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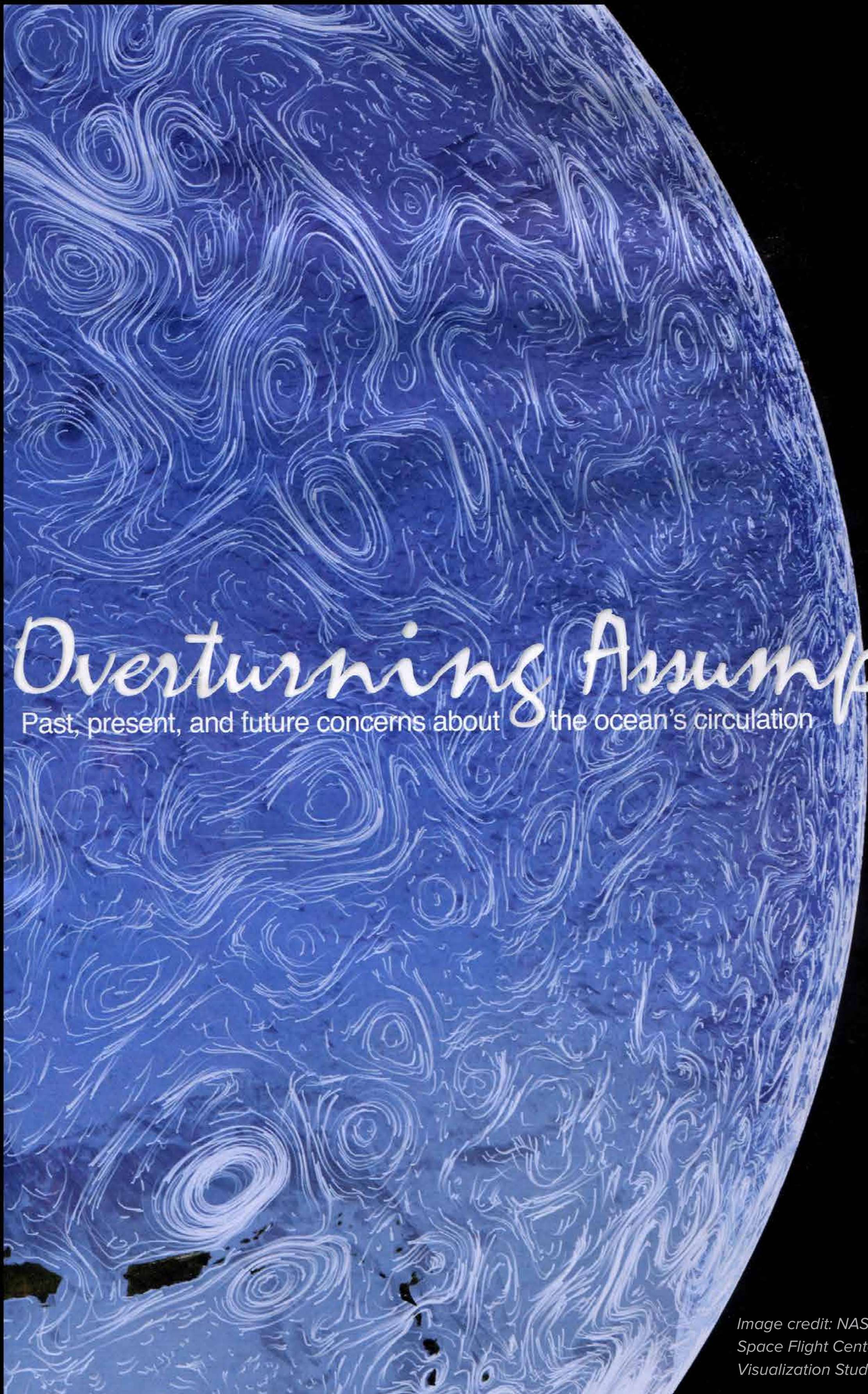

Overturning Assumptions

Past, present, and future concerns about the ocean's circulation

By M. Susan Lozier

Image credit: NASA/Goddard Space Flight Center Scientific Visualization Studio

The Roger Revelle Commemorative Lecture Series was created by the Ocean Studies Board of the National Academies in honor of Roger Revelle to highlight the important links between ocean sciences and public policy. M. Susan Lozier, the sixteenth annual lecturer, spoke on March 4, 2015, at the Baird Auditorium, Smithsonian Institution, National Museum of Natural History.

ABSTRACT. In 1800, Count Rumford ascertained the ocean's meridional overturning circulation from a single profile of ocean temperature constructed with the use of a rope, a wooden bucket, and a rudimentary thermometer. Over two centuries later, arrays of gliders, floats, and moorings are deployed across the span of the North Atlantic to measure the overturning circulation and its spatial and temporal variability. While Rumford appreciated the role the ocean's overturning plays in redistributing heat, today we understand its crucial role in sequestering anthropogenic carbon dioxide in the deep ocean. What we don't understand, however, are the mechanisms that control overturning strength and how and why the overturning will change in the decades ahead. This information is crucial to our understanding of the climate system because the extent to which the ocean will continue to be a heat and carbon reservoir depends on the strength of the overturning. Although we have reasons to reject the popularized ocean conveyor belt as a paradigm for the overturning, oceanographers are just now piecing together the complex flow patterns that carry warm waters poleward and cold water equatorward. As the pieces come together, some long-held assumptions are being overturned, and some new paradigms are surfacing.

BACKGROUND

In 1751, nearly two decades before Benjamin Franklin charted the Gulf Stream's path by measuring surface water temperature, a British sea captain aboard a slave-trading ship sailing from western Africa to the American colonies stopped in transit to measure the temperature of the deep tropical ocean. Captain Henry Ellis had been asked by Reverend Stephen Hales, an English clergyman with wide-ranging scientific interests, to make this measurement. Armed with a simple wooden bucket fitted with valves to capture water at selected depths and rope to lower the bucket over the side, Ellis and his crew laboriously created the first known temperature profile of the ocean. As Ellis noted in his letter back to Reverend Hales, the "cold increased regularly, in proportion to the depths, till it descended to 3900 feet." Successive draws at greater depths brought up water just as cold, which was 30°F (–1.11°C) colder than the air temperature at that time (Warren, 1981). Having dutifully noted the measurements in his letter to Hales, Ellis turned to more practical matters, writing: "This experiment, which seem'd at first by mere food for curiosity, became in the interim very useful to us. By its means we supplied our cold bath, and cooled our wines or water at pleasure; which is vastly agreeable to us in the burning climate" (Ellis, 1751).

Decades passed before the seemingly obvious fact of cold waters at depth was questioned. Upon reading Ellis's letter in the archives of the Royal Society of London, Count Rumford, an American-born British scientist, was puzzled as to how deep waters in the tropics could be so much colder than the temperature of the overlying atmosphere. While it was well known that wind-blown surface currents moved water from one part of the globe to another, the deep ocean in the eighteenth century was generally considered motionless. However, from this single profile of temperature, Rumford deduced the opposite. In 1800, he wrote: "It appears to me to be extremely difficult, if not quite impossible, to account for this degree of cold at the bottom of the sea in the torrid zone, on any other supposition than that of cold currents from the poles." Rumford further reasoned that this cold current at depth "must necessarily produce a current at the surface in an opposite direction" (Rumford, 1800). With these two sentences, Rumford described the overturning of the ocean, which almost two centuries later was popularized as the "great ocean conveyor belt" (Broecker, 1987; Figure 1). While Ellis's single profile of temperature in the tropics suggested a high-latitude origin for the deep tropical waters, a meridional cross section of ocean properties confirmed this origin. From measurements along 20°W during the German Atlantic expeditions from 1925–1927 (Merz, 1925), plumes of saline waters from the surface waters of the northern North Atlantic can be seen extending equatorward, interleaving with relatively fresh waters of Antarctic origin (Figure 2).

