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

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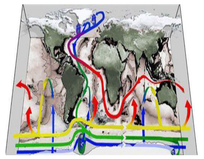
What is "MOC" (Meridional Overturning Circulation) ?

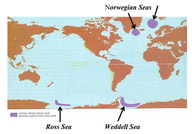


MOC: poleward flowing surface currents of warm/salty water (along meridians), which, once chilled, sink (i.e. overturn) and return to lower latitudes as very cold/deep waters.

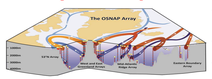
Overturning takes place primarily in 4 locations.

- 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

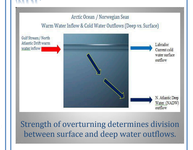
Ocean Gyres are circular surface currents driven by ***winds*** and influenced by ***Coriolis forces***.

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



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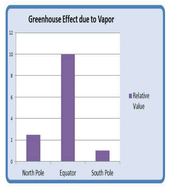
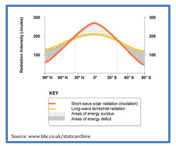
- ***Incoming*** radiation from the sun is a constant 341 Watts per Sq. Meter.
- ***Outgoing = Incoming:*** (i.e. Reflected @102 W m² + Longwave @239 W m² equals Solar Radiation @341 W m²)
- Average surface temperatures adjust to a level that maintains a ***balance*** between Input & Output.
- *Should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





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

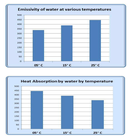
Changes in CO_2 levels have the most impact in Polar Regions where they modify the thermal blanket and affect outgoing emissions.

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

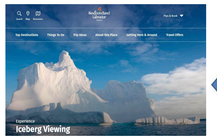
The impact of CO_2 is greater at the Poles

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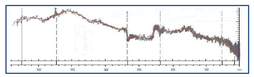
- ***Alpine-Himalayan & Laramide (Rocky Mountain) orogenies*** and the associated plateau uplifts increased silicate weathering and led to a gradual drawdown of atmospheric CO_2.
- The gradual lowering of CO_2 also contributed to the *cooling trend*.

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.***

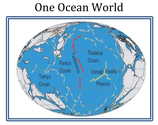
The "Zachos" Cenozoic Era Temperature Curve (65 Ma → Today)



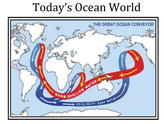
Increased MOC and Cold Water Sequestration ⇒ Global Cooling

- 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)

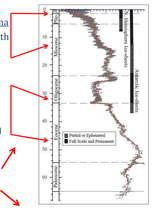
- Central American Seaway / Isthmus of Panama
- Indonesian Seaway – narrowed & drifted north
- E. & W. Mediterranean – closings & openings

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)

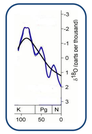
Ocean Building – (additions & new geography)

- 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?