

The Oceans' Role in Determining Earth's Climate

By Malcolm Cumming

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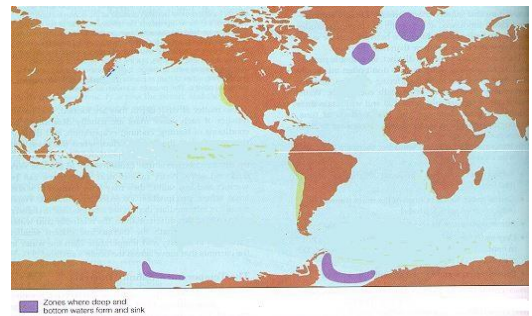
Abstract

Oceans play a large role in determining the ongoing temperature of the Earth's surface. A type of circulation, called Meridional Overturning Circulation (MOC), acts to redistribute the thermal content of the oceans between the surface and great depths without immediately altering their total thermal content. In so doing, MOC sequesters cold waters deep below the mixing layer. By removing a portion of the very coldest waters from the surfaces of the world's oceans, Earth's ability to absorb heat from the Sun is diminished. Earth appears in space to be a warmer body than it actually is and therefore absorbs heat from the sun at a reduced rate. Robust MOC has the ultimate effect of lowering global temperatures.

Recognition of the relation between MOC and global temperature opens a window for understanding the episodic cooling trend Earth's climate has undergone over the past 100-million years. There is a simple and direct link between the geophysical changes resulting from plate tectonics and subsequent changes to global surface temperatures. This new understanding of a primary cause of the "Cenozoic Cooling" gives us a fresh perspective enabling us to better explain high latitude glaciations, first in the Southern Hemisphere, then later in the Northern Hemisphere. In turn, a new understanding of northern glaciations, especially after the Mid-Pleistocene Transition (MPT), should help us understand how the slowdown of the Atlantic MOC (AMOC) will likely lead to additional warming above and beyond that directly caused by rising anthropogenic levels of carbon dioxide.

What is MOC and how does it modify Earth's surface temperature?

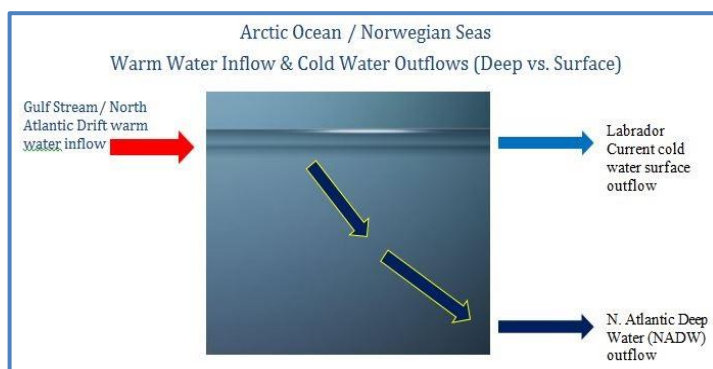
Meridional Overturning Circulation or MOC can be described as poleward flowing surface currents of warm/salty water (along meridians), which, once chilled, sink (i.e. overturn) and return to lower latitudes as very cold/deep waters. Overturning takes place in two locations in the Northern Hemisphere (in the Norwegian Sea and in the North Atlantic east of Greenland) and in two locations near Antarctica (over the shallow floors of the Ross and Weddell basins). These four areas meet the requirements necessary for the production of deep waters to take place – the presence of salty water at the surface along with low temperatures capable of chilling that water quickly.



The recipe for making surface water dense enough to sink to the very bottom and join the deepest waters of the world oceans consists of relatively salty water that is chilled quickly and thoroughly. First, water must be chilled fast enough to reach its maximum density before it begins to sink from the surface. Deep water formation requires a combination of extreme cold together with inertia against premature sinking. It is likely that shallow bottoms and rough topography are important factors that constrain the outflow of deep water and slow the decent of waters from the surface. Secondly, surface waters must have relatively high salinity in order to achieve sufficient density to sink and displace all waters lying underneath. Saline surface waters in high latitudes originate from equatorial regions where warm waters retain salt concentrated by high evaporation rates (e.g. Mediterranean and Caribbean Seas). Ocean basin geography that enables meridional circulation is a key factor to the existence of MOC. Another factor is the absence of (or reduced) ice-melt “freshening” that, otherwise, dilutes surface waters.

Perhaps the best way to explain how robust MOC results in lowered surface temperatures is to first understand that surface-only circulation (without overturning), otherwise referred to as Ocean Heat Transport (OHT), has very little direct impact on Earth’s ongoing temperature. The Stephan-Boltzmann Law tells us (and most GCMs confirm) that *for a given volume of ocean with a given total heat content (regardless of surface distribution), if subject to the same total of atmospheric insulating effects (even if varying by latitude) over a given period of time, there will be negligible (albedo and cloud feedbacks tend to cancel each other) change in overall global temperature.* MOC changes the equation by modifying the relative levels of Polar cooling and compensating Equatorial warming.

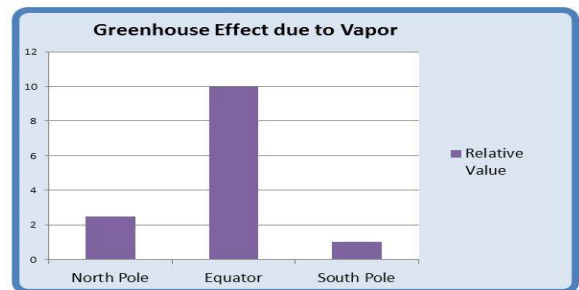
The Atlantic MOC (aka. AMOC) is a good example that demonstrates how robust MOC reduces the average global surface temperature at which Earth’s energy budget achieves balance. Winds and Coriolis forces (combined with density driven inflows) bring warm waters to the



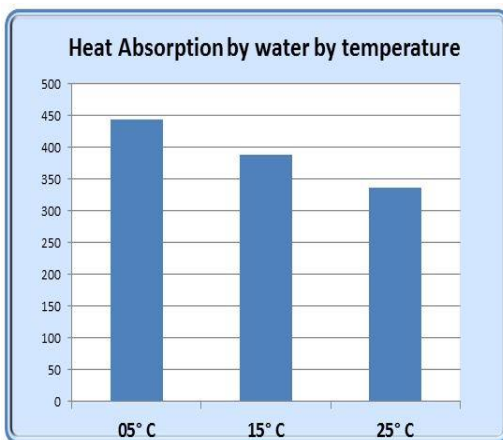
Arctic. Cold waters are displaced and must flow south, either at the surface or as deep/bottom waters. The strength of overturning in the Arctic determines the proportion of water that flows out as NADW opposed to the outflow at the surface (i.e. the Labrador Current).

