Connecting the State of Meridional Overturning Circulation to Human Global Food Security: The Consequences of A Redistribution of Ecosystems in Response to Weakening[1]

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Abstract: As global temperatures rise due to increasing concentrations of greenhouse gasses in the atmosphere, melting in Antarctica and Greenland is accelerating, initiating feedback systems that will result in record losses in sea and land ice by the end of this century if left unabated. The freshening of polar waters changes the production of deep-water masses such as the Antarctic Bottom Water and the North Atlantic Deep Water, which rely on salinity and temperature gradients to form. Thermohaline Circulation, dependent on these gradients, transports heat, nutrients, and carbon around the globe, but is disrupted as freshwater forcing from ice melt reduces the capacity for overturning of the Atlantic Meridional Overturning Circulation (AMOC). As the AMOC weakens, it changes the trajectory of the Gulf Stream, which produces a southerly shift to the Intertropical Convergence Zone (ITCZ), altering the temperature of the lower atmosphere and thus precipitation over most of the Northern Hemisphere. Multidecadal and multiannual atmospheric circulation patterns are also affected, increasing the intensity and prevalence of storms in some regions, and drought conditions in others. Such climatic changes can have implications for food security through variations in land and water availability for agriculture, and through changes to ocean circulation that alter upwelling and marine primary productivity. Many countries that would be affected are the least developed and are already, or most ~~at~~ risk of becoming, food insecure.

Key Words: Atlantic Meridional Overturning Circulation, distribution of marine and terrestrial ecosystems, human global food security, Thermohaline Circulation, Global Conveyor Belt, freshwater forcing, Dansgaard-Oeschger events

List of acronyms used in the paper.

Atlantic Meridional Overturning Circulation (AMOC)
El Niño Southern Oscillation (ENSO)
Intertropical Convergence Zone (ITCZ)
Meridional Overturning Circulation (MOC)

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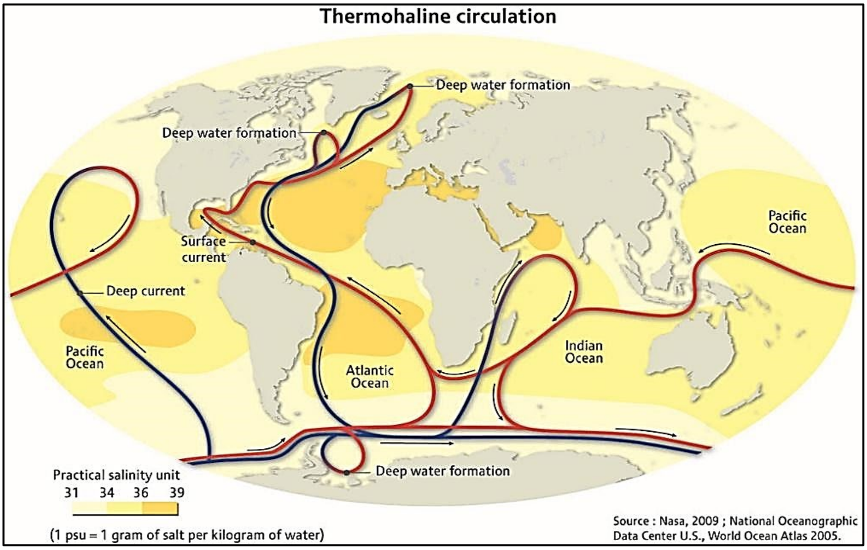
Introduction

The ocean surface is unevenly heated as differing angles of incidence vary incoming solar radiation, causing more efficient heating of the surface at low latitudes, and subsequently lower efficiency as latitude increases. The result is an excess of heat at lower latitudes, and a deficiency of heat at high latitudes. The Global Conveyor Belt, also known as Thermohaline Circulation, is the combination of deep and surface ocean currents that facilitate poleward transportation of equatorial heat, thereby compensating for the uneven heating of the surface. Nutrients and carbon also depend on this system for transport around the globe. Thermohaline circulation produces mixing of the entire water column via density differences in water masses due to variations in temperature and salinity. Seawater density increases with colder temperatures and greater salinity, and decreases with less salinity and warmer temperatures, thus cold, more saline water sinks, and warm, fresher water remains at the surface. The North Atlantic Deep Water mass forms as ice freezes out of the cold, polar waters of the Northern Atlantic, increasing salinity as water molecules combine form a solid and leave salts behind in the liquid. This is the major point of downwelling where Thermohaline circulation "begins" and is the starting point for the Atlantic Meridional Overturning Circulation (AMOC). The North Atlantic Deep Water flows South across the equator where it meets, and flows over, the Antarctic Bottom Water which has similarly formed in the Southern Ocean. There it splits, moving into both the Indian and Pacific Ocean basins. The Northern parts of both basins are sites of upwelling of large masses of bottom water, which fuels productivity in those areas. At the surface, the upwelled waters warm and travel South to circumscribe the Antarctic, and North through the Atlantic, dissipating heat to the polar regions. Thus, the Thermohaline Circulation (or Meridional Overturning Circulation) is responsible for transporting excess equatorial heat poleward, and benthic nutrients to the Pacific and Indian Ocean surface waters (Figure 1).

Of great importance to the US and Europe is the AMOC component of the Global Conveyor Belt, and specifically the Gulf Stream current, as this is responsible for maintaining climate as we know it along the US Eastern seaboard and much of Europe. Mild winters and temperate summers are a result of the Northern transport of excess heat received at the equator by the Gulf Stream current, the surface component of the AMOC that moves warm waters Northward along the Eastern coastline of North America, across the Atlantic towards Europe, ending in the Arctic Ocean to begin the cycle again. Great Britain is roughly the same latitude as Siberia, but a similar climate is ameliorated by the effects of this current. As the Gulf Stream passes Northern Europe, it cools and sinks, becoming part of the North Atlantic Deep Water. The sinking of this water mass creates a pressure gradient that pulls the Gulf Stream along its course, a positive feedback system. Consequently, an increase or decrease in the strength of the AMOC would be associated with a corresponding increase or decrease in the flow of the Gulf Stream (Figure 1), and concomitant changes in regional climate.



Source : Nasa, 2009 ; National Oceanographic Data Center U.S., World Ocean Atlas 2005.

Figure 1. Thermohaline circulation showing the approximate areas of deep-water formation in North Atlantic and Southern Ocean. Warm surface currents are denoted with red lines, and cold deep currents with blue lines.

Primary productivity in the oceans is limited to the photic zone, the upper 200m of water, as most wavelengths of light are absorbed or scattered below that point. The density-driven meridional overturning of the oceans carries downwelled, oxygen rich surface waters to benthic organisms, while nutrients from decayed organic matter on the ocean floor are brought to the surface through upwelling, providing nutrients essential for producers and surface dwellers. Important upwelling also occurs via wind circulation as diverging surface waters create a gravitational gradient allowing cold deep waters to rise (Figure 2). This tends to happen along coastlines and thus are the sites for the most productive fishing grounds (Figure 3). The thermocline, the ocean layer where temperature changes quickly with depth, varies seasonally and latitudinally and plays a part in mixing of the ocean as well, as decreased depth to the thermocline is associated with greater upwelling.

