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Key Points:
- We study a potential cause of observed time-averaged spatial variations of Antarctic Intermediate Water (AAIW) properties in the Caribbean Sea
- We quantify the vertical heat and salt fluxes resulting from the presence of thermohaline staircases in the region
- The combination of background turbulence and observed double diffusion mixing suffices to maintain the observed AAIW gradients

Supporting Information:
Supporting Information may be found in the online version of this article.

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Spatial Variations of Antarctic Intermediate Water in the Caribbean Sea Due To Vertical Mixing Along Its Path

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Abstract Because of its pronounced fresh signature, the properties of the northward-flowing Antarctic Intermediate Water (AAIW) affect the Atlantic Meridional Overturning Circulation. Hence, understanding modifications of AAIW along its path is important. Here, we analyze AAIW changes along its path in the Caribbean Sea and assess whether vertical fluxes from background turbulence and from double-diffusive mixing in thermohaline staircases can explain these variations. We deduce the occurrence rate of staircases (7%) and estimate the flux ratio ($\gamma = \frac{\alpha F_T}{\beta F_S} = 0.8$) from Argo float profiles. In combination with vertical fluxes from background turbulence, these values are used in a steady-state advection-diffusion model to estimate the effective diffusivity of salt that arises from double diffusion ($K_S^{dd} = \mathcal{O}(10^{-5}\ \text{m}^2\ \text{s}^{-1})$). This value for K_S^{dd} is similar to observed values (Schmitt, 2005, https://doi.org/10.1126/science.1108678), implying the observed modification of AAIW in the Caribbean Sea may be attributable primarily to vertical mixing in the region itself.

Plain Language Summary Ocean water with different temperature and salinity characteristics is continuously mixed by various mixing processes. One of these processes, referred to as double diffusion, induces small homogeneous layers (≈10 m) in the vertical. These layers are visible as stepped structures in vertical temperature and salinity profiles. In this study, we analyze these structures, which are referred to as thermohaline staircases, in the Caribbean Sea. We show that 7% of all temperature and salinity profiles from Argo floats in the Caribbean Sea contain these thermohaline staircases. In particular, we found that the spatial variations of temperature and salinity in the layer underneath the staircases, referred to as Antarctic Intermediate Water, can be explained primarily vertical heat and salt fluxes, when accounting for double-diffusive mixing and background turbulent mixing.

1. Introduction

Antarctic Intermediate Water (AAIW) is one of the major water masses in the Atlantic Ocean. This water mass, characterized by a pronounced salinity minimum, spreads northward through the Atlantic Ocean, where it contributes to the northward flowing branch of the Atlantic Meridional Overturning Circulation (Talley et al., 2011; Tsuchiya, 1989). Along its path, the salinity minimum of AAIW gets eroded through mixing in lateral and vertical directions (Tsuchiya, 1989). As a result, the characteristic salinity minimum can only be traced as far north as 20°N (Tsuchiya, 1989).

In the North Atlantic, AAIW mixes laterally with Mediterranean Under Water (Machín & Pelegrí, 2009; Talley et al., 2011; Tsuchiya, 1989). Moreover, it has been suggested that vertical mixing induced by double-diffusive processes acting in the water masses present in the layer above may also alter the properties of AAIW (Schmitt, 2005; St. Laurent & Schmitt, 1999; You, 1999). Double-diffusive mixing occurs because the molecular diffusivity of heat is two orders of magnitude larger than that of salt (e.g., Radko, 2013; Stern, 1960). In the North Atlantic Ocean and the Caribbean Sea, double-diffusive mixing occurs across the front between the cold and fresh AAIW and the overlying warm and saline Subtropical Underwater (STUW). This stratification type allows for the formation of double-diffusive salt fingers. These salt fingers can result in the subsequent formation of thermohaline staircases: sequences of subsurface mixed layers separated by thin interfaces with strong gradients in temperature and salinity (e.g., Radko, 2013; Stern, 1960). The staircases in the North Atlantic and Caribbean Sea are characterized by an effective diffusivity of salt that is larger than the effective diffusivity of heat across the interfaces (Lambert & Sturges, 1977; Schmitt, 2005). This yields a flux ratio below unity ($\gamma = \frac{\alpha F_T}{\beta F_S} < 1$, where

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F_T and F_S are the heat and salt fluxes and α and β are the thermal expansion and haline contraction coefficients, respectively; e.g., Radko, 2013). This implies that double-diffusive mixing is, in contrast to regular turbulent mixing, characterized by a negative effective diffusivity of buoyancy.

It remains unknown to what extent this negative buoyancy flux can affect the properties of AAIW. Moreover, variations in the properties and the spreading of the water masses on interannual and decadal time scales can affect the strength of the mixing processes in both lateral and vertical directions. Remarkably, in the North Atlantic Ocean, AAIW became warmer and saltier in the last decades (Arbic & Brechner Owens, 2001; Fu et al., 2018; Sarafanov et al., 2007; Schmidtko & Johnson, 2012), while it became warmer and lighter in the South Atlantic Ocean (Arbic & Brechner Owens, 2001; McCarthy et al., 2011; Schmidtko & Johnson, 2012). The South Atlantic trend has been attributed to warming trends near the AAIW formation region and to the decadal variability of the Agulhas Leakage (Hummels et al., 2015; Lübbecke et al., 2015; Schmidtko & Johnson, 2012). In contrast, the trend in the North Atlantic appeared to coincide with a slower northward and westward spreading of AAIW in this region (Fu et al., 2018, 2019). Another difference between the trends in the two hemispheres is that the salinity trends of AAIW are not uniformly positive in the South Atlantic, while this is the case in the North Atlantic (Curry et al., 2003; Durack & Wijffels, 2010; Fu et al., 2018; McCarthy et al., 2011; Schmidtko & Johnson, 2012).