The existence of strong overturning (with consequential strong cold water outflow at depth) results in a lessened cold water outflow toward lower latitudes at the surface – i.e. the Labrador Current is weakened. Studies in the past few decades estimate that deep water outflow through the Labrador Sea may range between 14 - 17 Sverdrups [Haine, 2008]. (1 Sverdrup = 1-million cubic meters/second.) Ocean surfaces in low latitude regions of the Atlantic remain slightly warmer as cold water return currents *at the surface* are diminished. This slightly warmer condition of tropical ocean surfaces remains as long as MOC remains robust. Unlike the process of high latitude overturning where originally warm surface waters sink straight to the bottom, there is no comparable process where cold deep waters rise directly to the surface in equal quantities. Upwelling centers are predominantly associated with Coriolis forces acting on boundary currents. Intermediate waters are drawn upward as surface waters curl away from the direction of flow. Cold deep waters of the oceans may remain sequestered for a thousand years or more.

Just as warm surface waters that flow into high latitudes give up heat under atmospheric conditions where the greenhouse effect is weak, cool surface waters returning to low latitudes absorb and retain solar heat. If the volumes exchanged were equal, the heat gained in the tropics would compensate for the heat lost at the poles. MOC has a cooling effect due to increased low latitude ocean surface temperature (by way



Equatorial vapor creates a greenhouse effect ~4 x the Arctic and ~10 x Antarctica [Schmidt, 2010].

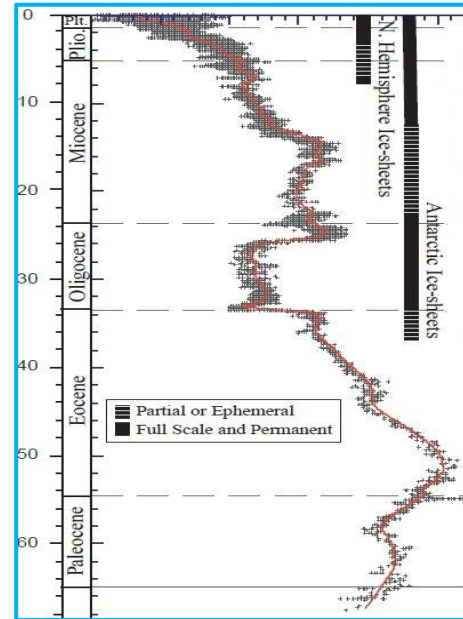


of the reduction of cold water input). The Stefan-Boltzmann Law states that something emits heat in proportion to its temperature – warmer objects emit more heat. Conversely, an ocean surface absorbs heat in an *inverse proportion* to its temperature – cooler ocean surfaces absorb heat more effectively.

In short, MOC diverts and lessens the flow of cold waters at the surface into lower latitudes. Earth appears to be a warmer body in space than it actually is. This results in the lowered rate of absorption of the Sun's radiant heat, thus leaving the planet in a cooler state.

The Relationship between Tectonics and Climate

A number of physical processes underwent noteworthy trends over the last 100-million years. Continents split apart and moved to new locations. In terms of the Wilson Cycle, one can say that the continents have been in “dispersal mode” since the latter part of the Cretaceous Era. Global average temperatures declined episodically, with a few periods of warming and other times of fairly stable levels, but generally, with a tendency to become cooler. Carbon dioxide levels rose and fell with a trend line that closely matches the temperature curve. Somewhat overlooked in scientific literature, regions in high latitude oceans developed as sites for deep water formation as ocean basins increasingly enabled meridional overturning circulation to occur. Tectonic plate movements reformed the number, size, shapes and geography of ocean basins. Changed connections between basins and altered sea floor topography increased the potential for the occurrence of MOC. This process can be referred to as Geophysically Influenced MOC or GIMOC.



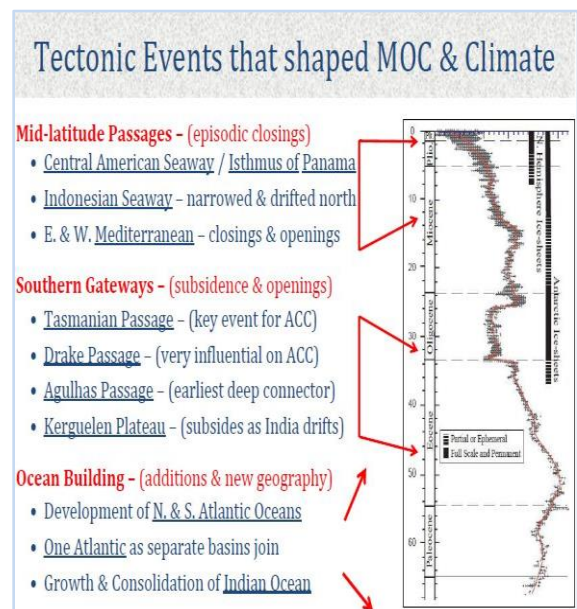
(Zachos, 2001)

Ever since Louis Agassiz proposed to a gathering of naturalists in Neuchâtel, Switzerland in 1837 his theory that thick ice had once covered the lowlands of Europe, answers to the question of what caused glaciations has remained elusive. Over the last 180 years, field work and analysis of ice and ocean sediment cores have given us a rich history of climate over the course of tens of millions of years. The question of “What caused the Ice Ages” has become more of one that asks “What caused the Earth’s climate to cool prior to and throughout the Cenozoic Era?” Many theories have been proposed – most have fallen by the wayside. One of the strongest contenders for explaining the Cenozoic Cooling is the idea that orogeny and tectonic uplift have caused a drawdown of CO₂ from the atmosphere.

A plausible case has been made that the concurrent rise of the Tibetan Plateau and formation of the Himalayan Mountains has led to increased silicate weathering which ultimately leads to increased formation of carbonate rock and subsequent removal of CO₂ from the atmosphere. It is likely that uplift and orogeny did contribute to some of the lowering of global temperatures through much of the Cenozoic Era. Perhaps without a CO₂ drawdown caused by increased rates of weathering, temperatures in the Plio-Pleistocene might not have cooled as much as they did.

However, it seems likely that reduced CO₂ levels could only have been responsible for a portion of overall temperature decline. The cooling curve derived from oceanic records indicates that the trend was anything but smooth. It is difficult to relate the entire episodic and somewhat erratic record of temperature change with a process derived from the very slow and steady processes of tectonic uplift and orogeny. In addition, as climate cooled, rates of weathering would slow down. Yet, after the Mid-Miocene, the rate of global cooling grew increasingly stronger. Seemingly, there were other processes at work to cool Earth over the long term.

Geophysicists and oceanographers have been assembling the chronologic history of ocean plate movements all the while climatologists have been chronicling temperature variations. Tectonic events appear to coincide with new temperature trends – throughout the Cenozoic tectonics has often been associated with changes in the slope of descending temperature trends. Whether it is the expansion and joining of the North and South Atlantic Ocean basins or the development of an Indian Ocean that evolved from a split-basin into a unified single ocean, the general long term trend of cooling coincides with ocean building that would have increased the potential for patterns of *meridional overturning circulation*. The Mid-Cenozoic opening of Southern Ocean “gateways” and the Late Cenozoic constrictions and closures of low latitude passages also coincide with changes (generally downward) to the climate/temperature curve. Increasing MOC activity, in all these instances, is likely the common denominator between the tectonics of “continental dispersal” and the long term, episodic, downward trend of global cooling.

