Role of MOC on Ancient Climates / Implications for Anthropogenic Climate Change

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Abstract

Our increasingly robust history of ancient climates indicates that high latitude glaciation is the ultimate product of an episodic cooling trend that began about 100-million years ago rather than a result of a yet-to-be identified modal change. Antarctic geography (continent surrounded by ocean) allowed ice to develop prior to significant glaciation in the Northern Hemisphere (ocean surrounded by land), but global ice volume generally increased as Earth cooled. The question of what caused the Ice Ages should be reframed as to "What caused the Cenozoic Cooling?" Records tell us that changes in temperature and CO2 levels rise and fall together, however it is not clear when CO2 acts as a driver versus when it is primarily an indicator of temperature change. The episodic nature of the cooling trend suggests other more dynamic phenomena are involved. It is proposed that oceanic meridional overturning circulation (MOC) plays a significant role in regulating Earth's surface temperature. Robust MOC has a cooling effect which results from its sequestration of cold waters (together with their increased heat-absorbing potential) below the surface. Unable to better absorb equatorial insolation for great lengths of time, oceanic deep waters are not able to fully compensate for the heat lost by warm-water transport to Polar Regions. A lag-time between cooling and subsequent warming yields lower operating temperatures commensurate with the strength of global MOC. The long-term decline in global temperatures is largely explained by the tectonic reshaping of ocean basins and the connections between them such that MOC has generally, but not uniformly, increased. Geophysically Influenced MOC (GIMOC) has caused a significant proportion of the lowering of global temperatures in the Cenozoic Era. Short-term disruptions in MOC (and subsequent impacts on global temperatures) were likely involved in Late Pleistocene glacial termination events and may already be compounding present anthropogenic CO2 induced warming. The immediate impacts of AMOC strength on North Atlantic and European temperatures coupled with the delayed and opposing effects on global temperatures offer explanations for phenomena including: Younger Dryas, Little Ice Age and the bipolar seesaw. (Please see supplemental file: Oceanic Geophysics & History of Climate(ver #02).pdf listed below.)

The Role of Meridional Overturning Circulation (MOC) on Ancient Climates
and implications for Anthropogenic Climate Change

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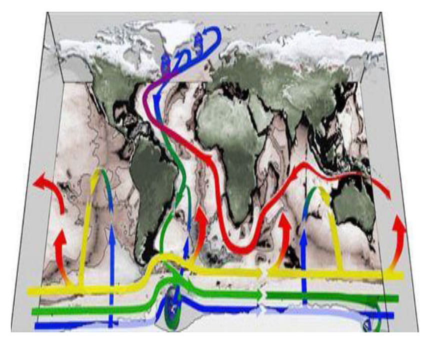
What is "MOC" (Meridional Overturning Circulation) ?

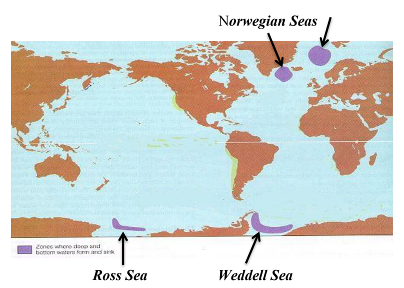


MOC: poleward flowing surface currents of warm/salty water (along meridians), which, once chilled, sink (i.e. overturn) and return to lower latitudes as very cold/deep waters.

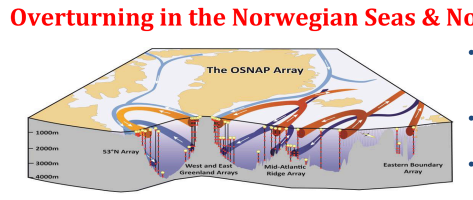
Overturning takes place primarily in 4 locations.

- Norwegian Seas (2 areas)
- Weddell Sea
- Ross Sea

(Note: overturning sites are fairly shallow which may be a factor in enabling downwelling to occur.)



Overturning in the Norwegian Seas & North Atlantic



- Water penetrating into the Nordic Seas & Arctic Ocean flows primarily *at the surface*.
- The volume of cold water flowing out is equals warmer water inflow.
- Overturning determines the split between surface and deep outflows.

Graphic courtesy of http://www.o-snap.org/ Overturning in the Subpolar North Atlantic Program

What Drives Overturning?

- **Buoyancy loss of surface water is so substantial, it becomes dense enough to sink and displace water at the bottom.**
- **Water density is maximized by a combination of becoming very cold while remaining relatively salty.**
- **The 4 regions where overturning takes place provide needed conditions where salty water can be quickly chilled.**

Very cold air & shallow bottoms

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.

Salty surface waters

Relatively saline surface waters in high latitudes originate from equatorial regions where warm waters retain salt concentrated by high evaporation rates (example: the Mediterranean Sea). Geography allowing the existence of meridional circulation is a key factor underlying the existence of MOC. Another factor is the absence of (or reduced) ice-melt "freshening" that, otherwise, dilutes surface waters.

What's the difference between OHT and MOC?

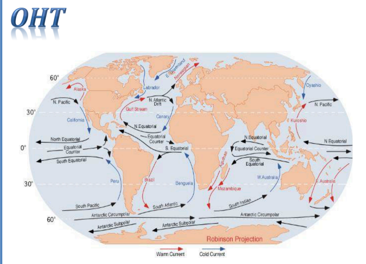
OHT – Ocean Heat Transport:

2D (two-dimensional) circulation that relocates warm and cold ocean waters, *but does not alter the total heat content of those surface waters*

MOC – Meridional Overturning Circulation:

3D (three-dimensional) circulation that: 1) relocates warm and cold ocean waters and; *2) allocates cold waters between the surface and the deep*

OHT



Source: http://oceanmotion.org/global-surface-currents.htm

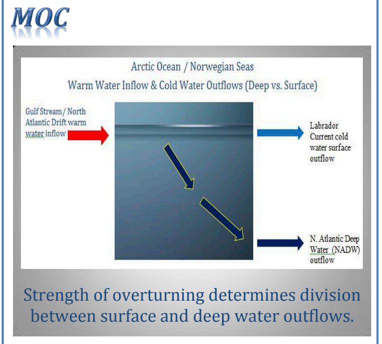
Ocean Gyres are circular surface currents driven by ***winds*** and influenced by ***Coriolis forces***.

Ocean Circulation affects climates at various latitudes and localities – shifting rain belts, deserts and changing coastal ecosystems.

(Long ago, alligators and breadfruit trees existed on Ellesmere Island. Likewise today, palm trees do well on the west coast of Scotland.)

