Spatial variability of the Arctic Ocean’s double-diffusive staircase

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ABSTRACT

The Arctic Ocean thermohaline stratification frequently exhibits a staircase structure that has been attributed
to the diffusive form of double-diffusive convection, overlying the Atlantic Water Layer. The staircase consists
of multiple mixed layers of order 1-m in thickness separated by sharp interfaces, across which temperature
and salinity change abruptly. Through a detailed analysis of Ice-Tethered Profiler measurements acquired be-
tween 2004 and 2013, the double-diffusive staircase structure is characterized across the entire Arctic Ocean.
Staircase properties (mixed-layer thicknesses and temperature and salinity jumps across interfaces) are ex-
amined in relation to a bulk vertical density ratio spanning the staircase stratification. It is shown that the
Lomonosov Ridge serves as an approximate boundary between regions of low density ratio (approximately
3 to 4) on the Eurasian side and higher density ratio (approximately 6 to 7) on the Canadian side. We find
that the Eurasian Basin staircase is characterized by fewer, thinner mixed layers than that in the Canadian
Basin, although the margins of all basins are characterized by relatively thin mixed layers. A double-diffusive
4/3-flux law parametrization is used to estimate vertical heat fluxes in the Canadian Basin to be O(0.1) Wm\(^{-2}\).
It is shown that the 4/3-flux law is not an appropriate representation of heat fluxes through the Eurasian Basin
staircase. In this region, molecular heat fluxes are computed where interfaces between mixed layers can be
resolved; they are found to be O(0.01) Wm\(^{-2}\). However, many uncertainties remain about the exact nature of
these fluxes.

1. Introduction

Arctic climate processes are strongly influenced by the existence and persistence of Arctic sea ice (Perovich et al.
2013), which is influenced by ocean heat. Water entering the Arctic from the Atlantic Ocean is a significant source
of this heat (e.g., Rudels et al. 2004). The distribution and fluxes of Atlantic Water Layer (AWL) heat is a central el-
ment of the Arctic Ocean heat budget. This study ex-
amines the temperature and salinity structure at the top boundary of the AWL (the Arctic Ocean’s thermocline),
from which infereices about vertical ocean heat fluxes, and their spatial distribution, can be made.

The heat transfer from the AWL to the upper ocean (and then to the sea ice) could have a substantial effect on sea
ice thickness (e.g., Aagaard et al. 1981; Rudels et al. 2004;
Carmack et al. 2015). In fact, there is sufficient heat con-
tained in the AWL that if it could be fluxed to the sur-
fase ocean in contact with sea ice, it would melt the en-
tire sea-ice pack (Maykut and Untersteiner 1971). How-
ever, at present, a strong density stratification (primarily
due to salinity – the Arctic halocline) effectively insulates
the surface ocean from AWL heat in the central basins of
the Arctic (e.g., Aagaard et al. 1981; Padman and Dillon
1987; Timmermans et al. 2008; Fer 2009). In the Arctic’s
central Canada Basin, vertical heat fluxes from the AWL
are negligible compared to typical summer ocean-to-ice
heat fluxes at the surface (e.g., Timmermans et al. 2008).
In the Eurasian Basin on the other hand, AWL heat fluxes
are believed to be an important factor in contributing to

Atlantic Waters have a general cyclonic circulation
around the Arctic Basin from where they enter through
Fram Strait and the Barents Sea opening. Where the
Lomonosov Ridge reaches the edge of the Russian con-
tinental shelf, the Atlantic inflow splits into two cyclonic
flows: one with waters circulating the entire Canadian
Basin, and the other with waters circulating the Eurasian

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Basin along the Lomonosov Ridge, and back towards Fram Strait (e.g., Rudels et al. 1994; McLaughlin et al. 2004). The AWL maximum potential temperature \( \theta_{\text{max}} \) in the Eurasian Basin is around 1.3 °C (where the depth of the \( \theta_{\text{max}} \) is approximately 280 m), and in the Canadian Basin \( \theta_{\text{max}} \approx 0.7 \) °C (where the depth of the \( \theta_{\text{max}} \) is approximately 390 m) (Fig. 1).

Above the depth of the AWL \( \theta_{\text{max}} \), both temperature and salinity increase with depth and the water column is prone to the diffusive form of double-diffusive convection (e.g., Turner and Stommel 1964; Schmitt 1994; Radko 2013); throughout much of the central Arctic basin, there exists a double-diffusive staircase at the top boundary of the AWL, which has been well studied (Melling et al. 1984; Padman and Dillon 1987, 1988; Timmermans et al. 2008; Polyakov et al. 2012). The double-diffusive staircase can be characterized by a density ratio, which is a measure of the change in density due to salinity across the staircase to the change in density due to temperature (e.g., Turner 1965). If the stabilizing effect of salinity is larger than the destabilizing effect of temperature (i.e., the density ratio is larger than 1 and the ocean is statically stable), double-diffusive staircases are often found in the ocean for density ratios up to \( \approx 10 \) (e.g., Kelley et al. 2003).