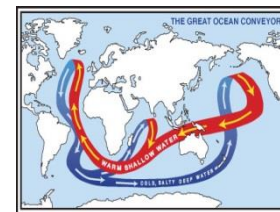
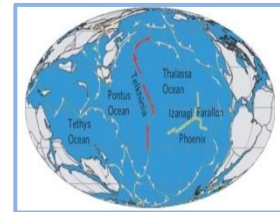


Earth’s 100-million-year temperature decline is likely the product of two phenomena that each directly drive down temperatures and also act to amplify the strength of the other. Cooling from CO₂ drawdown can help stimulate MOC – reductions in ocean temperatures resulting from robust MOC cause additional removal of CO₂ from the atmosphere. The contributions of each will be not be easy to determine, but the coincidence of tectonic events with changes in temperature trends indicates that variations in the strength of MOC has played a substantial role.

The Cenozoic Cooling – The Role of Geophysically Influenced MOC (GIMOC)

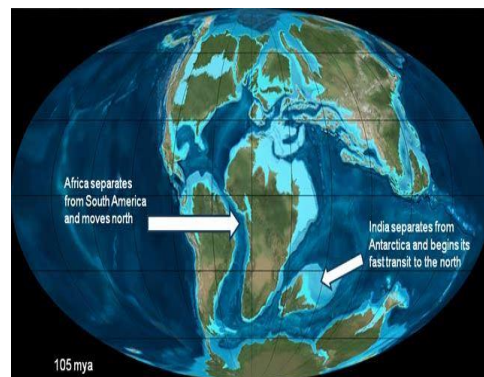
Realization that strong meridional overturning circulation lowers the temperature at which Earth's energy budget achieves balance offers a new perspective for understanding the episodic cooling trend of the last 100-million years. MOC directly links plate tectonics and continental drift to changes in climate. The geophysical changes to ocean basins and the connections between them have, for the most part, increased the potential for meridional circulation to take place. Geophysically influenced MOC or GIMOC throughout the Cenozoic may be responsible for the largest share of the cooling that took place.

In the Late Cretaceous, Earth was still a single-ocean world consisting of two megacontinents – Gondwana and Laurasia that were separated by the Tethys Seaway – and the *Panthalassic Ocean* which covered more than half the globe. The Panthalassic had a circulation pattern consisting merely of latitudinal eddies. The geography did not support meridional boundary currents. There were no locations in high latitudes suitable for overturning to occur, nor were there currents that would transport warm/salty waters from tropical regions. In today's world, we now have what's called the *Great Ocean Conveyor*. Warm waters (with relatively high salinity) are transported north and south by currents directed by continental coast lines and driven by winds and by density gradients created by sinking of waters to the depths of the oceans.



Let's look at some tectonic events that have contributed to the overall cooling trend of the Cenozoic Era and a few that are likely associated with significant turning points in the episodic trend that culminated in the cold temperatures of the Pleistocene.

Temperatures began to decline once the connection formed between the early *North and South Atlantic Oceans*. South America and Africa began to split apart ~120 Ma but remained joined along an east-west lateral fault located near the Equator, keeping the Atlantic basins separated from each other. By 105 Ma, the two continents, moving in opposite directions along their lateral connection, slid free of each other. South America began its clockwise rotation away from what is now the south coast of the northwest portion of Africa as the entire African continent began to move

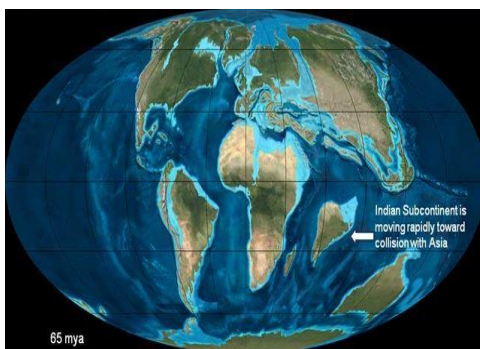


north. The gap between the formerly separate parts of the Atlantic Ocean widened at a rapid pace.

Planetary temperatures declined in the Late Cretaceous during a 20 to 30 million year period prior to the start of the Cenozoic Era. Research conducted by Kenneth MacLeod of the University of Missouri and colleagues has shown that by 70 Ma warm surface waters originating from the South Atlantic were sinking near Greenland. While this brought warmth to the North Atlantic, the rest of the globe was cooling [MacLeod, 2011]. The warm waters that flowed into the North Atlantic became part of a new circulation pattern that included the formation of deep waters flowing south and creating a void which helped draw more warm water from the tropical Atlantic. This early instance of overturning circulation in the Atlantic Ocean was made possible by the widening between the South and North Atlantic basins well underway by 70 Ma.

Fossils offer evidence indicating some Arctic coastal areas were relatively warm during lengthy periods of the Cenozoic while the planet as a whole was cooling. For years, scientists have pointed out the seemingly incongruous fact that fossil remains of alligators, turtles and breadfruit trees (more suited to warm climates) have been found on Greenland and Ellesmere Island. The presence of hardy varieties of these tropical specimens was likely due to a marine climate that didn't freeze. Considering that a significant cause of global cooling is due to the development of warm ocean currents in the high latitudes, the oddity of alligators in the far north should not be unexpected.

Global temperatures were on the upswing leading into the Cenozoic Era. Some of the impetus toward cooling was likely offset by tectonics in the *Indian Ocean*. Beginning in the Late Cretaceous, India separated from Antarctica and began its journey northward, trailed by a chain



of volcanic islands that continually formed over a hot spot located to the east of the Indian subcontinent. The islands and the subcontinent itself partially divided the Indian Ocean into eastern and western basins. The islands gradually sank and now form what is known as the 90-East Ridge [Kerr, 1978]. The subcontinent began to traverse the Equator soon after 65 Ma and didn't finish crossing it until colliding with Asia between ~45 Ma and 35 Ma. During the time India approached and then straddled the Equator, the subcontinent (and the island chain to the east and south) disrupted

circulation in the Indian Ocean. The cooling effect of the growing, connected Atlantic basins was probably largely offset by events in the Indian Ocean during the period leading up to the Eocene Thermal Maximum at ~53 Ma. It is interesting to speculate that the spike in temperatures known as the Paleocene-Eocene Thermal Maximum (PETM, ~55 Ma) that occurred just prior to the ETM may have resulted from a methane (CH₄) release caused by thawing of tundra and submerged stores of frozen methane locked in submerged continental shelves. It is entirely plausible that a major CH₄ thaw happened near the end of the millions of years of warming that followed an even longer span of Late Cretaceous cooling.

If the formation of the North and South Atlantic and Indian Oceans played the greatest role in Earth's temperature decline, a close runner-up was the development of the completely circular Southern Ocean. The separation of continental masses from Antarctica continued to open and expand pathways for ocean circulation well into the Cenozoic Era. Widening and subsidence of southern passages increased potentials for overturning in both hemispheres.