We speculate that these different trends might, in part, be attributed to double-diffusive mixing, as (a) thermohaline staircases are more pronounced in the North Atlantic than in the South Atlantic Ocean (van der Boog, Dijkstra, et al., 2021), and (b) the slower northward spreading of AAIW in the North Atlantic Ocean (Fu et al., 2018, 2019) results in a longer exposure of the AAIW core to double-diffusive salt fluxes. Consequently, the salinity of AAIW would increase more in the North Atlantic than in the South Atlantic Ocean. To gain more insight into this process, it is necessary to clarify whether the negative buoyancy flux of double-diffusive mixing can affect the properties of AAIW. In particular, the thermohaline staircases are intermittently present, which indicates that an influence of turbulent mixing on the properties of AAIW cannot be ruled out beforehand. As a first step, we will assess here the importance of vertical mixing on the properties of AAIW. To do so, we will disregard lateral mixing and assess whether the observed spatial variations of AAIW in the Caribbean Sea can be explained from vertical heat and salt fluxes induced by a combination of background turbulence and double-diffusive mixing, the latter due to the presence of thermohaline staircases in the layer above.

2. Data

We study the characteristics of AAIW by computing its time-averaged spatial variations in the North-Atlantic Ocean and in the Caribbean Sea (40°W–100°W and 0°N–33°N). We use the monthly averaged isopycnal climatology (MIMOC version 2.2) from Schmidtko et al. (2013) and average the temperature and salinity fields in time. Similar to Fu et al. (2019) and Schmidtko and Johnson (2012), we define AAIW as the salinity minimum between the neutral density ranges of 27.38 kg m^{-3}–27.82 kg m^{-3}, which were converted to potential density anomalies (27.2 kg m^{-3} < σ_0 < 27.6 kg m^{-3}) using Figure S15 of Abernathey et al. (2016). To obtain the salinity minimum of AAIW, we interpolate the temperature and salinity between the σ_0-layers of the climatology with a cubic spline interpolator and extract the salinity minimum from the interpolated curve.

In the remainder of this study, we interpret the spatial variations of temperature and salinity in the core of AAIW as the average trends of AAIW along its propagation path. That is, we assume that the time-averaged spatial variations of this subsurface water mass are solely induced by lateral and vertical mixing processes occurring in the region itself, and that we can exclude the influence of upstream variations (i.e., AAIW formation rates) on the AAIW properties in the region of interest. For this assumption to be valid, the timescales over which the temperature and salinity observations are averaged need to be longer than a typical advective time scale for AAIW. We estimate the latter as $T = L/U = \mathcal{O}\left(10^8 \text{s}\right) \approx 3$years, using a spatial scale of $L = \mathcal{O}\left(10^6 \text{m}\right)$ and a velocity of AAIW of $U = \mathcal{O}\left(10^{-2}\ \text{m s}^{-1}\right)$, following Fu et al. (2019). Because the MIMOC data set was computed using data from 1970 onwards (including a decade of Argo float data), the time-averaged temperature and salinity fields from that data set are considered sufficient to satisfy the above assumption. Note that multi-decadal variations in the mixing rates in the Caribbean Sea and North Atlantic Ocean could still affect the observed spatial variability. Therefore, the results can be interpreted as the average mixing rates in the Caribbean Sea and North Atlantic during the considered time period. In the Supporting Information S1, we use an order of magnitude analysis to show that fluxes from vertical mixing are up to one order of magnitude larger than those due to lateral mixing.

Because we aim to assess whether vertical fluxes can explain the variations of AAIW, we neglected the influence of lateral mixing. This implies that, when variations in AAIW cannot be explained by vertical fluxes only, lateral mixing has to be taken into account as well.

To estimate the vertical mixing by double diffusion, we use a global data set of thermohaline staircases obtained from Argo float profiles (van der Boog, Koetsier, et al., 2021). These thermohaline staircases are detected with an algorithm that exploits the vertical structure of staircase profiles. Before applying the algorithm, a quality control excludes all Argo float profiles with a too coarse vertical resolution to detect staircases from the analysis (van der Boog, Koetsier, et al., 2021). The algorithm first detects subsurface mixed layers, and then analyzes the characteristics of the interfaces in between. Next, sequences of mixed layers are identified as thermohaline staircases (for more details see van der Boog, Koetsier, et al., 2021). We extracted all 21,916 quality-controlled Argo float profiles that were located in the Caribbean Sea and North Atlantic (40°W–100°W and 0°N–33°N). We study 1,565 Argo float profiles in the Caribbean Sea (62°W–82°W and 10°N–18°N) in more detail. In particular, we analyze the temperature and salinity of the mixed layers in the thermohaline staircases. Similar to other staircase regions (Schmitt et al., 1987; Timmermans et al., 2008), the mixed-layer properties of different profiles are aligned (see Section 4). The relation between the aligned temperature and salinity are known as the lateral density gradients, which can be used as a measure for the flux ratio inside the staircase layer (Schmitt et al., 1987; Timmermans et al., 2008). McDougall (1991) validated this relation for a staircase region in the North Atlantic Ocean. He found that there, the lateral density gradients of the mixed layers result from a combination of the salt-finger fluxes and the vertical motion of the layer. The latter can be interpreted as a vertical flux divergence, which appears to be an effective mechanism to convert the properties of water masses (McDougall, 1991). Following previous examples near the Caribbean Sea (McDougall, 1991; Schmitt et al., 1987), we assume that the lateral density ratio ($R_{x,\rho} = \alpha T_x/(\beta S_x)$) of the mixed layers is equal to the flux ratio (γ). In this expression, the subscript x indicates the spatial derivative.

3. Spatial Variations of AAIW

We use the time-averaged properties of AAIW to analyze the spatial variations of this water mass in the North Atlantic Ocean and Caribbean Sea (Figure 1). Following our assumption that these spatial gradients represent the average temporal variation of AAIW along its path, we assess its properties along the main branch that was identified from maxima in silica concentrations in this region (Tsuchiya, 1989).

The main branch of AAIW crosses the equator along the western boundary of the Atlantic Ocean (A in Figure 1a). From there, the branch continues northward along the continental slope. Along this path (A–D in Figure 1a), both the temperature and salinity of AAIW increase. At first, these variations follow approximately the $\sigma_0 = 27.3$ kg m^{-3}-isopycnal (A–B in Figure 1b), but the density of AAIW increases as it approaches the Caribbean Sea (B–D in Figure 1b). This density increase results from a relatively strong salinity increase accompanied by weaker warming, implying that the flux ratio ($\gamma = \frac{\alpha F_T}{\beta F_S}$) into AAIW along this path is below unity.