Gyres merely ***redistribute heat*** over the surface; they ***do not change total average temperature***.

MOC



Strength of overturning determines division between surface and deep water outflows.

Overturning creates a "drawing effect" that adds to the wind forces that drive poleward currents.

⇨ ***MOC increases surface warmth at Poles.***

Overturning reduces cold surface outflows and weakens flow of equatorward surface currents.

⇨ ***MOC reduces surface chill at Equator.***

MOC's role in adjusting Global Average Temperature

ROBUST MOC = COOLER PLANET

- **Active MOC adjusts *Earth's Energy Budget* such that Earth's surface achieves balance at lower temperatures.**
- **Weak MOC allows cold waters to flow to lower latitudes *at the surface*, thereby absorbing the additional insolation that compensates for the heat lost near the Poles.**

Earth's Energy Budget

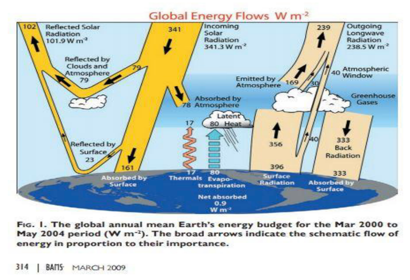


Fig. 1. The global annual mean Earth's energy budget for the Mar 2000 to May 2004 period (W m⁻²). The broad arrows indicate the schematic flow of energy in proportion to their importance.

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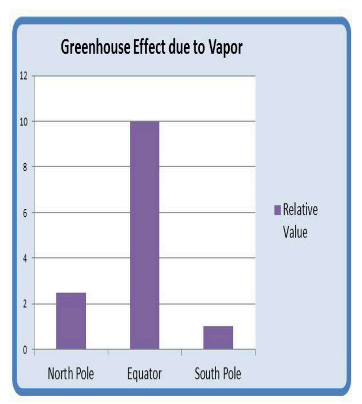
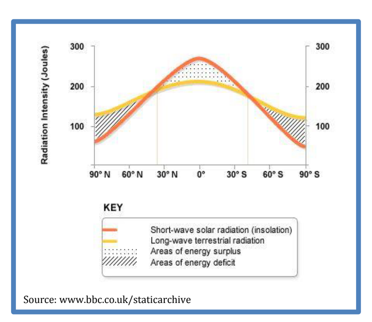
- ***Incoming*** radiation from the sun is a constant 341 Watts per Sq. Meter.
- ***Outgoing = Incoming:*** (i.e. Reflected @102 W m² + Longwave @239 W m² equals Solar Radiation @341 W m²)
- Average surface temperatures adjust to a level that maintains a ***balance*** between Input & Output.
- *Should conditions alter the amount of energy absorbed or emitted, surface **temperatures adjust** to new levels.*

- The Sun is a ***main sequence star*** that is gradually ***getting warmer*** on a timescale of 100s of millions of years (~1% / 100my).
- Earth's energy budget (and surface temperature) reacts mainly to:
  1) Changes in ***atmospheric transparency*** (i.e. Greenhouse Gases) and;
  2) The ***allocation of cold waters above and below the Euphotic Zone.***

Earth's Uneven Atmospheric Blanket

- **Water vapor contributes much to the greenhouse effect, but is not evenly distributed.**
- **Vapor is far more concentrated in the tropics than at the poles.**
- **Other GHGs (e.g. CO_2) are evenly distributed in the atmosphere.**
- **Water vapor's low influence at the poles means other GHGs are proportionally more influential in the high latitudes.**





Source: www.bbc.co.uk/staticarchive

Polar Deficits due to:

- **Thin** Atmospheric Blanket
- **Warm** surface water from Equator
- **Emissions** exceed Absorption

Equatorial Surpluses due to:

- **Thick** Atmospheric Blanket
- **Cool** surface water from Poles
- **Absorption** exceeds Emissions

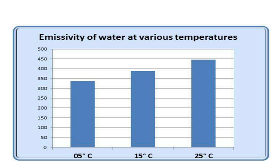
Changes in CO_2 levels have the most impact in Polar Regions where they modify the thermal blanket and affect outgoing emissions.

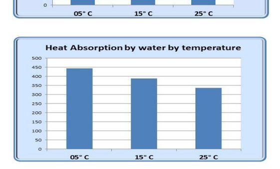
Changes in MOC activity have the most impact near the Equator where changes in ocean surface temperatures affect how much incoming insolation gets absorbed.

The Stefan-Boltzmann Law

Stefan–Boltzmann law: "Total radiant heat energy emitted from a surface is proportional to the fourth power of its absolute {Kelvin} temperature."

- This physical reality is why *warm* ocean surfaces *emit* heat at higher rates.
  ⇨ **Polar Regions** *shed more heat* when warm waters flow in at the surface.
- Conversely, *cool* ocean surfaces *absorb* heat at higher rates.
  ⇨ **Equatorial** oceans *soak up more heat* when covered by cool waters.





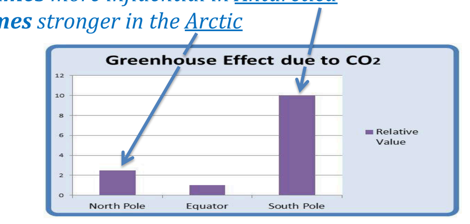
Regarding MOC, the following principle applies: "The greater the volume and time cold water is sequestered below the surface, unable to restore heat lost in the high latitudes, the cooler Earth's ongoing surface temperature will be."

Implications for the Anthropocene

Oceanic feedback amplifies warming from rising CO_2

The impact of CO_2 is greater at the Poles

Polar CO_2 GH warming is proportionally greater than at the Equator:
⇨ ***~10 times** more influential in Antarctica*
⇨ ***~4 times** stronger in the Arctic*

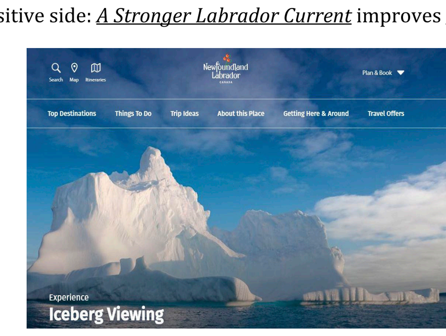


- ***High atmospheric moisture*** is responsible for much of the heat retention capacity of the atmospheric in the ***low latitudes.***
- Polar air lacks moisture – ***CO_2 occupies a greater portion of the GHGs*** that determine the insulating capacity of the atmosphere ***over the high latitudes.***
- Because atmospheric CO_2 levels rise and fall equally everywhere, ***Changes in CO_2 levels have proportionally greater impacts in high latitudes.***

Rising CO_2 is *slowing* the AMOC (Atlantic MOC) which, in turn, is *amplifying* Global Warming.

