Argo Observations of the Deep Mixing Band in the Southern Ocean: A Salinity Modeling Challenge

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Abstract The Southern Ocean plays an important role in mediating oceanic uptake of CO2 and heat due to a strong meridional overturning circulation. Gridded Argo float data for 2004–2017 were used to evaluate subsurface processes at the mixed layer depth (MLD) that occur in a narrow deep mixing band. Shifts in the value of the Turner Angle at the MLD indicate that early in the season the MLD deepens slowly as it encounters and is stabilized by a subsurface salt maximum. By September mixing has penetrated this salinity feature and the rate of deepening is faster once the MLD is deeper than the depth where the maximum salinity occurs (~150–200 m). This distinctive salinity layer is the result of surface Ekman transport of fresh water from the south and subsurface advection of high-salinity water from the north. Two configurations of the Community Earth System Model (CESM) ocean-ice forced hindcast experiments—one with 1° and the other with 0.1° horizontal resolution (Parallel Ocean Program low and high resolutions [POP-LR and POP-HR], respectively)—are compared with the Argo data for 2005–2009. POP-LR has a shallow MLD bias common to many Fifth Coupled Models Intercomparison Project (CMIPS) models, while POP-HR has a mix of deep and shallow MLD biases. While both models were able to replicate the large-scale processes leading to formation of a high-salinity layer, the salinity feature in POP-HR is too strong and deep. Neither model was able to replicate the vertical mixing processes leading to penetration of the subsurface salt maximum.

Plain Language Summary The Southern Ocean that circles the Antarctic continent is important in controlling the amount of global heat and carbon exchanges with the atmosphere because during the winter the surface waters mix deeply down into the ocean. Argo floats drift throughout the world oceans collecting temperature and salinity data from the surface to about 2,000-m depth. This study uses gridded Argo float data for 2004–2017 to understand the vertical mixing. We identify the importance of a subsurface high-salinity feature in the Southern Ocean that stabilizes the column and impacts the depth of vertical mixing, and we investigate the origin of this salinity feature. We also analyze the representation of the salinity feature in the Community Earth System Model (CESM) at both a coarse and a fine resolution for 2005–2009. We find that both model configurations capture the main processes leading to the formation of the high-salinity layer. However, neither model configuration was unable to replicate the vertical mixing processes leading to penetration of the subsurface salt maximum.

1. Introduction

The Southern Ocean is a crucial component of the climate system as it is a significant contributor in mediating uptake of heat (Kouketsu et al., 2011; Purkey & Johnson, 2010) and CO2 (Khatiwala et al., 2009). Throughout the year, but particularly in the winter months of July through September, strong wind, wave, and buoyancy forcing impact the Southern Ocean (Rintoul et al., 2001). Equatorward of both the maximum wind and the Subantarctic Front of the Antarctic Circumpolar Current (ACC), the strong surface forcing contributes to deep mixing and production of Subantarctic Mode Water (SAMW; Rintoul & Trull, 2001). The deep mixing is important for uptake of tracers, which is apparent from the high concentrations of carbon in SAMW (Sabine et al., 2004), for example. In the Southern Ocean, the deepest observed mixed layers occur during August and September in a narrow band of latitudes stretching from the western Indian Ocean to the eastern Pacific Ocean (Dong et al., 2008) that we have called the deep mixing band (DMB). Recent Argo observations show that the DMB can have mixed layers deeper than 700 m (Holte et al., 2017), though the Southern Annular Mode drives variations in mixed layer depth (MLD; Sallée et al., 2010).

Since early 2004 the Argo program has deployed thousands of floats worldwide that provide the first year-round profiles of temperature and salinity structure throughout the entire Southern Ocean (http://www.
argo.ucsd.edu; http://argo.jcommops.org). Prior to Argo profile availability, many studies (e.g., de Boyer Montégut, 2004; Rintoul & England, 2002) relied on sparse observations in the Southern Ocean. The Argo revolution in observations provides a unique opportunity for better understanding the subsurface structure and processes of the Southern Ocean, particularly during the autumn to winter months when the mixed layer deepens but few ship-board observations are available. Furthermore, the improved understanding of the Southern Ocean permits a more complete assessment of modeling capabilities.

To accurately predict present and future changes in heat content and CO₂ uptake, models need to represent with fidelity the Southern Ocean. Assessment of ~1° resolution climate models participating in the Fifth Coupled Models Intercomparison Project (CMIP5) has shown that modeled MLDs are too shallow, shifted equatorward, and have surface waters that are too fresh (Sallée et al., 2013). Simulations with various ocean-ice models with similar ~1° horizontal grid spacing and driven by Coordinated Ocean-ice Reference Experiment Phase 2 (CORE2) historical data also have similar mixed layer biases (Downes et al., 2015). However, the widespread bias across numerous coupled CMIP5 and ocean-ice only models suggests that the root cause may be related to missing fundamental vertical physics (Belcher et al., 2012; Fox-Kemper et al., 2011) or to a strong dependence of mixed layer deepening on resolution in the form of surface currents or fluxes (R. J. Small, personal communication, 12 June 2018).