The AWL staircase is characterized by well-mixed homogeneous layers generally between about 0.5 and 3.5 m thick, separated by high gradient interfaces across which potential temperature and salinity change by \( \delta \theta \approx 0.04 \) °C and \( \delta S \approx 0.01 \), respectively. The double-diffusive heat flux through the staircase may be estimated by computing the fluxes through individual interfaces, employing a parametrization (a 4/3 flux law which is proportional to \( \delta \theta^{4/3} \)) that depends on the potential temperature and salinity jumps across them (Kelley 1990). Reported AWL double-diffusive heat flux estimates range from 0.02-0.3 Wm\(^{-2}\) in the Canada Basin (Padman and Dillon 1987; Timmermans et al. 2008), to approximately 8 Wm\(^{-2}\) in the Laptev Sea (Polyakov et al. 2012) and 0.16 Wm\(^{-2}\) in the Amundsen Basin (Guthrie et al. 2015). These estimates are based on both direct microstructure measurements as well as on double-diffusive heat flux parametrizations. Recent work has shown, however, that in some regions of the Arctic Ocean, the use of a double-diffusive flux parametrization may not be appropriate (e.g., Carpenter and Timmermans 2014). Planetary rotation, for example, which is not accounted for in double-diffusive flux parametrizations, can reduce double-diffusive heat fluxes expected if the Ekman boundary layer is sufficiently thinner than the interface (Kelley 1987; Carpenter and Timmermans 2014). If the 4/3 flux parametrization (e.g., Kelley 1990) is appropriate, the parametrized heat flux should equal the molecular heat flux through an interface in the staircase for density ratios approximately larger than 2 (Carpenter et al. 2012; Sommer et al. 2013; Carpenter and Timmermans 2014). Timmermans et al. (2008) and Padman and Dillon (1987) find that this is the case in the Canada Basin. Here, calculated molecular fluxes from temperature measurements that resolve interfaces were estimated to be approximately 0.2 Wm\(^{-2}\), while the parametrization returned comparable values: 0.22 ± 0.10 Wm\(^{-2}\) (Timmermans et al. 2008).

In this paper, we present the first Arctic-wide characterization of the properties of the AWL thermocline and staircase. We take advantage of the high-resolution temperature and salinity data from Ice-Tethered Profilers (ITPs) (Krishfield et al. 2008a; Toole et al. 2011) that sampled over the entire central Eurasian and Canadian basins; we analyze data from the 2004–2013 period. The next section describes the ITP data and analysis methods. In section 3, we characterize the AWL across the basin by its potential temperature maximum (and salinity and depth at this maximum) and evaluate a bulk vertical density ratio across the depth range of the staircase. In section 4, we examine the details of the staircase structure (mixed layer thicknesses and vertical density ratios across individual mixed layers in the staircase), and identify regions across the Arctic basin where a staircase structure is present or absent. The validity of a 4/3 flux law parametrization for different regions is examined in section 5, where heat fluxes are also discussed. Finally, in section 6, we summarize and discuss the results.

2. Data and Methods

a. Ice-Tethered Profiler Measurements

ITPs measure conductivity, temperature, and pressure in the Arctic water column from several meters below sea ice through the core of the AWL (Krishfield et al. 2008a; Toole et al. 2011). ITPs consist of a surface buoy typically deployed in multi-year sea ice and a wire rope that hangs below to a depth of about 750 m. A CTD (conductivity-temperature-depth) profiling unit is attached to the wire, and the CTD crawls up and down through the water column (at \( \approx 25 \) cm s\(^{-1}\)). The data (including GPS information) are transmitted by satellite in near real time. A total of approximately 15,800 up-going profiles from 52 ITPs deployed throughout the Arctic Ocean between 2004 and 2013 are used in the analysis (Fig. 2). Note the CTD sensors are located at the top of the profiling unit and measurements made during down-going profiles are influenced by the wake of the profiler; for the finescale structures being examined here, only up-going profiles are used. Full vertical resolution measurements (\( \approx 25 \) cm for a 1 Hz sampling rate) are used.

