The AMOC needs a universally-accepted definition

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Abstract

The debate over the historical and future evolution of the Atlantic Meridional Overturning Circulation (AMOC) has united scientists around a single topic, but this community has yet to unite around a single definition of the AMOC. In an effort to focus the debate around dynamics rather than semantics, we recommend that the community universally adopt a definition of the AMOC in density coordinates. We present evidence that the traditional depth space definition is insufficient at capturing elements of this circulation, especially at high latitudes where the northward and southward limbs of the AMOC are separated horizontally rather than vertically. Instead, the AMOC in density coordinates more realistically captures the water mass transformation process at high latitudes, shifts the maximum AMOC from the subtropical to the subpolar North Atlantic where the majority of the deep waters are formed, and depicts the peak in meridional heat transport associated with the subtropical gyre.

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The debate over the historical and future evolution of the Atlantic Meridional Overturning Circulation (AMOC) has united scientists around a single topic, but this community has yet to unite around a single definition of the AMOC. In an effort to focus the debate around dynamics rather than semantics, we recommend that the community universally adopt a definition of the AMOC in density coordinates. We present evidence that the traditional depth space definition is insufficient at capturing elements of this circulation, especially at high latitudes where the northward and southward limbs of the AMOC are separated horizontally rather than vertically. Instead, the AMOC in density coordinates more realistically captures the water mass transformation process at high latitudes, shifts the maximum AMOC from the subtropical to the subpolar North Atlantic where the majority of the deep waters are formed, and depicts the peak in meridional heat transport associated with the subtropical gyre.

1. Motivation

The Atlantic Meridional Overturning Circulation (AMOC) consists of a complex set of currents in the Atlantic Ocean that move warm, saline water northward and return cold, fresh water southward. Despite this simple qualitative description, defining the AMOC quantitatively is not straightforward. Traditionally, oceanographers have defined it in depth coordinates: locate the depth where the currents shift from net northward to net southward and sum the meridional velocities above that depth. If one assumes the Atlantic/Arctic is a closed basin by considering the Bering Strait throughflow of ~1 Sv (Woodgate et al., 2018) below the detection level of the AMOC observing arrays (Cunningham et al., 2007; Lozier et al., 2019), and by neglecting net mass divergence and precipitation in the North Atlantic on timescales longer than 10 days (Kanzow et al., 2007), then the depth where the currents shift from net northward to net southward corresponds to the depth of maximum overturning, and the sum of the meridional velocity above it is equal to the maximum in the AMOC stream function.

There is historical precedent for this depth-space definition - oceanographers have measured the AMOC for decades in the subtropical North Atlantic, where strong thermal stratification provides enough baroclinicity in the water column that the warm northward limb of the AMOC can flow directly over the cold southward limb (Fig. 1). The longest direct measurements of the AMOC are from a repeat hydrographic line across 25°N that has been occupied since 1957 (Hall and Bryden, 1982), and the first continuous observations of the AMOC have been made since 2004 at the RAPID mooring array across 26.5°N (Cunningham et al., 2007). This latitude was chosen because the oceanic meridional heat transport (MHT) reaches its maximum in the subtropics (Ganachaud and Wunsch, 2003), and because much of the Gulf Stream was already being continuously measured in the Florida Straits by a defunct telephone cable (Sanford and Larsen, 1985; Barringer and Larsen, 2001).

But this focus on the subtropical North Atlantic has led to a definition of the AMOC that emphasizes its vertical dependency despite the AMOC shifting to a horizontal circulation pattern further north (*e.g.*Zhang and Thomas, 2021). In the subpolar North Atlantic and Nordic Seas, reduced vertical stratification does not permit opposing currents to flow directly over one another, and instead, the northward limb of the AMOC flows along the eastern side of the basin while the southward limb flows along the western side at similar depths. Here, though the northward and southward limbs are no longer differentiated in depth, their densities remain distinct. Thus when the meridional velocities are zonally summed in density classes, the northward and southward limbs remain distinct in the streamfunction, even at high latitudes where the canonical 'conveyor belt' lays on its side.

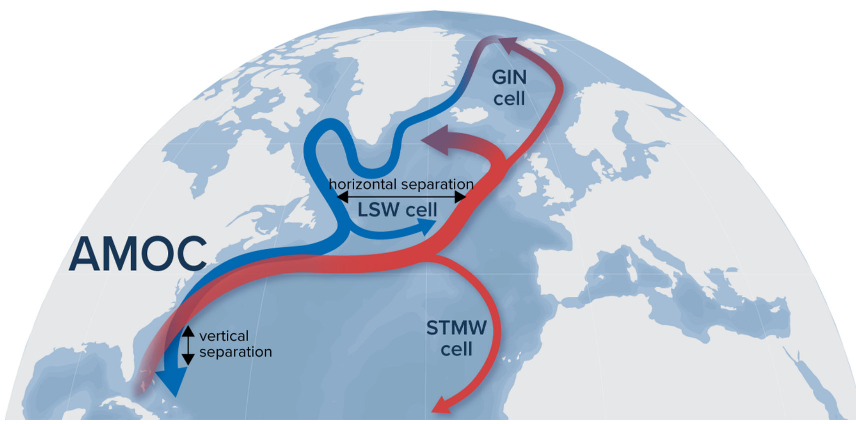

Figure 1. Schematic representation of the AMOC emphasizing the separation of the northward and southward limbs vertically in the subtropics and horizontally in the subpolar gyre and Nordic Seas. Note that the majority of subtropical and subpolar waters recirculate in their respective gyres, a process that is not depicted in this figure. The three cells apparent in the density-space streamfunction (Fig. 2b) are also shown: Greenland, Iceland, and Norwegian Seas (GIN) cell, Labrador Sea Water (LSW) cell, and subtropical mode water (STMW) cell.