The Community Earth System Model (CESM) is one of the models that have a shallow mixed layer bias in the Indian, Australian, and Pacific sectors where SAMW is formed. Accordingly, its SAMW properties, including deficient CFC-11 concentrations, indicate that the mixing is not deep enough (Weijer et al., 2012). This shallow bias is present in both coupled and ocean-ice hindcast nominal 1° horizontal resolution simulations (Danabasoglu et al., 2012; Weijer et al., 2012). However, configurations of coupled CESM with an eddy resolving 0.1° horizontal ocean resolution show improved surface flow, temperature, and salinity (Small et al., 2014). Also, 0.1° ocean-ice hindcasts simulate deeper mixed layers over a narrow DMB that is more like to observations (Li & Lee, 2017). Similar improvement in SAMW formation and MLDs with increased ocean model resolution has also been found in models other than CESM (Lee et al., 2011). However, the reason for the improvement in MLD with higher resolution is not known, while it may be related indirectly to increased resolution through other factors such as vertical and lateral physics, local surface forcing, local stratification, and changes to general circulation.

This study seeks to examine 14 years of gridded Argo observations to identify characteristics of the deepening of the MLD from April to September in the Southern Ocean. Then, we use these findings to assess the fidelity of the POP-LR and POP-HR at replicating the seasonal evolution that occurs in nature. Section 2 describes the Argo gridded data and model simulations analyzed in this study. It also discusses the MLD, algorithm used in this work, and metrics used for evaluation at the MLD. In section 3, we describe the Argo data and processes occurring from April through September during MLD deepening. We discuss the modeling challenges associated with modeling this deepening in section 4. Finally, section 5 comprises a discussion and conclusions.

2. Data and Methods

2.1. Argo Floats

The Argo profiles provide an essential data set for better understanding autumn and winter processes during deepening. We use monthly mean 1° × 1° gridded Argo data from Roemmich and Gilson (2009) freely available for the years 2004–2017 at http://sio-argo.ucsd.edu/RG_Climatology.html. In section 2, we will present Argo data for the 14-year period from 2004 to 2017. In section 3, we compare the data from Argo and the models over a 5-year period (2005–2009) in order to evaluate overlapping time periods for all data sets; however, analysis of the 14-year and 5-year time periods is essentially the same.

2.2. Model Simulations

This study evaluates two ocean-ice hindcasts for the period 2005–2009 using the Los Alamos Parallel Ocean Program (POP; Smith et al., 2010) ocean component and CICE4 (Hunke & Lipscomb, 2008) sea ice component of the CESM. The low-resolution (POP-LR) simulation has horizontal nominal grid spacing of 1° × 1° with 60 vertical levels. It is the OCN case analyzed by Danabasoglu et al. (2012) and is freely available as case g40.000 at http://www.cesm.ucar.edu/experiments/cesm1.0/. The eddy resolving high-resolution (POP-HR)
simulation has nominal grid spacing of 0.1° × 0.1° with 62 vertical levels. The results have been analyzed by Johnson et al. (2016) and are also freely available through 2009. In both configurations the thickness of the levels is 10 m near the surface and increases to 250 m at depth. Both simulations use interannual forcing from the CORE2 surface forcing data set (Large & Yeager, 2009), so the surface fluxes differ only by the effects of different sea surface temperatures and surface currents.

Both the POP-LR and POP-HR simulations use the K-Profile Parameterization (KPP) vertical mixing physics (Large et al., 1994) as modified by Danabasoglu et al. (2006). The extent of vertical mixing and entrainment is primarily governed by a diagnosed boundary layer depth ($\text{BLD; m}$) given by

$$\text{BLD} = \frac{R_{ic} \Delta V^2}{\Delta B - c NW}$$

(1)

where $R_{ic} = 0.3$ is a critical bulk Richardson number, $c$ is approximately constant, and $W$ is a combination of surface wind and buoyancy forcing. At the BLD, the buoyancy and velocity differences from the surface are $\Delta B$ and $\Delta V$, respectively, and the stratification is given by the square of the buoyancy frequency, $N$ (s$^{-2}$):

$$N^2 = g \left( \frac{\partial \theta}{\partial z} - \beta \frac{\partial S}{\partial z} \right)$$

(2)

POP-LR uses a recent variant of Gent-McWilliams eddy parameterization (Gent, 2011), while POP-HR is configured to resolve mesoscale eddies. Whether parameterized or resolved, the generation of mesoscale eddies lowers the potential energy of the water column by restratification in direct competition with the mixing of KPP (Gent, 2011).