MAPPING THE OVERTURNING

In the following decades, dozens of hydrographic cross sections were made along various latitudes and longitudes of the North and South Atlantic, creating a three-dimensional grid of temperature, salinity, and oxygen from which deep waters that formed in the Labrador, Mediterranean, and Norwegian-Greenland Seas were tracked and distinguished from those formed in the seas around Antarctica. A fair number of those sections were made during the 1957–1958 International Geophysical Year (IGY). Interestingly, Roger Revelle helped plan the US contribution to the IGY's oceanographic expeditions, having initiated several expeditions in the Pacific while he was the director of Scripps Institution of Oceanography. While these cross sections gave a spatial context to the deep water masses in the Atlantic, the Geochemical Ocean Section Study (GEOSECS) cruises of the early 1970s, designed to provide a baseline of ocean chemistry for the global ocean, provided, for the first time, a temporal context. A 1972 meridional section from the northern North Atlantic to the equatorial region (Figure 3) shows the penetration of tritium, a byproduct from the nuclear bomb testing in the 1950s and early 1960s, to great depths in the high latitudes. While prior measures of temperature, salinity, and oxygen had *suggested* the overturning circulation, the encroachment of tritium to depth in the northern reaches of the North Atlantic and its equatorward penetration vividly *illustrated* the overturning in action.

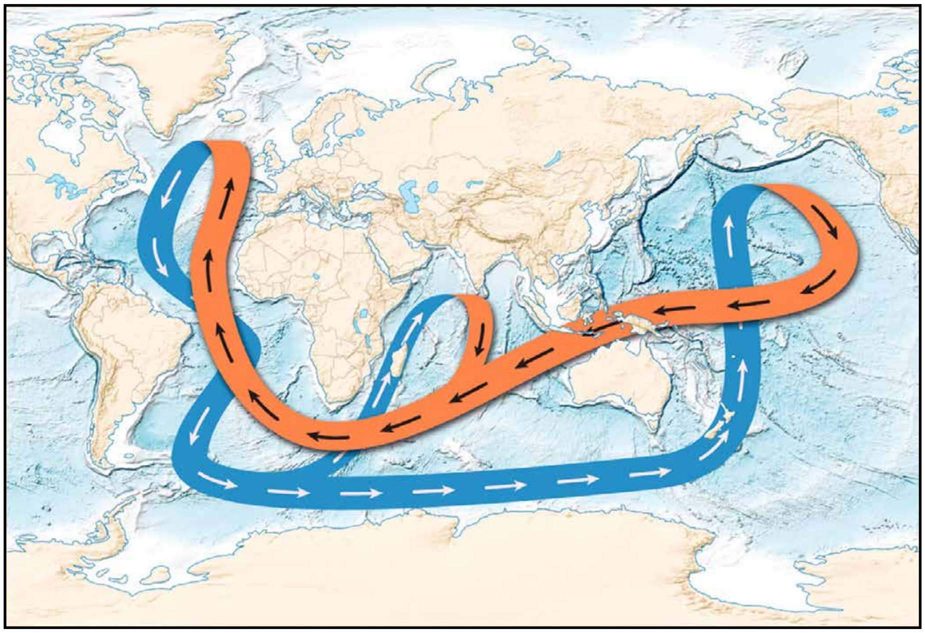

FIGURE 1. Schematic of the ocean conveyor belt. Arrows indicate direction of flow. Orange represents the warm, shallow waters of the upper limb of the conveyor belt. Blue represents the cold, deep waters of the deep limb. *From Lozier (2010), where it was adapted from Broecker (1987) by, and used with permission of, Joe LeMonnier*

STORAGE OF CARBON AT DEPTH

The uptake of tritium at the surface and its subsequent entry into the deep ocean sharply illustrated the deep ocean's capacity as a reservoir. This capacity has a relevance today unimaginable to Rumford, yet certainly envisioned by Revelle. From a series of ocean expeditions in the early 1990s, the concentration of

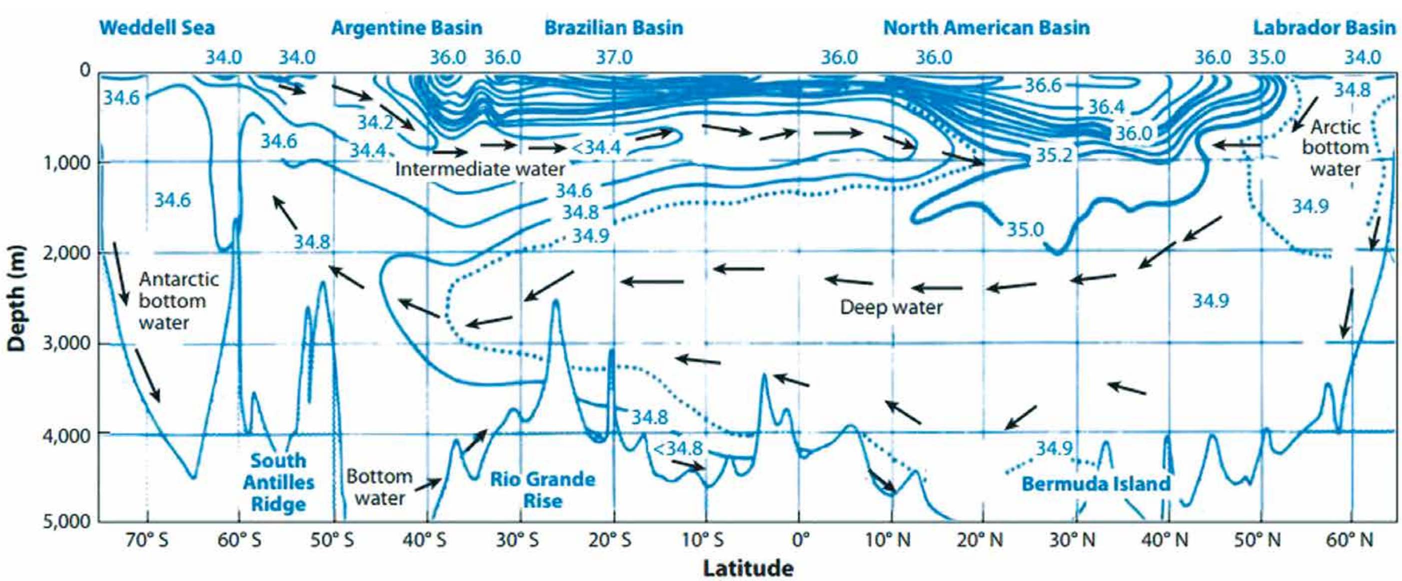

FIGURE 2. Meridional cross section of salinity in the western Atlantic Ocean constructed from measurements during the German Atlantic expeditions from 1925 to 1927. *From Lozier (2012), where it was adapted from Tchernia (1980), who had reprinted it from Merz (1925)*

anthropogenic carbon dioxide in the ocean was mapped along a route from the Aleutians in the North Pacific to the Southern Ocean, eastward to the Atlantic Ocean, and then northward to Iceland (Figure 4). The impact of the overturning circulation in the North Atlantic is revealed with this map: the high concentrations of anthropogenic carbon dioxide at great depths in this basin indicate that those deep waters were recently at the surface, exposed to the atmosphere. This map, coupled with quantification efforts revealing that approximately 30% of the anthropogenic carbon dioxide released since the Industrial Revolution is now stored in the ocean (IPCC, 2013), has raised a question critical to our understanding of how the ocean will respond and contribute to global climate change: to what extent will the deep ocean continue to be a reservoir for anthropogenic carbon dioxide?