Southern Gateways

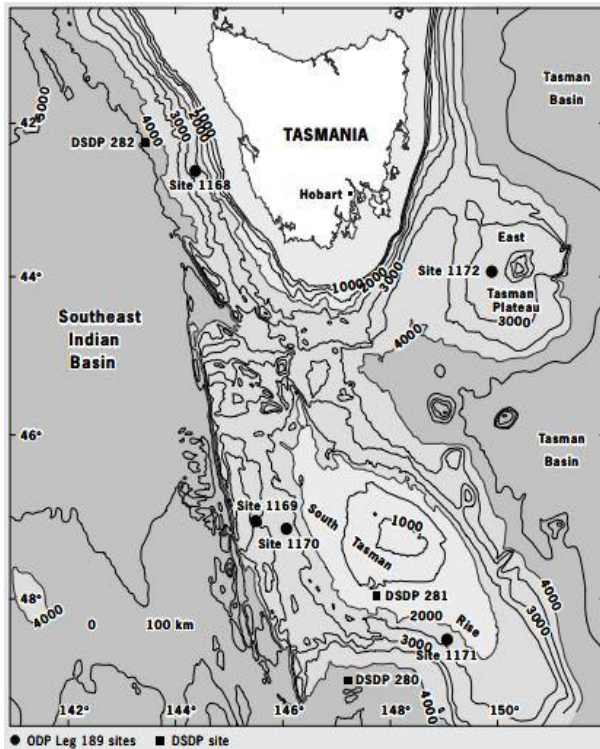
In the Early Cenozoic, the *Kerguelen Plateau*, an Antarctic continental shelf remaining after separation of the Indian sub-continent, subsided as India and its trailing archipelago of 90-East islands drifted north. At the same time, the deep water *Agulhas Passage* between South Africa & Antarctica widened and deepened as Africa moved north. Both opening "gateways" increased the potential for circum-Antarctic flow and for an increased water exchange between the Indian & South Atlantic Oceans. While the



Kerguelen Plateau was subsiding and the deep water Agulhas Passage was opening, the oceanic region between Tierra del Fuego and the Antarctic Peninsula began grow more favorable to substantial deep water flows. Islands between the Antarctic and South American continents (remnants of the once continuous Trans-Antarctic and Andes Mountains) gradually sank and the gateway known as the *Drake Passage* developed, enabling deep water flows from the Pacific and Southern Oceans into South Atlantic. As inter-basin flow among the major oceans increased, the "Ocean Conveyor" developed and oceanic overturning increased. All of this Southern

Hemispheric tectonics probably left its mark in the form of the 17-million year cooling trend that followed the Eocene Thermal Maximum (~53 Ma).

The ocean expanse between Tasmania and Antarctica was the last, and probably the most impactful, “gateway” to open in the Southern Hemisphere. Known as the *Tasmanian Gateway*, the tectonically active portion of the sea floor south of Tasmania underwent rapid (geologically



speaking) changes. A combination of sea floor subsidence and the rotation of a small oceanic plate opened a deep water channel just south of the island (~34 Ma). This allowed the relatively warm Australo-Antarctic Gulf (AAG) waters originating in the south eastern Indian Ocean to flow into the southern Pacific Ocean and ultimately into the Ross Sea region off Antarctica [Stickley, 2004]. The gateway also removed the last bottleneck preventing full development of the Antarctic Circumpolar Current (ACC). Rather than thermally isolating Antarctica, the ACC fostered the integration of circulation among the world’s oceans.

As the ACC flows eastward, Coriolis forces continually force surface waters away from the Antarctic Continent. Upwelling occurs behind the northward drifting surface waters, which soon sink and join intermediate waters flowing back toward Antarctica. Although the flow of warm and salty surface waters are blocked from directly reaching most Antarctic coasts, the salt content of tropical waters that are eventually distributed to regions where overturning takes place (i.e. the Weddell and Ross Seas) provide the salinity needed to enhance overturning. There is a direct link between the formation of the Tasmanian Gateway and the concurrent very significant global cooling that took place about 34 million years ago at the Eocene/Oligocene boundary.

Middle Latitude Seaways

Throughout most of the Oligocene, global temperatures remained fairly stable until an upturn (~26 Ma) brought about the slightly warmer climate that prevailed in the first half of the Miocene (~24-15 Ma). Elimination of major tropical connections between the great oceans came

about by the Middle Miocene (~15 Ma) with the closure of the eastern end of the *Tethys Sea* with the Indian Ocean and with the vastly reduced *Central American Seaway* connection between the Pacific and Atlantic Oceans [Zhang, 2011]. The cessation of low latitude flows between the major oceans forced the balancing of thermal and salinity differences to occur entirely by way of connections presented by the now completely circular Southern Ocean. Increased global MOC and resumed cooling were both initiated in the Middle Miocene.

Pliocene tectonic events fostered increased meridional circulation and contributed to increased Atlantic Ocean salinity. Three strategic locations (the Gibraltar Strait, the Indonesian Seaway, and the Isthmus of Panama) had similar impacts with respect to increasing global MOC which, in turn, led to accelerated cooling. Global temperatures dropped sufficiently, resulting in major glaciation on continental masses in the Northern Hemisphere.

Gibraltar Strait

The connection between the Mediterranean Sea and Atlantic Ocean was closed at the end of the Miocene (~5.6 Ma), thereby eliminating a major source of warm, salty inflow to the Atlantic [Kirk-Davidoff, 2007]. The reduced salinity would have weakened overturning, reduced the strength of the AMOC, and contributed to the short period of warming before the Pliocene. Sea levels rose about 70 feet, presumably as considerable Antarctic ice sheet melting took place [Than, 2013]. It is likely that the ensuing rise in sea level was rapid due to a feedback caused when coastal ice shelves were lifted and broke away. As ice drifted to warmer latitudes, subsequent melting caused additional sea level rise.

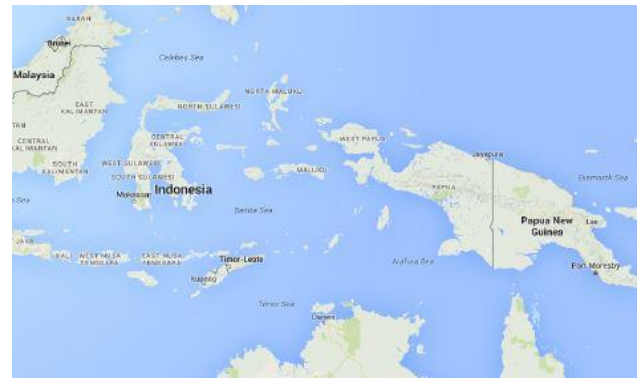
The isolated Mediterranean Sea became an endorheic basin. More water evaporated than was replaced by rivers. The water that was removed from the Mediterranean eventually cycled back into the world oceans, accounting for perhaps 8 meters (~26 feet) of the rise of the world's oceans. Heightened sea levels, combined with additional precipitation in the region, caused erosion that culminated in a breach at Gibraltar around 5.3 Ma [Kirk-Davidoff, 2007]. The erosion that opened the Gibraltar Strait may have taken a few hundred-thousand years. During the final breach, it is speculated



there may have been a cascade over a ledge east of Gibraltar a thousand times as large as Niagara Falls [Sullivan, 1974]. After the Mediterranean was reconnected with the Atlantic, MOC activity was restored, as were the cool temperatures that had existed before the Messinian Salinity Crisis. The changes coincide with, and were of enough significance to demark, the Miocene/Pliocene boundary.