For comparison with the gridded Argo data described in the previous section, both POP-LR and POP-HR were mapped to the Argo grid using Earth System Modeling Framework (ESMF) regridding.

2.3. MLD

A familiar and commonly used ocean diagnostic for vertical mixing is the MLD. Since calculating BLD requires information not available in Argo (e.g., shear), we follow de Boyer Montégut (2004) and use a sigma criterion as a definition of convenience to calculate MLD consistently in the Argo data, POP-LR, and POP-HR simulations. The sigma criterion uses the 0.03 kg/m$^3$ difference in density at depth from the surface of de Boyer Montégut (2004) and Dong et al. (2008), both of whom also discuss some issues with the determination of MLD using thresholds. The sigma criterion implies that $\Delta B$ at the MLD is roughly constant at 0.028 cm/s$^2$. Since the vertical density difference is proportional to the buoyancy force that must be overcome by surface forcing, the density criterion has been found to be more reliable than temperature or salt criteria (Lukas & Lindstrom, 1991), but neither the mean nor turbulent kinetic energy (Large et al., 1994) contributions to BLD in equation (1) are considered. A particular drawback to a threshold method in the Southern Ocean winter is that there is not always a clear potential density feature at the designated MLD. Thus, the MLD may just mark the location where the density overcomes the threshold over a gradual, monotonic density change, possible due to lateral processes or the grid averaging. A number of other methods to determine MLD exist (e.g., Holte et al., 2017) and may be more relevant ecologically (Carvalho et al., 2017), but none can differentiate between past and present vertical mixing or account for lateral processes.

Therefore, MLD may not relate directly to the more model relevant extent of surface forced mixing at a given place and time given by BLD (equation (1)). The difference between constant $\Delta B$ at the MLD and $\Delta B$ at the BLD can be highlighted by rearranging equation (1):

$$\Delta B \ (\text{BLD}) = c NW + \left( R_{ic} \frac{\Delta V^2}{\text{BLD}} \right).$$

(3)

In the limit of vanishing shear ($\Delta V = 0$), $\Delta B(\text{BLD}) = c NW$, such that $\Delta B$ increases with increasing stratification and/or surface wind or convective buoyancy forcing. Also, when the wind generates large surface velocities and increases shear ($\Delta V$), then $\Delta B$ can also become much bigger, leading to significantly deeper BLD, with the effect modulated at deeper BLD.
A further complication is that change in the depth (h) of either the boundary or mixed layer over time is equivalent to the difference between the entrainment rate, $w_v$, and the vertical velocity, $w_h$:

$$\frac{Dh}{Dt} = \frac{\partial h}{\partial t} - v_v \nabla h = w_v - w_h \tag{4}$$

where there can be horizontal advection by the horizontal velocity vector $v_v$ and $w_h$ times an appropriate temperature difference gives the entrainment flux that cools the mixed layer (Stevenson & Niiler, 1983). Thus, changes in mixed layer properties cannot be inferred from local changes in $h$, unless both the vertical velocity and the advection are known. The former is tractable to some degree, but not the latter. Insofar, as an isopycnal just below a layer of depth $h$ represents a material surface, its vertical displacement serves as a proxy for $w_h$ but only for short periods until the isopycnal is either entrained into the mixed layer, is displaced too far below the layer, or no longer represents the material surface because of mixing or lateral processes.

### 2.4. Stability at the MLD

Given the above issues with characterizing Southern Ocean deep mixing with MLD alone, we explored additional diagnostics given directly by Argo, by POP-LR, and by POP-HR. In particular, the static stability (equation (2)) at the MLD, decomposed into its temperature and salinity contributions, can be particularly informative. At the MLD, we calculate the vertical temperature and salinity gradients. Typically, the temperature gradient, $\partial_z \theta$, is positive and stabilizing, but there can be temperature inversions at the deep winter MLDS. Salinity gradients, $\partial_z S$, are highly variable and can be of either sign earlier in autumn. In order to directly compare their relative contributions to stratification we scale the vertical gradients by the thermal expansion coefficient ($\alpha; {^\circ}C^{-1}$) and saline contraction coefficient ($\beta; kg/g$) calculated at each point in each column using the equation of state (McDougall et al., 2003). Any vertical point in the water column can be represented in Figure 1 where we plot the scaled vertical salt gradient along the $x$ axis and the vertical temperature gradient along the $y$ axis.