2. Scientific Gain

When compressing the three-dimensional North Atlantic circulation into a two-dimensional streamfunction, the goal is to make the data more manageable and easily visualized, while retaining its essential components. In this section, we present evidence that the AMOC streamfunction in density coordinates retains more essential information than its counterpart in depth coordinates.

The depth space streamfunction (Fig. 2a), presents the AMOC as one large overturning cell covering all depths and all latitudes. In contrast, the density space streamfunction (Fig. 2b and 2c) identifies three distinct overturning cells that are important to the large-scale North Atlantic circulation:

1. a light overturning cell in the subtropical North Atlantic (30.50-34.8 kg/m^3 and 0°-40°N) that depicts the formation of Subtropical Mode Water (STMW)
2. an intermediate overturning cell spanning all latitudes but with a peak in the subpolar gyre (35.50-37.02 kg/m^3, 20°S-60°N) that depicts the formation of Labrador Sea Water (LSW) in the Labrador and Irminger Seas
3. a dense overturning cell in the Greenland, Iceland, and Norwegian (GIN) Seas (37.02-37.20 kg/m^3, 60°N-75°N) that depicts the formation of the densest water masses north of the Greenland-Scotland Ridge.

In depth coordinates, the STMW cell is only apparent in the upper 100 m between 10°N-20°N, and the incredible amount of water mass transformation (4 kg/m^3 between the northward and southward limbs) in this cell is lost (Fig. 2b). This is a critical omission because the STMW cell corresponds almost exactly to the peak oceanic MHT from 0°-40°N (Ganachaud and Wunsch, 2003), implying that this cell is indeed important to the MHT, one of the most societally-relevant aspects of the AMOC. Similarly, the strength of the GIN cell (4 Sv) in depth coordinates is only a fraction of its strength in density coordinates (6 Sv), and its importance to forming the densest water masses that spill over the Greenland-Scotland Ridge and fill the deep North Atlantic is not conveyed in depth coordinates.

The AMOC streamfunction in density coordinates also produces a more continuous streamfunction that correctly positions the AMOC maximum in the subpolar North Atlantic, where the majority of the southward limb waters are formed. In contrast, the depth-space streamfunction artificially shifts the maximum of the LSW cell into the subtropical gyre and away from the regions of deep-water formation in the subpolar North Atlantic and Nordic Seas. This southward shift of the maximum AMOC is due to the inability of the depth-space AMOC to capture the horizontal circulation. For example, consider that in depth coordinates, the southward flow of cold, fresh waters in the Labrador Current is negated by the northward flow of warm, saline water in the North Atlantic Current. When these two currents meet near the Grand Banks of Newfoundland, the cold, fresh water subducts under the warm, saline waters and the two limbs start to project back onto the vertical dimension. But this process yields a sharply discontinuous AMOC streamfunction in depth coordinates north of 35°N (Fig. 2a). Instead, summing the meridional velocity fields in density classes rather than depth levels highlights the water mass transformation that occurs as the water circulates cyclonically around the subpolar North Atlantic (Desbruyères et al., 2019), and produces a more continuous AMOC streamfunction between the subtropical and subpolar North Atlantic (Fig. 2b).

The AMOC streamfunction in density coordinates also differentiates between overturning cells that are confined to one gyre and the overturning cell that crosses gyre boundaries. This differentiation becomes essential when assessing forcing mechanisms of AMOC variability. For example, the mechanisms driving the AMOC at subtropical and subpolar latitudes of the North Atlantic are different and time scale dependent (e.g. Jackson et al., 2022). In essence, while wind and buoyancy forcing are both considered important at higher latitudes on interannual-to-decadal scales, in the subtropics wind forcing alone can explain a substantial portion of the variability (Yang, 2015; Kostov et al., 2021), especially on seasonal-to-interannual timescales (Moat et al., 2020). Opposing wind stress variability induced by the NAO in the subpolar and subtropical ocean can lead to opposing decadal AMOC variations, which indeed breaks the notion of a single metric diagnosing the basin-scale overturning cell (Lozier et al., 2010). It is thus imperative to represent the AMOC in density space to gain correct insights into its latitudinal-dependent mechanisms.