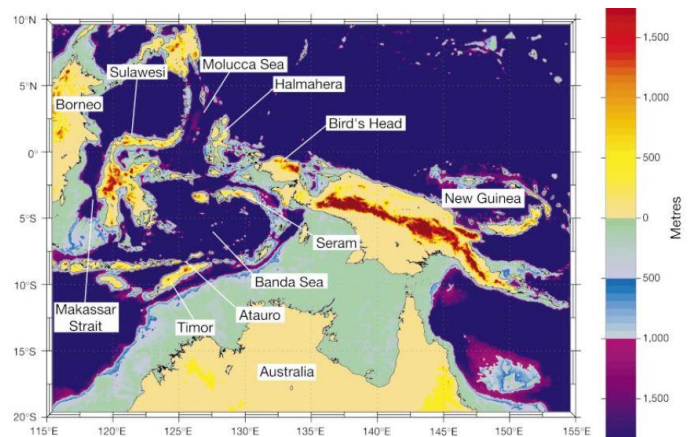
Indonesian Seaway

Tectonics involving the Indonesian Seaway likely contributed to cooling in the Pliocene. The Seaway, through which waters flow from the Pacific to the Indian Ocean, was wider and deeper five million years ago. The main pathway was likely through precursors of today's Molucca and Banda seas, between New



Guinea and Sundaland (the area that includes Sulawesi, Borneo, Java and Sumatra). Tectonic movements in the region are as rapid as anywhere else on Earth. The Molucca Sea is narrowing by about 100 km every million years [Cane, 2001] and becoming less deep as colliding ocean plates cause volcanic uplift and erosional sedimentation.

In addition to becoming more constricted, the Indonesian Seaway migrated across the Equator from the Southern to the Northern Hemisphere. Australia and New Guinea are moving together on the same oceanic plate northward at a rate of about 70 km every million years. Three to five million years ago, the northern coast of New Guinea was located 2°–3° south and to the east of its present location [Cane, 2001]. In the Early Pliocene, the old Molucca Sea entrance to the Indonesian Seaway was located *south of the Equator*. At that time, waters flowing westward into the Seaway drew Pacific Ocean waters from the South Pacific. Once the entrance migrated north of the Equator, Coriolis forces no longer directed warm waters from the South Pacific through the passage and into the Indian Ocean.



With their westward outflow greatly diminished, the warm Southern Hemispheric waters of the western Pacific were forced to join and enhance the surface currents that carry warm waters toward South America in the circulation pattern known as El Niño. Prior to 3 Ma, a permanent condition with fairly uniform sea surface temperatures across the low latitudes in the Pacific created a perennial El Niño [Federov, 2006]. After the contracture and relocation of the Indonesian Seaway an oscillation between El Niño and La Niña known as the El Niño-Southern Oscillation (ENSO) cycle began. When the ENSO is in its La Niña phase, much of the eastward flow of warm water is directed southward. Increased surface flows toward Antarctica increase Southern Ocean overturning and its cooling effect, lowering global temperatures. Perhaps the ENSO occurs when La Niña-phase warm water inflow to the Southern Ocean becomes excessive to a point in which overturning is curtailed. El Niño circulation allows time for Southern Hemispheric overturning to become reestablished. It appears that the transition from a permanent El Niño prior to the Indonesian Seaway closure to ENSO circulation in which La Niña cooling operates part of the time contributed additional cooling in the Pliocene.

The ENSO is a Pacific Ocean phenomenon. A similar Atlantic Multi-decadal Oscillation (AMO) is recognized as a 60-80 year cycle of fluctuating sea surface temperatures (SST) that occurs in the Atlantic Ocean. Perhaps the AMO originates with a cyclic strengthening and weakening of the AMOC? When overturning grows too active, excessive amounts of warm water are drawn from the North Atlantic and deep water formation is temporarily curtailed. European cools as the planet warms until, the AMOC returns to its more vigorous state.

Isthmus of Panama

The formation of the Isthmus of Panama was another likely cause of the accelerated cooling at the start of the Pliocene. Shoaling of the Isthmus of Panama, which began in the Mid-Miocene, had progressed to the point that the sill depth was a mere 150 meters by 6 Ma. Final shoaling began about 4.7 Ma, with final closure occurring about 2.5 Ma [Schmidt, 2007]. Prior to creation of the Panamanian land bridge, ocean currents rounding the top of South America spilled into the Pacific Ocean through the wide Central American Seaway. Closure of the Seaway cut off that exchange with the Pacific, leaving the Caribbean Sea with warmer and saltier water with which to fuel a greater Gulf Stream flow to the north [Kirby, 2008].

There is a natural tendency for the Atlantic Ocean to be saltier than the Pacific. A net export of water vapor from the Atlantic to the Pacific occurs due to the interplay of the Earth's wind

systems with its mountain ranges. The atmosphere transports water between the world's oceans through evaporation and rainfall. The American Cordillera blocks much of the temperate latitude westerly-wind systems from returning atmospheric vapor back to the Atlantic as rain. Additionally, the absence of mountains in Central America makes it possible for tropical easterly winds to carry water vapor from the Atlantic to the Pacific. This atmospheric transport of vapor away from the Atlantic Ocean leaves it with a higher salinity [Broecker, 2010, Chap 3].

The Isthmus of Panama strengthened meridional overturning circulation, particularly in the Atlantic. Absence of a Central American exchange with the Pacific shifted the balancing of Atlantic temperature and salinity differences almost entirely to the Southern Ocean. The strengthening of an interhemispheric circulation pattern in the Atlantic Ocean enhanced the delivery of warmer and saltier waters to the North Atlantic and Arctic Oceans. Subsequent increased overturning also enhanced its cooling effect.

To summarize, the timing of numerous geophysical events, along with their probable impacts on ocean circulation in general and MOC in particular, offer a good explanation for the broad trends of the Cenozoic Era's temperature curve derived from geologic evidence. Factors such as solar and orbital variations and levels of greenhouse gases can, at times, act as drivers, but more often are likely to act as reinforcing feedbacks. The role of meridional overturning circulation is unique in that it best describes a close link between the unidirectional trends of Cenozoic continental dispersal and Cenozoic cooling. Although continental drift is a slow, relentless process, some of the geophysical changes that result are anything but. Episodic events that change geography have caused the episodic, yet uniformly trending, changes in Earth's temperature history over the past 100-million years.