Next, the AAIW core deflects toward the west and passes the Lesser Antilles (Tsuchiya, 1989). During this passage, enhanced turbulent mixing changes the properties of AAIW (Garrett, 2003; Kunze & Llewellyn Smith, 2004; Whalen et al., 2012). This is visible as a warmer and saltier AAIW in the Caribbean Sea compared to the North Atlantic Ocean. Because AAIW is characterized by a salinity minimum (Section 2, Figure 2), this warmer and saltier AAIW in the Caribbean Sea implies that the typical cold and fresh signature of AAIW less pronounced in the Caribbean Sea than in the Atlantic Ocean. In contrast to double-diffusive mixing, this turbulent mixing near the Lesser Antilles predominantly induces changes along the isopycnal, as indicated by a similar density of AAIW in the Atlantic Ocean (D in Figure 1b) and Caribbean Sea (1 in Figure 1b).

Once in the Caribbean Sea, the AAIW density increases again along the direction of the mean flow (1–4 in Figure 1b). Similar to what was seen in the Atlantic Ocean (A–D in Figure 1), the density increase in the Caribbean Sea is dominated by an increase in salinity. Moreover, the temperature also increases along this path, which results in a flux ratio below unity. We quantify these temperature and salinity variations by correlating the temperature and salinity in the Caribbean Sea, where the properties were averaged per 2° × 2° (dashed box in Figure 1a). From this, we obtain a correlation with a slope of $T_x S_x^{-1} = 3.4$°C kg g^{-1}, where T_x and S_x are the horizontal gradients in temperature and salinity in downstream direction of AAIW, respectively. This correlation is significant on a confidence interval of 90%. This tendency to warmer and saltier properties of the cold and fresh

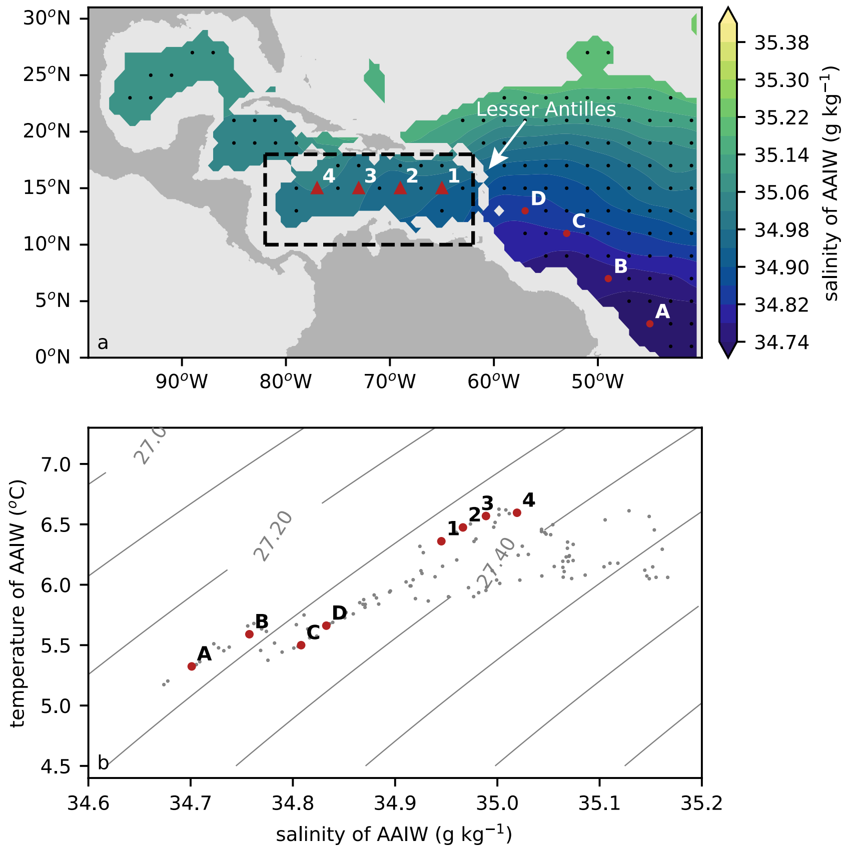

Figure 1. (a) Salinity of the Antarctic Intermediate Water (AAIW) core obtained from MIMOC (Schmidtko et al., 2013). The dashed box (62°W–82°W and 10°N–18°N) is used to compute properties of AAIW in the Caribbean Sea. (b) Conservative temperature and absolute salinity of AAIW core averaged per 2° × 2°. Location of the data points are indicated with black dots in panel (a). Gray contours highlight the isopycnals (σ_0). Letters A–D and numbers 1–4 correspond to the path of AAIW in the Atlantic Ocean and Caribbean Sea, respectively.

AAIW is in line with expectations that its properties could be modulated by a combination of double-diffusive and turbulent mixing (see Section 5 for the computation of these tendencies).

4. Double-Diffusive Fluxes in the Staircase Layer

To assess whether these spatial variations could be partly due to double-diffusive mixing in thermohaline staircases, we extract the distribution, occurrence rate, and properties of all detected mixed layers of the Caribbean staircases from the global data set of thermohaline staircases (Section 2; van der Boog, Koetsier, et al., 2021). One of these staircases is shown in Figure 2a. This staircase is located on the main thermocline and halocline between STUW and AAIW (Figure 2b), which is typical for all staircases in the Caribbean Sea (Figure 2c). To assess that these mixed layers originate from double-diffusive processes, we compute the Turner angle (Tu), which is an indicator for whether the water column is susceptible to double-diffusive mixing (Ruddick, 1983), for all profiles in the Caribbean Sea, with:

$$\mathrm{Tu} = \tan^{-1}\left(\alpha\frac{\partial T}{\partial p} - \beta\frac{\partial S}{\partial p}, \alpha\frac{\partial T}{\partial p} + \beta\frac{\partial S}{\partial p}\right). \quad (1)$$

here, the vertical gradients of the background temperature and salinity profiles are estimated using a central differences scheme after these are smoothed with a Hanning window of 100 dbar. As expected, most mixed layers are located at depth ranges with conditions that strongly favor salt fingering (71.3° < Tu < 90°, Figure 2d; Ruddick, 1983).