The relative contributions of temperature and salinity gradients to stability are conveniently given by the Turner Angle, $Tu$ (Ruddick, 1983; You, 2002):

$$Tu = \tan^{-1} \left( \frac{\partial \theta / \partial z}{\partial S / \partial z} - \beta \frac{\partial \theta / \partial z}{\partial S / \partial z} \right) \tag{5}$$

Figure 1 shows the physical interpretation of Tu. At $Tu = 0$, $-\partial \theta / \partial z$ and $(\partial S / \partial z)$ are equal and contribute equally to stable stratification. An increasing positive $Tu$ is indicative of the temperature contribution growing relative to salinity, and for 45° < $Tu$ < 90° the growth continues to more than compensate for an increasingly destabilizing $\partial S / \partial z$, until stratification becomes neutral at $Tu = 90°$. Conversely, $Tu$ becomes increasingly negative as the salinity contribution grows relative to temperature, and for $-45° > Tu > -90°$ the increasing salinity stabilizes and compensates for an increasingly destabilizing temperature inversion $(\partial \theta / \partial z < 0)$, until stratification becomes neutral at $Tu = -90°$. Double diffusion instabilities may become significant in the statically stable range of about 74° < $Tu$ < 90° (salt fingering) and $-70° > Tu > -90°$ (diffusive convection). For $Tu > 90°$ or $Tu < -90°$ the stratification is unstable. By assessing Tu at the MLD, we can determine the relative contributions of each component to local stabilization. Example values of Tu for Argo at location B (marked on Figure 2) are shown on Figure 1 for April (black), June (blue), and September (blue).

Lines of constant stratiﬁcation ($N^2/g$, as computed in equation (2)) are shown on Figure 1 by the parallel dashed grey lines with slope of unity. Where $N^2 = 0$ the column is no longer statically stable, and this occurs along the line given by $Tu = 90°$ or $-90°$. Greater values of buoyancy frequency indicate greater stability and stratiﬁcation. Figure 1 indicates that from April through September buoyancy frequency decreases...
as the MLD deepens, and the column becomes less stratified at the MLD. However, Tu does not evolve monotonically; the maximum positive value is in September and minimum negative value in June, with April values in between.

3. Analyses of Gridded Argo

This analysis will focus only on the 2004–2017 climatological monthly means of April, June, and September in order to illuminate processes involved in the transition from shallow summer mixed layers to deep winter mixed layers. Additionally, we focus on the DMB, defined here to be spatial locations where the Argo September MLD exceeds 250 m, and shown by the black contours of Figure 2 and following spatial maps.

In April the MLD (Figure 2a) is relatively shallow throughout the Southern Ocean and typically does not exceed 100 m. By June (Figure 2b), there are clear hot spots where the mixed layer has deepened more than 100 m in 2 months. By September (Figure 2c), MLDs in excess of 250 m develop in a relatively narrow band up to 10° of latitude (the DMB) between 40°–50°S in the Indian and Australian sectors of the Southern Ocean and 50°–55°S in the Pacific sector (Figure 2, black contours). These results are consistent with previous observation-based climatologies of Southern Ocean MLD over different periods and with different data products (Buongiorno Nardelli et al., 2017; de Boyer Montégut, 2004; Dong et al., 2008; Holte et al., 2017).

Why is the DMB so confined in latitude, as illustrated in Figure 3 at 90.5°E and 157.5°E? To answer this question, we first consider the impact of strong surface wind, wave, and buoyancy forcing present in the Southern Ocean (Rintoul et al., 2001). The surface wind stress magnitude in September is quite high in the DMB and exceeds 2 dyne cm$^{-2}$ across the DMB at 90.5°E (Figure 3c) and peaks at about 1.7 dyne/cm$^2$ in the DMB at 157.5°E (Figure 3d). However, the wind stress is as strong, or stronger poleward of the DMB, and the September surface heat flux loss also peaks poleward of the DMB at 90.5°E (Figure 3g) and at 157.5°E has similar magnitude both poleward and equatorward of the DMB as within the DMB (Figure 3h). The wind stress curl may be a factor in determining the location of the DMB because poleward of the DMB there is inferred Ekman suction driving upward motion, while in the DMB there is inferred Ekman pumping driving downward motion of up to 4 m/month (Figures 3e and 3f). While an Ekman pumping-driven displacement of ~10 m from April to June is of similar magnitude as the ~40 m deepening of the MLD over this time (Figures 3a and 3b), it is negligible compared to the ~250 m deepening from June to September. Additionally, the values of Ekman pumping-driven downwelling are larger equatorward of the DMB (Figures 3e and 3f). The surface flow of the ACC occurs poleward of the DMB (Figures 3i and 3j) as is the associated eddy kinetic energy as measured by the root-mean-square sea level height anomalies (Figures 3k and 3l). The eddy generation process extracts energy from the potential energy and results in restratification of the water column, which may be a factor...
in preventing deep mixing at latitudes with peak eddy activity. Overall there is no robust correlation between deep mixing and the surface forcing across these longitude sections of Figure 3 and indeed over most the DMB (see Figures S1–S4). Although some loss of correlation from lateral advection by the strong currents (e.g., equation (4)) is expected, consideration of subsurface conditions as observed by Argo warrants examination.