- Rising Atmospheric CO_2 levels are causing ***excessive warming*** in the Arctic.
- Arctic warming *reduces downwelling* – (Rapid chilling is suppressed)
  – (Salinity lowered by melting ice)
- Reduced downwelling *decreases inflow* from Gulf Stream/North Atlantic Drift
- Less inflow of salty waters *further decreases salinity and downwelling*
- Reduced warm water inflow *further reduces heat losses* – ***more warming***
- Reduced downwelling *increases surface outflow* – (stronger Labrador Current)
- Cooler surface waters in tropics *increase heat uptake* – ***more warming***
- ***IOW: Processes slowing the AMOC are causing additional warming!***

- On the positive side: *A Stronger Labrador Current* improves *Canadian Tourism*



Rising CO_2 is having similar impacts in the Southern Hemisphere

- ***Increased upwelling*** is observed along the ***Humboldt & Benguela Currents***.
- Upwelling occurs as ***Coriolis forces*** direct surface currents away from shore.
- Strengthened cold water "eastern boundary currents" suggests a ***weaker MOC***.
- ***A Southern Hemispheric MOC slowdown will add to Global Warming.***

The Bad News:

The high impact rising CO2 has near the Poles weakens MOC. Reduced MOC acts as an amplifying feedback to compound the direct warming effect CO2 has on global temperature.

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Potential Good News:

Curtailing the rate of injection of CO2 into the air (if done soon enough) could quickly foster partial recovery of overturning. As MOC strengthens, it will initiate reverse feedbacks that can grow to reverse some of the present-day warming.

The Relationship *between* Tectonics and Climate

Plate Tectonics** & **Orogeny** have lowered **CO_2** & enhanced **MOC

Drifting Continents have been in *"dispersal mode"* for 100 million years.

- ***Tectonic plate movements*** have reformed the *number, size, shapes and geography of ocean basins*. Changes to the connections between basins and the topography of the sea floor began in the *Late Cretaceous* and continued throughout the *Cenozoic Era*.
- ***Geophysical changes*** tended to episodically increase Meridional Overturning Circulation (MOC), contributing to the *episodic cooling* characteristic of the Cenozoic Era.

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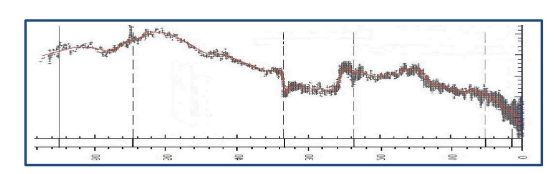
- ***Alpine-Himalayan & Laramide (Rocky Mountain) orogenies*** and the associated plateau uplifts increased silicate weathering and led to a gradual drawdown of atmospheric CO_2.
- The gradual lowering of CO_2 also contributed to the *cooling trend*.

Tibetan Uplift and CO_2 drawdown ⟹ Global Cooling

- Uplift of the ***Tibetan Plateau*** occurred throughout much the Cenozoic Era and was likely accompanied by ***increased silicate weathering*** …
  (Calcium Silicates + H_2O + CO_2 ⟹ Calcium + Bicarbonates + Silicic Acid)
  … This could have ***removed CO_2*** from the atmosphere and contributed to a ***portion of the long trend of temperature decline***.
- The ***proportion of cooling*** attributable to lowered CO_2 should reflect a ***steady, uniform, downward trend*** reflective of the ***slow and steady nature of tectonic uplift***.
- ***The episodic (not always downward) trend of the Cenozoic Cooling suggests that other factors were also involved – ones more closely tied to the episodic geophysical changes associated with Plate Tectonics.***

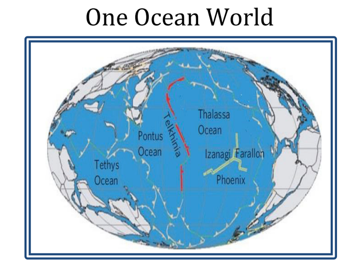
The "Zachos" Cenozoic Era Temperature Curve (65 Ma → Today)



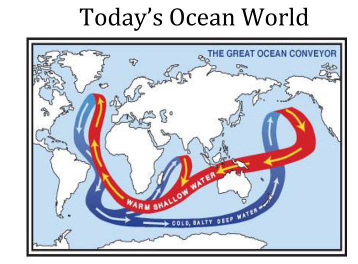
Increased MOC and Cold Water Sequestration ⟹ Global Cooling

- Starting in the Cretaceous and continuing throughout the Cenozoic Era, the predominantly ***one-ocean world*** of the Panthalassic "Superocean" evolved into the modern ***multi-ocean world*** of today.
- A new geography and geophysical ocean structure allowed development of ***meridional currents*** and created locations conducive to ***overturning***.

One Ocean World



Today's Ocean World



→ "If you build it, MOC will come." ←

Tectonic Events that shaped MOC & Climate

Mid-latitude Passages – (episodic closings)

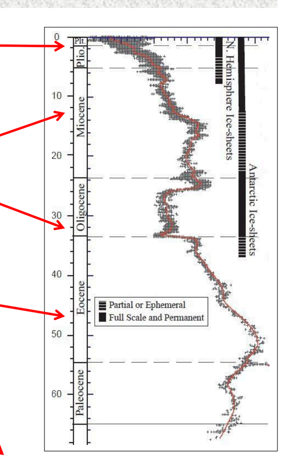
- Central American Seaway / Isthmus of Panama
- Indonesian Seaway – narrowed & drifted north
- E. & W. Mediterranean – closings & openings

Southern Gateways – (subsidence & openings)

- Tasmanian Passage – (key event for ACC)
- Drake Passage – (very influential on ACC)
- Agulhas Passage – (earliest deep connector)
- Kerguelen Plateau – (subsides as India drifts)

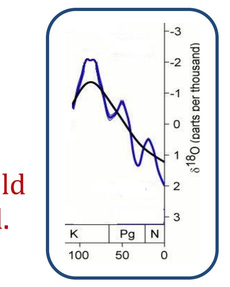
Ocean Building – (additions & new geography)

- Development of N. & S. Atlantic Oceans
- One Atlantic as separate basins join
- Growth & Consolidation of Indian Ocean



The Cenozoic Cooling: Turning Points & Discontinuities

- Earth began cooling ~100 Ma.
- The Cenozoic opened with a warming.
- After ~52 Ma, episodic cooling took hold and persisted without a major reversal.