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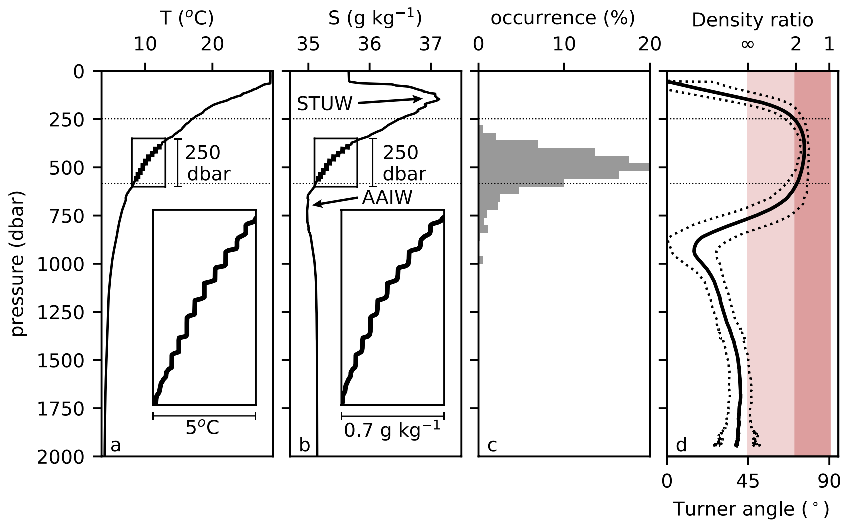

Figure 2. (a) Temperature and (b) salinity profile of Caribbean staircase obtained with Argo float 4901720 at 75.5°W and 13.9°N on 9 November 2018. (c) Depth of detected mixed layers of all thermohaline staircases in the Caribbean Sea (62°W–82°W and 10°N–18°N, dashed box in Figure 1) obtained from van der Boog, Koetsier, et al. (2021). (d) Average Turner angle (Ruddick, 1983) computed from 1,565 Argo float profiles in the Caribbean Sea. The dashed lines indicate one standard deviation from the mean Turner angle. The (dark) red shading indicates Turner angles that are susceptible to (strong) salt fingering. The upper and lower bound of the Turner angles with strong salt-fingering are indicated by the horizontal lines in all panels. The density ratios that correspond to these Turner angles are indicated on the upper axis. The inlays show a zoom over 250 dbar and 5°C and 0.7 g kg^{-1} of the thermohaline staircase. The approximate locations of AAIW and saline Subtropical Underwater are indicated in panel (b).

The spatial distribution of thermohaline staircases in the Caribbean Sea (Figure 3a) is in line with previous observations (Lambert & Sturges, 1977; Morell et al., 2006; van der Boog et al., 2019). In total, 7% of all Caribbean profiles contain staircases. The staircases are clustered in two regions: one around 70°W and one in the Panama Colombia Gyre (PCG) in the southwest of the basin. Another staircase region, known as C-SALT, is present in the adjacent part of the North Atlantic Ocean and it, notably, coincides with a region where the average AAIW density also increases along its path (point B–D in Figure 1a).

When staircases are persistent in time and space, the temperature and salinity in each mixed layer increases due to the vertical heat and salt flux through the interface above (McDougall, 1991; Schmitt et al., 1987). This gradual increase, reflected by the alignment of the properties of each subsequent mixed layer, is the lateral density ratio (see Section 2). Following McDougall (1991), we set this lateral density ratio equal to the flux ratio to compute the flux ratio inside each layer. The flux ratio decreases with depth from $\gamma = 0.83$ in the warmest layer toward $\gamma = 0.79$ in the coldest staircase layer (Figure 3b).

5. The Effective Diffusivity of Salt in AAIW

To assess whether vertical fluxes from turbulent mixing and double-diffusive mixing can quantitatively explain the time-averaged spatial variations of AAIW, we combine the results obtained in the previous sections in steady-state advection-diffusion equations for temperature and salinity:

$$US_x = K_S^{eff} S_{zz}, \tag{2}$$

and for heat:

$$UT_x = K_T^{eff} T_{zz}, \tag{3}$$

where, U is the advective velocity and T_x and S_x correspond the time-averaged spatial derivatives of AAIW temperature and salinity that were obtained in Section 3 ($T_x S_x^{-1} = 3.4$ °C kg g^{-1}). K_S^{eff} and K_T^{eff} are the effective