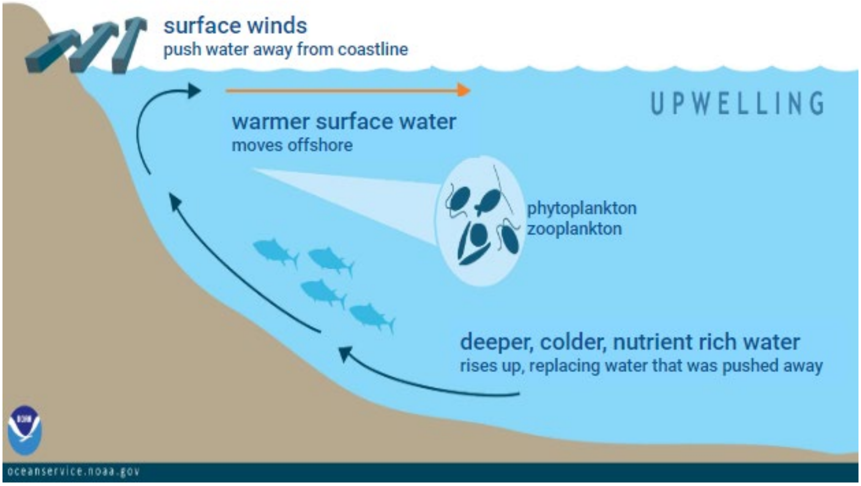


Figure 2. Upwelling. Surface water divergence creates a pressure gradient that allows cold, deep water full of nutrients to rise to the surface (NOAA 2005, with minor aesthetic changes).

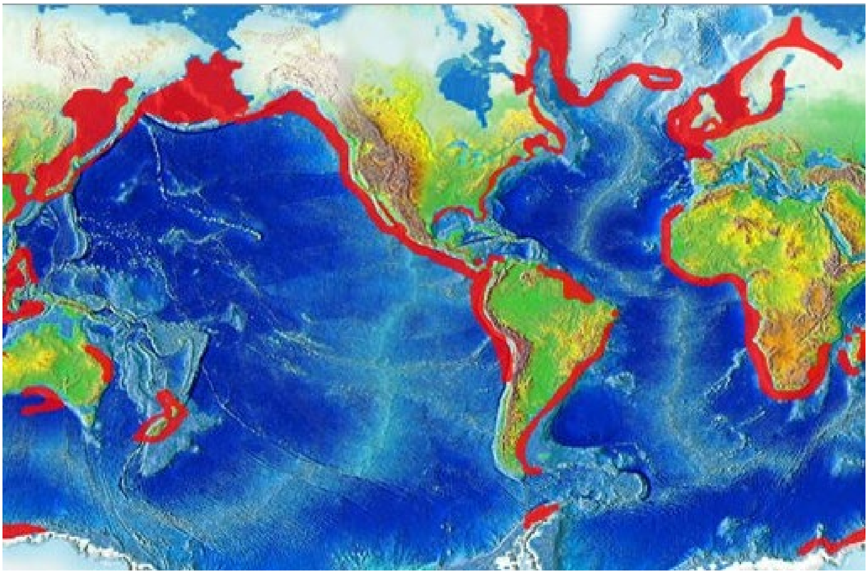


Figure 3. Areas in red denote major sites of coastal upwelling (NOAA 2005).

The concern considered by this paper is that changes in climate that would accompany a slowing of the AMOC will have a wide range of direct and indirect effects on the world food supply. This literature review will explore evidence, both paleoclimatic and modeled, of climate change induced changes to sea level, oscillations, and deep-water formation, investigate evidence of current changes observed in the strength of Meridional Overturning Circulation (MOC), and evaluate the pursuant effect on marine and terrestrial ecosystems. Using those results, the possible effects on food security due to disruptions in agriculture and fisheries in the most vulnerable countries around the world will be explored.

Freshwater Forcing

The bulk of research addresses freshwater forcing as the predominant variable in determining the strength of the AMOC. Freshwater forcing refers to the influx of fresh meltwater that would be associated with warmer polar temperatures, reducing the salinity, and thus inhibiting deep-water mass formations, weakening the MOC, and affecting the poleward distribution of heat. Sverdrups (Sv), a unit of flow of a volume of water, is used to measure overturning; 1 Sv = 10^6 m^3 s^{-1}. As stated above, the formation of deep-water masses creates a pressure gradient that pulls surface waters downward and produces overturning circulation. The temperature variations between surface and deep-water that would cause buoyancy changes are not present in polar waters, as heating efficiency is low, effectively eliminating the thermocline. Thus, salinity becomes the determining factor in density differences. The surface waters moving poleward tend to be high salinity as they are heated equatorially, increasing evaporation. Therefore, addition of freshwater at the poles through runoff, increased precipitation or melting of land or sea ice, decreases salinity and has a significant effect on the strength of overturning (Lago and England 2019).

Paleoclimatic evidence for climate effects of weakening AMOC

Studies of oxygen isotopes from subtropical Atlantic drill cores and Greenland ice cores document changes in climate over the past 80,000 years correlated to weakening and strengthening of the AMOC (Figure 4). A study of the entire length of the Greenland Ice-core Project, Summit core, revealed large degrees of variations in climate over the past 250,000 years, indicating that instability rather than stability is the norm (Dansgaard et al. 1993). Sediment and planktonic foraminifera data, dating back 130,000 years from the North Atlantic, reveal coarse-grained dropstone layers approximately every 11,000 years. These deposits most likely occurred as icebergs carried their glacial sediments southward before melting, providing evidence for colder ocean temperatures much further south than what we experience today, and are thought to be due to a slowing of the AMOC (Heinrich 1988). Because poleward heat transport is dependent upon a functioning AMOC, it stands to reason that a weakened AMOC is associated with colder Northern Hemisphere temperatures.

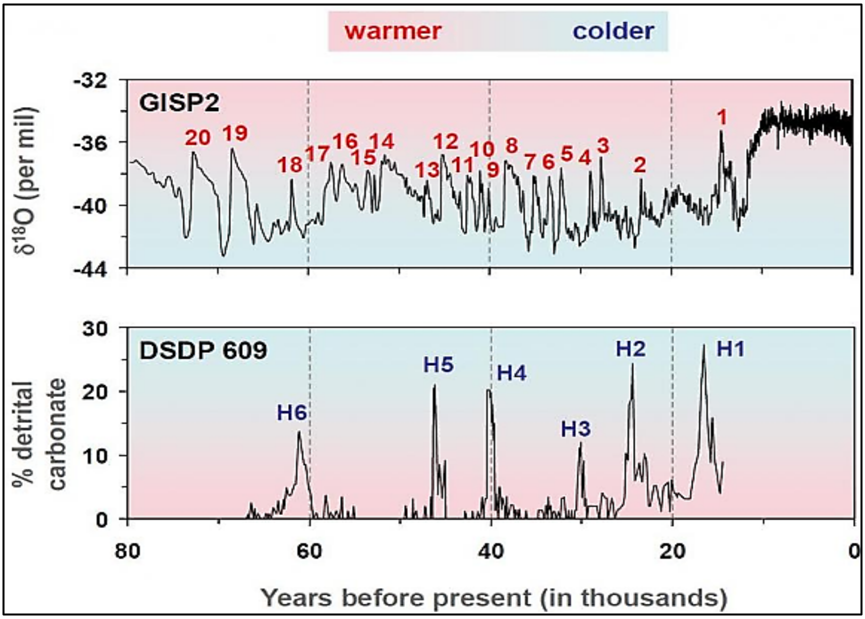


Figure 4. Dansgaard-Oeschger Cycles and Heinrich Events. The upper graph shows Dansgaard-Oeschger Cycles, the lower graph maps Heinrich Events. Relative air temperatures are indicated by shading, red is warmer, blue is colder (NOAA 2010)

A drastic example of abrupt cooling is the Younger Dryas period, a sudden cooling event beginning about 12,800 years ago. The climate had started to warm following the last glacial maximum, but then suddenly reversed. Lasting 1,300 years, this cooling occurred over a period of only several decades and is evidenced (and named) by the widespread presence of *Dryas octopetala* Linnaeus (Rosaceae), a polar tundra plant whose pollen record is found in sediment cores from this period across Europe. Hypotheses for the onset of the Younger Dryas involve the influx of fresh water to the Arctic Ocean from the Laurentide ice sheet, causing a decrease in surface water salinity, and a subsequent reduction in North Atlantic Deep Water formation and slowing of the AMOC (Rainsley et al. 2018). The result of such a slowdown was an abrupt change in climate to a cold, dry tundra over most of Europe, the Middle East, and Northwestern Asia, evidenced by samples of Oxygen and Carbon isotopes from fossilized gazelle teeth and sediment data (Hartman et al. 2018, Jacob et al. 2005). Sea ice would have been present as far south as the Mediterranean. Effects of the cooldown were not limited to the Atlantic basin. Sediment cores show an increase in windblown dust, pollen cores from lake beds near the Pacific coast of North America indicate cold weather vegetation during the same time period, and similar paleoproxies support the presence of subarctic currents reaching the Southern California coast (Calvin 1998).