Ocean building – MOC - Temperatures

***Atlantic Ocean** – (joined basins reach both poles)*

- North & South basins were ***separately growing wider*** ~100 Ma.
- African/American separation ***connected north & south basins*** by ~70 Ma. *{Warm waters were reaching Ellis Island – "alligators & breadfruit trees".}*
- ***"Ocean Conveyor"*** circulation became ***increasingly possible*** between poles.

***Indian Ocean** – (expansion & consolidation)*

- Basin ***split by Indian subcontinent & trailing island chain*** in Early Cenozoic.
- India crossed Equator & collided with Asia. Islands sank (forming 90° E Ridge).
- This created a ***unified Indian Ocean*** with an ocean gyre after ~40 Ma.

***Southern Ocean** – (growth as continents separate)*

- ***Open ocean areas expanded*** as Africa, Australia & South America separated.
- ***Antarctic coastal shelves subsided*** as continents separated.
- Circulation from low latitudes increasingly ***enabled overturning***.

Southern Gateways – Opening Circulation

- ***Agulhas Passage*** – (between S. Africa & Antarctica)
  - Deep water passage widened and deepened as Africa moved north.
  - Increased water exchange between Indian & South Atlantic Oceans.
- ***Kerguelen Plateau*** – (Antarctic shelf remaining after India separation)
  - Plateau subsided as India and trailing archipelago drifted north.
  - Potential for circum-Antarctic flow increased.
- ***Drake Passage*** – (between Tierra del Fuego and Antarctic Peninsula)
  - Islands sank and deep passage developed as continents separated.
  - Enabled increasing deep water flow from Southern Ocean into Atlantic.

Widening and subsidence increased circulation. As oceans became better connected, potential for meridional currents and overturning increased.

- ***Tasmanian Passage*** – (Key to a completely circular Southern Ocean)
  - Opened quickly – strategic sea floor block ***subsided & rotated (~34 Ma)***.
  - Allowed Antarctic Circumpolar Current (ACC) to flow unobstructed.
  - Closely associated with major cooling at Eocene/Oligocene boundary.

Antarctic ice, having existed at high elevations in the interior for tens of thousands of years, transitioned into continental ice sheets on East Antarctica {and West?} after the "Oi-1" cooling.

Demise of the Tethys Sea & Miocene Climate

→ The *Early Miocene (~23 Ma)* Tethys Sea was a major source of saline waters flowing into the Indian Ocean.

→ Shuffling ocean plates (India's collision) intermittently closed, reopened, and finally permanently closed the East Tethys Sea by the *Mid-Miocene (~15 Ma)*.

→ *Miocene temperatures* were likely affected by consequent changes to Indian Ocean salinity and meridional circulation.

Mid-latitude Passages & the Final Big Chill

Indonesian Seaway	Mediterranean Sea	Isthmus of Panama

Events at three (3) locations began ~10 Ma and culminated by the end of the Pliocene (~2.6 Ma). All played roles in ***altering ocean salinity profiles*** that led to ***increased overturning*** and significant ***decreases in global temperatures***.

Indonesian Seaway: Narrowing and northward drift over the Equator restricts Pacific flow into the Indian Ocean. Instead, ENSO circulation causes warm West Pacific waters to flow east (El Niño) or south (La Niña). Southward flows ***increased MOC and cooling.***

Mediterranean Sea: Closing and subsequent reopening at Gibraltar lowered and then increased Atlantic salinity. The effects show up as Early Pliocene warming followed by rapid cooling due to lasting ***increases to AMOC strength***.

Isthmus of Panama: Closing of the Central American Seaway increased salinity of the Atlantic Ocean by eliminating the shortcut that had allowed the faster exchange of waters with the Pacific Ocean. A stronger/saltier Gulf Stream ***increased the AMOC***.

Dynamics of the Great Ice Age Glaciations

Pleistocene baseline temperatures made repeated northern glaciations inevitable*

* (excepting the current period of anthropogenic warming)

Terminations are key to understanding Post-MPT glacial/interglacial cycles

Northern Hemispheric Glaciation (NHG)

- ***Major NHG needed colder global temperatures*** – only started ~3 Ma, long after ice sheets were well established on Antarctica.
  ⇒ Land surrounding ocean vs. ocean surrounding land ⇐
- ***Early glaciations remained below maximum limits***. Nor did they completely disintegrate. Glacial extents fluctuated in rhythm with Earth's ***~41,000-year obliquity (tilt) cycle***.
  ⇒ Antarctica also had 41-kyr tilt cycles in the Miocene. ⇐
- In North America, early glaciations were ***greater in the west***. Ice gripped the Cordillera for 100s of thousands of years at a time.
  ⇒ Yosemite was completely filled by ice 1 Ma {but not since}. ⇐
- Pleistocene cooling continued and the grip of ice grew. The rates of ice sheet expansion and contraction remained fairly even.

The Mid-Pleistocene Transition (MPT)

- **Shoaling of the Thermocline** – *(Cold waters fill the abyss)*
  - Deep waters ***equalized*** between the North Atlantic and Arctic Ocean. {*Abyssal inflows through Gardar & Feni Drift zones halted by 2.6 Ma*}
  - During MPT (~2.4 – 0.9 Ma) inflows confined to ***shallower*** depths.
  - Nordic Seas received a ***more vigorous***, broader spread of warm, salty water – with an ***eastward shift*** of the mass of inflow.
  - ***Overturning increased*** dramatically – so did ***global cooling.***
- **North American ice sheets grow** – *(Centers move eastward)*
  - Ice sheets ***grew to outer margins*** – less sensitive to tilt variations.
  - ***Cordilleran*** ice sheets diminish as ***Laurentide*** expands.
  - Northern glaciations ***transition*** from ~41- to ~100-Kyr cycles.
  - Growth of Northern Hemispheric ice sheets are limited by a new ***system dynamics*** consisting of at least four (4) variables which ***consistently*** lead to system collapses called ***Terminations***.

The Great Ice Age of the last 800,000 years has the form of seven separate glaciations, each terminating in an "interglacial". Initially unsettled, interglacial climates soon entered a cooling phase that inevitably reinitiated another glacial period. The full glacial/interglacial cycles each lasted about 100,000 years.