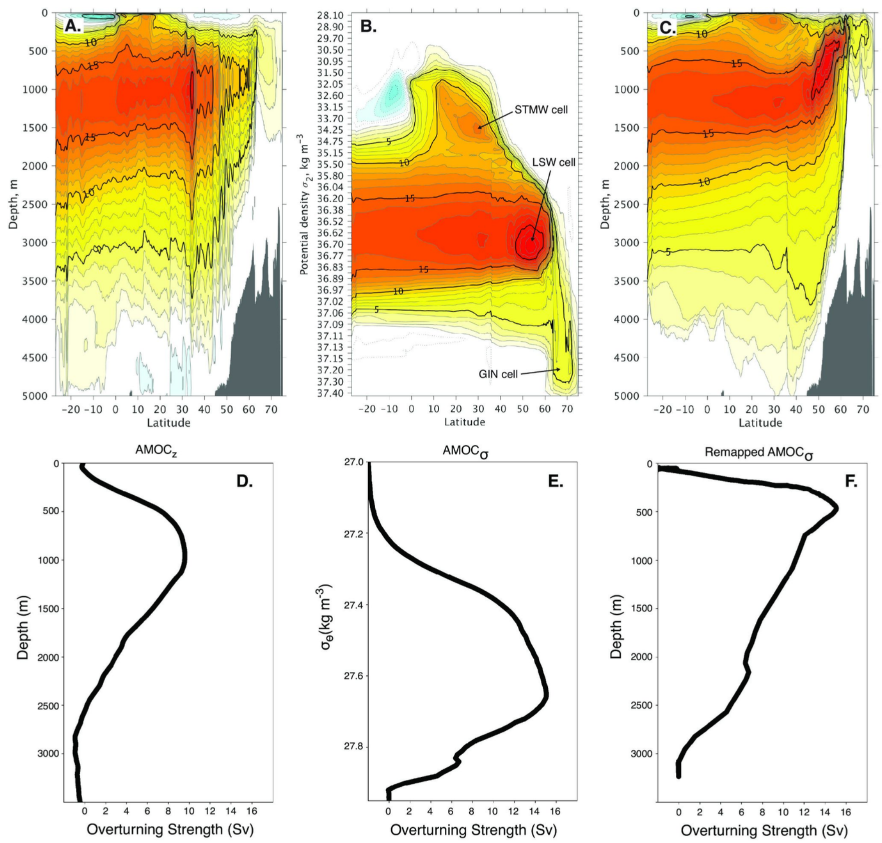

Figure 2. The time-mean AMOC streamfunction from (**A-C**) a high-resolution (1/12°) ocean simulation (HYCOM) and (**D-F**) the first four years of data from the OSNAP mooring array (Li et al., 2021). The left column (**A, D**) displays the streamfunction in depth coordinates, the middle column (**B, E**) in density coordinates ($?_2$ in **B** and $?_?$ in**E**), and right column (**C, F**) in density coordinates remapped into depth space using the zonal mean depth of each density layer. Note the non-linear y-axis in panel **B** . Panels**A-C** are reproduced from Xu et al. (2018). (c) American Meteorological Society. Used with permission.

3. Confusion

The AMOC streamfunction in density coordinates is confusing to non-experts - where the various cells are located in the water column is not clear, and the typical conveyor belt analogy gets convoluted when zonally-sloped isopycnals become important. Thus, how to visualize the AMOC in density space and communicate it to wide audiences is vital to facilitating its widespread adoption. This can be done by remapping the streamfunction in density space into depth coordinates at the depth of each density layer. Practically, this process involves calculating the zonal-mean depth at each latitude for each isopycnal, and then plotting the values of the density-space streamfunction at those depths (Fig. 2c and 2f; McIntosh and McDougall, 1996; Young, 2012; Xu et al., 2018; Rousselet et al., 2020). This yields a streamfunction that more accurately connects the size of the feature in the ocean with the size of the circulation feature in the figure, and makes the results more immediately understandable to a wider audience.

Further complicating this matter is the language used when referring to the AMOC – the “upper limb” is often referred to as the northward component and the “lower limb” as the southward component. But those terms are rooted in the depth-coordinate definition. Instead, it is more accurate to refer to the “northward limb” and “southward limb”.

The literature is also divided between the two definitions, which leads to confusion when results are compared. The most prominent example of this divide is that the RAPID array at 26degN has been reporting their AMOC data in depth coordinates for nearly 20 years (Moat et al., 2020), while the Overturning in the Subpolar North Atlantic Program (OSNAP) publishes their results in density coordinates (Lozier et al., 2019; see panels D-F in Fig. 2). Though the maximum AMOC value at RAPID is not sensitive to the choice of coordinate system (compare Fig. 2a with 2b at 26degN), the depth space definition diminishes the STMW cell and thus the RAPID streamfunction in depth space misses an opportunity to provide direct in situ data about the STMW cell. Similarly, many physical oceanography modeling and reanalysis papers have published their AMOC metrics in density coordinates (*e.g.* , Lumpkin and Speer, 2006; Lherminier et al., 2007; Marshall and Speer, 2012; Kwon and Frankignoul, 2014; Xu et al., 2016; Hirschi et al., 2020; Biastoch et al., 2021; Yeager et al., 2021), while most climate studies use depth coordinates for historical and logistical reasons (*e.g.* , Caesar et al., 2018; Jackson and Wood, 2018; Weijer et al., 2020; Liu and Federov, 2021). Output from the various CMIP models contain an AMOC variable that is defined in depth coordinates, and recalculating this variable in density coordinates would require accessing each models' velocity and density fields. Repeating this calculation for tens of models each with various runs spanning hundreds of years is prohibitive for most users (Weijer et al., 2020; Jackson and Petit, 2022).