Current state of AMOC

The literature included in this review demonstrates robust evidence for a weakening of the AMOC over the last several millennia and into the future given unabated anthropogenic forcing, however the extent to which weakening will occur and over what time scale, along with the likelihood of a complete collapse, garner less agreement and are difficult to quantify given the complex nature of cryo-, hydro-, and atmospheric interactions. In 2001, the United Kingdom's Natural Environment Research Council's "Rapid Climate Change" program (RAPID) was initiated to monitor the AMOC, the first opportunity to collect empirical data on the strength of overturning. Since 2004, this mooring array across the Atlantic at 26°N has been used to collect data on the volume of overturning, temperature, as well as biological and chemical data, to increase our understanding of how the AMOC affects climate variability and biogeochemical cycles.

Northern Hemisphere

Recent studies stand out in their ability to utilize paleoproxies and data from RAPID to assess the degree to which weakening has occurred, and project trends in strength and a timeline for possible collapse. Caesar et al. (2021) conducted an analysis of the three AMOC proxies (surface ocean temperature, water mass characteristics, and physical evidence of deep water currents) with samples from across the Northern Hemisphere over the last 2000 years using 30–100-year time intervals (data dependent). Mean values of each proxy were compared over each successive time interval, exposing a fairly stable overturning circulation until a progressive reduction in strength of overturning appears over the last century, accelerating over the last few decades (Caesar et al. 2021). These observations were consistent with the almost two decades of empirical data from RAPID, and indicate the need for a better understanding of the mechanisms behind the slowing circulation (Caesar et al. 2021). In 2023, Susanne and Peter Ditlevsen released a study that demonstrated a high probability for a collapse of the AMOC around midcentury, and before 2100. Using sea surface temperature proxies from the North Atlantic they identified tipping point indicators for collapse that appear in their modeling as early as 2025 (Ditlevsen and Ditlevsen 2023).

Changes catalogued from stations moored at 25° N indicate a thirty percent slowing in the AMOC from 1957 to the early 2000s (Bryden et al. 2005), the change being measured in Sv. The changes found by Bryden appear to be in recirculation of the thermocline waters. Northward Gulf Stream transport has remained fairly constant, but the depth of southward movement is reduced, which could indicate a decrease in North Atlantic Deep Water formation (Bryden et al. 2005). In other words, more of the northward Gulf stream water is returning southward within the thermocline than is returning at depth (3000-5000 m).

Findings from the RAPID array have shown a larger than expected degree of seasonal variability, as well as variability from year to year (NERC 2017). A marked decline in transport was noted in the winter of 2009-2010, and there has been an overall decline in the strength of overturning since the launch of the array. The decline is at a volume of 0.5 Sv per year and has occurred about 10 times faster than previous climate models suggested (NERC 2017). Further studies of data from the RAPID array have supported Bryden's 2005 research. Data collected between 2004 and 2012 were analyzed and determined to show similar changes in the depth of transport (Smeed et al. 2014). Overall, there was a decrease in flow of 2.0 Sv over that time period, but contrary to other studies (Bryden et al. 2005), a reduction of 0.5 Sv was also observed in the Gulf Stream (Smeed et al. 2014). Consistent with Bryden, was the observation that most of the decline in southward flow was due to an increased southward return of warmer waters above the thermocline, which was balanced by a significant slowing in North Atlantic Deep Water formation below 3000 m (Smeed et al. 2014). In fact, the decline in the lower transport of North Atlantic Deep Water was measured at 7% (Smeed et al. 2014). NOAA's MOVE array located in the low latitude Atlantic provided supporting information for these findings, as studied by Send et al. (2011). Between 2000 and 2009, a decrease of 3 Sv was observed in the southward volume of North Atlantic Deep Water (Send et al. 2011); assuming 2-3 years for advection between 26°N and 16°N the conclusions are comparable.

Sources for the decline in the deep water return flow of North Atlantic Deep Water can be explained by changes occurring in the Labrador Sea due to accelerated melting of Greenland's ice sheets. Referring back to Figure 1, the lower arm of downwelling in the North Atlantic is in the Labrador Sea. Using NASA's GRACE satellite, Yang et al. (2016) modeled freshening of the Labrador Sea, including the previously unaccounted for freshwater input from Greenland (Yang et al. 2016). The clockwise currents of the subpolar gyre around Greenland directed 70% of the additional meltwater from Greenland into the Labrador Sea, which decreased production of North Atlantic Deep Water (Yang et al. 2016). Taken in concert, evidence for a reduction in flow volume of the AMOC since the mid-20th century is well-established, and in concurrence with the findings of the IPCC 6th Assessment (IPCC 2023).

Southern Hemisphere

The Antarctic Bottom Water and the Antarctic Circumpolar Current are the Southern Ocean components of the Global Conveyor Belt. Similarly, to North Atlantic Deep Water, Antarctic Bottom Water forms as cold, salty water sinks, and then circumscribes the Antarctic and flows northward into the Atlantic, Pacific, and Indian Ocean basins. However, there appears to be a decrease in Antarctic Bottom Water formation over the past decades, creating a positive feedback loop that could have far reaching consequences. As sea surface temperature rises due to anthropogenic climate change, the Antarctic Bottom Water has been warming, freshening, and decreasing in volume (Purkey and Johnson 2013). Increased surface temperatures have been melting glacial ice, which has freshened the waters, decreasing their density. This warmth appears to be coming from both the surface, and from warmer upwelled waters, which then melt the undersides of the ice shelves and glaciers, with most of the freshening occurring in the leg of Antarctic Bottom Water that feeds into the Pacific basin (Purkey and Johnson 2013). The result is a decrease in the volume of Antarctic Bottom Water being formed, which initiates the process of isopycnal heave, where the void left by the absence of cold, deep, salty water is filled with warmer water from above. In turn, this warmer water is now communicating heat deeper in the water column, further warming the existing Antarctic Bottom Water (Purkey and Johnson 2013) and exacerbating melting. This heat circumscribes the Antarctic along the entire lower track of the MOC (Figure 1) and is transmitted North in the deep water of the Indian, Pacific, and Atlantic basins. Thermal expansion within the Antarctic Bottom Water could be responsible for up to 1 m of sea level rise by this century's end, and up to 16 m by 2500 (Lago and England 2019). Modeling with phase 5 of the Coupled Model Intercomparison Project, a collaborative program that assumes atmospheric-oceanic circulation coupling, does not include parameters for ice sheet or shelf melt, and thus may underestimate how freshening will affect circulation patterns in the deep ocean. Incorporating Antarctic ice melt into their modeling, Lago and England (2019) project a near collapse of Antarctic Bottom Water formation within the next 50 years. The loss of this leg of the deep ocean circulation would have global effects on nutrient cycling, carbon sequestration and heat storage.