Glacial Terminations – *(Four Causes)*

- ***Isostatic Depression:*** Sinking land lowers the altitude of an ice sheet's surface. ***Regelation*** prevents a maximal sheet from regaining lost height. ***Warmer*** conditions tip mass balance.
- ***Ocean Ridge Activity:*** Lower sea levels reduce pressure and increase ocean ridge venting. Increased release of ***CO_2*** causes ***warming*** that coincides with glacial maximums.
- ***MOC Weakening:*** Extended sea ice cover physically reduces MOC, especially the AMOC. Reduction of ***MOC*** dampens Earth's cooling mechanism, leading to greater ***warmth***.
- ***Orbital Precession:*** Mid-latitude precessional ***warming*** is strongest at vulnerable ice fronts. When the precession effect is strong, its ~21,000 year cycle helps to fine-tune Termination sequences to coincide with the ~100,000 year cycles of the post-MPT.

Interglacials – (Returning to Pleistocene baseline)

- ***Abrupt climate change:*** Terminations are times of catastrophic floods and iceberg armadas. Turbulent disruptions of strengthening MOC produce large temperature fluctuations.
- ***Interglacial cooling:*** When glacial collapse ends, ocean circulation returns to stability and robust MOC cools climate once again.
- ***Reglaciation:*** inevitably occurs – The record is a reliable 7 out of 7!

Considering the PETM

The Paleocene/Eocene Thermal Maximum (~55 Ma) came near the end of a 10-Myr warming that followed a 30-Myr cooling. Some ocean currents reversed during the 170,000 year PETM. Did disruption of MOC kick off a CH_4 melt and/or amplify a CO_2 caused warming spike?

The Oceans' Role in Determining Earth's Climate

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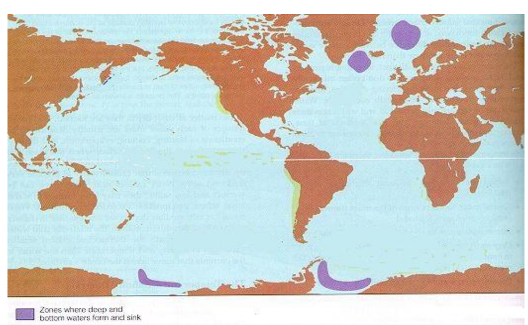
Abstract

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?

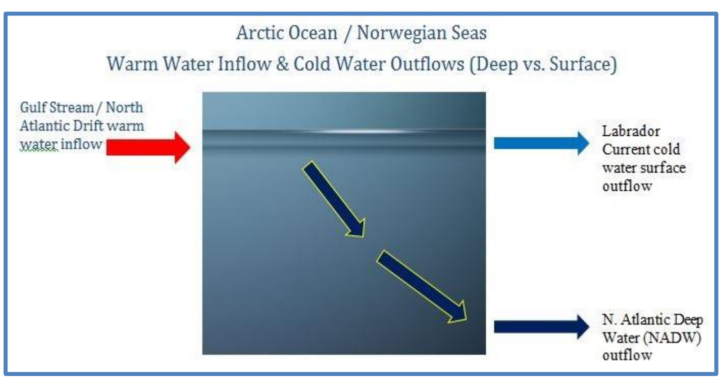
Meridional Overturning Circulation or MOC can be described as poleward flowing surface currents of warm/salty water (along meridians), which, once chilled, sink (i.e. overturn) and return to lower latitudes as very cold/deep waters. Overturning takes place in two locations in the Northern Hemisphere (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.

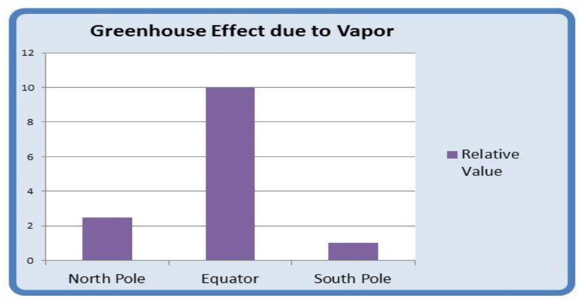
Perhaps the best way to explain how robust MOC results in lowered surface temperatures is to first understand that surface-only circulation (without overturning), otherwise referred to as Ocean Heat Transport (OHT), has very little direct impact on Earth's ongoing temperature. The Stephan-Boltzmann Law 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).

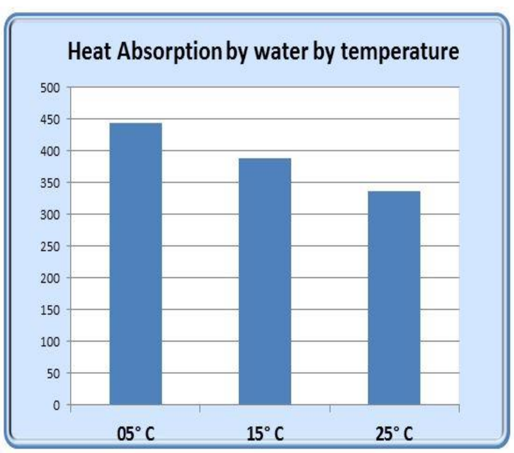


The existence of strong overturning (with consequential strong cold water outflow at depth) results in a lessened cold water outflow toward lower latitudes at the surface – i.e. the Labrador Current is weakened. Studies in the past few decades estimate that deep water outflow through the Labrador Sea 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 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.



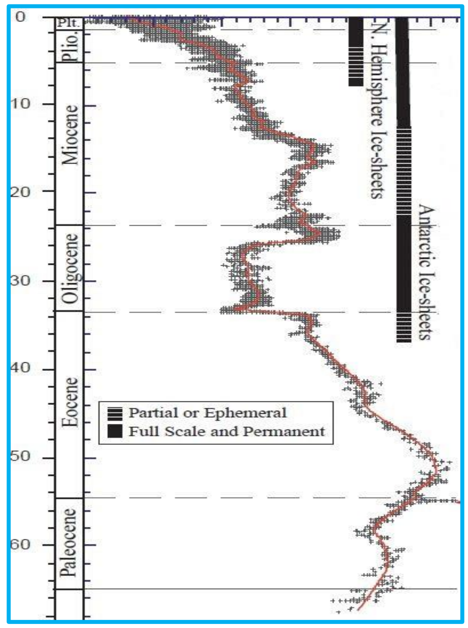
Equatorial vapor creates a greenhouse effect ~4 x the Arctic and ~10 x Antarctica [Schmidt, 2010].



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.