Another source of confusion between studies is the choice of AMOC metric. As evident in the density-space AMOC streamfunction (Fig. 2), the AMOC consists of multiple overturning cells that do not span all latitudes. Thus the AMOC is likely not meridionally coherent (e.g. Bingham et al., 2007; Lozier et al., 2008; Jackson et al., 2022), and it is difficult or near impossible to represent the wider North Atlantic circulation using a single metric, i.e. the traditional maximum streamfunction in depth coordinates (e.g., Vellinga and Wood, 2008; Drijfhout et al., 2012; Liu and Fedorov, 2021). In both climate models (Hirschi et al., 2020) and ocean reanalyses (Karspeck et al., 2017), the latter metric is located within the subtropics, where wind forcing dominates (Zhao and Johns, 2014). However, in density coordinates, the maximum transport is consistently found at higher latitudes (Hirschi et al., 2020), sometimes shifted northward by as much as 20deg of latitude (Biastoch et al., 2021), where buoyancy forcing and horizontal gyre circulation play a dominant role (Chafik and Rossby, 2019; Zhang and Thomas, 2021). This latitudinal disconnect has confused oceanographers for decades: how can a meridionally-oriented current not be meridionally coherent? The recirculation cells depicted in the density space streamfunction illuminate the answer by identifying features that are confined to specific latitudinal ranges, and should not be expected to be meridionally coherent.

Another source of confusion in the literature is whether variability in the AMOC leads or lags variability in the dense overflow waters. The maximum AMOC in depth space at 45degN in a 600 year run of the Community Earth System Model leads variability in the overflow strength by 2-3 years (Danabasoglu et al., 2020), whereas the maximum AMOC in depth space between 27.5degN and 32.5degN in a 1600 year run of the HadCM3 coupled climate model lags variability in the overflows by 10 years (Hawkins and Sutton, 2008). Although the inconsistency between these two studies may be attributed to the overflow parametrization in the different models, it could also simply be a result of the AMOC definitions (subpolar vs. subtropical) used in these studies, and the relative importance of wind and buoyancy forcing at each of these latitudes. As the production of overflow water in the Nordic Seas is considered an important diagnostic of AMOC stability (Chafik and Rossby, 2019) and therefore could provide an early warning of future rapid changes of the broader North Atlantic circulation, avoiding such unnecessary confusion of the AMOC definition is critical.

4. Recommendations

- Studies should define the AMOC in density coordinates because it is more closely aligned with the AMOC's climatic influence, and thus why we care about the AMOC. There are also additional benefits like the streamfunction is more continuous in density space, and that it retains more information of the three-dimensional circulation including correctly positioning the maximum AMOC in the subpolar North Atlantic.
- Observational arrays at all latitudes (*e.g.*, RAPID, OSNAP, SAMOC) should produce AMOC values

in density coordinates to provide consistency between arrays (e.g., Fig. 2e). We acknowledge the added degree of difficulty in measuring the AMOC in density coordinates at these observational arrays – it requires knowledge of the full density and velocity fields across the basin. To provide consistency through time, there is a benefit to publishing both density space and depth space AMOC values at the existing arrays.

- The modeling community (especially the CMIP community) should establish the density space AMOC streamfunction as a standard output variable from their models, as is currently true of the depth-space AMOC streamfunction.
- Studies should remap the density-space AMOC into depth coordinates (Fig. 2c, f) so that the streamfunction can be easily interpreted by non-experts.
- Studies should identify the geographic region and time scale for any AMOC metric. Comparing results that use different coordinate systems, metrics, and data sources requires isolating differences between these three variables. Being specific at which latitude the AMOC is diagnosed, projected, and reconstructed is critical to clearly explaining the driving mechanisms behind AMOC variability and change. This point is also important when comparing proxies or model output to available estimates.
- The maximum AMOC in depth coordinates is likely insufficient to summarize AMOC variability, and could be very sensitive to the data used. This is especially true for studies that highlight: (a) AMOC dynamics, (b) the role of watermass transformation, (c) the importance of the horizontal circulation, and/or (d) AMOC variability at higher latitudes.