Ocean chemistry, biology, and physics regulate carbon uptake across the ocean surface. Indeed, Revelle himself made critical contributions to the understanding of how bicarbonate chemistry controlled the ocean's absorption of atmospheric carbon dioxide. Yet, a strong determinant of the chemical and biological properties involved in the ocean's carbon cycle is the physical movement of water. Ocean currents and mixing play a large role in the export of carbon dioxide to depth and its subsequent ventilation to the atmosphere. On the largest scale, this brings us back to the ocean's overturning circulation, because nowhere is the carbon uptake across the sea surface greater than in the subpolar region of the North Atlantic (Takahashi et al., 2009; Figure 5). Ocean overturning is believed to play a strong role in creating this carbon sink: as northward-flowing surface waters cool, they absorb additional CO_2; and as the cooling ensues, more and more deep water, exposed to the atmosphere, will take up CO_2.

Thus, understanding the fate of the ocean as a carbon reservoir hinges critically on our understanding of overturning variability. Just a decade ago, the accepted paradigm for this variability was fairly straightforward. As explained in a recent review (Lozier, 2012), the strength of the overturning has long been assumed to be related to the strength of the formation of convective water masses in the Labrador Sea and the input of deep Arctic waters across the sills of the Greenland-Scotland Ridge. Expanding on Rumford's original conjecture, twentieth-century oceanographers explained that as the surface waters in the high latitudes warmed or freshened, convective activity in those regions would diminish, leading to a commensurate diminishment of the overturning because production of dense water masses would ebb.

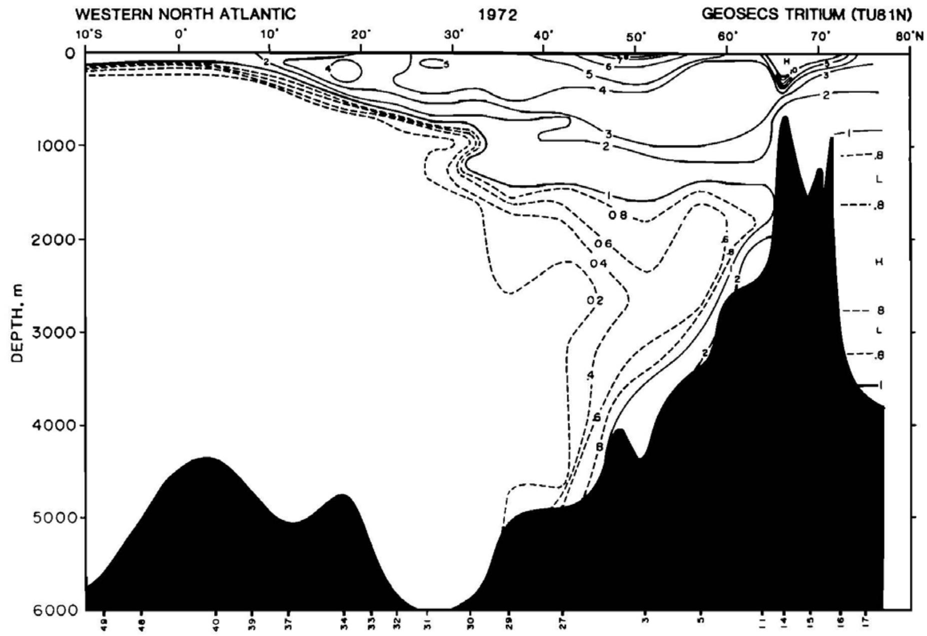

FIGURE 3. Concentration of tritium, a byproduct of nuclear bomb testing, along a section in the western North Atlantic, showing the penetration of this tracer from the surface waters to depth. Measurements were made in 1972 as part of the GEOSECS program. *From Östlund and Rooth (1990)*

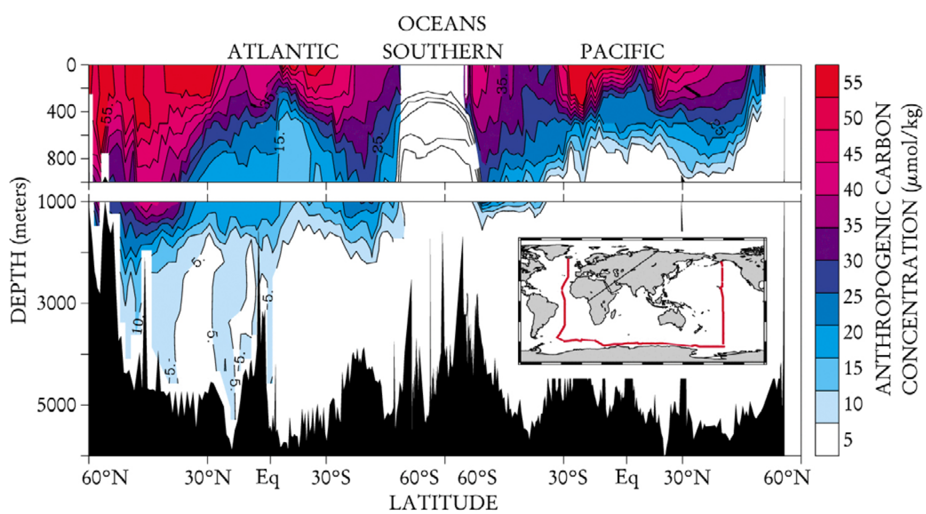

FIGURE 4. Anthropogenic carbon concentration in the ocean along a track shown as a red line in the inset. Of particular note is the penetration of carbon to depths of ~4,000 meters in high latitudes of the North Atlantic. *Reproduced with permission from Sarmiento and Gruber (2002), © 2002, American Institute of Physics*

ABRUPT CLIMATE CHANGE

Based on studies of paleoceanographic data that showed variability on millennial time scales in deep ocean temperatures (Broecker and Peng, 1982; Broecker, 1991), the conveyor belt representation of the ocean's overturning neatly illustrated this accepted paradigm. Alternate periods of global cooling and warming were attributed to the slowing of the ocean's overturning, itself a product of the cessation or diminishment of deepwater production at high latitudes in the North Atlantic. These millennial-scale changes were too remote to warrant the attention of most physical oceanographers, whose focus in the 1980s and early 1990s was primarily on interannual to decadal-scale climate variability in the ocean basins. A study in the mid-1990s changed that remove; from an examination of synchronous changes recorded in ice sheets in Greenland and Antarctica, the disruption of global atmospheric temperatures was conjectured to be on the scale of years to decades (Alley et al., 1997). The proposed mechanism for the disruption was the ocean's overturning circulation.

This link between the ocean's overturning and past rapid climate change was the focus of a 2002 National Research Council (NRC) publication entitled *Abrupt Climate Change: Inevitable Surprises*. With the publication of this study, the distance between the paleoceanographer's world and the physical oceanographer's world further collapsed. In a 2003 *Science* article, Alley and colleagues, the authors of the NRC publication wrote: "Although abrupt climate changes can occur for many reasons, it is conceivable that human forcing of climate change is increasing the probability of large, abrupt events." As such, abrupt climate change was brought to the forefront of not just modern oceanographic studies, but also to the forefront of climate change science and policy and, in a direction that simultaneously thrilled and dismayed oceanographers, to Hollywood, as manifested by the release of the 2004 film *The Day After Tomorrow*. A shutdown of the conveyor belt was billed, on many fronts, as a disaster waiting to happen. A study published in 2005 heightened that worry; from an examination of five synoptic surveys, a team of oceanographers concluded that the overturning circulation at 26.5°N in the North Atlantic had declined by 30% over the past five decades (Bryden et al., 2005).