Northern Hemispheric Glaciations

Limited glaciation in the Northern Hemisphere had gone on for tens of millions of years prior to the Pliocene build-up which culminated in the occurrence, about one-million years ago, of large-amplitude glacial cycles, each lasting about 100,000 years. The growth of ever-larger ice volumes during glacial phases is easily equated with the ongoing decline in global temperatures that began in the Middle Miocene and continued (after a brief reversal) through the Pliocene and into the Pleistocene. The presence of major ice sheets at the Last Glacial Maximum (LGM) was associated with only a small drop in global average temperature. One recent study suggests temperatures at the LGM were a mere $4.0^{\circ}\text{C} \pm 0.8^{\circ}\text{C}$ cooler than today [Annan, 2013]. The

role that meridional overturning circulation played in lowering Earth's global temperature and causing the last great glaciations to grow large, may also offer an explanation as to what caused them to terminate with such catastrophic collapse sequences.

Deep-sea cores with their records of ice-rafting indicate Greenland possessed a more or less continuous ice sheet since 18 Ma, perhaps longer [Thiede, 2011]. By 4.6 Ma, the ice sheet had become large enough to extend over the entire shelf of southern Greenland. The Greenland Ice Sheet would repeatedly reach that massive size five times during the Pliocene and Pleistocene [Nielsen, 2013].

Expanded Northern Hemispheric glaciation beyond Greenland began in high latitude, mountainous regions in the Arctic. An early phase of ice growth likely occurred on and around Svalbard Island in the northern Barents Sea around 3.6 Ma. A transitional growth phase beginning about 2.4 Ma saw ice sheets expand from land and shallow coastal shelves into the southern Barents and northwestern Kara seas. At the same time, intermittent glacial expansions extending beyond coastal shelves are documented for the northern/western Barents Sea and off the northern coasts of Greenland and Canada. It seems there was a synchronous response of all circum-Atlantic and Arctic ice sheets to the downward slope of the temperature curve during the Late Pliocene [Knies, 2009].

The average ice volume in the Northern Hemisphere grew over the approximately million years between ~3.5 Ma and ~2.5 Ma. Total North American ice volumes fluctuated in close association with Earth's 41-Kyr orbital obliquity cycle [Lisiecki, Raymo, 2007]. The newly established ice sheets on the expansive land masses throughout the Northern Hemisphere were sensitive to the small changes in latitudinal insolation.

As cooling continued in the Pleistocene, North American glaciations inevitably grew in size and became centered mid-continent and to the east. At the same time ice excursions were reduced in Alaska, western Canada, and down the Cordillera [Duk-Rodkin, 2004]. This increase in ice volumes and eastward movement of glaciation is likely tied to increased overturning and its cooling effect. The increase in overturning and deep water formation also led to the shoaling of the thermocline. As cold deep waters further filled the oceans, inflows from the North Atlantic into the Norwegian Seas and Arctic Ocean through deeper passages such as the Gardar and Feni drifts ceased as bottom waters equalized on either side of the Greenland-Scotland Ridge (GSR). The topography of the GSR meant that waters flowing into the Arctic became spread over a

wider area and consisted of warmer, more saline surface waters that could flow over shallower shelves farther to the east [Hassold, 2006]. This further enhanced overturning, subsequent climate cooling and likely contributed to the eastward movement of glaciation centers.

Glaciation profiles change

Plio-Pleistocene glacial/interglacial cycles in the Northern Hemisphere first occurred with durations that closely matched Earth's 41-Kyr obliquity cycle. Interglacial conditions existed for the larger portion of each cycle, exhibiting a *positive skewness* in the $\delta^{18}\text{O}$ ice volume record [Lisiecki, Raymo, 2007]. Fluctuations in temperatures in the high latitudes caused by cyclic changes in Earth's tilt were sufficient to regulate the growth and reductions of the northern continental ice sheets.

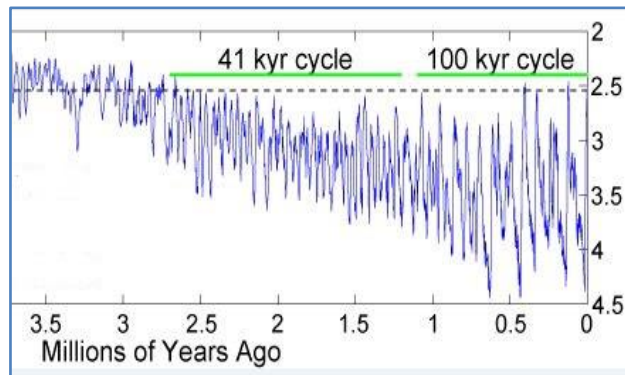
With each successive glaciation, continental ice sheets grew thicker and covered greater expanses, especially in the eastern half of North America. Self-sustaining mechanisms began to operate as ice sheets became larger. Albedo and CO_2 feedbacks further contributed to the size and longevity of ice sheets. As glacial conditions persisted for longer durations and occupied increasing proportions of each 41-Kyr cycle, the positive skewness value in the climate record lessened.

Larger ice sheets brought about a new dynamic to the decay process. Glacial retreat increasingly involved collapse events rather than simple melting. The *saw-tooth asymmetry* that became more evident in the $\delta^{18}\text{O}$ record, beginning around 2.5 Ma, reflects a more rapid collapse of glaciations in relation to their pattern of growth [Lisiecki, Raymo, 2007]. This new condition, where ice sheets rapidly diminished, served to keep glacial phases shorter than 20,500 years (less than half of a 41-Kyr cycle) for the roughly million year period between 2.5 and 1.4 Ma.

Starting about 1.4 Ma, the durations of glacial periods began to exceed those of interglacials [Lisiecki, Raymo, 2007]. The *skewness* of the isotopic climate curve changed from positive (interglacials lasting longer than glacials) to negative (relatively longer glacials). Once the durations of glacials became longer than half of the obliquity cycle, some of the ice accumulated during one cycle could "carry over" into the next. Starting ~1.4 Ma, Northern Hemispheric glaciations took on new characteristics and began a new growth phase.

The next half million years (~1.4 – 0.9 Ma) is appropriately called the Middle Pleistocene Transition (MPT). Glacial/interglacial cycles transitioned into ones that lasted longer than 41,000

years. In a short amount of time (geologically speaking), glacial/interglacial cycles increased to durations of ~100-Kyr. Post-MPT Ice sheets grew to enormous sizes until conditions necessary to halt and reverse further growth intervened. When this occurred, continental glaciations collapsed so catastrophically and



completely, the term Terminations is used to describe their demise. The transition from 41-Kyr to 100-Kyr cycles was not unique to the Pleistocene. The benthic $\delta^{18}\text{O}$ record indicates that, until the end of the Mid-Miocene Climatic Optimum (~14 Ma), Antarctic ice volumes also fluctuated in tune with 41-Kyr obliquity cycles [Huybers and Tziperman, 2008]. When Miocene cooling resumed, Antarctic glaciers further expanded and glacial cycles transitioned to having ~100-Kyr durations [Holbourn, 2005].