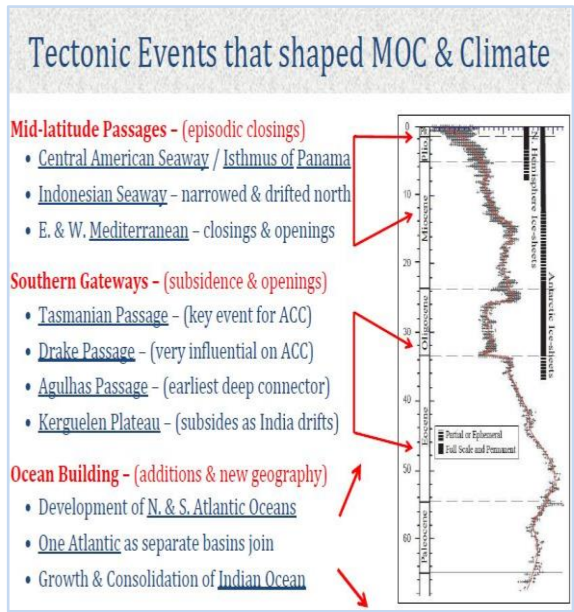
(Zachos, 2001)

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 CO_2 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 CO_2 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 CO_2 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 CO_2 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.

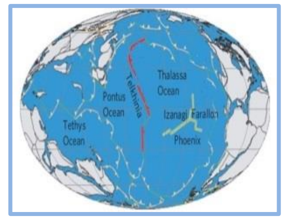
Geophysicists and oceanographers have been assembling the chronologic history of ocean plate movements all the while climatologists have been chronicling temperature variations. Tectonic events appear to coincide with new temperature trends – throughout the Cenozoic tectonics has often been associated 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 patters 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.



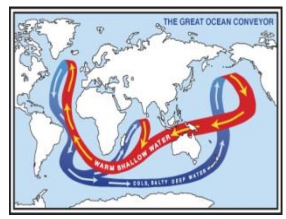
Earth's 100-million-year temperature decline is likely the product of two phenomena that each directly drive down temperatures and also act to amplify the strength of the other. Cooling from CO_2 drawdown can help stimulate MOC – reductions in ocean temperatures resulting from robust MOC cause additional removal of CO_2 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.

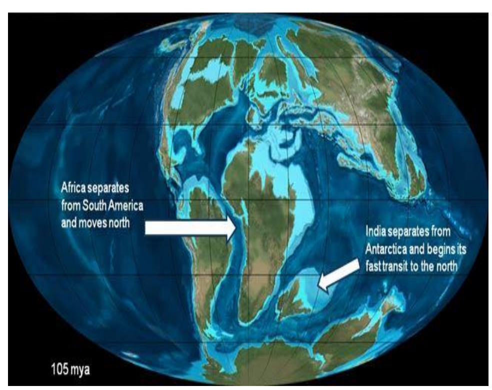


In the Late Cretaceous, Earth was still a single-ocean world consisting of two megacontinents – Gondwana and Laurasia that were separated by the Tethys Seaway – and the ***Panthalassic Ocean*** which covered more than half the globe. The Panthalassic had a circulation pattern consisting merely of latitudinal 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

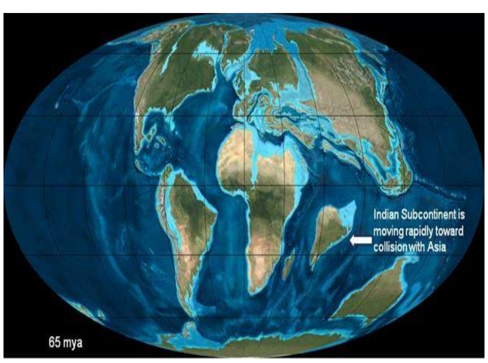


north. The gap between the formerly separate parts of the Atlantic Ocean widened at a rapid pace.

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.

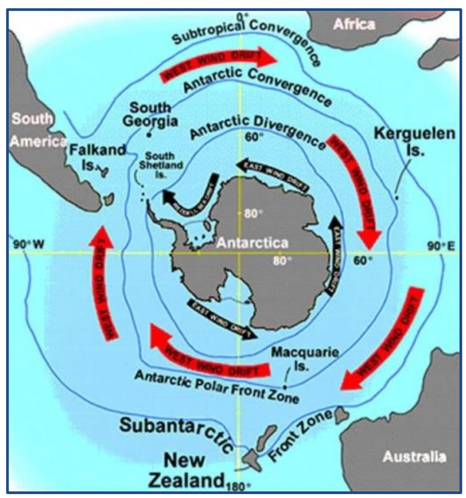
Global temperatures were on the upswing leading into the Cenozoic Era. Some of the impetus toward cooling was likely offset by tectonics in the ***Indian Ocean***. Beginning in the Late Cretaceous, India separated from Antarctica and began its journey northward, trailed by a chain of volcanic islands 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 (CH_4) release caused by thawing of tundra and submerged stores of frozen methane locked in submerged continental shelves. It is entirely plausible that a major CH_4 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.

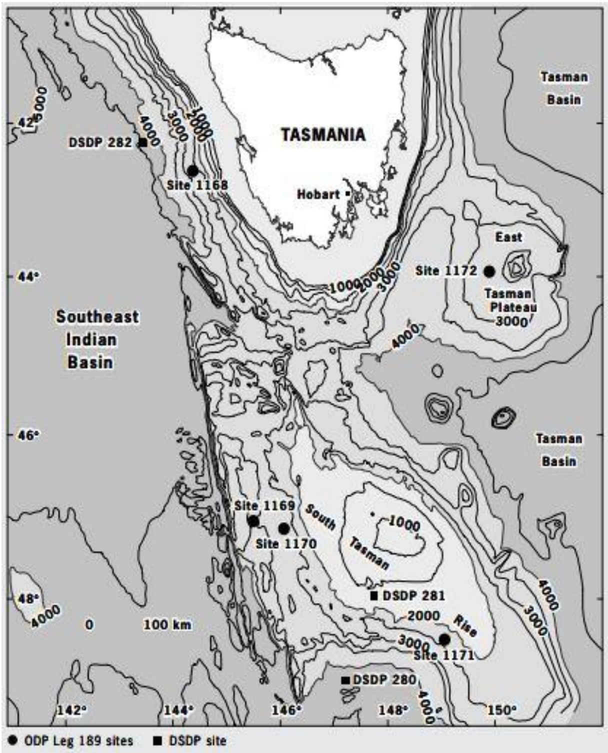
Southern Gateways



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

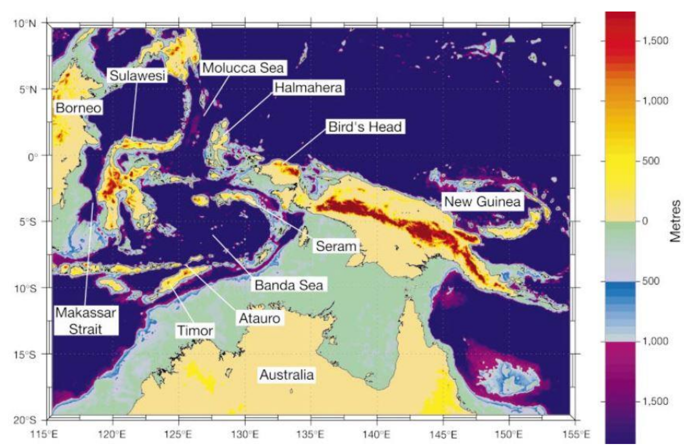
The connection between the Mediterranean Sea and Atlantic Ocean was closed at the end of the Miocene (~5.6 Ma), thereby eliminating a major source of warm, salty inflow to the Atlantic [Kirk-Davidoff, 2007]. The reduced salinity would have weakened overturning, reduced the strength of the AMOC, and contributed 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° C ± 0.8° 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