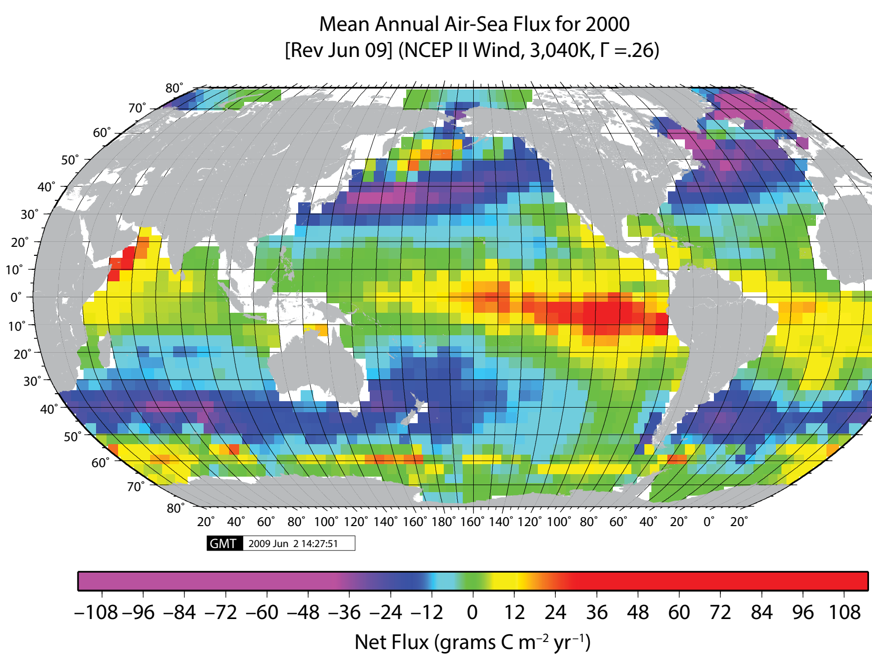

FIGURE 5. The annual flux of CO_2 across the air-sea interface, produced from surface water measurements taken since 1970. Negative values indicate a flux of CO_2 into the ocean; positive values indicate a CO_2 flux out. Note the large negative values in the northern North Atlantic. *From Takahashi et al. (2009)*

A CLOSER LOOK AT OVERTURNING

Needless to say, concern about abrupt climate change triggered by a slowing of the ocean's overturning spawned a concentrated focus on our current understanding of this circulation feature and, subsequently, a series of observational efforts to shore up that understanding. As a result of this focus, the language used to describe the ocean's overturning started to change. As pointed out by Wunsch (2002), the "conveyor belt" and the "thermohaline circulation," the latter used to denote density-driven flow, had both been used interchangeably for decades to describe the overturning, yet they have no clear definition and certainly no mathematical constructs. Oceanographers instead began to refer to the ocean's overturning as the meridional overturning circulation (MOC), defined as the zonally and depth-integrated northward flow at any particular latitude.

Though the lexicon surrounding the overturning began to change at that time, our understanding of its structure and variability was still very much rooted in the concepts derived from the paleoceanographic literature. In other words, though we were now discussing the MOC, its working model was still the "conveyor belt." As such, just a decade ago oceanographers generally understood that:

1. The ocean's overturning varied on annual to decadal to millennial time scales.
2. The waters that composed the lower limb of the meridional overturning circulation were carried continuously along deep western boundary currents.
3. Gulf Stream waters that transited from the subtropical to the subpolar gyre constituted the upper limb of the meridional overturning circulation. This upper limb flowed in a continuous

path from the tropical Atlantic to the Nordic Seas as the waters returned to their formation sites.

4. Temporal variability in overturning transport and properties was coherent from one latitude to the next, such that the measure of the overturning at one particular latitude was sufficient.
5. The MOC's transport and property variability primarily resulted from transport and property variability of deep North Atlantic water masses.

FOCUS ON THE ATLANTIC OCEAN

Interest in the MOC congealed around the Atlantic basin for reasons explained in a 2007 report (US CLIVAR AMOC Planning Team, 2007): "The Atlantic component of this circulation, the Atlantic Meridional Overturning Circulation (AMOC), has long been considered the dominant element of the MOC, in large part because the majority of water masses that compose the lower limb of the overturning circulation originate in the North Atlantic. The AMOC transports mass, heat, and freshwater from the mid-depth and upper waters at the southern boundary of the South Atlantic into the northern North Atlantic and beyond into the Arctic Ocean: cold, dense water is returned southward at depth. The AMOC is thought to play an important role in the maintenance of the observed meridional temperature structure in the Atlantic and therefore, if perturbed, the consequences to climate, particularly in the North Atlantic and for the continents surrounding the North Atlantic, could be significant."

The AMOC focus was shared by Europeans and Americans alike. Over the past decade, a number of observational and modeling studies on both sides of the Atlantic have served to revamp our conceptual understanding of the AMOC, its structure and variability. The studies that have proven to be most pivotal to this revamping are discussed in turn.

1. The Rapid Array

Starting in 2004, the UK and the United States put in place an array of instruments across the North Atlantic basin at 26°N that would provide the first continuous direct measure of the overturning. The Rapid Climate Change-Meridional Overturning Circulation and Heat Flux Array (Rapid array) consists of moored instruments along the western and eastern boundaries of the basin and on either side of the Mid-Atlantic Ridge. This array complements a long-standing measure of flow through the Florida Straits and is accompanied by a satellite measure of the directly wind-forced surface currents. One year after deployment, the data were recovered and analyzed to yield a time series of the overturning strength at that latitude. Figure 6 shows the results, published in 2007 (Cunningham et al., 2007), where the overturning (in red) is the sum of three components: the wind-driven surface flow, the western boundary flow, and the flow in the interior of the basin. To understand the extent to which these results defied our expectations, recall that just two years earlier, five synoptic surveys taken over the span of five decades were used to ascertain the long-term slowdown of the overturning. In that study, as in past studies, the expectation was that the overturning varied slowly. Thus, a synoptic survey, lasting weeks, would suffice to give more or less an annual measure of the overturning.

