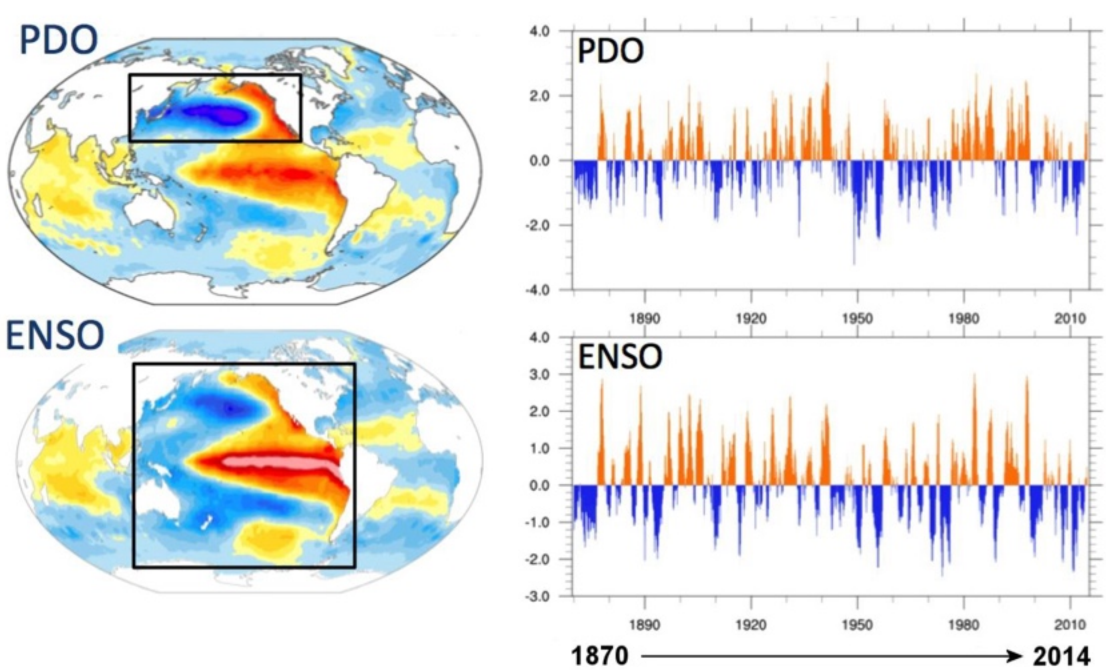

FIGURE 32 – Record of PDO and ENSO Magnitudes

There are similar longer-term temperature cycles in the Atlantic Ocean, referred to as AMO (Atlantic Multi-decadal Oscillations). Figure 33 shows a recent historical record of these temperature swings.

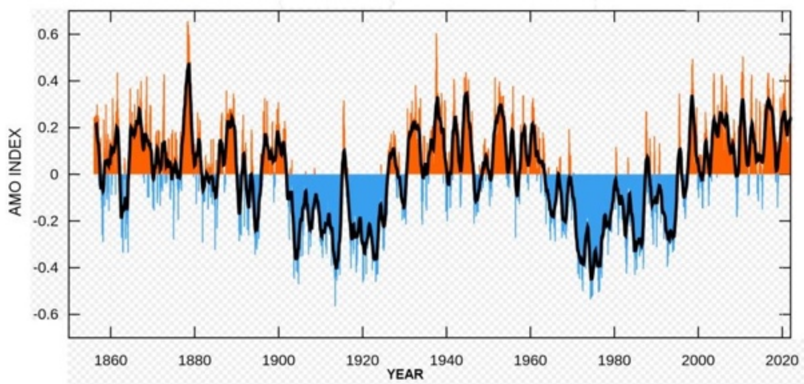

FIGURE 33 – AMO (Atlantic Multi-Decadal Oscillation) Index

GLACIATIONS

There was a period of time when the popular media was making a big issue of the "Retreat Of The Glaciers"

The Earth has been ice-free (even at the poles) for most of its history. However, these iceless periods have been interrupted by several major glaciations (called Glacial Epochs) and we are in one now in the 21st Century. Each glacial epoch consists of many advances and retreats of ice fields. These ice fields tend to wax and wane in about 100,000, 41,000 and 21,000 year cycles (under the influence of Milankovitch Cycles). Each advance of ice has been referred to as an "Ice Age" but it is important to realize that these multiple events are just variations of the same glacial epoch. The retreat of ice during a glacial epoch is called an Inter-Glacial Period and this is our present climate system.