The temporal lag between CTD channels is corrected during processing through examination of the temperature-salinity finestructure of the double-diffusive staircase. Temporal lags can often be exhibited by spikes in salinity at the staircase interfaces. Here, both the final
processed data (Level III) as well as full-resolution Level I data are used, for which accuracies of temperature and pressure are \( \pm 0.001 \) °C and \( \pm 1 \) dbar, respectively. Salinity accuracy is \( < 0.005 \) for the Level III data, and likely worse for the Level I data; however, absolute accuracy does not factor in the vertical salinity gradients considered here. Profiles which exhibited salinity spikes from uncorrected sensor response were excluded from the analysis. Full data processing details are in Krishfield et al. (2008a,b); Johnson et al. (2007) and at www.whoi.edu/itp.

b. Characterizing the Thermocline and Double-Diffusive Staircase

We characterize the AWL by its prominent potential temperature maximum, \( \theta_{\text{max}} \). Salinity and depth values at the \( \theta_{\text{max}} \) for each profile were also determined. To avoid the selection of spurious maxima (or potential temperature maxima associated with warm Pacific Water intrusions in the Canadian sector), \( \theta_{\text{max}} \) estimates are restricted to pressures \( \geq 100 \) dbar and \( < 500 \) dbar, and salinities \( \geq 34 \). Profiles where \( \theta_{\text{max}} > 6 \) °C or \( < -1 \) °C were also excluded from the data set. These criteria were confirmed to exclude only spurious values; further, they are consistent with previous studies indicating \( \theta_{\text{max}} \approx 1-3 \) °C, and the depth at these potential temperature maxima range from \( \approx 200-400 \) m (Rudels et al. 1999; Timmermans et al. 2008; Lenn et al. 2009; Polyakov et al. 2012).

A bulk density ratio, \( \bar{R}_\rho \), specifies the relative contributions of the bulk salinity gradient to density and the bulk potential temperature gradient to density as

\[
\bar{R}_\rho = \frac{\alpha \Delta \rho}{\rho \Delta \theta},
\]

where \( \Delta \theta \) and \( \Delta S \) are vertical potential temperature and salinity changes respectively across some specified depth interval (chosen to be much larger than a typical mixed layer thickness), and \( \alpha = -\partial \rho / \partial \theta \) and \( \beta = \rho^{-1} \partial \rho / \partial S \) are the coefficients of thermal expansion and saline contraction, respectively. Another characterization of the staircase is via the interface density ratio, \( R_\rho \), which quantifies the relative contributions of the salinity gradient on density and the potential temperature gradient on density across each interface in the staircase:

\[
R_\rho = \frac{\beta \Delta S}{\alpha \Delta \theta}.
\]

Both the small-scale \( R_\rho \) characterizing individual steps, and the larger-scale bulk \( \bar{R}_\rho \), have been calculated in this study.

The depth of the \( \theta_{\text{max}} \) provides a reference point for the choice of an appropriate depth range across which to characterize the staircase. A specified depth above the AWL \( \theta_{\text{max}} \) that indicated a deep bound on the staircase region was visually identified for each ITP (with the exception of ITP 56 drifting in the Eurasian Basin, where two bounds were determined on either side of warm fronts). The deep bound was selected to avoid the interleaving intrusions that are generally found in depths around the core of the AWL. For ITPs that drifted in the Eurasian Basin, this bound was \( 106 \pm 23 \) m above the AWL \( \theta_{\text{max}} \), and in the Canadian Basin was \( 142 \pm 13 \) m above the AWL \( \theta_{\text{max}} \). An interval of \( 50 \) m above the deep bound was considered for the determination of bulk water-column properties in the staircase region.

Four representative profiles from (1) the central Eurasian Basin, (2) the boundary of the Eurasian Basin, (3) the central Canada Basin, and (4) the boundary of the Canada Basin indicate how the appropriate depth range changes from region to region (Fig. 3). The bulk density ratio, \( \bar{R}_\rho \), was computed based on bulk potential temperature and salinity gradients (from end-point differences) over these 50 m depth intervals; \( \alpha \) and \( \beta \) were computed at the mid-depth of the interval.

Any value of \( \bar{R}_\rho \) greater than 10 or less than 1 was excluded. Close inspection of the profiles indicated that values in these ranges were associated with spurious temperature and/or salinity measurements or isolated mischaracterization of the double-diffusive staircase interval.