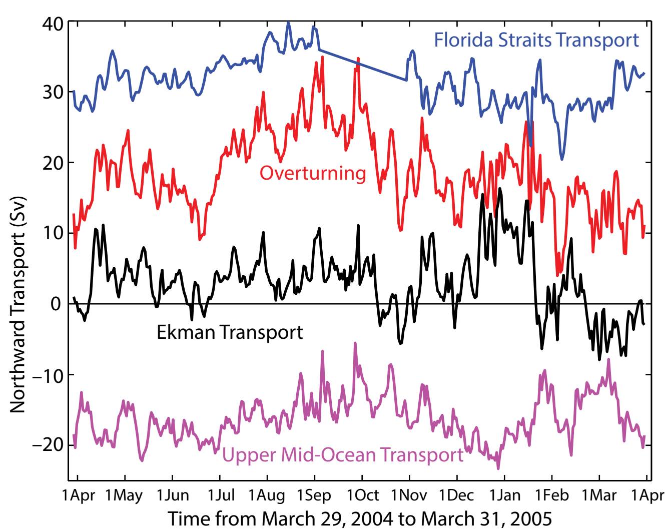

FIGURE 6. Time series of the meridional overturning circulation at 26°N, measured from the Rapid array. The meridional overturning circulation is the sum of the Gulf Stream transport through the Florida Straits, the wind-driven Ekman current, and the mid-ocean geostrophic transport. *From Cunningham et al. (2007), printed with permission from AAAS*

The Rapid array results turned this expectation on its head by revealing exceptionally strong variability on times scales much shorter than a year. To put this variability in stark relief, consider that over the course of one year of continuous measurements, the overturning strength increased sixfold. It took nothing more than this one plot to understand that measurements over the several weeks it takes for a ship to cross the basin are insufficient to portray the overturning strength on any time scale other than those weeks. In other words, synoptic measures of the overturning could not be considered representative of the overturning on longer time scales. This time series also revealed the strong, and heretofore unsuspected, role of the wind-forced surface flow in creating variability. As mentioned above, oceanographers had for years rather conveniently termed the overturning as the thermohaline circulation, on the premise that it was density-driven. This result, as well as a number of modeling studies, added momentum to the call for abandoning this term.

The Rapid array is now entering its eleventh year. These observations have immeasurably aided efforts to model AMOC variability because they have provided the first data for the essential task of groundtruthing. The importance of this time series to our understanding of the AMOC and its variability cannot be overstated.

2. Non-Conveyor Pathways

A cornerstone of the conveyor belt paradigm is the structure of deep currents moving equatorward and surface currents moving poleward. Based on a theory from the late 1950s (Stommel, 1958), oceanographers expected the deepwater masses from the northern North Atlantic to make their way to the rest of the global ocean via deep western boundary currents (Figure 7). Subsequent measures of these boundary currents revealed that they were indeed conduits for deepwater masses, but not until the last decade was it revealed that the boundary currents were not the sole conduit for the deep waters to flow equatorward (Bower et al., 2009). Sequential releases of subsurface floats over a period of three years in the early 2000s in the Labrador Sea revealed a strikingly different image for the structure of the lower limb (Figure 8). In fact, the pattern of these float pathways could hardly be seen as "structure" because the floats followed myriad pathways from the subpolar area to the subtropical region. Thus, past studies that interpreted the strength of the deep western boundary current as the strength of the overturning circulation needed to be reconsidered. Indeed, a quantitative analysis of these observational floats, as well as accompanying model studies, revealed that the dominant pathway for the deep waters to transit the subtropical ocean was in the interior, not along the western boundary. The "pipeline" for deep waters, though not taken literally, was certainly dismantled once these float pathways were revealed. Why does this matter? If we are to understand the extent to which the ocean is a reservoir for carbon, the spatial extent of that reservoir is vitally important. Additionally, the fate of the carbon once exported to depth helps us predict when and where it might resurface.

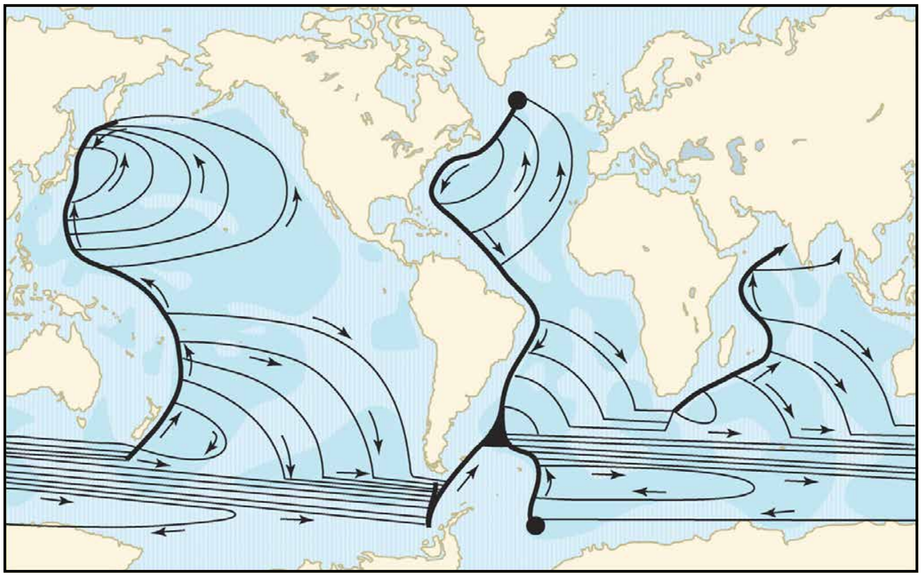

FIGURE 7. The abyssal flow field, as theorized by Stommel in 1958. Sources of water masses to the North Atlantic are denoted by black dots. These water masses spread equatorward via western boundary currents (thick lines) that feed a poleward interior circulation (thin lines). Arrows indicate direction of flow. *From Lozier (2010)*

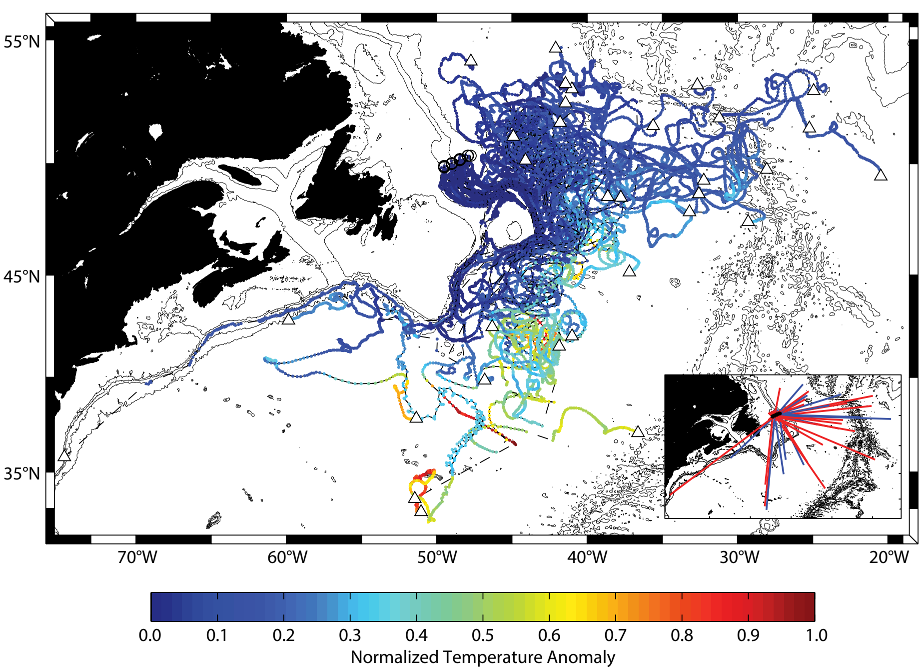

FIGURE 8. Trajectories of 40 acoustically tracked floats released at 700 m and 1,500 m in the deep western boundary current in the Labrador Sea and followed for two years. Daily float positions are indicated with color-coded dots, where the color denotes the change in temperature along the float's path. The inset shows the two-year displacement vectors for the 700 m (red) and 1,500 m (blue) floats. *From Bower et al. (2009)*

3. Rethinking the Gulf Stream Pathway

The upper limb of the overturning has also come in for some revamping. Perhaps the most well-known component of this upper limb is the Gulf Stream, the strong boundary current that runs northward along the southeastern US coast and then heads out to sea at the latitude of Cape Hatteras. The Gulf Stream brings warm waters northward such that when these waters meet the colder overlying atmosphere at higher latitudes, the ocean transfers a tremendous amount of heat to that atmosphere. Such was the narrative that Matthew Fontaine Maury, a nineteenth century naval officer and oceanographer, formulated to explain why northwestern Europe has such a relatively mild climate compared to similar latitudes in Canada. Most of those Gulf Stream waters, once they head eastward out to sea, turn back to the south, circulating in what is known as the subtropical ocean gyre, which is a wind-forced circulation feature. A fraction of those Gulf Stream waters, about 20–25%, however, plays a pivotal role in the overturning. These waters do not stay within the subtropical gyre; rather, they are the "throughput" waters that form the upper limb of the AMOC (Fratantoni, 2001).