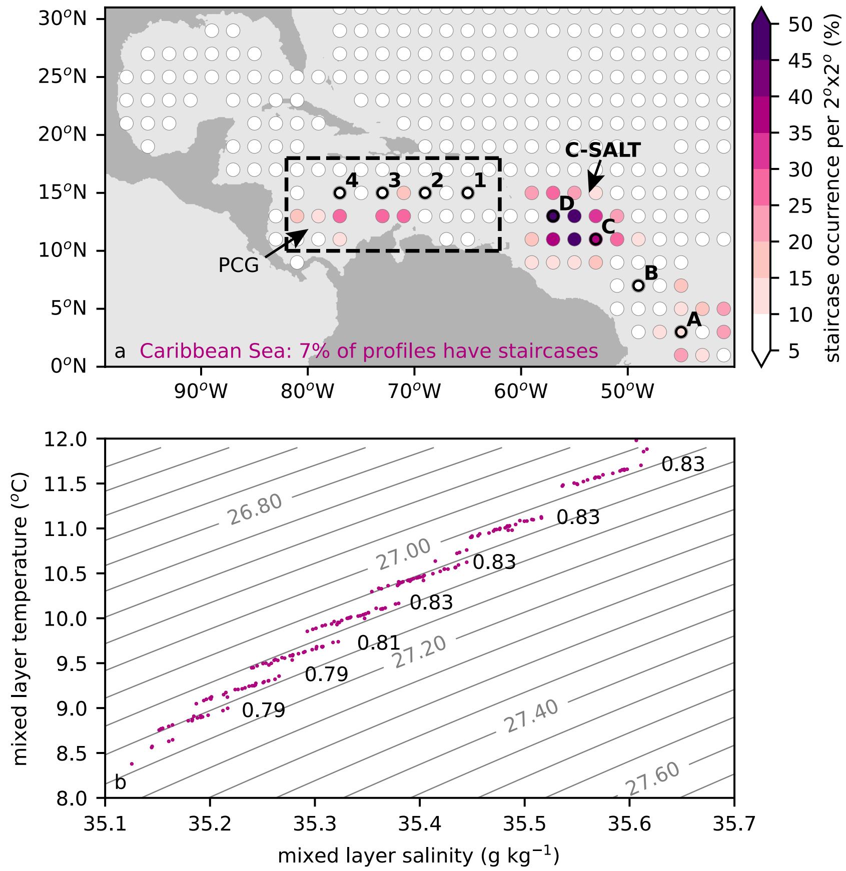

Figure 3. (a) Occurrence of thermohaline staircases in the Caribbean Sea and North Atlantic Ocean averaged per 2° × 2° and obtained from van der Boog, Koetsier, et al. (2021). Only data points containing more than 10 observations are shown. Dashed box (62°W–82°W and 10°N–18°N) is used to compute the occurrence of staircases in the Caribbean Sea. Numbers 1–4 and Letters A–D indicate the same locations as in Figure 1. (b) Temperature and salinity in the thermohaline staircases with more than four steps in the Caribbean Sea (dashed box in panel a); gray contour lines highlight the isopycnals (σ_0). Numbers indicate the slope the aligned points, corresponding to the lateral density flux ratio ($R_{x,\rho}$). The locations of the Panama Colombia Gyre and C-SALT are shown in panel (a).

diffusivities of salt and heat, respectively. The second order vertical derivatives of temperature and salinity are indicated with T_{zz} and S_{zz}, respectively.

Using Equations 2 and 3, we determine the gradients ($T_x S_x^{-1}$) that would arise when only considering background turbulence or only double-diffusive mixing is present. When only background turbulence is present, the effective diffusivity of heat is equal to the effective diffusivity of salt ($K_S^{eff} = K_T^{eff}$). We obtain:

$$3.7^o\mathrm{C\,kg\,g^{-1}} < \frac{T_x}{S_x} = S_{zz}^{-1} T_{zz} < 5.0^o\mathrm{C\,kg\,g^{-1}}, \tag{4}$$

using the 25th and 75th percentile values for $S_{zz} T_{zz}^{-1}$ (see Supporting Information S1). These numbers imply that vertical fluxes from background turbulence increase both the temperature and salinity of AAIW, as was also observed ($T_x S_x^{-1} = 3.4$ °C kg g^{-1}, Section 2). However, vertical fluxes from turbulence would result in stronger warming compared to the observations.

If we solely consider double-diffusive mixing, the relation between the effective diffusivity of heat and salt is given by Kelley (1990):

$$K_T^{dd} = \gamma R_\rho^{-1} K_S^{dd}, \tag{5}$$

where, R_ρ corresponds to the density ratio $R_\rho = \alpha T_z/(\beta S_z)$. Using this relation, we obtain the following gradients:

$$0.21^{o}\mathrm{C\,kg\,g^{-1}} < \frac{T_x}{S_x} = \frac{\gamma}{R_\rho} S_{zz}^{-1} T_{zz} < 0.43^{o}\mathrm{C\,kg\,g^{-1}}, \tag{6}$$

suggesting that double-diffusive mixing, similar to the vertical turbulent fluxes, increases the AAIW temperature and salinity. However, double-diffusive mixing results in smaller gradients compared to turbulent mixing, which implies that the buoyancy flux of each mixing mechanism differs.

From Equations 4 and 6 it follows that any combination of vertical fluxes from background turbulence and double-diffusive mixing results in warmer and saltier AAIW. This implies that, if both turbulent and double-diffusive mixing occur in a region, $T_x S_x^{-1}$ can have any magnitude between these boundaries. Because the magnitude of the observed lateral gradients ($T_x S_x^{-1} = 3.4$°C kg g^{-1}) is within these boundaries, we suggest that both double-diffusive and turbulent mixing affect the properties of AAIW. Therefore, we consider both mixing mechanisms and introduce a as a measure for the occurrence of double diffusion. We define the effective diffusivity as $K^{eff} = aK^{dd} + (1-a)K^{turb}$, where the superscripts dd and turb correspond to double-diffusive mixing and turbulence, respectively. For simplicity, we assumed here that double-diffusive mixing does not occur simultaneously with turbulent mixing, and we use the presence of thermohaline staircases ($a = 0.07$) as a measure for the occurrence of double diffusion. Moreover, we assume that turbulent mixing in the ocean interior ($K^{turb} = 10^{-5}$ m^2 s^{-1}) is limited (Toole et al., 1994). This results in the following steady-state advection-diffusion equation for salt when both turbulent mixing and double-diffusive mixing are present ($0 < a < 1$):

$$US_x = aK_S^{dd} S_{zz} + (1-a)\,K^{turb} S_{zz}, \tag{7}$$

and for heat:

$$UT_x = a\gamma R_\rho^{-1} K_S^{dd} T_{zz} + (1-a)\,K^{turb} T_{zz}. \tag{8}$$

We rewrite Equation 7 as a function of the advective velocity and substitute that into Equation 8 to obtain K_S^{dd} as a function of K^{turb}:

$$K_S^{dd} = \frac{(1-a)\,K^{turb}}{a} \frac{1 - S_x^{-1} T_x S_{zz} T_{zz}^{-1}}{S_x^{-1} T_x S_{zz} T_{zz}^{-1} - \gamma R_\rho^{-1}} = \frac{(1-a)\,K^{\mathrm{turb}}}{a} \frac{1 - bS_x^{-1} T_x}{bS_x^{-1} T_x - \gamma R_\rho^{-1}}, \tag{9}$$

where, $b = S_{zz} T_{zz}^{-1}$. This equation computes the ratio between K_S^{dd} and K^{turb} given the a, b and $T_x S_x^{-1}$. This implies that a high staircase occurrence results a lower K_S^{dd} (i.e., double-diffusive mixing can be less efficient) and a low staircase occurrence results in a higher K_S^{dd} (i.e., higher effective diffusivities are required to obtain the observed lateral gradients).