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The Atlantic Meridional Overturning Circulation (AMOC) consists of a complex set of currents in the Atlantic Ocean that move warm, saline water northward and return cold, fresh water southward. Despite this simple qualitative description, defining the AMOC quantitatively is not straightforward. Traditionally, oceanographers have defined it in depth coordinates: locate the depth where the currents shift from net northward to net southward and sum the meridional velocities above that depth. If one assumes the Atlantic/Arctic is a closed basin by considering the Bering Strait throughflow of ~1 Sv (Woodgate et al., 2018) below the detection level of the AMOC observing arrays (Cunningham et al., 2007; Lozier et al., 2019), and by neglecting net mass divergence and precipitation in the North Atlantic on timescales longer than 10 days (Kanzow et al., 2007), then the depth where the currents shift from net northward to net southward corresponds to the depth of maximum overturning, and the sum of the meridional velocity above it is equal to the maximum in the AMOC stream function.

There is historical precedent for this depth-space definition - oceanographers have measured the AMOC for decades in the subtropical North Atlantic, where strong thermal stratification provides enough baroclinicity in the water column that the warm northward limb of the AMOC can flow directly over the cold southward limb (Fig. 1). The longest direct measurements of the AMOC are from a repeat hydrographic line across 25°N that has been occupied since 1957 (Hall and Bryden, 1982), and the first continuous observations of the AMOC have been made since 2004 at the RAPID mooring array across 26.5°N (Cunningham et al., 2007). This latitude was chosen because the oceanic meridional heat transport (MHT) reaches its maximum in the subtropics (Ganachaud and Wunsch, 2003), and because much of the Gulf Stream was already being continuously measured in the Florida Straits by a defunct telephone cable (Sanford and Larsen, 1985; Barringer and Larsen, 2001).

But this focus on the subtropical North Atlantic has led to a definition of the AMOC that emphasizes its vertical dependency despite the AMOC shifting to a horizontal circulation pattern further north (*e.g.* Zhang and Thomas, 2021). In the subpolar North Atlantic and Nordic Seas, reduced vertical stratification does not permit opposing currents to flow directly over one another, and instead, the northward limb of the AMOC flows along the eastern side of the basin while the southward limb flows along the western side at similar depths. Here, though the northward and southward limbs are no longer differentiated in depth, their densities remain distinct. Thus when the meridional velocities are zonally summed in density classes, the northward and southward limbs remain distinct in the streamfunction, even at high latitudes where the canonical 'conveyor belt' lays on its side.

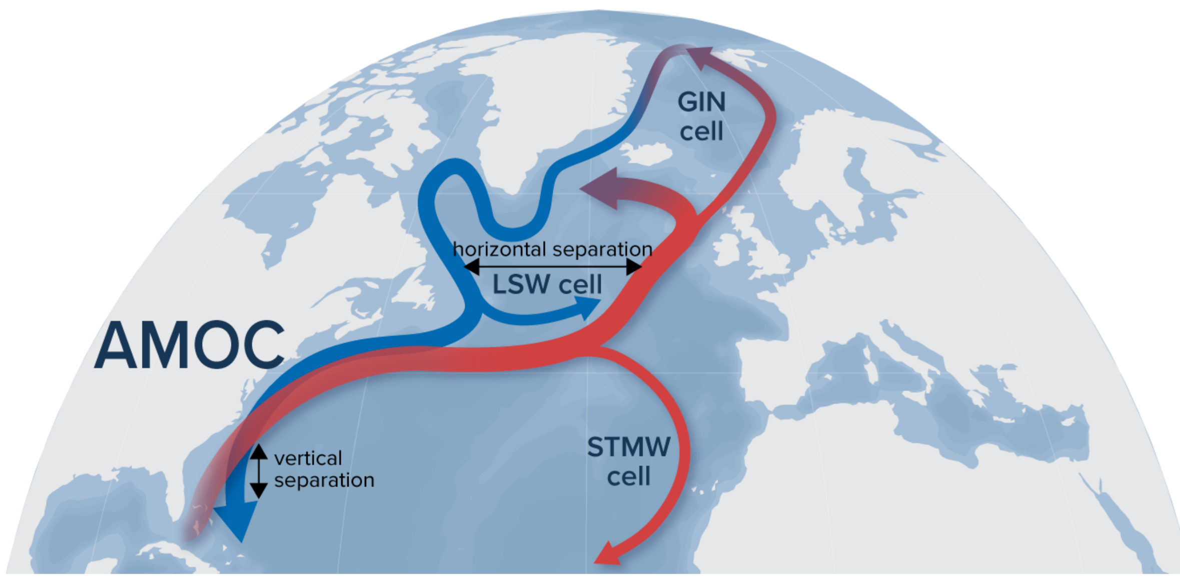

Figure 1. Schematic representation of the AMOC emphasizing the separation of the northward and southward limbs vertically in the subtropics and horizontally in the subpolar gyre and Nordic Seas. Note that the majority of subtropical and subpolar waters recirculate in their respective gyres, a process that is not depicted in this figure. The three cells apparent in the density-space streamfunction (Fig. 2b) are also shown: Greenland, Iceland, and Norwegian Seas (GIN) cell, Labrador Sea Water (LSW) cell, and subtropical mode water (STMW) cell.

2. Scientific Gain

When compressing the three-dimensional North Atlantic circulation into a two-dimensional streamfunction, the goal is to make the data more manageable and easily visualized, while retaining its essential components. In this section, we present evidence that the AMOC streamfunction in density coordinates retains more essential information than its counterpart in depth coordinates.