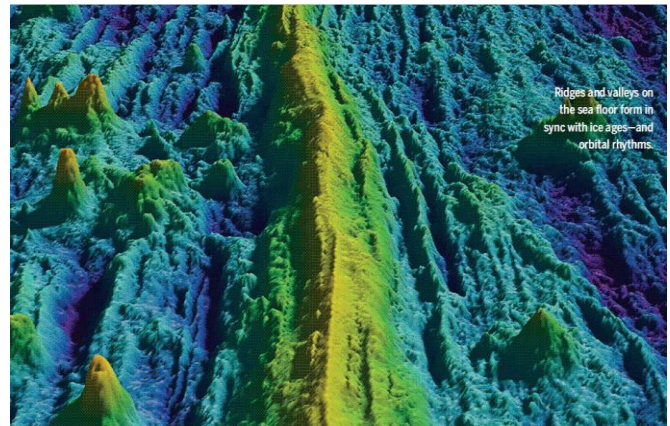
Post-MPT Terminations – inevitable system collapse sequences

After the MPT (~0.9 Ma) ice sheets throughout the Northern Hemisphere repeatedly survived multiple tilt cycles. In addition to their longevity, there is another distinguishing characteristic of Post-MPT glaciations. Northern ice sheets catastrophically collapsed, and glacial periods terminated, with a regularity that approximated every 100,000 years. Because of its tight correspondence with the geologic record, the 41-Kyr cycle appears to have played a key role in regulating ice volumes *before* the MPT. After the MPT, glaciations, in effect, lasted about 2.5 tilt cycles, apparently with those cycles having a minimal role in the timing of 100-Kyr glaciations. Evidence from the last glaciation (the Wisconsin) shows us that four semi-related mechanisms may have combined to initiate termination sequences.

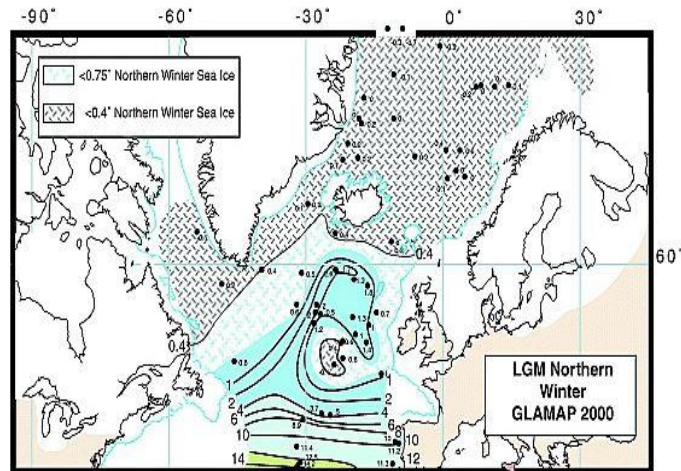
1) Isostatic depression lowers mass balance and promotes unstable shelf ice. The viability of the Northern Hemispheric ice sheets was undercut by their enormous size. The Laurentide ice sheet slowly depressed the land underneath. The isostatic rebound that has occurred since the continental glaciers melted gives evidence that the land at some locations, lying under the weight of thousands of feet of ice, was depressed by almost 1000 feet [Bluemle, 2005], lowering the altitude of the surface of the ice sheet without reducing its thickness. Warming at the glacial surface due to its lower altitude may have been a factor in reducing the sustainability of the ice. The mass balance (the measure of annual accumulation compared to the annual melting) of

Northern Hemispheric ice remained positive through numerous 20,000 year precession cycles, but turned negative as ice sheets grew to their largest size and reached their most southern points [Abe-Ouchi, 2013]. Isostatic depression in the interior also caused coastal shelves to rise. The combination of raised coastlines and low sea levels leading into the Last Glacial Maximum (~26 Kya) allowed glacial ice to expand over the continental shelves. When the Laurentide ice sheet began to melt, interior isostatic rebound caused coastal lands to subside at the same time sea levels were rising. Ice sheets on the continental shelves quickly disintegrated. It is likely that isostatic depression and massive excursions of ice over coastal shelves exerted the same destabilizing effects on all Post-MPT glaciations.

2) Heightened ocean ridge volcanism increases carbon dioxide levels. Recent studies of the seafloor on either side of the Australian-Antarctic Ridge show that levels of volcanic activity at the ridge varied in cycles of roughly 100,000 years [Crowley et al., 2015], similar to glacial cycles in the Late Pleistocene glaciations. Early theories suggested that reduced pressure as sea levels fell led to increased volcanic activity at mid-ocean ridges (a.k.a. spreading centers and divergent plate boundaries). Evidence from the eastern side of the Pacific Ocean supports this hypothesis. It appears there has been enhanced hydrothermal activity on the East Pacific Rise during the last two glacial terminations [Lund, 2016]. A more recent study at the Juan de Fuca Ridge suggests that increased volcanism occurs when sea levels are high, or on the rise [Middleton, 2017]. It is plausible that emissions of CO₂ increased with the heightened volcanism. Mid-ocean volcanism and rising levels of atmospheric CO₂ may have occurred when sea levels were lowest or on the rise; at the time of maximum glaciation or as ice sheets began to melt and become increasingly unstable. This may be yet another factor contributing to the collapse of the Great Ice Age glaciations. A recent study of stomata on fossil leaves once living at the K/T boundary indicates that CO₂ levels may have been lower than previously thought at a time of global warmth [Hand, 2017], revealing that a moderate increase in CO₂ can be associated with considerable warming.



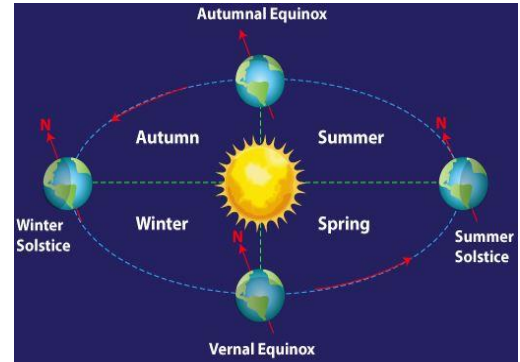
3) *Reduced MOC induced cooling at the peak of glaciation.* As the planetary ice volume expanded, sea levels dropped. The flow of North Atlantic surface water over the shallow sills into the Nordic Seas would certainly have been greatly diminished. In turn, reduced meridional circulation would diminish the efficiency of the planet's oceanic cooling mechanism. Overturning circulation in the ocean was physically cut off, not only by lower sea levels, but also by sea ice throughout much of each year. The final advance of the Laurentide ice lobes changed circulation patterns such that sea ice formed south of the Iceland Faeroe Ridge, perhaps reaching well into the North Atlantic, during glacial winters [Sarnthein, 2003]. By the time North American ice lobes reached their southernmost boundary, they were now subject to warming forces competing with the dwindling effectiveness of the albedo and CO₂ cooling feedbacks that had supported their earlier growth.



Climate warming was well underway when ice sheets in both North America and Antarctica began their retreat about 20,000 years ago [Steig, 2013]. That global warming was likely primarily due to earlier changes to ocean circulation patterns that reduced MOC and, in turn, allowed warming to occur. A recent study [Chen, 2016] reveals that MOC circulation in the North Atlantic (AMOC) was beginning to slow 22,000 years ago and was substantially reduced during Heinrich Stadial 1 (HS1, 18.0 to 14.6 ka). It should also be noted that CO₂ levels had increased a few thousand years before the LGM [Jahn, 2005]. The extent to which those increases drove a portion of the atmospheric warming versus the amount that the increases in CO₂ were caused by warming itself must wait a better understanding of the roles that each of the destabilizing factors played in terminations. It is likely that the rise in pre-LGM temperatures was substantially driven by a combination of climate dynamics with the increased level of carbon dioxide acting as a strong positive feedback.