The lower 25 m of each 50 m depth segment for a given profile was taken as the depth interval to characterize individual mixed layers and interfaces in the staircase. Mixed layers are consistently most prominent in this range (mixed layer thickness tends to increase with depth). While the depth interval of 50 m is best for the calculation of \( \bar{R}_\rho \) (a smaller depth interval may be influenced by individual mixed layers), we find that \( \bar{R}_\rho \) calculated over the lower 25 m differs by less than 15% from \( \bar{R}_\rho \) calculated over 50 m. Mixed layers in the staircase are taken to lie where the potential temperature difference between two adjacent data points in a profile was less than a threshold value (between 0.001 and 0.006 °C), which was determined to be most appropriate (by trial and visual inspection) for each ITP. The potential temperature gradient \( \partial \theta / \partial z \) in a mixed layer was required to be less than a second threshold value (between 0.001 and 0.009 °C m\(^{-1} \)) which was also determined for each ITP. The detection of at least three mixed layers, not including the first and last mixed layer (that may have been only partially sampled) and a sum of mixed layer depths of at least 6.25 m, were required to mark a staircase as present in that profile. The minimum requirement of 6.25 m ensures that a significant portion (at least 25%) of the depth interval is occupied by mixed layers. Mean mixed layer thickness, \( \bar{h} \), was calculated by averaging the thicknesses of mixed layers in each profile, excluding the first and last mixed layers in the 25 m segment. We compare our method for determining mixed layer thickness with that described by Polyakov et al. (2012), again excluding the first and last
mixed layers from the mean. Polyakov et al. (2012) find the anomaly between potential temperature and potential temperature averaged over 3-m depth, and take mixed layers to be located between the local minima and maxima of the anomaly with respect to depth (see their Fig. 3). Using the profile set from ITP 1 as representative of the Canadian Basin, we find $\bar{h} = 2.20 \pm 0.52$ m, while the method described by Polyakov et al. (2012) gives $\bar{h} = 1.83 \pm 0.39$ m. Using the profile set from ITP 38 as representative of the Eurasian Basin, we find $\bar{h} = 2.18 \pm 0.78$ m, while the method of Polyakov et al. (2012) gives $\bar{h} = 1.18 \pm 0.31$ m. Although we appreciate that neither method is perfect, the generally smaller values of the method of Polyakov et al. (2012) appear to be related in some cases to spurious detection of very small “mixed layers.” The density ratio, $\nu$, was computed over individual interfaces using the values of $\delta \theta$ and $\delta S$ between adjacent mixed layers.

AWL staircase interface thicknesses, $\delta h$, have been described previously in various sectors of the Arctic Basin using microstructure measurements. Polyakov et al. (2012) estimate interface thicknesses in the Laptev Sea of $1 < \delta h < 5$ m, and Padman and Dillon (1989) find $\delta h \approx 0.15$ m in the Canada Basin. Interface thicknesses in the Amundsen Basin were found to be, on average, 0.1 m (Guthrie et al. 2015). Given these measurements and estimates, and the limiting vertical ITP resolution of 0.25 m, interfaces generally tend to be too thin in the Canadian sector to be resolved with the ITP measurements. ITPs can resolve interface thicknesses in parts of the Eurasian Basin where interfaces are thicker (Fig. 4). Where interfaces are too thin to be resolved by ITP measurements, it remains possible to infer heat fluxes using a double-diffusive flux law parametrization, provided we can rely on the verification of past studies that such a flux law is appropriate in the region in question.

For the thicker interfaces in the Eurasian Basin, that can be resolved in ITP data, interfaces were identified as the regions between adjacent mixed layers (the thickness between the top of one mixed layer and the bottom of that adjacent). If the interface was thicker than a threshold value, which was determined by inspection for each ITP (and taken to be between 1.75 and 2.5 m), it was excluded from the analysis of interfaces. If at least two interfaces were present in a staircase region, the mean interface thickness, $\overline{\delta h}$, was calculated for the profile. We again compare our method for determining interface thickness with that described by Polyakov et al. (2012), where inflection points in a vertical profile of potential temperature anomaly (potential temperature compared to 3-m vertically-averaged potential temperature) define the depths of mixed layers/interfaces. Using the profile set from ITP 38 (in the Eurasian Basin), we find $\overline{\delta h} = 1.12 \pm 0.31$ m, while the method of Polyakov et al. (2012) gives $\overline{\delta h} = 0.64 \pm 0.17$ m. While there is uncertainty in both methods, we corroborate our interface thickness calculations by comparing the mean interface thickness for a profile to the median interface thickness for a profile. Across the Eurasian Basin, these values vary by less than 5% (i.e., spurious anomalously thick interfaces are not significantly biasing the values).

c. Heat fluxes

The main motivation for investigating the double-diffusive staircase is for its relevance to vertical heat fluxes from the AWL to the overlying water layers. Typically, heat fluxes through double-diffusive staircases are computed using parametrizations formulated by empirical fits to laboratory and oceanographic data. One of the most commonly used double-diffusive parametrizations for the heat flux (in Wm$^{-2}$) is given by Kelley (1990):

$$F_H = 0.0032 e^{4.8/ho_p^{0.72}} \frac{\alpha \kappa}{\Pr} \frac{1}{\rho} \frac{1}{\delta \theta} \frac{h}{\overline{\delta \theta}^{4.3}}, \quad (3)$$

where $c_p$ is the specific heat of water, $\kappa$ is the molecular diffusivity of heat, $g$ is gravity, and $\Pr = v/\kappa$ is the Prandtl number, where $v$ is the kinematic viscosity. The value of this formalism is that only the temperature jump across a double-diffusive interface must be resolved, and not the interface thickness (which is often too thin to be resolved without microstructure measurements). In regions where interfaces can be resolved, a molecular heat flux $F_M$ can be computed across an interface, $F_M = \rho c_p \kappa \frac{\overline{\delta \theta}}{\delta \theta}$. A reasonable check as to the validity of the 4/3 flux parametrization in this region can be made by comparing the magnitudes of $F_M$ and $F_H$; we discuss this further in Section 5.