3.1. Stability at the MLD

In order to understand the processes that occur during winter deepening of the MLD and that confine the DMB, we now consider the stratification at the MLD. The monotonic decrease in buoyancy frequency at the MLD from April through September, shown by the colored points on Figure 1, is ubiquitous throughout the DMB where the seasonal deepening of several hundred meters takes place. In order to quantify the contributions of salt and temperature to stability at the MLD, we evaluate $T_u$ within the DMB in April, June, and September.

In April, the DMB tends to have both salinity and temperature contributing to stabilization of the MLD (Figure 4a; $45^\circ > T_u > -45^\circ$). In general, in the southernmost parts of the DMB salinity tends to be the more important (blues), while temperature plays the larger role over the northernmost parts (browns).
most of these locations (Figure 4b) have negative values of $Tu$, indicating that salt has become the more important stabilizer at the deeper MLD. In the Indian and Australian sectors there are regions where temperature inversions are stabilized by the salinity gradient ($Tu < -45^\circ$, purples), though nowhere is there significant diffusive convection. By September, the values of $Tu$ have shifted to mostly positive, indicating that temperature at the MLD has become the bigger (browns), and sometimes only (reds), stabilizer, but there are no longer any locations where the salinity gradient alone stabilizes the MLD (Figure 4c). Additionally, there are a number of locations along the northern edge of the DMB where salt fingering appears significant (Figure 4c, white contours), which would tend to locally destabilize at the MLD.

Throughout the DMB there is a spread of $Tu$ values, but overall the seasonal progression of Figure 1 emerges clearly. In April (Figure 5, black) $Tu$ is relatively well distributed between 45 and $-45^\circ$, but the negative swing in June (blue) indicates a greater role for the salinity gradient in stabilizing at the MLD. However, in September (red) temperature contributes to stability at the MLD everywhere ($Tu > -45^\circ$) and at most locations, and everywhere MLD exceeds 400 m, it is more important than salinity ($Tu > 0^\circ$).

### 3.2. Seasonal Evolution of the Subsurface Salinity

The seasonal shifts in $Tu$ discussed above are a manifestation of the MLD approaching a subsurface salinity maximum in June before mixing through the maximum and becoming mostly temperature stabilized by September. At each of the locations A–E marked in Figure 2, there is a strong (0.1 to 0.3 psu) increase in salinity at around 100-m depth in April with a maximum salinity around 150 m (Figure 6, black profiles). At all these sites, except D in the far eastern Pacific, this feature is distinctly peaked over ~50 m with a sharp gradient of increasing salinity above the maximum and a sharp gradient of decreasing salinity below. By June the peak salinity is found slightly deeper, possibly due to downwelling (Figures 3e and 3f), as is the MLD, but the distinctive April shape remains. However, by September, at all locations inside the DMB, the MLD has penetrated through the salinity feature and deepened to more than 300 m. However, the salinity at these sites is only well mixed down to ~100–200 m above the MLD. Below 300 m at all sites except D, the salinity decreases toward the deep salinity minimum in all 3 months. Indeed, the presence of a subsurface salinity maximum co-located with the DMB is a common feature of the Southern Ocean in April, and at most locations the salinity feature is mixed out by September (Figures 6f–6h) similar to the process described for sites A–D. In contrast, at site E (Figure 6e) in...
the Atlantic sector outside the DMB the mixing is insufficient to erode the subsurface salinity maximum and salinity is well mixed to the MLD. Similarly, Figure 6h suggests that salinity stratification may inhibit deep mixing poleward of the DMB at 90.5°E (Figure 3a).