Climatic effects of a weakened MOC

Ample evidence exists for decreasing strength of MOC over the last centuries, as demonstrated thus far in this review. In this section we will now turn our focus to research modeling the effects of such a downturn on the redistribution of heat as poleward transport diminishes, oceanic-atmospheric oscillations and the ITCZ, and rising sea levels.

Redistribution of heat

An additional result of a weakened AMOC is greater stratification of ocean layers and less deep-water mixing. Paleoproxies, photosynthetic single celled organisms in ocean floor sediment cores, that date to the last glacial maximum provide evidence for a decreased volume of North Atlantic Deep Water reaching the Southern Ocean (Howe et al. 2016). This allowed for more Antarctic Bottom Water to flow northward, increasing stratification due to the extremely cold and salty characteristics of the Antarctic Bottom Water. In Lago and England's (2019) freshened model, North Atlantic waters only sink to intermediate depths and do not reach the deep Atlantic basin, allowing for the northward push of Antarctic Bottom Water. Mixing subsides due to a strong temperature and salinity gradient between the surface and Antarctic Bottom Water incursion. Since the interaction of the North Atlantic Deep Water and Antarctic Bottom Water at depth in the Southern Ocean is partially responsible for upwelling in that region, along with wind driven upwelling (Howe et al. 2016), productivity and heat transfer in the North Atlantic is diminished. With little to no North Atlantic Deep Water formation, the Antarctic Bottom Water fills the North Atlantic, poleward pull for warm equatorial surface waters is depleted, and the heat balance for the Northern hemisphere is disrupted. The changes in Gulf Stream transport observed above by Smeed et al. (2014) alter heat distribution across the Atlantic via the Canary Current, resulting in cooling of the ocean and Northern Europe (Smeed et al. 2014). Other observed changes by Jackson et al. (2015) using the Met Office Unified Model (HadGEM3) GC2 configuration, include a southern change to the direction of heat transport in the South Atlantic, supporting the drop in sea surface temperature (Jackson et al. 2015), reducing heat redistribution North of the equator.

Oceanic-Atmospheric Oscillations and the Intertropical Convergence Zone (ITCZ)

The strength of overturning in the Atlantic has been shown to have a correlative effect on several atmospheric oscillation patterns such as the North Atlantic Oscillation, the El Niño Southern Oscillation (ENSO), and the Atlantic Multidecadal Oscillation. An in-depth examination of the normal climatic effects of each oscillation is beyond the scope of this paper, rather, literature relating to a change of intensity in response to variation in AMOC is included.

The North Atlantic Oscillation determines the severity of the Westerlies and the positioning of the North Atlantic storm track. Using the 3rd climate configuration of the HadCM3, Brayshaw et al. (2009) found that in response to a shutdown of the AMOC, there was an Eastward shift to the North Atlantic Oscillation which generated an intensification of North Atlantic storm formations, causing them to reach deeper into Western Europe, and bringing with it lower temperatures and decreased precipitation (Brayshaw et al. 2009). These findings were supported using two other computer models from the Max Planck Institute for Meteorology, which determined that a weakened AMOC and resultant increased positive phase to the North Atlantic Oscillation produced cooler European temperatures, decreased precipitation, and increased snow cover which increased albedo and created a positive feedback loop (Jacob et al. 2005). The work by Jacob et al. (2005) also determined that winter storms were more frequent and of greater intensity on the Northern track, and that this was largely due to an increased pressure differential between the air masses that affect the North Atlantic Oscillation, presumably as a result of decreased sea surface temperature (Jacob et al. 2005).

The effects of a weakened AMOC extend beyond the North Atlantic, manifesting as warming of the Tropical and South Atlantic (Brayshaw et al. 2009). An observed southerly deviation in the ITCZ over the Pacific basin results in increased tropical precipitation (Brayshaw et al. 2009) which can cause flooding and alterations to ecosystems, both marine and terrestrial. Paleoclimatic oxygen isotope proxy data shows a 5-10° southward shift in the ITCZ produced drying in the Northeastern tropical Pacific which correlated to weakened summer monsoons over India and Eastern Asia (Zhang and Delworth 2005). Using modeling with adjustments made for single steady-state AMOC stability assumptions, Liu, et al. (2017) obtained a similar outcome for the ITCZ which produced a significant southern shift in tropical rainfall patterns (Liu et al. 2017). As a result, precipitation decreased at low latitudes between 0° and 30°N, and increased south of the equator, with the greatest effects seen in Central America and Northeast Brazil, respectively (Liu et al. 2017).

The southerly changes to the ITCZ correlated to a weakened AMOC have been observed to exhibit indirect effects on climate through weakening of eastern Pacific annual cycles, and an increase in the intensity and variability of ENSO (Timmermann et al. 2007). The study found that North Atlantic cooling following a weakened AMOC, and the resulting southward shift in the ITCZ, created positive feedback that increased cooling in northern latitudes and warming in southern latitudes around the equator (Timmermann et al. 2007). As temperatures in the Atlantic decreased, the decline was transferred to the northeastern tropical Pacific through coupled atmospheric processes over Central America, quickening the Northeast Tradewinds and weakening the eastern Pacific annual storm cycle (Timmermann et al. 2007). With the concurrent warming south of the equator depressing the Southeast Trade Winds, ENSO conditions were exacerbated. An additional finding was that the ENSO response was asymmetrical, meaning that the El Niño phase showed greater response to the experimental conditions (weakened AMOC) than the La Niña phase, which would generate increased rainfall in South America and Southwestern U.S., warm extremes for the Western and Northern US and Southern Canada, cold extremes in the Southern US, and drought in Indonesia and Northern Australia (Timmermann et al. 2007). As the Pacific cold tongue is decreased, an intensified El Niño phase also increases the depth to the thermocline along the Western coasts of South America, Mexico, and the US, which decreases upwelling and marine productivity in the region (Figure 5).

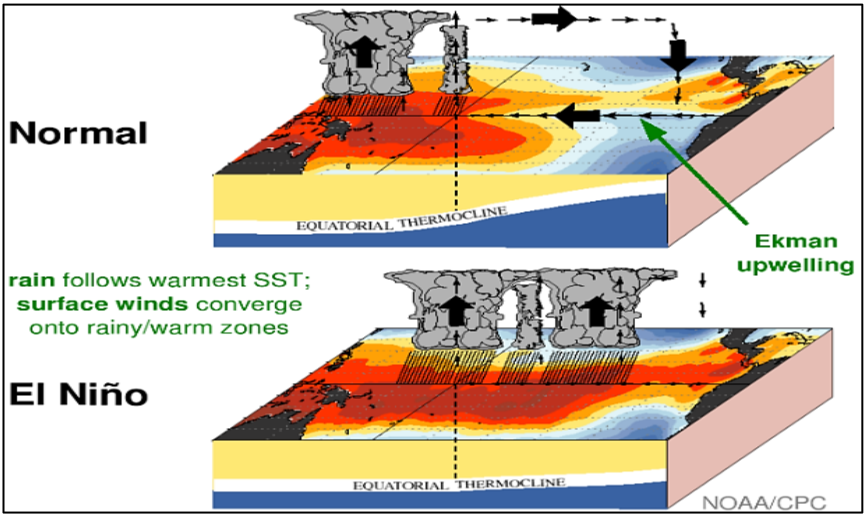


Figure 5. Normal atmospheric conditions in the Pacific Ocean vs. El Niño conditions. Note reduction of Pacific cold tongue, shift of precipitation, and increased thermocline (Wittenberg 2009, https://www.gfdl.noaa.gov/el-nino-media).