3. Bulk Properties of the AWL

The AWL $\theta_{max}$, salinity of the $\theta_{max}$, depth of the $\theta_{max}$, $\overline{R_p}$, and $\overline{h}$ show significant spatial variability across the Arctic Basin over the study period. In contrast, temporal variability in AWL properties appears to be negligible. The AWL typically exhibits much smaller seasonal and interannual variability than surface waters more directly influenced by seasonally-varying surface buoyancy fluxes and wind-driven variability. We observe that in the Canadian Basin, the $\theta_{max}$ changes at a rate of $-0.02 \pm 0.16$ $\degree$C per year (over 2004-13), and in the Eurasian Basin, the $\theta_{max}$ changes at a rate of $-0.01 \pm 0.30$ $\degree$C per year (i.e., there is no statistically significant trend in either of the two main basins over the decade of ITP measurements). The spatial difference in $\theta_{max}$ over a section from $\approx 44^\circ$E, $85^\circ$N to $\approx 135^\circ$W, $72^\circ$N is around 2$\degree$C. Therefore, the influence of temporal variability may be neglected compared to basin-wide spatial variability, and we consider the large-scale spatial patterns presented here to be effectively synoptic.
a. Properties of the AWL $\theta_{\text{max}}$

As the Atlantic Water enters the Arctic Basin and circulates eastward, heat is lost through turbulent ocean mixing with cooler waters (as well as surface buoyancy fluxes) and also through double-diffusive heat fluxes. The AWL is appreciably cooler in the Canadian sector, where $\theta_{\text{max}} \approx 0.73 \, ^\circ\text{C}$, whereas in the Eurasian Basin, $\theta_{\text{max}} \approx 1.30 \, ^\circ\text{C}$ (Fig. 5a). The AWL $\theta_{\text{max}}$ is coldest in the northeast Canadian Basin off the coast of Ellesmere Island. Here, the waters have propagated cyclonically over the full extent of the Arctic Basin. Maximum and minimum observed $\theta_{\text{max}}$ are 4.10 $^\circ\text{C}$ and -0.68 $^\circ\text{C}$, respectively (Fig. 5a). A secondary cyclonic circulation of Atlantic Water occurs in the Eurasian Basin along the Lomonosov Ridge, as evidenced by the temperature distribution of $\theta_{\text{max}}$.

The AWL salinity at $\theta_{\text{max}}$ is highest closest to the inflow region and freshens following the decrease in $\theta_{\text{max}}$, again because of turbulent mixing with overlying fresher waters and double-diffusive salt fluxes as the AWL circulates the basin (Fig. 5b). The AWL core is shallowest near Fram Strait (approximately 200 m deep) and increases (by mixing processes and downwelling) along the cyclonic pathway with maximum depths found in the central Beaufort Gyre region (approximately 440 m deep), where deepening of isopycnals arises as a result of the large-scale anticyclonic wind forcing (Proshutinsky et al. 2009) (Fig. 5c).

b. The bulk density ratio $R_p$

The bulk density ratio, $R_p$, is lowest in boundary regions of the Eurasian Basin, where the AWL core is warmest (Fig. 5d). In the Eurasian Basin, $R_p = 4.0 \pm 1.3$. $R_p$ increases along the cyclonic pathway of the AWL around the Arctic Basin, and takes values of $R_p = 6.3 \pm 1.4$ in the Canadian Basin. Low values of $R_p$ near the Atlantic Water inflow region are best described by larger vertical potential temperature gradients than in other regions; the temperature gradient overlying $\theta_{\text{max}}$ is proportional to $\theta_{\text{max}}$. The largest values of $R_p$ are found in the regions of coolest AWL $\theta_{\text{max}}$, where potential temperature gradients are smallest (Fig. 6a). Although for all values there is a near-linear relationship between $\theta_{\text{max}}$ and the salinity at $\theta_{\text{max}}$ (not shown), there is no clear relationship between bulk salinity gradients and the salinity at $\theta_{\text{max}}$.

Values of $R_p$ show a bimodal distribution, with peaks at approximately 3 and 6, corresponding to values in the Eurasian and Canadian Basins, respectively (Fig. 6b). The second, smaller peak around $R_p \approx 6$ appears to be associated with the slightly higher values in the northeastern Canadian Basin. These differences in $R_p$ are manifest in the differing slopes of $\theta$-$S$ plots (in the region of the staircase) of representative profiles in the respective basins (Fig. 1c).