It is evident from the shape of the salinity feature that early in autumn as deepening begins but the MLD is still above the maximum of the feature, the large salinity gradient stabilizes the MLD and inhibits further deepening. However, if the MLD is able to penetrate the high-salinity layer and reach the peak salinity at around 150-m depth, the salinity gradient becomes unstable and would act to facilitate mixing and deepening of the MLD. The annual cycle of MLD and salinity profiles at locations A–D (Figure 7) show that MLD deepening rate changes through the autumn and winter and suggest that the subsurface salinity feature has an impact on moderating the rate of deepening. While the surface wind stress and surface fluxes also increase in magnitude in autumn and would contribute to deeper MLD, their role is difficult to quantify. However, the poor correlation between the DBM and the stronger winter surface forcing (Figure 3) suggests that the primary modulator of the rate of deepening is not surface-driven. Early in the autumn, from approximately April through July, the MLD is located above the subsurface salinity maximum and deepens slowly, as would be expected if the salinity gradient acts to stabilize the MLD and inhibit mixing. However, sometime in July the MLD appears to penetrate the subsurface salinity maximum and the rate of deepening increases until the September maximum MLD. This increase in deepening is also consistent with the salinity gradient acting to destabilize the MLD once mixing has penetrated the depth of the salinity maximum.

Figure 8 shows salinity along the Indian to Pacific sector transect marked in Figure 2. The Agulhas retroflection supplies the Southern Ocean with high-salinity water that can be traced westward across the Indian Ocean sector. The apparent increases in salinity in the Australian, Mid-Pacific, and East-Pacific sectors
suggest that there are additional, though much weaker, sources of salinity feeding these regions. Also, evident are sources of fresh surface water around both 180 and 250°E. The net result is a nearly continuous subsurface salinity maximum in April with the MLD lying above. In June, the MLD is still above the salinity maximum, which by September has been eroded away allowing the MLD to be significantly deeper. The impact of salinity appears to be largest in the Indian and Australian sectors and to diminish in both magnitude and, possibly, importance toward the Eastern Pacific.

In order to explore the origin of the subsurface salinity maximum feature, the April salinity has been mapped (Figure 9) to isopycnals along transects from 55 to 35°S at 90.5°E in the Indian sector and 157.5°E in the Australian sector. At both longitudes, a subsurface salinity maximum is evident across the DMB. The most saline water to the north (25.6 < \sigma < 26.8) appears to move poleward as a front until being overridden by fresh surface water driven from the south by Ekman transport associated with the strong westerly winds (Rintoul & England, 2002). The result of these two opposing flows is the clear peaked nose of the subsurface salinity maximum (see Figures 6–9), with the peak salinity set at the surface to the north. Thus, the magnitude of the salt maxima is likely related to the net surface freshwater flux in subtropical basins, as well as the Ekman transport. The changes in salinity with latitude along any particular isopycnal and equivalently the increasing

Figure 7. Time series of monthly mean salinity (psu; colors) and mixed layer depth (m; black dots) for Argo at locations (a) A, (b) B, (c) C, and (d) D indicated on Figure 2. The dashed black lines indicate April, June, and September.
density of the salinity maximum indicate that the processes that occur during the descent of the salinity maxima are somewhat diabatic, which is unsurprising given the plethora of processes that affect the water column at these latitudes (see Figure 3).

4. The Modeling Challenge

This analysis considers the 2005–2009 period common to Argo, POP-LR, and POP-HR. Furthermore, it will focus on mean April, June, and September months of transition from shallow summer mixed layers to deep winter mixed layers. The analysis in section 3 suggests that modeling this transition may not be

Figure 8. Salinity (psu; colors) and mixed layer depth (m; black dots) along the Southern Ocean transect shown in Figure 2 for Argo in (a) April, (b) June, and (c) September. Latitudes and longitudes as well as approximate locations are noted on the x axis; locations of constant longitude profiles are noted by white stars.

Figure 9. April salinity (psu) for Argo mapped to isopycnals along a transect of constant longitude spanning 55 to 35°S for longitudes (a) 90.5°E and (b) 157.5°E. The black lines indicate the deep mixing band as denoted in Figure 3.
straightforward and comparisons of POP-LR and POP-HR against Argo provide an opportunity to assess their fidelity in this regard.

In April, the POP-LR and POP-HR simulations produce similar MLD but have shallow biases in the Indian and Pacific sectors of the DMB (Figures 10b and 10e) compared to Argo (Figure 2a). Like Argo, both POP-LR and POP-HR have deepest MLD in September (Figures 10a and 10d). The DMB, as defined by model MLD > 250 m in September (Figures 10a and 10d, dashed black contours; Figure S5) corresponds well to the Argo DMB for POP-HR. POP-LR has much less extensive regions with MLD deeper than 250 m, though where they occur these areas tend to overlap with to the Argo-observed DMB. Because we are interested in the observed DMB and processes occurring there due to its importance for uptake, we focus primarily on the DMB as defined by the MLD in September from Argo (Figure 10, black contour). The MLD in POP-LR (Figure 10c) is too shallow everywhere in the DMB but can be too deep outside the DMB (e.g., south of Western Australia). On the other hand, POP-HR deep MLD is more confined to the DMB, so shallow biases are reduced in extent. However, there are even larger deep biases (e.g., south of Tasmania and west of Drake Passage).