In addition to our estimate of K_S^{dd}, we study how the vertical derivatives of temperature and salinity affect the effective diffusivity, because these variables (R_ρ and b) introduce a high uncertainty to our computations (Figure 4). The observed values of b and R_ρ yield effective diffusivities of salt of 3.6×10^{-5} m^2 s^{-1} $< K_S^{dd} <$ 2.4×10^{-4} m^2 s^{-1}, where the bounds indicate the 25th and 75th percentiles (dashed lines in Figure 4b). Note that, due to the high uncertainty of b, the vertical mixing could be in principle smaller than horizontal mixing in some cases. However, these computations indicate that, on average, this is not the case.

For validation, we compare these most frequently occurring values to the, to our knowledge, only direct observations of the effective diffusivity of salt within a staircase layer in the North Atlantic and eastern Caribbean Sea (Schmitt, 2005). This observed diffusivity of salt ($K_S^{dd} = 0.9 \times 10^{-4}$ m^2 s^{-1}, green line in Figure 4) is located within our 25th and 75th percentile range. This implies that, because these diffusivities are similar, our computed diffusivity of salt has a realistic magnitude. This similarity indicates that it is possible to explain the time-averaged lateral gradients of AAIW by considering vertical fluxes from both turbulent and double-diffusive mixing. Furthermore, it also suggests that the staircase occurrence provides a realistic measure for the occurrence of double-diffusive mixing.

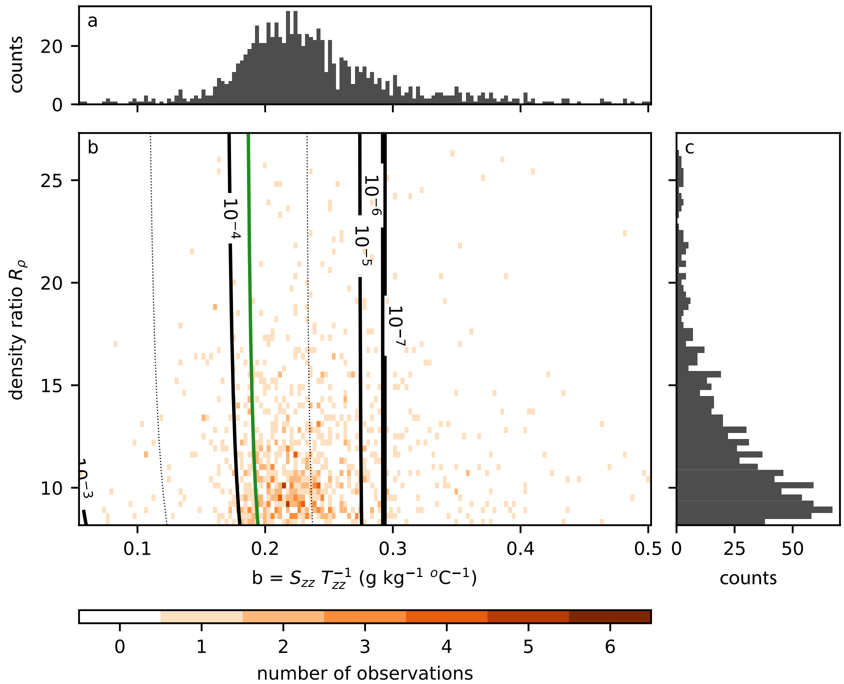

Figure 4. (a) Histogram of values of b obtained from observations from Argo floats profiles between 600 and 750 dbar. (b) Effective diffusivity of salt (K_S^{dd}) as a function of b and R_ρ. The green line corresponds to observations of Schmitt (2005). Dashed lines indicate the 25th and 75th percentile of the computed values of K_S^{dd}. The orange shading shows the number of observations with values of b and R_ρ. (c) Histogram of values of the density ratio, R_ρ, obtained from Argo floats profiles between 600 and 750 dbar. The axes ranges in panels (a) and (c) correspond to the 5th and 95th percentile of the observed values of b and R_ρ. Details on the computations of R_ρ, K_S^{dd}, and b can be found in the Supporting Information S1.

6. Discussion

We explored whether vertical mixing suffices to explain the observed time-averaged spatial variability of AAIW along its pathway from the North Atlantic through the Caribbean Sea. We found that the temperature, salinity and density of AAIW increase along its path of propagation and that these increases are consistent with changes induced by vertical fluxes from turbulence and double-diffusive mixing. More specifically, these fluxes can explain the AAIW property gradients when estimating the magnitude of the vertical mixing and horizontal advection terms in a steady-state advection diffusion model. This estimate indicated that vertical mixing can potentially give rise to the observed water-mass transformation of AAIW along its path through the Caribbean Sea.

Previous studies attributed spatial variation of AAIW in the Atlantic Ocean to lateral mixing with warmer and saltier MUW (Machín & Pelegrí, 2009; Talley et al., 2011; Tsuchiya, 1989). However, while MUW is omnipresent in the Atlantic Ocean, this is not the case for the semi-enclosed Caribbean Sea (Hernández–Guerra & Joyce, 2000; Morrison & Nowlin, 1982; van der Boog et al., 2019). Hence, it is unlikely that lateral mixing with MUW plays a dominant role in setting the spatial variations of AAIW properties in the Caribbean. Although this does not rule out any impact of lateral mixing with other water masses, we show here that vertical mixing provides an alternative explanation to the observed lateral gradients of AAIW in this region.

In our computations, we have neglected the influence of the multi-decadal variations on the observed spatial gradients. Therefore, the results of this study explain the time-averaged gradients contained in the MIMOC data set and solely indicate that vertical mixing has the potential to adjust the properties of AAIW. Because several studies (Arbic & Brechner Owens, 2001; Fu et al., 2018; Sarafanov et al., 2007; Schmidtko & Johnson, 2012) observed (multi-)decadal variation in AAIW properties, it would be interesting for a future study to add a time-dependent component to these equations to assess to what extent variations in vertical mixing can explain the variability of the AAIW properties. Multi-decadal variations in vertical mixing could, for example, be induced by the salinification of STUW that has been observed in the past decades (Durack & Wijffels, 2010), and that could affect the stratification and possibly the characteristics of the double-diffusive mixing.