The depth space streamfunction (Fig. 2a), presents the AMOC as one large overturning cell covering all depths and all latitudes. In contrast, the density space streamfunction (Fig. 2b and 2c) identifies three distinct overturning cells that are important to the large-scale North Atlantic circulation:

1. a light overturning cell in the subtropical North Atlantic (30.50-34.8 kg/m^3 and 0°-40°N) that depicts the formation of Subtropical Mode Water (STMW)
2. an intermediate overturning cell spanning all latitudes but with a peak in the subpolar gyre (35.50-37.02 kg/m^3, 20°S-60°N) that depicts the formation of Labrador Sea Water (LSW) in the Labrador and Irminger Seas
3. a dense overturning cell in the Greenland, Iceland, and Norwegian (GIN) Seas (37.02-37.20 kg/m^3, 60°N-75°N) that depicts the formation of the densest water masses north of the Greenland-Scotland Ridge.

In depth coordinates, the STMW cell is only apparent in the upper 100 m between 10°N-20°N, and the incredible amount of water mass transformation (4 kg/m^3 between the northward and southward limbs) in this cell is lost (Fig. 2b). This is a critical omission because the STMW cell corresponds almost exactly to the peak oceanic MHT from 0°-40°N (Ganachaud and Wunsch, 2003), implying that this cell is indeed important to the MHT, one of the most societally-relevant aspects of the AMOC. Similarly, the strength of the GIN cell (4 Sv) in depth coordinates is only a fraction of its strength in density coordinates (6 Sv), and its importance to forming the densest water masses that spill over the Greenland-Scotland Ridge and fill the deep North Atlantic is not conveyed in depth coordinates.

The AMOC streamfunction in density coordinates also produces a more continuous streamfunction that correctly positions the AMOC maximum in the subpolar North Atlantic, where the majority of the southward limb waters are formed. In contrast, the depth-space streamfunction artificially shifts the maximum of the LSW cell into the subtropical gyre and away from the regions of deep-water formation in the subpolar North Atlantic and Nordic Seas. This southward shift of the maximum AMOC is due to the inability of the depth-space AMOC to capture the horizontal circulation. For example, consider that in depth coordinates, the southward flow of cold, fresh waters in the Labrador Current is negated by the northward flow of warm, saline water in the North Atlantic Current. When these two currents meet near the Grand Banks of Newfoundland, the cold, fresh water subducts under the warm, saline waters and the two limbs start to project back onto the vertical dimension. But this process yields a sharply discontinuous AMOC streamfunction in depth coordinates north of 35°N (Fig. 2a). Instead, summing the meridional velocity fields in density classes rather than depth levels highlights the water mass transformation that occurs as the water circulates cyclonically around the subpolar North Atlantic (Desbruyères et al., 2019), and produces a more continuous AMOC streamfunction between the subtropical and subpolar North Atlantic (Fig. 2b).

The AMOC streamfunction in density coordinates also differentiates between overturning cells that are confined to one gyre and the overturning cell that crosses gyre boundaries. This differentiation becomes essential when assessing forcing mechanisms of AMOC variability. For example, the mechanisms driving the AMOC at subtropical and subpolar latitudes of the North Atlantic are different and time scale dependent (e.g. Jackson et al., 2022). In essence, while wind and buoyancy forcing are both considered important at higher latitudes on interannual-to-decadal scales, in the subtropics wind forcing alone can explain a substantial portion of the variability (Yang, 2015; Kostov et al., 2021), especially on seasonal-to-interannual timescales (Moat et al., 2020). Opposing wind stress variability induced by the NAO in the subpolar and subtropical ocean can lead to opposing decadal AMOC variations, which indeed breaks the notion of a single metric diagnosing the basin-scale overturning cell (Lozier et al., 2010). It is thus imperative to represent the AMOC in density space to gain correct insights into its latitudinal-dependent mechanisms.