4.1. Turner Angle at the MLD

In different ways, neither model simulation reproduces Figures 4 and 5 from Argo in the DMB. In April nearly all of the POP-LR points (Figure 11a, black) are at Tu > 0°, compared to the broader range of Argo (Figure 5)

Figure 10. Parallel Ocean Program-low-resolution mixed layer depth (POP-LR MLD; m) in (a) September and MLD bias (POP-Argo, m) in (b) April and (c) September. POP-high-resolution (HR) MLD (m) in (d) September and MLD bias (m; POP minus Argo) in (e) April and (f) September. The solid black contour corresponds to the deep mixing band from Argo as shown on Figure 2. The dashed black dashed contour indicates the model DMB for (a) POP-LR and (f) POP-HR defined as September MLD > 250 m, identically to the Argo definition.
Figure 11. $Tu^\circ$ and mixed layer depth (MLD; m) as in Figure 5, except for (a) Parallel Ocean Program-low resolution (POP-LR) and (c) POP-high resolution (HR). $Tu^\circ$ and MLD bias (m; POP minus Argo) for (c) POP-LR and (d) POP-HR. Values are shown for April (black), June (blue), and September (red).

Figure 12. $Tu^\circ$ at the mixed layer depth (MLD) as in Figure 4 except for POP-LR (a, b, c) and POP-HR (d, e, f). black contours correspond to the DMB from Argo.
and POP-HR (Figure 11c, black). This indicates that the POP-LR temperature gradient tends to play the lead role in stabilizing the column (Figure 12a, browns), because the MLD has not penetrated enough into stabilizing salt by April and indeed POP-LR has a shallow bias of up to 50 m is reflected in Figure 11b. Like Argo, as described above, by June Tu for both POP-LR and POP-HR (Figures 11a and 11c, blue) has shifted to more salt stabilization, but the POP-LR shallow biases have grown much more (Figure 11b).

By September, both POP-LR and POP-HR show many more points with $\text{Tu} < -30^\circ$ (Figure 11, red) than Argo, indicating that salt is playing too great a role in stabilizing the column. These spurious points correspond to less shallow biases in POP-LR (Figure 11b), but there is not a consistent relationship between MLD biases and points that successfully complete the seasonal transition to $\text{Tu} > 0^\circ$ (Figure 11a). POP-LR does have large regions north of the DMB with salt fingering (Figure 12c, white contours) that would locally destabilize the MLD and are similar, though too extensive, compared to regions seen in Argo (Figure 4c). In contrast, large biases of both signs in POP-HR are associated with locations that fail to complete the seasonal Tu transition (Figure 11d), but a relatively small number of points do complete the seasonal transition to $\text{Tu} > 0^\circ$ (Figure 11b). Most of these points have deep biases (Figure 11d) and occur near Tasmania (Figure 12f) where salt fingering might locally destabilize the MLD in a similar way as shown by Argo (Figure 4c). In general, however, POP-HR tends to have too many locations where diffusive convection (Figures 12e and 12f) would act to locally destabilize the MLD that are not present in the Argo observations (Figure 4). Although the overall September shallow bias is POP-LR is significantly greater than that of POP-HR, the root-mean-square differences are similar because of POP-HR’s large positive biases.

We now examine the April through September changes in Tu along the Indian to Pacific sector transect. For Argo, the seasonal shift in Tu toward negative values from April to June and then more positive values June to September is characterized by the black trace falling above the blue and below the red (Figure 13a). These Argo seasonal shifts are particularly evident from the mid-Indian sector through the Australian sector, but the changes are less pronounced in the Pacific sector. Breakdowns in this pattern tend to occur outside the DMB (e.g., around the dateline and in the west Indian Ocean sector). In the Australian region both POP-LR (Figure 13b) and POP-HR (Figure 13c) have Tu seasonal shifts toward more negative values, which

![Figure 13. Tu (°) at the mixed layer depth in April (black), June (blue), and September (red) along the Southern Ocean transect for (a) Argo, (b) Parallel Ocean Program-low resolution (POP-LR), and (c) POP-high resolution (HR).](image-url)
is consistent with Argo. However, in both the Indian and mid-Pacific regions both models miss the positive shift in $T_u$ from June to September. This inability for the models to replicate the seasonal cycle of $T_u$ at many locations suggests that they are missing some fundamental process related to deep stratification and MLD deepening in the real ocean. The many locations of September $T_u < 0^\circ$ in POP-LR and POP-HR suggest that mixing related to the subsurface salinity may be particularly problematic.