The effects of a slowdown in MOC on the Atlantic Multidecadal Oscillation are difficult to quantify, due to its long-term period (60-80 years) and an instrument record that covers little of the cycle. To address this deficiency in confidence using observed instrumental data alone, Knight, Folland and Scaife (2006) used a 1400-year model on HadCM3 with both controlled and weakened AMOC experimental conditions. The results were consistent with observed instrumental data and showed that a slowing of overturning circulation resulted in a push towards the warm (positive) stage of the Atlantic Multidecadal Oscillation, from March to May, producing a northerly deviation of the ITCZ over the Atlantic. In the experimental model, the anomalous climatic effects included a northward movement of Atlantic precipitation, a decrease in precipitation over Northeastern Brazil coupled with an increase for the African Sahel, and increased precipitation over Northwestern Europe with a parallel decrease over the U.S. (Knight et al. 2006). Also, of concern is a decrease in U.S. river flows, and the increasing incidence and severity of hurricanes as opposing vertical forces in the lower atmosphere increase differentials in wind speed and direction (Knight et al. 2006). Taken together, the effects of decreased overturning in the AMOC on atmospheric oscillations could result in disruptions to climate, affecting crop yields and marine productivity.

Effects on sea level

A decrease in meridional overturning strength has been correlated with nonuniform increases in sea level. This occurs through diabatic heating as the observed return of warmer waters above the thermocline, resulting in increased heat conduction and thermal expansion (Bryden et al. 2005, Send et al. 2011, Smeed et al. 2014). Sea level rise has been correlated to heightened incidence and magnitude of damaging weather systems, and more severe storm surge and flooding (Walsh et al. 2014). Flooding and saltwater intrusion from sea level rise negatively impact agriculture and water resources for communities (FAO 2019) which can have devastating results for those already experiencing an inadequate supply of resources.

During the winter of 2009-2010, there was an extreme instance of sea level rise over the Northeastern coastline of the U.S. The highest value was an increase of 128 mm north of New York City and was attributed to a 30% weakening in the AMOC as measured by RAPID (Goddard et al. 2015). This magnitude of a rise in a two-year period is the greatest seen in the history of tidal gauge records (Goddard et al. 2015). Over the study period 2004-2017, Volkov et al. (2019) used in situ observation and collected data supporting a negative correlation between Atlantic meridional overturning strength and Mediterranean Sea levels, values of which were over and above the observed interannual variability, in some places by 6 cm (Volkov et al. 2018). Using an integrated assessment over a variety of disciplines, Kuhlbrodt et al. (2009) projected that following a sizable decline of the AMOC, a sea level rise of up to 80 cm by 2050 could be expected along North Atlantic coastlines, in addition to the eustatic increase in sea levels expected from global warming over that time (Kuhlbrodt et al. 2009). Most severely affected were the Eastern U.S. seaboard, Europe, and Russia, with Greenland seeing an increase of 50 cm, and measurements could exceed 1 m if coupled with increased global warming (Kuhlbrodt et al. 2009). Other findings from Kuhlbrodt et al. include the complete cessation of mixing during the winter months, resulting in a decline in the combining of water through the entire column in the northern Atlantic and decreased productivity in marine ecosystems (Kuhlbrodt et al. 2009).

Because of the contrasting effects on climate between the Northern and Southern hemisphere that coincide with a weakened meridional overturning system, any cooling from the decreased poleward AMOC heat transport would be accompanied by a warming south of the equator (Rahmstorf et al. 2015). Thus, a discussion of sea level rise associated with a reduced overturning circulation warrants inclusion of observations using Antarctic melting scenarios. Modeling a partial disintegration of the West Antarctic Ice Sheet, Bamber et al. (2009) found the largest changes in sea level occurred in a band around the Earth at 40°N. After a 100-year run, using a fast melt scenario of 6.4 mm/yr, the U.S. Pacific and Atlantic coasts, and the boundaries of the Indian Ocean saw a rise in sea levels of the maximum 81 cm (Bamber et al. 2009). The input did not include ice melt from Greenland, making these results conservative in nature.

Biological effects of a weakened MOC

Other than in passing, to this point the focus has been on the physical science of overturning circulation and currents, heat transport and ocean-atmosphere interactions, and the changes in climate that could ensue from weakened MOC. Essential for our understanding of how these will impact human food security is a discussion of marine and terrestrial productivity, and how these are affected by the changes described above.

Effects on marine productivity

One of the few studies to assess the direct impact of a downturn in meridional overturning on marine primary production, Schmittner's 2005 research discovered deepening of the thermocline leading to decreased upwelling and deep water mixing as the result of a weakened AMOC (Schmittner 2005). The greatest effects were seen in the North Atlantic above 35°N, where he projected a decrease of over 50% in phytoplankton biomass by year 500 of the simulation (Schmittner 2005). The decrease in nutrient concentration in the mixed layer as a result of the decline in upwelling, led to an overall collapse of plankton productivity and biomass to less than 50% of the initial values (Schmittner 2005). Moreover, global marine snow, particulate organic matter falling through the water column, declined by 20% (Schmittner 2005). Marine snow acts as the source of nutrients for benthic organisms and will eventually move throughout the meridional overturning system to be upwelled as nutrients for primary production. In the Indian and Pacific oceans, the decline was slower, but by year 1000 of the run, biomass had decreased to about a third (Schmittner 2005). The least effect was seen in the Southern Ocean, but input from Antarctic ice melt that would affect upwelling was not included in the model (Schmittner 2005).

A 2004 study by Sarmiento et al. found that in response to a reduction in overturning strength, polar productivity in the Northern Hemisphere was decreased by 42%, and by 17% south of the equator (Sarmiento et al. 2004). There was a decrease in nutrient supply due to reduced vertical mixing, forcing phytoplankton to spend more time at depth, where there is not enough light for adequate photosynthesis.

In contrast to Schmittner (2005), Kuhlbrodt et al. (2009) used projections of global warming coupled with a collapse of deep-water circulation. In this modeling set the researchers used a scenario that produced a total collapse of AMOC by 2150. Run scenarios by Kuhlbrodt et al. (2009) found that the greatest loss in Net Primary Productivity (NPP) was due to a decline in the mixed layer depth resulting in a decrease in the availability of nutrients (Kuhlbrodt et al. 2009). Also, the decrease in nutrients and NPP was determined to be due to *warming* of the mixed layer, rather than a change in the thermocline (Kuhlbrodt et al. 2009). While the most recent IPCC assessment (2023) cites medium confidence that a complete collapse would not occur before 2100, some argue that this determination is built on modeling that does not incorporate the current accelerated thawing of either Greenland or Antarctic land ice, grossly underestimating freshwater forcing on deep water circulation (Goddard et al. 2015, Rahmstorf et al. 2015, Pedro et al. 2018).

Using data obtained above, the researchers modeled the impact of the findings on the larval growth of Arcto-Norwegian cod, *Gadus morhua* Linnaeus, 1758 (Gadidae). The collapse of the meridional overturning had produced a south and westward shift in the polar front (Kuhlbrodt et al. 2009). As a result of this parameter, more larvae and juveniles were transported to Arctic waters, making their survival unlikely (Kuhlbrodt et al. 2009). Further studies of North Atlantic cod have found that the observed downturn since the mid-1900s is correlated to increasing temperature at depth in the oceans between Greenland and Norway (Fogarty et al. 2007, Meier et al. 2011).

Yang et al. (2020) observed a northern displacement of the subpolar gyre in the North Atlantic, which could be attributable to repositioning of the Atlantic subtropical circulation and the Gulf Stream. Both have been attributed to a reduction in overturning flow (Rahmstorf et al. 2015) due to weakened overturning circulation. Subpolar gyres are areas of high NPP, as nearshore surface currents bring deep water with high nutrient concentration to the surface. The cold water is less stratified, and so there is greater exchange between deep and surface waters. This is extremely necessary for photosynthesis in the oceans, so a latitudinal shift in fish stock would follow the movement of primary producers. Because these changes occur without regard to political boundaries, maritime borders could hinder fish harvesting that follows a latitudinal movement in stocks and resulting in deep economic effects for fishing communities.