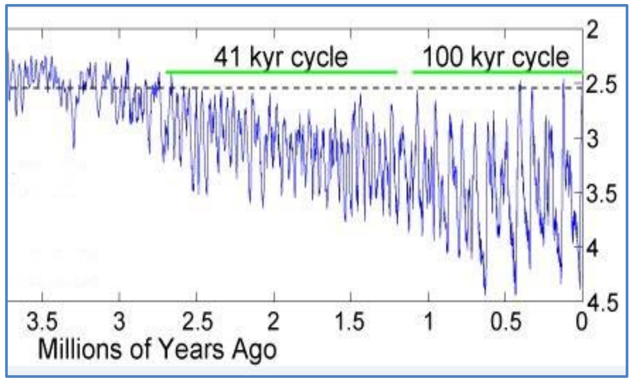
Plio-Pleistocene glacial/interglacial cycles in the Northern Hemisphere first occurred with durations that closely matched Earth's 41-Kyr obliquity cycle. Interglacial conditions existed for the larger portion of each cycle, exhibiting a *positive skewness* in the $\delta^{18}O$ ice volume record [Lisiecki, 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 $\delta^{18}O$ 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 $\delta^{18}O$ 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].



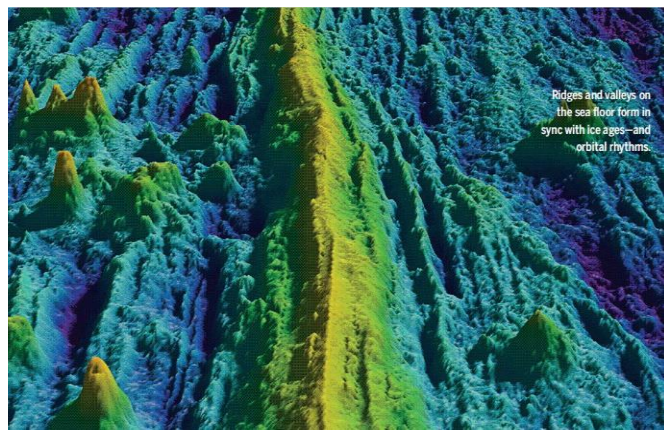
Post-MPT Terminations – inevitable system collapse sequences

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.

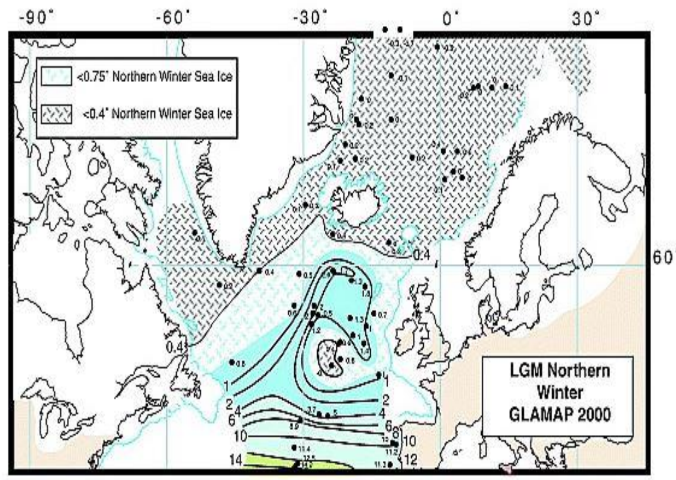
1) Isostatic depression lowers mass balance and promotes unstable shelf ice. The viability of the Northern Hemispheric ice sheets was undercut by their enormous size. The Laurentide ice sheet slowly depressed the land underneath. The isostatic rebound that has occurred since the continental glaciers 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 CO_2 increased with the heightened volcanism. Mid-ocean volcanism and rising levels of atmospheric CO_2 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 CO_2 levels may have been lower than previously thought at a time of global warmth [Hand, 2017], revealing that a moderate increase in CO_2 can be associated with considerable warming.

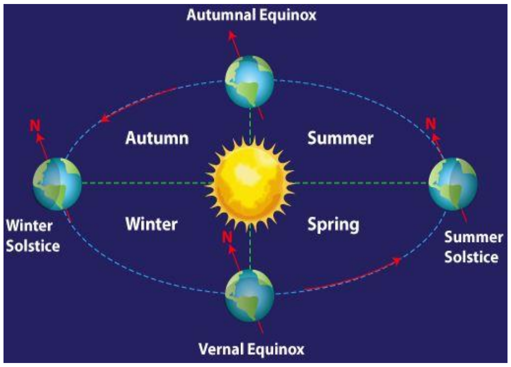


3) Reduced MOC induced cooling at the peak of glaciation. As the planetary ice volume expanded, sea levels dropped. The flow of North Atlantic surface water over the shallow sills into the Nordic Seas would certainly have been greatly diminished. In turn, reduced meridional circulation would diminish 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 CO_2 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 CO_2 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 CO_2 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 CO_2 (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 CO_2, 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 CO_2 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 Wunch 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 CO_2 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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Oceanic overturning slowdown may amplify CO_2 caused warming

Strengthened tropic-bound cold water currents increase insolation uptake

By **Malcolm Cumming**

Observation and modeling of the Atlantic Meridional Overturning Circulation (AMOC) system indicates it has been slowing down over the last few decades (1) by anywhere from 15% (2) to perhaps ~20% (3). The Gulf Stream is the northward flowing component of the AMOC. Evidence of a slowdown in Gulf Stream flow is corroborated by two recently recognized phenomena. The salinity of the Nordic Seas has been lowered by a decreased inflow of warm/saline waters from the North Atlantic (4).