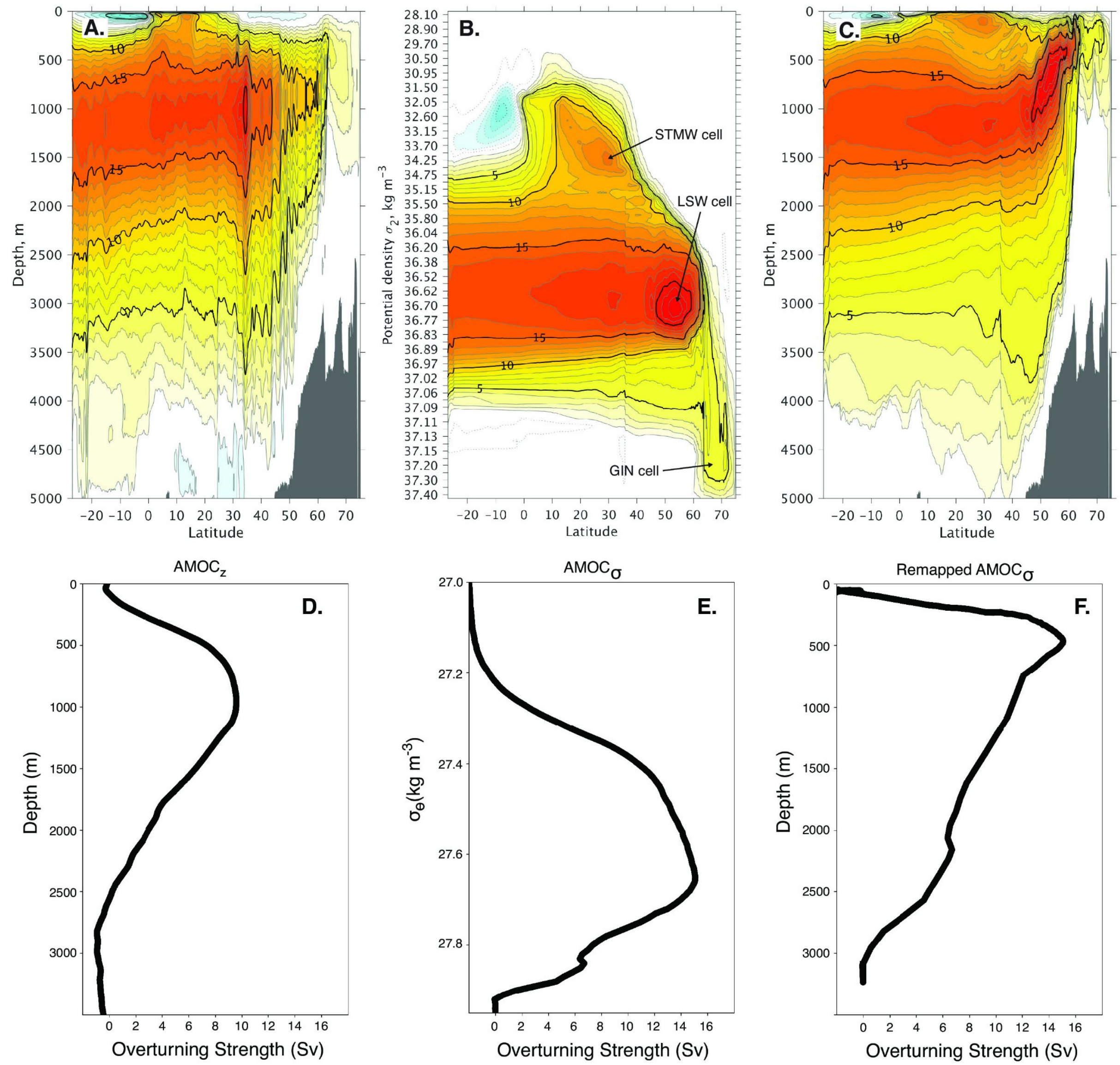

Figure 2. The time-mean AMOC streamfunction from (**A-C**) a high-resolution (1/12°) ocean simulation (HYCOM) and (**D-F**) the first four years of data from the OSNAP mooring array (Li et al., 2021). The left column (**A, D**) displays the streamfunction in depth coordinates, the middle column (**B, E**) in density coordinates ($_2$ in **B** and in **E**), and right column (**C, F**) in density coordinates remapped into depth space using the zonal mean depth of each density layer. Note the non-linear y-axis in panel **B**. Panels **A-C** are reproduced from Xu et al. (2018). © American Meteorological Society. Used with permission.

3. Confusion

The AMOC streamfunction in density coordinates is confusing to non-experts - where the various cells are located in the water column is not clear, and the typical conveyor belt analogy gets convoluted when zonally-sloped isopycnals become important. Thus, how to visualize the AMOC in density space and communicate it to wide audiences is vital to facilitating its widespread adoption. This can be done by remapping the streamfunction in density space into depth coordinates at the depth of each density layer. Practically, this process involves calculating the zonal-mean depth at each latitude for each isopycnal, and then plotting the values of the density-space streamfunction at those depths (Fig. 2c and 2f; McIntosh and McDougall, 1996; Young, 2012; Xu et al., 2018; Rousselet et al., 2020). This yields a streamfunction that more accurately connects the size of the feature in the ocean with the size of the circulation feature in the figure, and makes the results more immediately understandable to a wider audience.

Further complicating this matter is the language used when referring to the AMOC – the "upper limb" is often referred to as the northward component and the "lower limb" as the southward component. But those terms are rooted in the depth-coordinate definition. Instead, it is more accurate to refer to the "northward limb" and "southward limb".