Furthermore, the findings in this study raise the question whether vertical fluxes can affect AAIW properties in the Atlantic Ocean as well. Because we explored a combination of vertical fluxes from background turbulent and double-diffusive mixing, we speculate on its effect on AAIW properties below the staircase region in the Atlantic Ocean (B-D in Figure 3a). The higher occurrence of thermohaline staircases compared to the Caribbean Sea ($a_{atlantic} > a_{caribbean}$) would result in a lower $T_x S_x^{-1}$ in the Atlantic Ocean. Notably, this is also observed as the region of with lower $T_x S_x^{-1}$ (B–D in Figure 3a) coincides with the C-SALT staircase region (B–D in Figure 1a).

Overall, the results of this study provide an alternative explanation for the time-averaged spatial variations of AAIW in the Atlantic Ocean and Caribbean Sea, namely from vertical fluxes instead from lateral fluxes. These results are in line with previous studies that suggested that vertical fluxes from thermohaline staircases could affect the properties of water masses (Johnson & Kearney, 2009; Schroeder et al., 2016). Therefore, we argue that such alternative explanations should be considered when studying water-mass transformation.

Data Availability Statement

The data used in this study were collected and made freely available by the International Argo Program and the national programs that contribute to it (http://doi.org/10.17882/42182). The Argo Program is part of the Global Ocean Observing System. The global data set of thermohaline staircases are available at: http://doi.org/10.5281/zenodo.4286170. The MIMOC data set can be assessed at: https://www.pmel.noaa.gov/mimoc/

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References

Abernathey, R. P., Cerovecki, I., Holland, P. R., Newsom, E., Mazloff, M., & Talley, L. D. (2016). Water-mass transformation by sea ice in the upper branch of the Southern Ocean overturning. *Nature Geoscience*, *9*(8), 596–601. https://doi.org/10.1038/ngeo2749

Arbic, B. K., & Brechner Owens, W. (2001). Climatic warming of Atlantic intermediate waters. *Journal of Climate*, *14*(20), 4091–4108. https://doi.org/10.1175/1520-0442(2001)014<4091:cwoaiw>2.0.co;2

Curry, R., Dickson, B., & Yashayaev, I. (2003). A change in the freshwater balance of the Atlantic Ocean over the past four decades. *Nature*, *426*(6968), 826–829. https://doi.org/10.1038/nature02206

Durack, P. J., & Wijffels, S. E. (2010). Fifty-Year trends in Global Ocean salinities and their relationship to Broad-Scale warming. *Journal of Climate*, *23*(16), 4342–4362. https://doi.org/10.1175/2010JCLI3377.1

Fu, Y., Karstensen, J., & Brandt, P. (2018). Atlantic meridional overturning circulation at 14.5N in 1989 and 2013 and 24.5N in 1992 and 2015: Volume, heat, and freshwater transports. *Ocean Science*, *14*(4), 589–616. https://doi.org/10.5194/os-14-589-2018

Fu, Y., Wang, C., Brandt, P., & Greatbatch, R. J. (2019). Interannual variability of Antarctic intermediate water in the tropical North Atlantic. *Journal of Geophysical Research: Oceans*, *124*(6), 4044–4057. https://doi.org/10.1029/2018JC014878

Garrett, C. (2003). Internal tides and ocean mixing. *Science*, *301*(5641), 1858–1859. https://doi.org/10.1126/science.1090002

Hernández–Guerra, A., & Joyce, T. M. (2000). Water masses and circulation in the surface layers of the Caribbean at 66W. *Geophysical Research Letters*, *27*(21), 3497–3500. https://doi.org/10.1029/1999GL011230

Hummels, R., Brandt, P., Dengler, M., Fischer, J., Araujo, M., Veleda, D., & Durgadoo, J. V. (2015). Interannual to decadal changes in the western boundary circulation in the Atlantic at 11S. *Geophysical Research Letters*, *42*(18), 7615–7622. https://doi.org/10.1002/2015GL065254

Johnson, G. C., & Kearney, K. A. (2009). Ocean climate change fingerprints attenuated by salt fingering? *Geophysical Research Letters*, *36*(21), L21603. https://doi.org/10.1029/2009GL040697

Kelley, D. E. (1990). Fluxes through diffusive staircases: A new formulation. *Journal of Geophysical Research*, *95*(C3), 3365–3371. https://doi.org/10.1029/JC095iC03p03365

Kunze, E., & Llewellyn Smith, S. (2004). The role of Small-Scale topography in turbulent mixing of the Global Ocean. *Oceanography*, *17*(1), 55–64. https://doi.org/10.5670/oceanog.2004.67

Lambert, R. B., & Sturges, W. (1977). A thermohaline staircase and vertical mixing in the thermocline. *Deep Sea Research*, *24*(3), 211–222. https://doi.org/10.1016/S0146-6291(77)80001-5

Lübbecke, J. F., Durgadoo, J. V., & Biastoch, A. (2015). Contribution of increased Agulhas leakage to tropical Atlantic warming. *Journal of Climate*, *28*(24), 9697–9706. https://doi.org/10.1175/JCLI-D-15-0258.1

Machín, F., & Pelegrí, J. L. (2009). Northward penetration of Antarctic intermediate water off Northwest Africa. *Journal of Physical Oceanography*, *39*(3), 512–535. https://doi.org/10.1175/2008JPO3825.1

McCarthy, G., McDonagh, E., & King, B. (2011). Decadal variability of thermocline and intermediate waters at 24S in the South Atlantic. *Journal of Physical Oceanography*, *41*(1), 157–165. https://doi.org/10.1175/2010JPO4467.1

McDougall, T. J. (1991). Interfacial advection in the thermohaline staircase east of Barbados. Deep Sea Research Part A. *Oceanographic Research Papers*, *38*(3), 357–370. https://doi.org/10.1016/0198-0149(91)90073-O