Effects on terrestrial productivity

When evaluating the effects of a reduced volume of meridional overturning, the de facto conditions would be a confluence of interacting processes, each with its own sensitivity and feedback systems. Therefore, the results we will discuss in this section must be understood to be isolated, and subject to the in-situ effects of many other factors. As an example, while any substantive decline in the AMOC will undoubtedly bring about circulation changes in the Gulf Stream, altering the position of the polar front in the Atlantic and cooling air temperatures for much of the Northern Hemisphere, this will likely be mitigated by the warming effects of increasing concentrations of greenhouse gasses (Delworth et al. 2006).

In Vellinga and Wood's 2002 modeling study using HadCM3 with no global warming input, a decrease in the northward transport of heat produced Northern hemisphere cooling by as much as 8°C in some places, and 1-2°C on average (Vellinga and Wood 2002). Colder and drier temperatures were observed, primarily because of the southern deviation of the ITCZ, thereby resulting in decreased soil moisture and NPP, and Global NPP by terrestrial vegetation dropped by 5% (Vellinga and Wood 2002). The cooling effect was greatest during the winter, which increased the severity of the Northern Hemisphere seasonal cycle; the presence of snow in the northwestern and middle areas of Europe was extended by a couple months compared to present day climatic averages (Vellinga and Wood 2002). The southerly shift in the ITCZ caused changes in precipitation patterns through shifting of Hadley circulation, such as decreased Northern Hemisphere mid-latitude rainfall, wetter climate in southwestern US, and decreased precipitation over Central America (Vellinga and Wood 2002). Such changes would affect agriculture throughout the Northern Hemisphere, through shorter growing seasons, precipitation differences and access to land availability as suitable habitat changes latitude. The research from Kuhlbrodt et al. (2009) documented reduced European crop production due to extreme weather events and shorter growing periods (Kuhlbrodt et al. 2009). The estimated reduction in arable farmland in Great Britain, for example, would be from 32% to 7%, decreasing British agricultural output by over 10% (Ritchie et al. 2020). These statistics could have drastic implications for a developing country depending on those exports.

In the winter of 2009-2010, the observed slowing of the AMOC resulted in higher-than-normal temperatures in the Southern Hemisphere, and a decline in rainfall levels (Jackson et al. 2015). This coincided with a drought in the Amazon rainforest during 2010 that killed off large numbers of trees over 6.4 x 10^8 acres (Lewis et al. 2011). As those trees decay and are decomposed, an estimated 5 x 10^{12} kg of carbon will be released into the atmosphere, thereby creating a feedback system that will increase warming and thus further melting that will decrease deep water formation and produce greater slowing of the AMOC. A similar drought was recorded in 2005, though not as extensive, and was also associated with a smaller downturn in deep ocean circulation (Bozbiyik et al. 2011). Products from the Amazon provide food and economic support for millions of people, mostly forest smallholders (FAO 2023); decreases in precipitation that create large scale reductions in productivity, such as seen from the 2005 and 2010 droughts can affect the livelihood for millions who are already at risk of food-related insecurity.

Köhler, Joos, Gerber, and Knutti (2005) found that a freshwater induced collapse of the AMOC caused an initial cooling (over 20 years) over Eurasia, which resulted in southward displacement of the timberline and a contraction in the distribution of arctic and sub-tropical forests (Köhler et al. 2005). Heightened terrestrial albedo attributable to a reduction in tree cover at higher latitudes created positive feedback that increased cooling and furthered the tree dieback (Köhler et al. 2005). In sub-tropical latitudes, changes in precipitation resulted in the replacement of grasses by “rain-green trees” (Köhler et al. 2005); the overall vegetation response to the forcing was consistent with pollen records from the Younger Dryas (Rainsley et al. 2018). Although these studies modeled a collapse of the AMOC, and again, the IPCC cites medium confidence that such a scenario would not occur, the 6th assessment does indicate that weakening throughout the 21st century is highly likely, making these configurations worthy of consideration (IPCC 2023).

Current climate related changes to fisheries

There has been little controlled exploration into the direct causality of decreased strength of MOC and changes to global fisheries over the last several decades. However, as described in this paper there is ample evidence of climatic changes correlated to slowed circulation which could contribute to transitions in fisheries that would threaten global supply. For this reason, this section will briefly summarize some of the research into current observed climate-related changes to global fisheries in the context of the effects of slowing overturning circulation.

Sea level rise related

As waters rise, salinity and tidal patterns change in estuaries and inland fisheries, and saltwater intrusion detrimental to agriculture can follow. The effect of sea level rise on fisheries can exacerbate the poverty and food insecurity that exists in many of the countries that depend on fisheries for income and food supply (Akpoilih and Ekeanyanwu 2010). Extremely problematic is the potential for decline in fishery production that could occur as marine primary production is affected by rising seas. Currently the acute effects of sea level rise are seen in

Small Island Developing States (SIDS), but incremental effects can be seen in coastal areas around the world. According to the IPCC Sixth Assessment Physical Science Report, the average global sea level has increased by about 20 cm over the last century, and 100-year flooding will probably be seen annually by 2050 (Fox-Kemper et al. 2021). In conjunction with water temperature changes, sea level changes alter the physical and chemical properties of coastal waters and affect marine and estuary ecosystems. Damage to mangroves, wetlands, and coral reefs that provide essential habitat for fish stocks is expected as sea levels change over the current century. Developing countries, including SIDS, tend to have a high dependence on aquatic food systems for both direct nutrition and the economic supply chain associated with the aquatic food industry (Tigchelaar et al. 2021). Thus, climate driven disruptions to such can have a disproportionate impact on those populations.

Temperature related

The examples that follow provide evidence for ecological shifts resulting from projected changes in temperature either directly due to slowed MOC, or as a secondary response via oscillations described in previous sections. Warmer ocean temperatures in the Humboldt Current off the Western coast of South America decrease upwelling and thus primary productivity in response to enhanced El Nino conditions from slowing thermohaline circulation (Salvatteci et al. 2022). During the last interglacial, similar conditions observed in organic carbon, lipids, and diatoms from sediment samples off Peru supported fish species smaller than the anchovies present in the current today (Salvatteci et al. 2022). This is consistent with the gill oxygen limitation theory, which describes a universal ecological response for aquatic species of smaller body size in response to warmer temperatures and reduced oxygen availability (Salvatteci et al. 2022). This indicates the possibility of smaller fish species inhabiting Humboldt current fisheries in a response to weakened meridional overturning, which could in turn alter organisms present in successive trophic levels.

In 2012 a marine heat wave in the Gulf of Maine altered the distribution of squid species, resulting in the collapse of the shrimp fishery in the region (Richards and Hunter 2021). The shrimp were not shown to have relocated to northern waters and water temperatures remained within acceptable parameters, albeit the upper range, for normal recruitment, so these factors did not explain the collapse of the fishery Richards and Hunter 2021). Although this is an example of the competing influences of warming surface temperatures due to greenhouse gases and cooling due to repositioning of the Gulf Stream, it demonstrates changes in species interactions that occur as climatic changes force migrations, and the socioeconomic effects of such movements. At its peak, the Gulf of Maine shrimp fishery produced as much as 30 million pounds of shrimp a year and was valued at 10 million pounds in 2011 (Associated Press 2023). Because many employed in the direct harvesting move seasonally between species, the loss of summer income from shrimp has deep economic effects. Along the New England coast up to 30% of the economy is intertwined with the fishing industry (The Island Institute 2018).