A visual map of the sea surface temperatures in the North Atlantic has long given a clear indication of the pathway of this throughput (Figure 9). A pathway of warm temperature from the Gulf Stream in the subtropical region leads to the eastern basin of the subpolar gyre; these are the waters that feed the deepwater formation sites in the subpolar basin and further north in the Norwegian-Greenland Sea. With such a pathway, the expectation has been that if the AMOC diminished or increased in strength, there would be a commensurate change in the sea surface temperature in this region. It turns out, however, that there is scant evidence for the throughput of *surface* waters from the subtropical to the subpolar gyre (Brambilla and Talley, 2006; Burkholder and Lozier, 2014). Instead, the throughput is accomplished via subsurface pathways that deliver heat and salt to the subpolar gyre. In addition to the task of "restructuring" the AMOC's upper limb, oceanographers are left asking the question: how and on what time scales does variability in the AMOC return flow, namely the upper limb, impact sea surface temperatures in the regions of deepwater formation? An answer to this question is essential to our understanding of feedbacks in the climate system.

4. Latitudinal Changes in Overturning

A characteristic of a conveyor belt is its continuity. Though this imagery was used to only loosely describe the structure of the overturning, the continuous nature of the overturning was generally assumed. In other words, oceanographers expected that overturning changes measured at one latitude would match the overturning changes measured at another, particularly in the Atlantic Ocean where deep waters collectively move equatorward. When the Rapid array was deployed in 2004, the expectation was that it would measure *the* AMOC. However, starting a decade ago, a modeling study (Bingham et al., 2007) suggested that overturning variability was not coherent from one gyre to another. And more recently, a study that compares the AMOC from the Rapid array to that estimated from Argo floats at 41°N finds that the measures are not the same (Mielke et al., 2013). Why not? While oceanographers are actively exploring this question, one answer appears to be that wind forcing at different latitudes and over different gyres can account for some of this difference. It also matters on what time scale you make the measurement. Regardless, it is now evident that there is not a single measure of the AMOC, something that we clearly did not understand just a short decade ago.

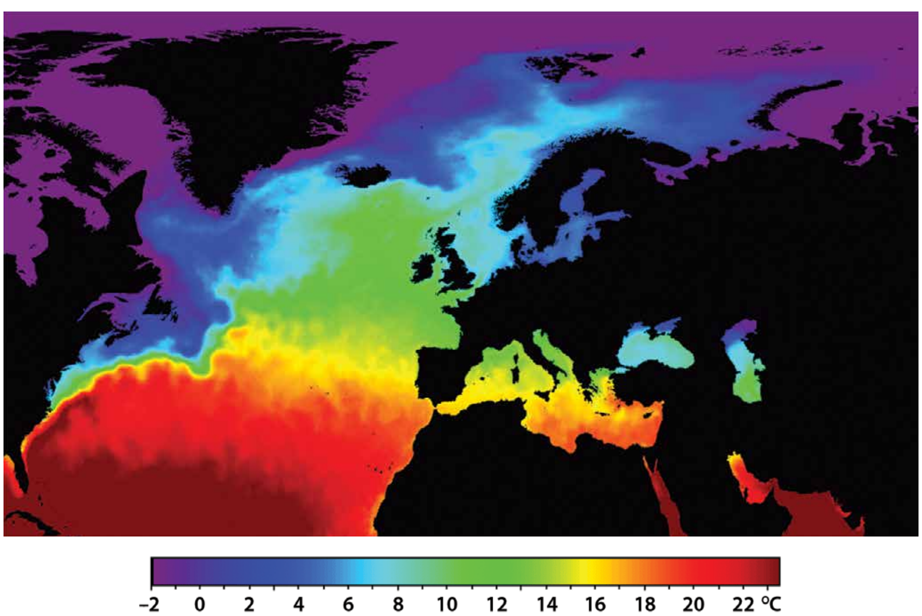

FIGURE 9. Sea surface temperature for the North Atlantic in January of 2008, measured from satellites. *Image courtesy of Valborg Byfield, National Oceanography Center, Data from OSTIA.*

5. Linking Deepwater Formation to Overturning Changes

For decades, our explanation of why cold, deep waters move equatorward from the northern North Atlantic began with an explanation of water mass formation at high latitudes: during the winter as the surface waters lose their heat to the cold atmosphere, the surface waters become more dense and, because heavy waters over light waters create an unstable situation, these waters overturn and mix, creating a large mass of water with homogeneous properties. Why these water masses subsequently spread to the rest of the globe has generally been explained with either a "push" or "pull" hypothesis (Visbeck, 2007): the waters are pushed by the formation process or they are pulled by wind forcing that upwells deep waters to the surface. Today, oceanographers generally understand that the overturning circulation depends upon many factors: internal mixing supplied by tides and winds, remote and local wind and buoyancy forcing, and the impact of eddies on all of these processes. The *change* in the overturning circulation, however, has long been linked to changes in the formation of water masses in the North Atlantic. If the surface waters warm or become fresher, the expectation is that the overturning would commensurately decrease. Fewer overturned waters equal fewer exported waters.

This expectation held until this linkage was put to the test. An analysis of hydrographic sections across the Labrador Sea from 1990 to 1997 (Pickart and Spall, 2007) revealed that although the convective activity (i.e., the production of water masses) in that basin was the strongest ever recorded during those years, the AMOC measure in that basin, expected to strengthen, was not affected. Subsequent to that study, data from a moored array at 53°N (Fischer et al., 2010; Figure 10) in the deep western boundary current of the Labrador Sea revealed a gradual warming of the waters from 1997 to 2009, indicating a decrease in convective activity; yet, there was no detectable change in the strength of the deep western boundary current. According to the current paradigm, it should have weakened. Similarly, recent studies of property and transport changes over the high latitude sills leading into the North Atlantic have not given any clear indication of variability that can be linked to local buoyancy forcing (Dickson et al., 2008; Jochumsen et al., 2012).

What is going on? Though oceanographers have neatly partitioned the circulation into that driven by winds and that driven by buoyancy forcing at the sea surface, we now understand that the circulation cannot be so neatly divided. Also, we now realize that remote forcing may play as much or more of a role as local forcing in affecting ocean circulation. Thus, after a number of modeling, theoretical, and observational studies, we now understand that if the amount of water mass in one winter increases by one Sverdrup (a unit of volume equal to 10^6 m^3 s^{-1}), it does not mean that one Sverdrup more will be exported to lower latitudes as part of the AMOC in that same year. What then sets just how much the AMOC varies? That question, discussed below, looms large.

WHAT DO WE KNOW?