Morell, J. M., Corredor, J. E., & Merryfield, W. J. (2006). Thermohaline staircases in a Caribbean eddy and mechanisms for staircase formation. *Deep Sea Research Part II: Topical Studies in Oceanography*, *53*(1–2), 128–139. https://doi.org/10.1016/j.dsr2.2005.09.013

Morrison, J. M., & Nowlin, W. D. (1982). General distribution of water masses within the eastern Caribbean Sea during the winter of 1972 and fall of 1973. *Journal of Geophysical Research*, *87*(C6), 4207. https://doi.org/10.1029/JC087iC06p04207

Radko, T. (2013). *Double-diffusive convection*. Cambridge University Press. https://doi.org/10.1017/CBO9781139034173

Ruddick, B. (1983). A practical indicator of the stability of the water column to double-diffusive activity. *Deep Sea Research Part A. Oceanographic Research Papers*, *30*(10), 1105–1107. https://doi.org/10.1016/0198-0149(83)90063-8

Sarafanov, A., Sokov, A., & Demidov, A. (2007). Water mass characteristics in the equatorial North Atlantic: A section nominally along 6.5N, July 2000. *Journal of Geophysical Research*, *112*(C12), C12023. https://doi.org/10.1029/2007JC004222

Schmidtko, S., & Johnson, G. C. (2012). Multidecadal warming and shoaling of Antarctic intermediate water. *Journal of Climate*, *25*(1), 207–221. https://doi.org/10.1175/JCLI-D-11-00021.1

Schmidtko, S., Johnson, G. C., & Lyman, J. M. (2013). MIMOC: A global monthly isopycnal upper-ocean climatology with mixed layers. *Journal of Geophysical Research: Oceans*, *118*(4), 1658–1672. https://doi.org/10.1002/jgrc.20122

Schmitt, R. W., Ledwell, J. R., Montgomery, E. T., Polzin, K. L., & Toole, J. M. (2005). Enhanced diapycnal mixing by salt fingers in the thermocline of the tropical Atlantic. *Science*, *308*(5722), 685–688. https://doi.org/10.1126/science.1108678

Schmitt, R. W., Perkins, H., Boyd, J., & Stalcup, M. (1987). C-SALT: An investigation of the thermohaline staircase in the western tropical North Atlantic. *Deep Sea Research Part A. Oceanographic Research Papers*, *34*(10), 1655–1665. https://doi.org/10.1016/0198-0149(87)90014-8

Schroeder, K., Chiggiato, J., Bryden, H. L., Borghini, M., & Ben Ismail, S. (2016). Abrupt climate shift in the western Mediterranean Sea. *Scientific Reports*, *6*(1), 23009. https://doi.org/10.1038/srep23009

St. Laurent, L., & Schmitt, R. W. (1999). The contribution of salt fingers to vertical mixing in the North Atlantic tracer release experiment. *Journal of Physical Oceanography*, *29*(7), 1404–1424. https://doi.org/10.1175/1520-0485(1999)029<1404:tcosft>2.0.co;2

Stern, M. E. (1960). The "Salt-Fountain" and thermohaline convection. *Tellus*, *12*(2), 172–175. https://doi.org/10.3402/tellusa.v12i2.9378

Talley, L. D., Pickard, G. L., & Emery, W. J. (Eds.). (2011). *Descriptive physical oceanography: An introduction* (6th ed.). Academic Press. (OCLC: ocn720651296).

Timmermans, M.-L., Toole, J., Krishfield, R., & Winsor, P. (2008). Ice-Tethered Profiler observations of the double-diffusive staircase in the Canada Basin thermocline. *Journal of Geophysical Research*, *113*, C00A02. https://doi.org/10.1029/2008JC004829

Toole, J. M., Schmitt, R. W., & Polzin, K. L. (1994). Estimates of diapycnal mixing in the Abyssal Ocean. *Science*, *264*(5162), 1120–1123. https://doi.org/10.1126/science.264.5162.1120

Tsuchiya, M. (1989). Circulation of the Antarctic intermediate water in the North Atlantic Ocean. *Journal of Marine Research*, *47*(4), 747–755. https://doi.org/10.1357/002224089785076136

van der Boog, C. G., de Jong, M. F., Scheidat, M., Leopold, M. F., Geelhoed, S. C. V., Schulz, K., et al. (2019). Hydrographic and biological survey of a surface-intensified anticyclonic eddy in the Caribbean Sea. *Journal of Geophysical Research: Oceans*, *124*(8), 6235–6251. https://doi.org/10.1029/2018JC014877

van der Boog, C. G., Dijkstra, H. A., Pietrzak, J. D., & Katsman, C. A. (2021a). Double-diffusive mixing makes a small contribution to the global ocean circulation. *Communications Earth and Environment*, *2*(1), 46. https://doi.org/10.1038/s43247-021-00113-x

van der Boog, C. G., Koetsier, J. O., Dijkstra, H. A., Pietrzak, J. D., & Katsman, C. A. (2021b). Global dataset of thermohaline staircases obtained from Argo floats and Ice-Tethered Profilers. *Earth System Science Data*, *13*(1), 43–61. https://doi.org/10.5194/essd-13-43-2021

Whalen, C. B., Talley, L. D., & MacKinnon, J. A. (2012). Spatial and temporal variability of global ocean mixing inferred from Argo profiles. *Geophysical Research Letters*, *39*, L18612. https://doi.org/10.1029/2012GL053196

You, Y. (1999). Dianeutral mixing, transformation and transport of Antarctic intermediate water in the South Atlantic Ocean. *Deep Sea Research Part II: Topical Studies in Oceanography*, *46*(1–2), 393–435. https://doi.org/10.1016/S0967-0645(98)00111-8

References From the Supporting Information

Groeskamp, S., LaCasce, J. H., McDougall, T. J., & Rogé, M. (2020). Full-depth global estimates of ocean mesoscale eddy mixing from observations and theory. *Geophysical Research Letters*, *47*(18), e2020GL089425. https://doi.org/10.1029/2020GL089425