In the Southern Hemisphere, where ocean temperatures are expected to rise in response to slowed meridional overturning (Lee et al. 2023, Fox-Kemper et al. 2021, Jackson et al. 2015) many developing nations in Southeast Asia that are already experiencing moderate to high levels of food insecurity, such as Malaysia, Indonesia, and other SIDS (FAO 2022) face the threat of fishery collapse as higher temperatures alter range distribution, predator/prey relationships, and recruitment (Lee et al. 2023). For coastal economies in Africa and Asia where fish comprises as much as 50% of dietary protein (FAO 2022), a shift in fishery productivity could exacerbate food insecurity and threaten economic stability. According to the FAO (2022), developing countries more than doubled their fish consumption between 1961 and 2017, with the least developed countries seeing a doubling of consumption during that period. These increases are primarily due to increased production and an expansion of imports from countries such as China, India, and Chile, themselves with percentages of food insecurity that place them in at least the moderate range (FAO 2022). The impacts of Southern Ocean warming therefore would be felt by both importing and exporting countries.

Storm related

Much research has been done concerning the effect of multidecadal and multiannual atmospheric processes on marine NPP and fisheries, some of which is included in this paper, as correlations have been made between a reduction in overturning strength of the AMOC and the strength of such oscillations. After strong ENSO conditions, both in exceptionally warm El Niño and cold La Niña, Indian Ocean tuna stocks decreased as warm, nutrient poor water was prevented from mixing by the intensified atmospheric conditions (Kumar et al. 2014). The deepening of the thermocline due to strong El Niño decreased primary production through reduced upwelling and mixing, increasing stratification and affecting food availability (Kumar et al. 2014). Tuna populations decreased around the Eastern boundaries of the Indian Ocean, as habitat shifted to higher latitudes (Kumar et al. 2014). In agreement are findings by Suárez-Sánchez et al. (2004) that used historic fishing data from the Eastern Pacific and found the lowest biomass of tuna following strong El Niño events (Suárez-Sánchez et al. 2004).

Variability in the Atlantic Multidecadal Oscillation has been associated with temperature dependent habitat switching in phytoplankton and zooplankton

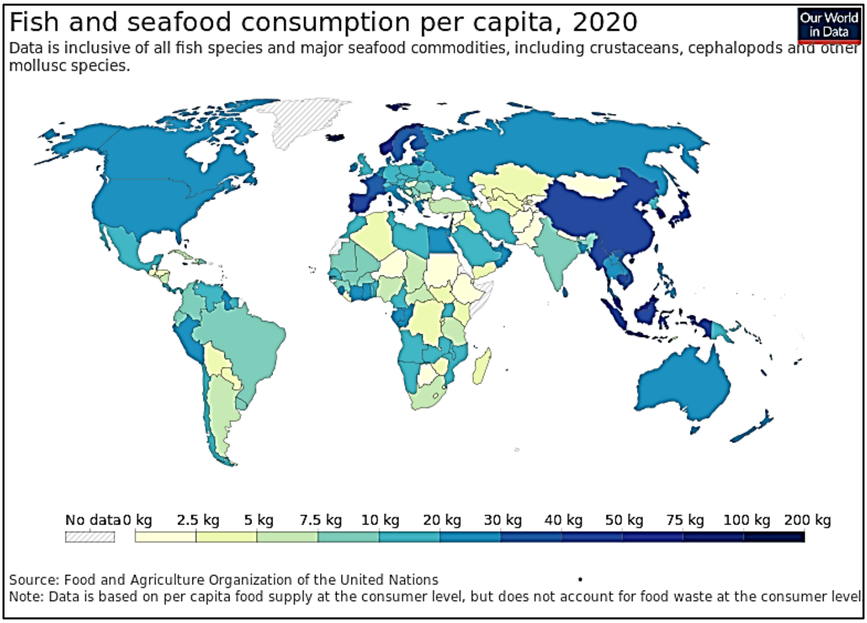
(Edwards et al. 2013). This group found concurrent shifts among sardine and herring, resulting in region-wide alteration in fish stocks influenced by the Atlantic Multidecadal Oscillation (Edwards et al. 2013). Bluefin tuna habitat conditions and locations also changed in response to these cycles, and abrupt habitat changes across the North Atlantic were found to coincide with shifts in the variability of the oscillation (Faillettaz et al. 2019).

Fishery dependent economies

Most of the world's fisheries occur in areas of upwelling. When the thermocline deepens, as occurs anytime there is greater stratification in the ocean, upwelling is depressed, and primary production can be reduced (Hoegh-Guldberg and Bruno 2010). Periods of ENSO, or other atmospheric disturbances discussed above, sea level rise, and a downturn in MOC, have the potential to affect phytoplankton activity through a downturn in the availability of deep waters. Producers at the lowest levels of ocean food chains require nutrients that are found mostly in the lower ocean. Without proper overturning and upwelling, those nutrients cannot reach surface waters, and the oxygen produced during photosynthesis cannot reach organisms that live on the ocean bottom. About three billion people are dependent upon fish as their main form of protein, and most of those people are from underdeveloped nations (Bennett et al. 2018) (Figure 6). In addition, more than 43 million people have jobs that are part of the fishing industry, many of whom are from countries already battling food insecurity (Barange et al. 2014). Many African, Southeast Asian, and South American nations fall into this category (FAO 2023). Disruptions to marine food webs that can occur from a downturn in circulation put the populations of these and other nations at risk for serious food deprivation.

In its 2022 *State of World Fisheries and Aquaculture* report the FAO reported that the majority of people involved in fish harvesting, 84 %, were in Asia, with another 14% located in Africa, Latin America, and the Caribbean. Two thirds of global inland fisheries are in Asia, with most of the rest in Africa. These numbers demonstrate the dependence of many developing and least developed countries on fisheries and aquaculture for direct economic value and as a part of GDP. The observed changes in volume and location described in the previous section can have direct and lasting effects on nations highly dependent on imports and subsistence catches. Latitudinal shifts in habitat could also mean changes in maritime boundaries, eliminating those sources of food and economic profit, or exacerbating tensions between neighboring countries.

Inland fisheries are also under duress, and the most stressed fall in countries that are already experiencing the highest levels of food insecurity, particularly in Sub-Saharan Africa and Southern Asia (FAO 2022). Vulnerability is high and resilience is compromised by socio-political issues such as conflict, income, and resource inequalities, and non-existent or ineffective institutional infrastructure, which reduces the ability of countries to cope with external disruptions such as extreme weather events or environmental changes (FAO 2022).


Fish and seafood consumption per capita, 2020

Data is inclusive of all fish species and major seafood commodities, including crustaceans, cephalopods and other mollusc species.

Source: Food and Agriculture Organization of the United Nations

Note: Data is based on per capita food supply at the consumer level, but does not account for food waste at the consumer level

Figure 6. Fish-and-seafood-consumption-per-capita-map by Max Roser is licensed under CC BY-SA 3.0. To view a copy of this license, visit https://creativecommons.org/licenses/by-sa/3.0/?ref=openverse .

Current climate related changes to terrestrial food production

As with the case in investigating fishery responses to slowing MOC, there is little research at present that directly connects slowing with continental climatic changes, largely due to the difficulty in isolating the effects of circulation from climatic changes associated with greenhouse gases, and the reciprocal interactions of oscillations with other climate patterns. Therefore, we must look as well to the literature that addresses secondary responses to weakened MOC such as alterations in the ITCZ and oscillations, as well as increasing global temperatures.

Changes in continental climate patterns associated with a weakened AMOC could threaten global supplies of wheat, of concern because wheat accounts for a greater portion of global trade than all other crops combined (FAO et al. 2023). The top global wheat producers are China, India, and the Russian Federation, accounting for 41% of global production, followed by the United States and Canada (FAO et al. 2023). European countries as a whole, however, outproduce all countries except China (FAO et al. 2023). The US is the highest exporter of corn, rice, wheat, and soy, therefore reductions in US production could greatly affect those countries that rely on imports of these commodities for food security, primarily in least developed nations and SIDS (FAO et al. 2023). Australia ranks 5th in global wheat exports, and Brazil and Argentina are in the top 5 for exports of all the above commodities (FAO et al. 2023), therefore warming and drying in the Southern Hemisphere is also of concern.