Over the past decade, this slow unraveling of the conveyor belt paradigm has seemingly left us with more questions than when we started our observational and modeling focus on the AMOC. It is good, then, to review what we do know about this circulation feature. We know that the majority of the deep ocean is filled with waters that acquired their properties at the surface in the high latitudes of the North Atlantic. We know that those waters return to the upper ocean primarily in the Southern Ocean via wind-forced upwelling, but also via mixing in the Indian and Pacific Oceans. Once upwelled, these waters return to their formation sites along circuitous routes across the globe. Wind and tidal mixing provide the energy necessary to upwell water from depth. We understand that this overturning produces a net poleward heat flux that, in partnership with the atmosphere, offsets the differential heating of our planet.

WHAT DON'T WE KNOW?

With the unraveling of the conveyor belt paradigm, a host of questions are left unanswered, but chief among them is: what mechanism drives the overturning variability? Though the current understanding of the stability of the overturning, gleaned from modeling studies, has led a recent US National Research Council (NRC) committee to conclude that there

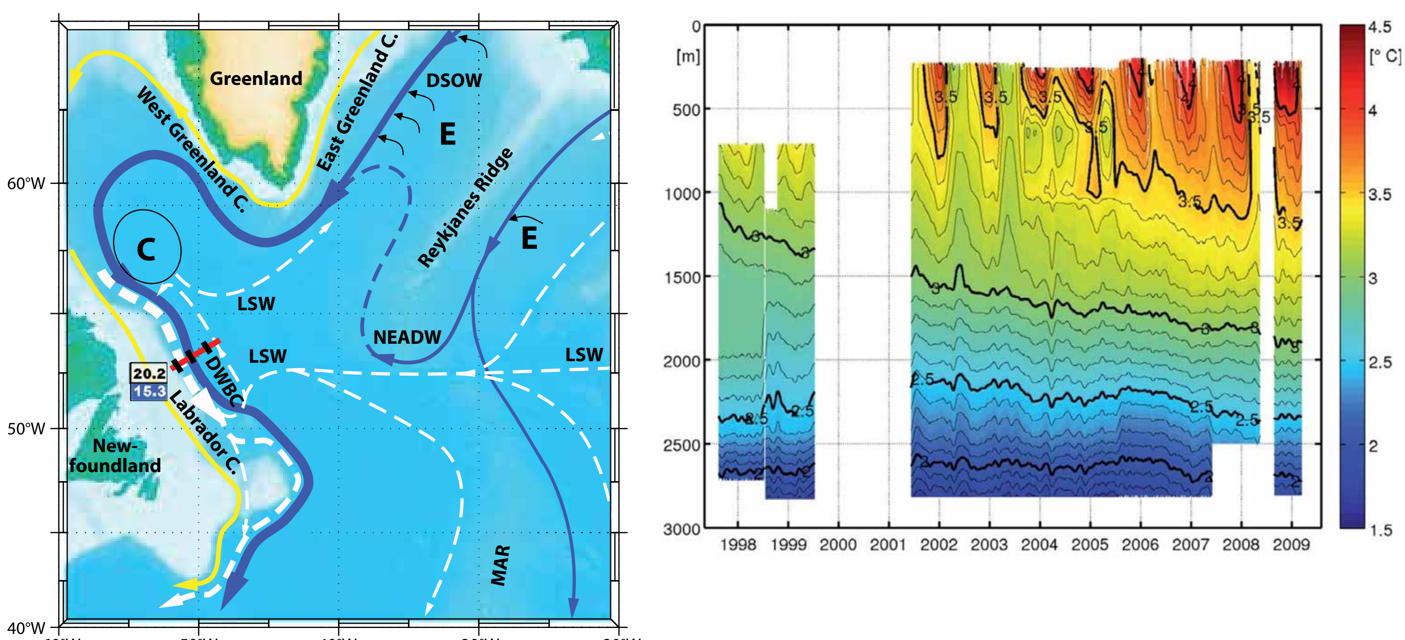

FIGURE 10. (left) The Labrador Sea in the North Atlantic with the site of a long-term mooring array situated in the deep western boundary current denoted by the red line. (right) The evolution of the temperature field in the center of the deep western boundary current. Note the warming of the waters from near the surface down to ~2,000 m in the latter part of the record. *From Fischer et al. (2010)*

is a low probability of abrupt change this century (NRC, 2013), change in the overturning does not have to be abrupt for it to have significant impact. Modeling studies indicate that overturning variability affects North Atlantic sea surface temperatures (Knight et al., 2005; Delworth et al., 2007), which in turn affect rainfall over the African Sahel, India, and Brazil; Atlantic hurricane activity; and summer climate over Europe and North America (Sutton and Hodson, 2005; Knight et al., 2006; Zhang and Delworth, 2006; Smith et al., 2010). Critically, overturning variability, via the influx of warm northward surface flow, has been linked to the decline of Arctic sea ice (Serreze et al., 2007) and mass loss from the Greenland Ice Sheet (Rignot and Kanagaratnam, 2006; Holland et al., 2008; Straneo et al., 2010), both of which have profound consequences for climate variability. Finally, AMOC variability can potentially impact the carbon sink in the North Atlantic, which currently accounts for 41% of the annual mean global air-sea CO_2 flux, with nearly half of that flux occurring north of 50°N (Takahashi et al., 2009). Thus, the question as to what drives the overturning variability deserves considerable attention.

Underscoring the importance of this question is the current IPCC projection, based on an ensemble of climate models, of AMOC slowdown in the twenty-first century. The slowdown is attributed to the inhibition of deep convection at high latitudes in the North Atlantic, due to the warming of surface waters at those latitudes. These climate models are in concert with our assumptions of the past 50 years about the linkage between the formation of water masses and the overturning, but, as detailed here, a collection of observational and ocean modeling studies conducted over the past decade call into question a direct linkage between deep water mass formation and AMOC variability. Meanwhile, Arctic sea ice loss continues apace (Figure 11), creating an anticipated freshwater source downstream at the formation sites of the deep waters.

THE PATH AHEAD

Agreeing on the importance and urgency of understanding overturning variability, the international community launched a new observing system in the subpolar North Atlantic in the summer of 2014. Led by the United States, with contributions from the UK, Germany, the Netherlands, Canada, France, and China, the Overturning in the Subpolar North Atlantic Program (OSNAP), is designed to provide a continuous record of the overturning circulation and its associated fluxes of heat and freshwater in the subpolar North Atlantic. Because the majority of the globe's deep waters originate in the North Atlantic and because of the tight coupling between changes in the Arctic and the North Atlantic, a measure of the overturning in the subpolar North Atlantic basin will give the ocean community its best chance at determining the factors that drive its variability.

The OSNAP observing system (Figure 12) consists of two legs: the first extends from southern Labrador to the southwestern tip of Greenland and across the mouth of the Labrador Sea, and the second from the southeastern tip of Greenland to Scotland. The observing system also includes subsurface floats in order to trace the pathways of overflow waters in the basin. The first estimate of the overturning from the OSNAP array will not be available until the summer of 2016, when all moorings are first recovered. Given the results from the Rapid array, oceanographers have one firm expectation: that the OSNAP results will make us think in new ways about the ocean. No doubt other assumptions will be overturned.