The literature is also divided between the two definitions, which leads to confusion when results are compared. The most prominent example of this divide is that the RAPID array at 26°N has been reporting their AMOC data in depth coordinates for nearly 20 years (Moat et al., 2020), while the Overturning in the Subpolar North Atlantic Program (OSNAP) publishes their results in density coordinates (Lozier et al., 2019; see panels D-F in Fig. 2). Though the maximum AMOC value at RAPID is not sensitive to the choice of coordinate system (compare Fig. 2a with 2b at 26°N), the depth space definition diminishes the STMW cell and thus the RAPID streamfunction in depth space misses an opportunity to provide direct in situ data about the STMW cell. Similarly, many physical oceanography modeling and reanalysis papers have published their AMOC metrics in density coordinates (*e.g.*, Lumpkin and Speer, 2006; Lherminier et al., 2007; Marshall and Speer, 2012; Kwon and Frankignoul, 2014; Xu et al., 2016; Hirschi et al., 2020; Biastoch et al., 2021; Yeager et al., 2021), while most climate studies use depth coordinates for historical and logistical reasons (*e.g.*, Caesar et al., 2018; Jackson and Wood, 2018; Weijer et al., 2020; Liu and Federov, 2021). Output from the various CMIP models contain an AMOC variable that is defined in depth coordinates, and recalculating this variable in density coordinates would require accessing each models' velocity and density fields. Repeating this calculation for tens of models each with various runs spanning hundreds of years is prohibitive for most users (Weijer et al., 2020; Jackson and Petit, 2022).

Another source of confusion between studies is the choice of AMOC metric. As evident in the density-space AMOC streamfunction (Fig. 2), the AMOC consists of multiple overturning cells that do not span all latitudes. Thus the AMOC is likely not meridionally coherent (e.g. Bingham et al., 2007; Lozier et al., 2008; Jackson et al., 2022), and it is difficult or near impossible to represent the wider North Atlantic circulation using a single metric, i.e. the traditional maximum streamfunction in depth coordinates (e.g., Vellinga and Wood, 2008; Drijfhout et al., 2012; Liu and Fedorov, 2021). In both climate models (Hirschi et al., 2020) and ocean reanalyses (Karspeck et al., 2017), the latter metric is located within the subtropics, where wind forcing dominates (Zhao and Johns, 2014). However, in density coordinates, the maximum transport is consistently found at higher latitudes (Hirschi et al., 2020), sometimes shifted northward by as much as 20° of latitude (Biastoch et al., 2021), where buoyancy forcing and horizontal gyre circulation play a dominant role (Chafik and Rossby, 2019; Zhang and Thomas, 2021). This latitudinal disconnect has confused oceanographers for decades: how can a meridionally-oriented current not be meridionally coherent? The recirculation cells depicted in the density space streamfunction illuminate the answer by identifying features that are confined to specific latitudinal ranges, and should not be expected to be meridionally coherent.

Another source of confusion in the literature is whether variability in the AMOC leads or lags variability in the dense overflow waters. The maximum AMOC in depth space at 45°N in a 600 year run of the Community Earth System Model leads variability in the overflow strength by 2-3 years (Danabasoglu et al., 2020), whereas the maximum AMOC in depth space between 27.5°N and 32.5°N in a 1600 year run of the HadCM3 coupled climate model lags variability in the overflows by 10 years (Hawkins and Sutton, 2008). Although the inconsistency between these two studies may be attributed to the overflow parametrization in the different models, it could also simply be a result of the AMOC definitions (subpolar vs. subtropical) used in these studies, and the relative importance of wind and buoyancy forcing at each of these latitudes. As the production of overflow water in the Nordic Seas is considered an important diagnostic of AMOC stability (Chafik and Rossby, 2019) and therefore could provide an early warning of future rapid changes of the broader North Atlantic circulation, avoiding such unnecessary confusion of the AMOC definition is critical.

4. Recommendations

- Studies should define the AMOC in density coordinates because it is more closely aligned with the AMOC's climatic influence, and thus why we care about the AMOC. There are also additional benefits like the streamfunction is more continuous in density space, and that it retains more information of the three-dimensional circulation including correctly positioning the maximum AMOC in the subpolar North Atlantic.
- Observational arrays at all latitudes (*e.g.*, RAPID, OSNAP, SAMOC) should produce AMOC values in density coordinates to provide consistency between arrays (e.g., Fig. 2e). We acknowledge the added degree of difficulty in measuring the AMOC in density coordinates at these observational arrays – it

requires knowledge of the full density and velocity fields across the basin. To provide consistency through time, there is a benefit to publishing both density space and depth space AMOC values at the existing arrays.

- The modeling community (especially the CMIP community) should establish the density space AMOC streamfunction as a standard output variable from their models, as is currently true of the depth-space AMOC streamfunction.
- Studies should remap the density-space AMOC into depth coordinates (Fig. 2c, f) so that the streamfunction can be easily interpreted by non-experts.
- Studies should identify the geographic region and time scale for any AMOC metric. Comparing results that use different coordinate systems, metrics, and data sources requires isolating differences between these three variables. Being specific at which latitude the AMOC is diagnosed, projected, and reconstructed is critical to clearly explaining the driving mechanisms behind AMOC variability and change. This point is also important when comparing proxies or model output to available estimates.
- The maximum AMOC in depth coordinates is likely insufficient to summarize AMOC variability, and could be very sensitive to the data used. This is especially true for studies that highlight: (a) AMOC dynamics, (b) the role of watermass transformation, (c) the importance of the horizontal circulation, and/or (d) AMOC variability at higher latitudes.

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