4) *Precession is a destabilizer and acts as a pacemaker of glacial terminations.* The orientation of Earth's axis precesses in a cycle having duration of 25,771.5 years. However the precession that affects the timing of Earth's distance from the Sun in relation to its seasons is not

so precise. Earth's elliptical orbit itself is subject to a rotation called apsidal precession. The combination of the axial and apsidal precession cycles have a duration which averages approximately 23,000 years. Apsidal/axial precession cycle dictates that about every 23,000 years, Earth will be at the perihelion (closest to the Sun) of its orbit during the Northern Hemispheric winter. This was the case about 22,000 years ago. Northern seasons were less extreme with warmer winters and cooler summers [Imbrie & Imbrie, 1979]. When the glacial retreat began, about 19,000 years ago, the transition toward longer and warmer summers was underway. Of the two orbital parameters, precession and obliquity, the former seems to have the greatest effect on insolation in lower latitudes, whereas the tilt cycle has a greater influence on insolation farther north at about 65° N [Imbrie & Imbrie, 1979]. The change in insolation at the southernmost lobes of the Laurentide ice sheet seems to have been an important factor in starting the collapse of North American glaciation [Clark, 2009].



Post-MPT Glacial Life Cycles

A confluence of warming processes that developed as ice sheets grew into states of high vulnerability was the ultimate cause for initiating repeated deglaciation sequences over the last million years. These triggering mechanisms, together with the confluence of ice-eliminating factors, such as lessening albedo (caused by decaying and shrinking ice), weakening coastal buttressing (flotation of shelf ice), and rising CO₂ (due to effervescence from warming oceans), interacted until the continental ice sheets all but disappeared. In the Northern Hemisphere, the key attribute of glaciations over the last million years (excepting Greenland) was their near total wasting away.

The relatively short periods of the interglacials were times of renewed global cooling. After each main sequence of glacial collapse, abrupt swings in climate occurred during the faltering restart of a robust MOC pattern of global ocean circulation. Once MOC was well reestablished, the remainder of each interglacial was a time when temperatures declined until reaching baseline Pleistocene levels. The inevitable collapse scenario followed by renewed cooling was reliably repeated seven or eight times until climatic conditions lead to yet another round of Northern Hemispheric glaciation.

Conclusion

The GIMOC principle provides a plausible explanation of the process that produced the episodic downward trend of global temperatures starting before, and continuing through, the Cenozoic Era. The long-held belief that continental drift has played a role in Earth's cooling is now buttressed by the revelation that robust MOC has a cooling effect and that the dispersal mode of continental drift over the last 100-million years has generally strengthened global MOC.

The fact that global temperatures and atmospheric carbon dioxide levels have tracked together adds to our understanding of climate change on all time frames. Atmospheric CO₂, when its level is forced, can be a *driver* of temperature change. This is obviously happening today, and has happened in the past. Throughout much of Earth's history, oceanic overturning has directly caused temperature changes, whereupon CO₂ has acted as an *amplifier* of temperature changes. Without the amplifying feedback provided by the greenhouse gas, the Cenozoic Cooling might have been less dramatic and the amplitude of glacial/interglacial cycles might have been smaller or even nonexistent.

This paper introduces an overlooked natural process (oceanic overturning and cold water sequestration) that provides exciting insights about Earth's long cooling trend and about the dynamics of Post-MPT glacial/interglacial cycles. Any student of Ice Age theories will, no doubt, have noticed a lack of discussion about Milanković elliptical cycles. Just over 40 years ago, an article published Science Magazine showed great promise for achieving a breakthrough in understanding the Ice ages [Hays, Imbrie, Shackleton, 1976]. In their paper entitled "Variations in the Earth's Orbit, Pacemaker of the Ice Ages", James Hays, John Imbrie and Nicholas Shackleton reported on geologic evidence spanning 400,000 years that indicated glaciations in the Northern Hemisphere had each lasted about 100,000 years. The authors pointed out that those durations closely matched the length of Earth's elliptical cycles calculated by astronomical mathematician Milutin Milanković. Although they did not offer an explanation for a mechanism linking the geologic and astronomic cycles, they felt that one would be forthcoming. They believed ongoing research would resolve issues of lag times and allow the cycles to be synchronized, whereupon a mechanism would reveal itself.

By 2004, the record of temperatures and glaciations had been extended back ~800,000 years. Carl Wunsch studied the statistical associations between the ever-improving geologic record and the Milankovitch cycles. In searching for a direct correspondence, he reported that "The fraction of the

record variance attributable to orbital changes never exceeds 20%”. Moreover, he found that any 100-Kyr cycle control by quasi-periodic insolation forcing is likely “indistinguishable” from chance [Wunsch, 2004]. In other words, the geologic and astronomic cycles, may be similar, but they just don’t match. Ice sheets that are within maximal margins are sensitive to Earth’s obliquity (~41 Kyr) cycle. It is also likely that Earth’s various precession cycles will create a tendency for termination events to cluster around multiples of about 20,000 years. Beyond that, continuing to search for stronger causal links is not likely to be productive as it appears that glacial initiations are the inevitable consequence of renewed interglacial cooling back to Pleistocene base-line temperatures, with those interglacials taking place after “system collapses” known as Terminations.

The GIMOC theory is in the tradition of uniformitarian geology. By presenting an explanation that relates Earth’s cooling temperature to a cycle of continental disbursement, it is not necessary to invoke ideas of “mode” changes in order to explain the “onset” of Northern Hemispheric Glaciations, nor to explain the “transition” from 41-thousand to 100-thousand year glacial cycles. An analogous “41-to-100 Kyr” transition happened in the Antarctic in the Mid-Miocene [Holbourn, 2005]. In addition, post-MPT ~100 Kyr glaciations did not occur in a “delicate balance” under slim odds – they occurred reliably 7 out of 7 times. Glaciations and their cycles no longer appear to be unlikely climate anomalies. They are simply the natural consequence of a natural cooling phenomenon.

Implications for the Anthropocene

It appears the tremendous release of CO₂ into the atmosphere with its disproportionate warming effect in high latitudes is also causing a substantial lessening in the strength of global MOC. Reduction of deep water formation (due to warming and freshening from ice melt water) is not only slowing down the AMOC, but is accompanied by a strengthening of the Labrador Current [Maillet, 2007]. Recent findings of increased upwelling along the Benguela and Humboldt currents [García-Reyes, 2015] may indicate a similar increase in Southern Hemispheric cold water surface flows and reduced overturning. The reduction of cold water *sequestration*, coupled with an increased flow of cold water *at the surface* toward low latitudes, will both contribute to dialing back Earth’s cooling mechanism. It appears the direct warming resulting from the anthropogenic release of carbon dioxide into the atmosphere will be accompanied by additional warming from a previously unrecognized feedback.

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