There is another clue pointing to a slowing of Atlantic circulation. A portion of the considerable rise in sea levels along much of the US East Coast is probably attributable to a weakening of the North Atlantic Gyre (5). The Coriolis-forced circular flow of a gyre causes water levels to rise in the center – correspondingly sea levels along coastlines (outside the gyre) are lowered. When an oceanic gyre weakens, internal sea levels fall and coastal sea levels rise.

At first glance, it might seem counterintuitive that despite a weakening of the Gulf Stream and its North Atlantic Drift extension and the slowdown of the AMOC in general, the Labrador Current is getting stronger (6). The increased flow has not been overlooked by the tourism industry of Labrador and Newfoundland (7). Viewing icebergs now rivals whale-watch excursions in popularity. The explanation for the increased outflow of Arctic cold water *at the surface*, despite a reduced inflow, is that deep water production and outflow have been reduced.

The process that creates deep water is called *overturning*. Surface water is transformed to make it dense enough to displace all waters below and sink to the bottom. Water density is maximized when it is both extremely cold and relatively saline. The Nordic Seas and locations off the Ross and Weddell Seas provide the extreme cold necessary for rapidly chilling surface waters. Those three locations are also well-placed to receive inflows from meridional surface currents that deliver salty (by way of also being warm) waters from low latitudes. Should either high latitude warming or a reduction of salinity occur, overturning is weakened. That seems to be happening today. Not only is there a slowdown of the AMOC, recent findings of increased upwelling along the Benguela and Humboldt currents (8) likely indicate a similar increase in cold water surface outflows due to reduced overturning in the Southern Hemisphere.

Rising CO_2 and reduced overturning

The reduction of high latitude overturning, especially in the Arctic, is a result of the rise in atmospheric CO_2 levels, now over 400 ppm. Carbon dioxide has a far greater impact on temperatures in the Polar Regions than in the tropics. The reason is due to the relative differences made by water vapor and CO_2 in contributing to greenhouse effects in high and low latitude atmospheres. Water vapor is a very effective greenhouse gas (GHG). At the Equator, high vapor creates a greenhouse effect about four (4) times stronger than in the Arctic – around ten (10) times stronger than in the Antarctic (9). In contrast, insulating capacities of polar atmospheres are influenced to a greater extent by other (non-vapor) GHGs such as CO_2. Atmospheric carbon dioxide levels are disbursed evenly around the globe. Therefore, as CO_2 levels rise, they have a proportionally greater influence in increasing polar greenhouse effects. This accounts for much of today's disproportionate rise in Arctic temperatures.

Strong Arctic warming eliminates the first requirement of overturning – rapid chilling of surface water at a rate fast enough to remove enough heat to allow it to reach maximum density before it sinks away from the surface. But it does more. The rapid increase in atmospheric temperatures has triggered a massive increase in ice melt from Greenland glaciers. The fresh water that pours into the Arctic Ocean and Norwegian Seas dilutes the salinity of surface waters, further slowing the overturning process. In turn, the slowdown of deep water production reduces the draw of inflowing warm, saline waters, further reducing the salinity of surface waters.

Of the water that flows into the Norwegian Seas and Arctic Ocean, the slowdown in overturning increases the proportion that flows out at the surface and decreases that which flows out at depth. Studies in the past few decades estimate that deep outflow through the Labrador Sea may range between 14 and 17 Sverdrups (10). (1 Sverdrup = 1-million cubic meters/second.) Deep/bottom waters formed by overturning (e.g. North Atlantic Deep Water (NADW), Antarctic Bottom Water (AABW)) remain below the thermocline for a thousand years or more. Decreased deep water production means that greater amounts of cold water will be returned more quickly to lower latitudes at the surface. Rather than being sequestered for great lengths of time, surface waters are readily able to exchange thermal content with the atmosphere and space.

The Stephan-Boltzmann Law

An increase in the presence of cool surface waters at various locations in the lower latitudes affects the rate of heat absorption from solar radiation. We may be more familiar with the stated finding of the Stephan-Boltzmann Law which says that heat emitted from a surface is proportional to the fourth power of its {absolute} temperature. The math behind the formula also involves a difficult to fathom constant with a value of 5.6704 times 10 to the -8th power. The practical meaning of the law is that water radiates heat proportionally to its temperature – the warmer the temperature, the more heat is radiated. The law of proportionality also means that cooler water radiates less heat.

Conversely, the Stephan-Boltzmann Law tells us that cool water can absorb insolation at a higher rate than warm water. In other words, whereas heat *emission is proportional* to surface temperature, heat *absorption is inversely proportional* to surface temperature. Cold water absorbs heat more readily than warm water. Put another way, cold water has a higher heat-absorbing capacity than warm water.

The amount of energy required to raise one gram (1 cubic cm) of water by 1° Celsius is loosely defined as one (1) calorie. However, the Stephan-Boltzmann Law of proportionality demands the definition of a calorie must also refer to the initial temperature of the water being warmed. For example, it takes less energy to increase a gram of cool water starting at 14.5°C by 1°C than a gram starting at 24.5°C. These differently "sized" calories are more aptly called 15° and 25° calories respectively. The relative differences between these calories can be easily determined by comparing the (greater) rise in temperature accumulated by cold versus warm water (given similar volumes and the same time and amount of applied heat).

Increased low latitude ocean surface warming

The reduction of high latitude overturning means there is an ongoing switch between cold water return flows at depth and greater present-day return flows at the surface. The strengthening of the Labrador Current, together with the increased upwelling associated with the Benguela, Humboldt, Canary and California eastern boundary currents (8) and their presumed strengthening, is bringing increased volumes of cool surface waters to Equatorial latitudes. The result will be an increase in the amount of insolation absorbed at the surface and ultimately added to the heat content of the oceans.

The increased capacity for low latitude ocean surfaces to absorb heat is merely the inverse of the more intuitive, and perhaps more widely accepted, concept that western boundary currents such as the Gulf Stream and Agulhas Current deliver warm water to high latitudes where an increased rate of heat loss acts to cool temperatures. In effect, the slowdown of the AMOC is telling us that a countervailing warming in the low latitudes is being reestablished that is partly offsetting the cooling that takes place near the Poles.

Direct measurements of surface flows and temperatures in the subtropical and tropical regions of the North Atlantic, together with modeling of oceanic circulation under various levels of high latitude overturning should help confirm the validity of the concepts presented in this article. It is important to determine if there is an unrecognized feedback that is amplifying the direct warming resulting from rising atmospheric CO_2 levels. Upon further investigation, we may well find that the directly CO_2-caused reduction in oceanic overturning is expanding the flow of cold surface waters (with their heightened heat absorbing potential) to the tropics which, in turn, causes the low latitude oceans to absorb heat at a higher rate and further warm the world's oceans.

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