The existing Plio-Pleistocene Glacial Epoch began about 3 million years ago and is linked to the tectonic construction of the Isthmus of Panama which prevented the circulation of Atlantic and Pacific waters and eventually triggered a slow sequence of events that finally led to cooling of the atmosphere and the formation of new ice fields by about 2.5 million years ago.

Thus far, the Earth has had around 15 to 20 individual major advances and subsequent retreats of the ice field in our current Glacial Epoch (see earlier Figure 3). The last major advance of glacial ice peaked about 18,000 years ago at the Last Glacial Maximum (LGM), and since that time the ice has generally been retreating although with some short-term interruptions. What we are presently experiencing in Greenland and other continents is a rapid melting of surrounding sea ice by rising ocean temperatures and a widening of the Gulf Stream. Greenland's continental glaciers are also retreating due to an accumulation of atmospheric soot and a reduction of fresh snow to cover it. Although the earth currently appears to be warming, we will inevitably enter another glacial period in a few thousand years.

SEA LEVEL

There is a great deal of publicity (and in some cases, hysteria) surrounding predicted increases in sea level which will result in wide-spread flooding. If the earth maintains a constant vertical profile, the sea level is purely a function of the total volume of water in the oceans. As the earth's surface temperature increases, not only will the sea's volume and evaporation rates increase, but ultimately ice in the Arctic and Antarctic regions will melt, thereby increasing the volume of water in the oceans, and raising the sea level. Note that the melting of ice that is currently floating in the oceans will not result in an increase in sea level; it is only the ice that is presently on land that will have an effect if it melts.

The press has made much of the claim that "The Glaciers Are Melting", and concluded that this is being caused by man's recent contribution to atmospheric CO_2. However, as described earlier, records show that the recent glacial retreat has been occurring for hundreds of years, and is normal behaviour between glaciations. Figure 34 shows the historical sea level extending back to before the K-T Event.

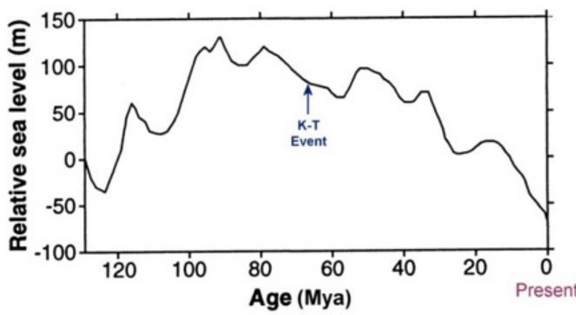

FIGURE 34 – Historical Sea Level Since Before the K-T Event

If the mountain snowpacks and the icecaps on Greenland and Antarctica do melt, there is no doubt that the average sea level will rise. In our particular region (Western Canada), this is offset by the fact that the earth's surface is actually rising due to rebound from the ice ages, and (in the Victoria region) due to tilting of Vancouver Island from relative motion of the plates beneath it.

In South East Alaska, every year more land is actually being "reclaimed" from the ocean as the land rebounds from the heavy ice load it was previously subjected to.

The global average sea level is currently increasing by about 3 mm per year, and this is expected to continue. Figure 35 plots the sea level from a number of different locations since the Last Glacial Maximum (LGM) and through the Holocene to the present.

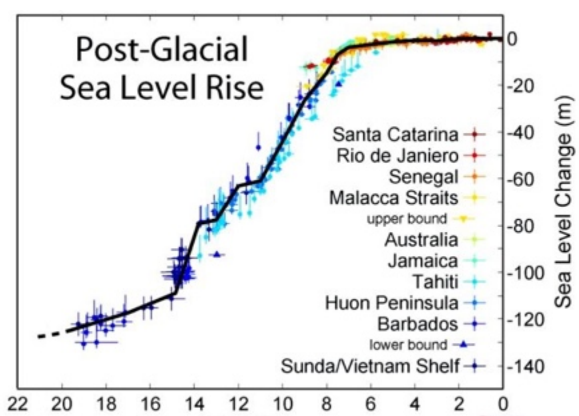

FIGURE 35 – Historical Sea Level Since the Last Glacial Maximum