4. Staircase Properties

a. Presence or Absence of Mixed Layers

A well-defined staircase exists throughout most of the central Arctic Basin but is generally not observed along the boundaries of the Eurasian Basin, including near the Atlantic Water inflow (Fig. 7a). It is unclear whether this is due to the dominance of turbulent mixing over double diffusion. In the Eurasian Basin, the AWL thermocline is closer to the surface and less sheltered by the overlying stratification from winds and surface buoyancy forcing. It is likely that turbulent diffusivities are higher in the shallower Eurasian Basin thermocline, inhibiting double-diffusive convection (e.g., Rippeth et al. 2015). The distribution of a staircase structure (Fig. 7a) provides a conservative estimate with profiles marked as having no staircase if the criterion described in Section 2b is not satisfied. The boundary regions are generally characterized by fewer, thinner mixed layers, and the 25-m region over which mixed layers were calculated often does not exhibit a staircase structure over the entire interval. Rather, only a few, isolated mixed layers are found in the 25-m depth interval.

b. Mixed Layer Thicknesses & Interface Properties

Mean mixed layer thicknesses, $h$, are generally in the range 0.5 to 3.5 m, with similar values between the Canadian Basin and Eurasian Basin (Figs. 7b, 8). Across the entire Arctic Ocean, mean mixed layer thicknesses do not exhibit a spatial pattern. In the Eurasian Basin, where interfaces are resolved by ITP profiles, values of mean interface thicknesses, $\overline{\Delta h}$, generally fall between 0.5 and 2 m (Figs. 7c, 8). $\overline{\Delta \theta}$ across interfaces does not appear to be correlated with $h$. $\overline{\Delta \theta}$ across interfaces is, on average, higher in the Eurasian Basin than in the Canadian Basin, following a similar pattern to $\theta_{\text{max}}$ and $\Delta \theta$ across the 50-m staircase region. $\overline{\Delta S}$ across interfaces takes similar values in the Eurasian and Canadian Basins, though several high values are found in the eastern Canadian Basin, where $\theta_{\text{max}}$ is smallest (Figs. 8, 9). Comparably, $R_p$ and $R_p$ exhibit similar patterns around the basin, although with slight differences that could be due to curvature in the thermocline gradient over the depth interval of interest, or to mixed layers not being precisely resolved. Timmermans et al. (2008) find similar results between $R_p$ and $R_p$ in the Canada Basin, with $R_p$ calculated over individual mixed layers varying between 2 and 7 and bulk $R_p$ values in the same region varying between 3 and 6.

Finally, it is of interest to compute the Rayleigh number, $Ra \equiv g \alpha \overline{\Delta \theta} h^3 / \nu \kappa$. The term $(\delta \theta)^{4/3}$ in the 4/3 flux law (e.g., Kelley’s parametrization used here) originates from the relationship between the Rayleigh number and the ratio of convective to conductive heat flux. Here, $Ra$
describes the relative effects of the thermal buoyancy forcing to viscosity and diffusion across an interface. We find values of $Ra$ in the Eurasian Basin are higher than those in the Canadian Basin, suggesting that buoyancy effects are stronger there than in the Canadian Basin (Fig. 8). This is discussed in context with heat fluxes in the next section. The distributions of $\bar{R}$, $R_P$, and $Ra$ (Fig. 8) found in the Eurasian Basin are comparable to those described by Guthrie et al. (2015).

5. Heat Fluxes

Previous studies have shown that Kelley’s 4/3-flux parametrization agrees with observed heat fluxes in the Canadian Basin (Padman and Dillon 1987; Timmermans et al. 2008). Applying the parametrization (3) to the ITP data, we derive heat fluxes of $O(0.1 \text{ Wm}^{-2})$ for this region. Highest fluxes are found near the western boundary of the Lomonosov Ridge, consistent with where the AWL is warmest in the Eurasian Basin where it enters from the Eurasian Basin (Fig. 10a). It is of note that heat fluxes in the Canadian Basin cannot be predicted from a cyclonic pathway around the periphery of the basin; high values of heat flux found in the central Beaufort Gyre are consistent with the separation of the AWL from the vicinity of the Northwind Ridge and eastward penetration (possibly by double-diffusive intrusions) into the central basin (McLaughlin et al. 2004).