SUMMARY

For over 200 years, the ocean's overturning circulation has principally been described based on property distributions at depth in the global ocean. Property gradients in temperature, salinity, and oxygen have been used to describe the structure of the deep limb of the overturning, and reconstructions of temperatures from the sediment record have long been used to describe its temporal variability. Only

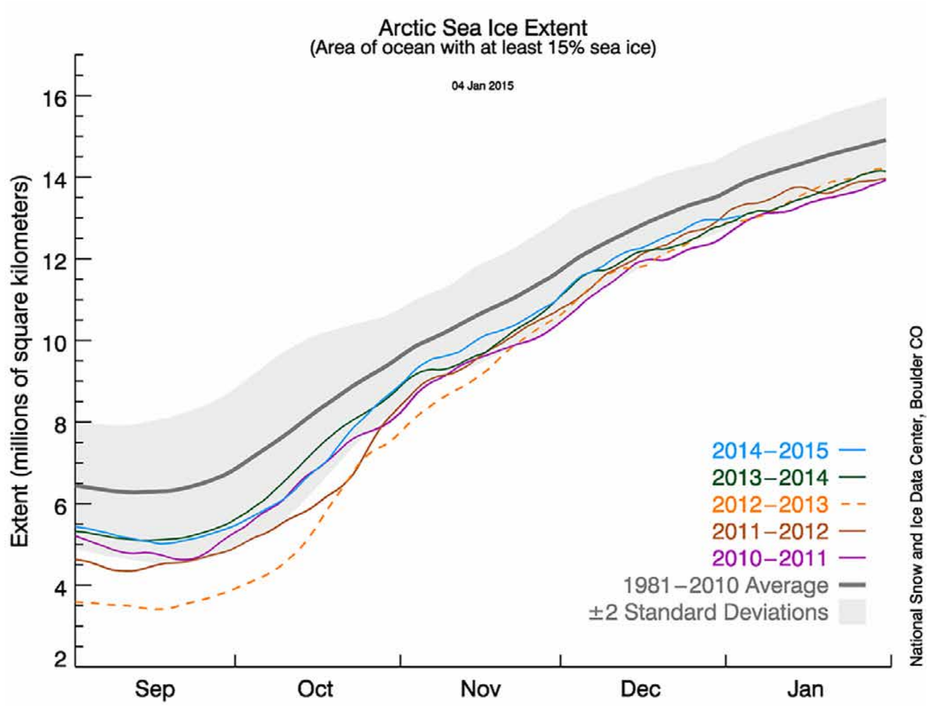

FIGURE 11. Seasonal change in the spatial extent of Arctic sea ice for the past five years compared to the 1981–2010 average (in gray). The minimum in Arctic sea ice generally occurs in September, at the end of the summer warming. *Image courtesy of the National Snow and Ice Data Center (NSIDC), University of Colorado, Boulder*

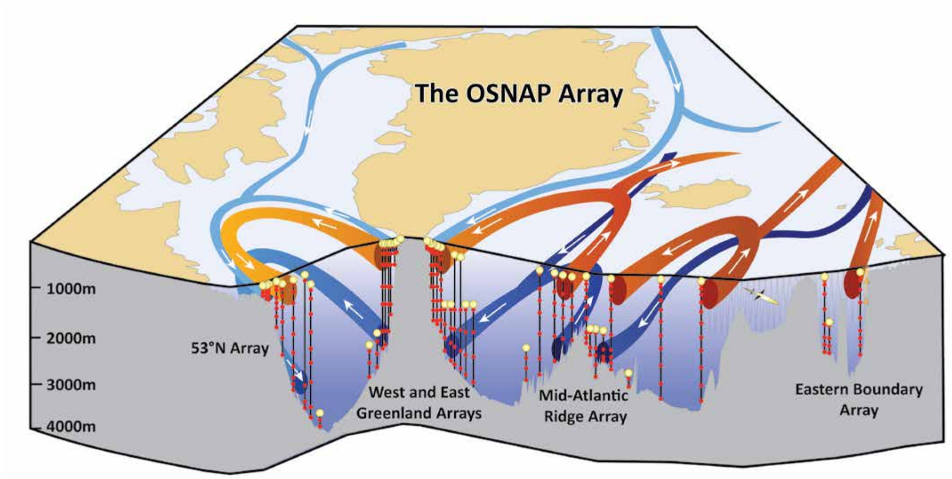

FIGURE 12. Schematic of the Overturning in the Subpolar North Atlantic Program (OSNAP) observing system, deployed in the summer of 2014. Arrays of current meters span the boundary currents in the Labrador, Irminger, and Iceland Seas, as well as in Rockall Trough. Deep arrays have been deployed on both sides of the Reyjkanes Ridge. The observing system will allow for monthly estimates of the overturning circulation, as well as the flux of heat and freshwater across the array. Subsurface floats deployed in the deep waters for the purpose of tracing water mass pathways are also part of the OSNAP program, as are gliders that patrol the waters above the Hatton/Rockall Bank. A contribution to this observing system from the People's Republic of China is expected to be in place in the summer of 2015. *Image courtesy of Overturning in the Subpolar North Atlantic Program (OSNAP). Schematic credit: Penny Holliday, National Environmental Research Council, UK*

in the past decade, when oceanographers have been able to more readily measure the velocity field of the ocean, has the disconnect between the overturning as we understand it now and that previously inferred from ocean properties become so apparent. This disconnect has caused a rapid deconstruction of the conveyor belt, whereby much of what we thought we knew about the overturning has been called into question. However, the importance of the overturning to climate and climate variability remains intact, prompting the international community to launch a new observing system so that a twenty-first century understanding of the ocean's overturning can be constructed.

A twenty-first century understanding is vitally important because the start of this century has ushered in further confirmation of a warming climate. The overturning is expected to slow in response to a warming, and such slowing has possible implications for climate variables such as continental precipitation, sea ice melt, and hurricane activity. Yet, our understanding to date of overturning variability has been built almost entirely upon modeling studies, and in recent years some observations have given oceanographers reasons to think that our twentieth century understanding of overturning variability needs to be reconstructed, starting with new observations. Fortunately, this century has also ushered in ocean technology and international partnerships that together make possible the measurement of the ocean's overturning on scales unimaginable to Rumford and, indeed, even to Revelle. In years to come, future oceanographers may well be surprised at our limited sampling, but for now we expect these measurements to yield light years of progress.

Roger Revelle

For almost half a century, Roger Revelle was a leader in the field of oceanography. Revelle trained as a geologist at Pomona College, and received his PhD in oceanography from the University of California, Berkeley, in 1936. As a young naval officer, he helped persuade the Navy to create the Office of Naval Research (ONR) to support basic research in oceanography and was the first head of ONR's geophysics branch. Revelle served for 12 years as the Director of Scripps (1950–1961, 1963–1964), where he built up a fleet of research ships and initiated a decade of expeditions to the deep Pacific that challenged existing geological theory.

Revelle's early work on the carbon cycle suggested that the sea could not absorb all the carbon dioxide released from burning fossil fuels. He organized the first continual measurement of atmospheric carbon dioxide, an effort led by Charles Keeling, resulting in a long-term record that has been essential to current research on global climate change. With Hans Suess, he published the seminal paper demonstrating the connection between increasing atmospheric carbon dioxide and burning of fossil fuels. Revelle kept the issue of increasing carbon-dioxide levels before the public and spearheaded efforts to investigate the mechanisms and consequences of climate change.

Revelle left Scripps for critical posts as Science Advisor to the Department of the Interior (1961–1963) and as the first Director of the Center for Population Studies at Harvard (1964–1976). Revelle applied his knowledge of geophysics, ocean resources, and population dynamics to the world's most vexing problems: poverty, malnutrition, security, and education.

In 1957, Revelle became a member of the National Academy of Sciences to which he devoted many hours of volunteer service. He served as a member of the Ocean Studies Board, the Board on Atmospheric Sciences and Climate, and many committees. He also chaired a number of influential Academy studies on subjects ranging from the environmental effects of radiation to understanding sea level change.

Photo credit: SIO Archives, UCSD

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