A collapse of the AMOC induced through freshwater forcing by Jackson et al. (2015) resulted in cooler year-round temperatures with a reduction in precipitation in Northern and Western Europe, conditions not conducive to the production of agriculture at current levels. The experimental conditions produced a Southward shift in the ITCZ, consistent with other studies, not only over the Atlantic, but over other ocean basins as well, which would alter the Indo-Asian storm track, consistent with the results from preceding and subsequent studies (Delworth et al. 2008, Orihuela-Pinto et al. 2022). Concerningly, other studies cited within the work by Jackson et al. (2015) indicate that higher resolution models may be necessary to capture the actual reduction in summer precipitation, and that there may be a much greater precipitation response to a weakened AMOC than previously understood (Jackson et al. 2015). Climatic changes resulting from a southerly shift in the ITCZ as described in previous sections could threaten food supply for countries already experiencing moderate to high food insecurity. Reduced precipitation in India and Southeast Asia due to weakened Indian and Asian monsoonal patterns, as well as drought in the African Sahel, Caribbean and the central basins of North America were found to result from shifting of storm patterns (Delworth et al. 2008, Orihuela-Pinto et al. 2022), and these regions contain nations that are among the most food insecure.

Modeling of interbasin responses to a weakened AMOC by Orihuela-Pinto et al. (2022), found that repositioning of the ITCZ in response to circulation changes produced more La Niña type stable conditions in the Pacific basin, which would contribute to warming and aridification in the lower latitudes of the Americas. In general, a colder Northern hemisphere at higher latitudes and warmer overall Southern hemisphere were observed (Orihuela-Pinto et al. 2022), the latter being consistent with all the climate modeling referenced in this review: warmer temperatures and decreased precipitation in the Southern Hemisphere as a response to slowing in the AMOC.

When considered in concert with the crop production statistics that introduced this section, these results paint a picture of global agricultural trade that would have to undergo drastic restructuring in response to severely weakened or collapsed AMOC. Temperature is known to be a determining factor in wheat production, and it is estimated that increasing temperatures could reduce output by 6% for every degree Celsius (Asseng et al. 2015). In looking at the potential for disruptions in global winter wheat production, Nehbandani et al. (2023) found that arable acreage in the areas currently most productive for this crop (Eastern China, Eastern U.S. and Europe), was very likely to decrease in response to current climatic trends, with the effect of warming being more prevalent than drying. Although this study used global warming due to greenhouse gasses as the driver for change, the results of winter wheat crop production decreasing in response to higher temperatures is of relevance when applied to warming and drying in Argentina, Brazil, and Australia shown to occur in response to AMOC strength, as well as a potential loss of European production due to cooling.

Discussion

Because there is robust evidence for changes associated with a weakening of MOC, it is important to consider how long-term variability will alter biome distribution, and thus the distribution of global agriculture and fisheries. Between the 5th and 6th Assessments of the IPCC, the degree of certainty of the "unlikely" (IPCC 2014) complete collapse of the AMOC has decreased; the most current report describes a 90% probability that weakening will occur over this century, and should an abrupt collapse occur, it would have far reaching climatic effects as covered in this review (IPCC 2023). Because the likelihood of severe and abrupt global changes to circulation increases with warming, the IPCC acknowledges that beyond 2100 complete collapse cannot be excluded from further scenarios (IPCC 2023), thus it is important to consider all possibilities moving forward. In the Food and Agriculture Organization of the United Nations (FAO) 2023 *State of Food Security and Nutrition in the World* report, statistics show that about 2.4 billion people around the world are exposed to moderate or severe food insecurity, which includes 8% of residents in North America and Europe (FAO 2023). Where income and wealth inequalities are greater, economic downturns have a larger effect on those already suffering, especially in low-income countries. Disruption to the global food supply would exacerbate this, with a disproportionate effect on countries who rely heavily on trade in primary commodities (FAO 2023). The United States (US) is responsible for 50% of the food supply for countries who rely heavily on food imports, with Europe providing most of the other half (FAO 2023). Therefore, even though those countries are not likely to be directly affected by the changes described in this paper, a disruption in their food export would likely have a detrimental effect on less developed economies that are supported by those products. North Africa, much of the Middle East, and the Balkans, for example, obtain almost 70% of food from imports, which has been greatly affected by the war in Ukraine, increasing their dependence on Western products (FAO 2023).

Currently there are thirty-two nations that cannot depend on internal sources for their own food supply, which includes much of Africa and the Middle East, and North Korea (Cago 2017, FAO 2023). Many more rely on supplementation from imports to sustainably feed and prevent starvation within their populations. These numbers are on the rise, in part due to the COVID-19 pandemic and the war in Ukraine, resulting in over fifty percent of the populace of Earth predicted to depend on food sourced from outside their country by 2050 (FAO 2023). Conflict, drought, land, and water availability, all affect the ability of a country to feed its inhabitants. More than 10% of people in the world, mostly from underdeveloped nations, depend on fishing or fish related industries for their income, and almost 60% depend on agriculture (Béné et al. 2015). In Central America, where over 10% of the population experiences severe food insecurity (FAO 2023), the already evident ramifications of global warming on the coffee and chocolate industries are expected to be greatly affected by precipitation decreases projected to accompany a decline in overturning of the AMOC (Köhler et al. 2005, Kuhlbrodt et al. 2009, Ritchie et al. 2020).

Ocean-atmospheric coupling and the interdependence of physical processes make prediction difficult, but the literature is robust in documenting the influence of MOC on global climate. Although there is much consensus within study areas, agreement between model sensitivities and specific subtopics is limited and describes the need for larger temporospatial scale studies that incorporate multiple systems that until now have mostly been studied as isolated phenomena. Little research has been published on the specific effects of decreased overturning circulation on marine and terrestrial productivity. Most has focused on the isolated effects of warming, without including the climatic changes and oscillation effects correlated to such a downturn. Certainly, this is an area that warrants further research given the magnitude of effect on global food supply.

Without question, the need exists for longer-term direct observation of the deep ocean circulation. Unfortunately, there exists only a little more than a decade of data collection from moored arrays over the Atlantic. More have been constructed over the last five years, at 65°N and at 35°S (Yang et al. 2020), but this data is new, and it is difficult to draw conclusions about the strength of overturning. Information collected from the variety of arrays that have been established show clear interannual variations in the amount of water being moved through this system, and there is much evidence for interaction between atmospheric oscillations and ocean processes. What must be determined, however, is the extent to which the seasonal and year to year changes are simply that or are part of a longer-term trend toward destabilization of the ocean circulation system. It appears that at least another two decades of data are necessary to make this important distinction (Liu et al. 2017); the question now is whether over that time, changes will occur to our oceans and atmosphere which will progress unconstrained, with little option for policy making and human actions to have any real effect.

Much discussion exists around the point at which feedback systems will make a return to normal conditions impossible, and an AMOC shutdown will just have to play out. Some of these hinges on whether the ocean around Antarctica will continue to perform as a reserve for heat and CO_2, or whether the changes occurring will cause a shift to a source of heat and carbon, thereby exacerbating climate change processes (Purkey and Johnson 2013). Tipping points on large and small scales exist throughout the climate system and are interconnected in ways we are just beginning to understand. Most research on this subject is inconclusive, and almost every study ends with "more data must be collected" or with suggestions of areas for further study. As many advances have been made in this field over the last decades, multitudes more are waiting in the wings.

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