In the Eurasian Basin, the validity of the 4/3 flux law remains to be examined; for this we can compare the magnitudes of $F_M$ and $F_H$. For example, for values of $\delta \theta$ in the Eurasian Basin, application of Kelley’s 4/3 flux law yields a heat flux of $0.73 \text{ Wm}^{-2}$. To support a molecular heat flux of this magnitude, interfaces would need to be as thin as 0.05 m. However, ITP measurements indicate they are typically a little more than 1 m thick (Fig. 4b). It is possible that due to the thicker interfaces, rotation plays an important role in double-diffusive convection here, which is not accounted for in Kelley’s 4/3 flux parametrization (Kelley 1987; Carpenter and Timmermans 2014). This could be the case since the Ekman layer thickness of a laminar interface ($\approx 0.1 \text{ m for the Eurasian Basin}$) is significantly smaller than the interface thickness (Carpenter and Timmermans 2014). On the other hand, we cannot rule out the presence of small mixed layers within what we are taking to be the thicker Eurasian Basin interfaces given the relatively coarse resolution of the profiles, in which case a 4/3 flux parametrization may apply. In the absence of better resolved interfaces, we restrict application of the 4/3 flux law to the Canada Basin.

By computing the molecular heat flux through each interface using the change in potential temperature across each interface and the resolved interface thickness, averaged per profile, we find molecular heat fluxes of $O(0.01 \text{ Wm}^{-2})$ in the Eurasian Basin (Fig. 10b). The lower heat fluxes in the Eurasian Basin compared to the Canadian Basin are not consistent with the expectation that higher $Ra$ in the Eurasian Basin would yield larger heat fluxes (due to the relationship between $Ra$ and a convective heat flux, although this exact relationship is unclear). It is also important to note that the low values of $R_P$ in the Eurasian Basin could indicate that actual fluxes are larger than the $F_M$ estimates (based on molecular diffusion acting on the resolved gradients) due to the increasing disturbance of the interfaces by turbulence.

6. Summary and Discussion

Properties of the AWL and double-diffusive staircase at its top boundary have been analyzed using ITP data from across the Arctic Basin collected between 2004 and 2013. For the first time, this study takes advantage of the high vertical resolution ITP data sampling the detailed structure of the thermohaline staircase laterally across the entire Arctic. As Atlantic Water circulates around the Arctic Basin, its maximum core potential temperature and salinity decrease, as expected. The bulk density ratio, $\bar{R}_p$, is lowest in boundary regions of the Eurasian Basin where the AWL is warmest, and increases along the cyclonic pathway of the AWL around the Arctic Basin. There is no apparent relationship between $R_P$ and staircase mixed layer thicknesses across the basin. Well-defined mixed layers exist throughout the majority of the central Arctic Basin, while an absence of mixed layers is most pronounced along boundaries and in the interior of the Eurasian Basin. It is not known whether the lack of a staircase structure is due to the dominance of turbulent mixing over double diffusion. Furthermore, in the absence of a double-diffusive flux to maintain the staircase structure, staircases would not persist very long: an interface would increase in thickness by molecular conduction alone by about 20 cm in 1 day, thereby smoothing out the profile and reducing the distinct staircase structure.

In the Canadian Basin, using a double-diffusive 4/3 flux law parametrization, the distribution of vertical heat fluxes through the staircase is estimated to be $O(0.1) \text{ Wm}^{-2}$. Interfaces appear to be approximately resolved in the Eurasian Basin, where we conclude that the 4/3 flux law does not yield an appropriate representation of heat fluxes. Molecular heat fluxes in the Eurasian Basin are estimated to be $O(0.01) \text{ Wm}^{-2}$, which are at least one order of magnitude smaller than heat fluxes reported by Polyakov et al. (2012) and Guthrie et al. (2015) for the region. However, it is unclear if Eurasian Basin heat fluxes are well-represented by a laminar molecular heat flux calculation at such low $R_P$. The discrepancy in heat fluxes between the two basins is counterintuitive, as fluxes in the Eurasian Basin are smaller where the source water is warmer. Future work will investigate possible explanations for this discrepancy.
Further questions remain as to the transition from laminar to turbulent interfaces. Future work will examine DNS results of heat fluxes for interfaces at low $R_p$ in relation with measured heat fluxes to determine the limitations of 4/3 flux parametrizations in an ocean setting. Additional data at higher vertical resolution are necessary for closer inspection of interfaces in the Eurasian Basin.

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References


FIG. 1. (a) Potential temperature $\theta$ (°C) and (b) salinity profiles in the central Eurasian Basin (red), where the $\theta_{\text{max}}$ of the AWL is around 300 m depth, and central Canadian Basin (blue), where the $\theta_{\text{max}}$ of the AWL is around 400 m. (c) The same representative profiles in $\theta - S$ space from the Eurasian Basin (red) and Canadian Basin (blue). Isopycnals are labelled, and the dashed red line is the freezing line. Profiles are from Ice-Tethered Profiler measurements in spring 2008.
Fig. 2. (a) Locations (black dots) and (b) temporal distribution (in bins of 1 year) of ITP profiles used in this study. ITP up-going profiles returned between 2004 and 2013 are analyzed here (a total of $\approx 15,800$ ITP profiles with a vertical resolution of $\approx 25$ cm). Red letters (A, B, C, D) in (a) correspond to the profiles shown in Fig. 3.
Fig. 3. Four potential temperature (°C) representative profiles (locations marked in Figure 3(a)): (a) in the central Eurasian Basin (A: ITP 56, 29 May 2012), (b) at the boundary of the Eurasian Basin (B: ITP 7, 29 Sep 2007), (c) at the boundary of the Canadian Basin (C: ITP 8, 23 May 2009), and (d) from the central Canadian Basin (D: ITP 1, 26 Jun 2006), indicate the appropriate thermocline region in various areas of the Arctic Basin. Given these differences, in order to properly quantify the double-diffusive staircase, a unique “lower depth” of the 50-m staircase interval (marked by green stars from the profiles shown) was determined for each ITP. Blue stars delineate the shallow bound. The red star indicates the AWL \( \theta_{\text{max}} \) in each profile. Insets in each panel show a zoom-in of the potential temperature profile in the 50-m depth interval.
FIG. 4. (a) Potential temperature, $\theta$ ($^\circ$C), profiles in the staircase region in (a) the Canadian Basin and (b) the Eurasian Basin. Interfaces are too thin to be resolved in the Canadian Sector. Interfaces can be resolved with ITP measurements in the Eurasian sector, as more data points are returned between mixed layers than in the Canadian Basin. Blue dots indicate ITP data points approximately every 25 cm. Green stars indicate the beginning and end of the staircase region, while red stars indicate the beginning and end of respective mixed layers.
FIG. 5. (a) Map of $\theta_{\text{max}}$ ($^\circ$C) across the Arctic Basin. (b) Map of salinity at $\theta_{\text{max}}$. (c) Map of depth (m) at $\theta_{\text{max}}$. (d) Map of $R_p$. As Atlantic Water circulates around the basin, its core $\theta_{\text{max}}$ and salinity at core $\theta_{\text{max}}$ decreases, while its depth at core $\theta_{\text{max}}$ and $R_p$ increases. Changes in the properties of $\theta_{\text{max}}$ are due to both downwelling and mixing.
Fig. 6. (a) Scatter plot of $\alpha \Delta \theta$ vs. $\beta \Delta S$ with contours of $R_\rho$ overlain. Large values of $R_\rho$ (appearing as a lower branch in the plot) are found in the Canadian Basin, while low values of $R_\rho$ (upper branch) are found in the Eurasian Basin. Values of $R_\rho > 10$ have been excluded. (b) PDF of $R_\rho$ for all profiles. The two main peaks (with $R_\rho \approx 3$ and $R_\rho \approx 6$) generally correspond to the Eurasian Basin and the Canadian Basin, respectively. The greater density of $R_\rho \approx 6$ observations (compared to those with $R_\rho \approx 3$) is a result of more ITP profiles in the Canadian Basin. The bin width is 0.1.
Fig. 7. (a) Map indicating presence (blue) or absence (yellow) of a well-defined double-diffusive staircase. Well-defined mixed layers exist throughout the majority of the central Arctic Basin, with an absence of mixed layers most pronounced along boundaries of the Eurasian Basin. (b) Map of mean mixed layer thickness, $h$ (m). There is no apparent spatial pattern in $h$. (c) Map of mean interface thickness, $\delta h$ (m). Interface thicknesses in the Eurasian Basin do not exhibit a distinctive pattern.
Fig. 8. PDFs of $\delta \theta$ (°C), $\delta S$, $\delta h$ (m), $\bar{h}$ (m), mean interface $R_p$ over a profile (distinct from $R_{\rho}$), and $R_{\rho}$ in (a) the Canadian Basin and (b) the Eurasian Basin. Bin sizes are 0.01 °C, 0.003, 0.25 m, 0.25 m, 0.5, and 0.5, respectively. The mean value ($\pm$ 1 standard deviation) is given on each panel.

Fig. 9. (a) Map of mean potential temperature difference across interfaces, $\bar{\delta} \theta$ (°C). (b) Map of mean salinity difference across interfaces, $\bar{\delta} S$. 
FIG. 10. Heat fluxes (Wm$^{-2}$) in (a) the Canadian Basin (computed using the 4/3 flux law) and (b) the Eurasian Basin (computed as a molecular flux across interfaces). Heat fluxes in the Canadian Basin are $O(0.1)$ Wm$^{-2}$, with the highest values near the eastern Lomonosov Ridge. Heat fluxes in the Eurasian Basin are $O(0.01)$ Wm$^{-2}$.