4.2. Modeled Subsurface Salinity and Temperature

At each of the locations A–D both models tend to have subsurface salinity maxima in June (Figure 14); however, the features differ in some important ways from those in Argo (Figure 6). Both simulations are too fresh at the surface compared to Argo, and while POP-LR has a modest increase in salinity with depth, POP-HR has a large increase in salinity with depth. The result is that in April, POP-LR tends to have too small salinity gradient, while POP-HR has too large gradient. While POP-LR has a clear salinity feature that is similar, though less pronounced, than in Argo, the POP-HR feature tends to be too broad and to span a larger depth. Of particular concern is that both models increase in salinity at depth (>300 m) at locations C and D, which contrasts the Argo decrease toward the deep salinity minimum. The result is that for both POP-LR and POP-HR in September the salinity is not always well mixed through to the MLD and that the MLD is frequently at a depth where the salinity gradient acts to inhibit rather than to enhance mixing.

As illustrated on Figure 15, differences between the September and April salinity and temperature profiles at locations A–D reveal what processes may be occurring throughout the deepening season. Changes at depths below the MLD are most likely related to horizontal advection. They are generally small in Argo and near zero in POP-LR, but changes in POP-HR are not only much greater, they can be of either sign, with heating and salinification at A and B and cooling and freshening at C and D. Changes above the September MLD are a
balance between vertical redistribution due to mixing and net gain or loss due to the combined effects of advection and surface fluxes. At point A, Argo shows mixing to the MLD in salt, and a net cooling, similar to POP-LR, but the salinity of the upper 100 m of POP-HR increases far too much, while there is too little net cooling, suggesting extra advection of warm salty water or too much evaporation. The situation at point B is similar except for a net freshening in Argo that is not in POP-LR. At both points C and D Argo changes are consistent with a vertical redistribution of salt, with some freshening at C, and net cooling above the MLD. POP-LR shows some similar characteristics, but the freshening at C is missing and the net cooling is less, whereas the net freshening and cooling of POP-HR is similar to Argo and extends to a similar depth.

We now compare the modeled April salinity along the Indian to Pacific transect to Argo (Figure 8). Like Argo, both POP-LR (Figure 16a) and POP-HR (Figure 16b) have the most saline water in the eastern Indian sector with decreasing salinity toward the Pacific sector. But both models have fresh biases compared to Argo. The POP-LR fresh bias is particularly large, which is consistent with findings that low-resolution models overestimate leakage of the salty Agulhas water into the Atlantic basin thereby leading to too fresh water in the Indian sector of the Southern Ocean (Weijer et al., 2012). Interestingly, POP-HR develops a strong fresh bias.
from around the mid-Indian through the Pacific sector. Nonetheless, a subsurface increase in salinity is present in both models. Along this transect, the POP-LR salinity feature extends only to the Australian sector, while the POP-HR feature extends well into the western and mid-Pacific sectors, which is more consistent with Argo. However, the POP-HR feature is deeper (~300–500 m) than in Argo (~150–200 m), though the reasons for this remain unclear.

**Figure 16.** April salinity (psu; colors) and mixed layer depth (m; black dots) as in Figure 8 except for (a) Parallel Ocean Program-low resolution (POP-LR) and (b) POP-high resolution (HR).

**Figure 17.** April salinity (psu) as in Figure 9 but for (a and c) Parallel Ocean Program-low resolution (POP-LR) and (b and d) POP-high resolution (HR).
The models appear to also have sources of salinity in approximately the correct locations in the Australian, Mid-Pacific, and East-Pacific sectors as well as the sources of fresh surface water around both 180° and 250°E. Consistent with Argo (Figure 9), the models have a subsurface maximum in salinity between 39 and 48°S at 90.5°E, with POP-LR (Figure 17a) arguably in better agreement with Argo, and between 44 and 53°S at 157.5°E, where POP-HR (Figure 17d) is the better match. While the magnitude of the salinity differs, the subsurface salinity structure on isopycnals is similar to Argo and suggests that the models are generally capturing both the correct Ekman transport from the south and the subsurface salinity transport from the north necessary to create the subsurface salt feature that mediates MLD deepening.

5. Discussion and Conclusions

The availability of gridded Argo data (Roemmich & Gilson, 2009) throughout the Southern Ocean allows for more thorough investigations of deep mixing throughout autumn and winter and of the related biases in ocean models such as POP-LR and POP-HR. In particular, the shallow mixing biases of POP-LR and other CMIP-5 models and both the deep and shallow biased of POP-HR are of interest because of the implications of uptake and production of SAMW related to winter mixing.

The Southern Ocean generally has low stratification year-round and small vertical gradients. The exception is the presence of a subsurface salt maximum around 150- to 200-m depth, whose geographical extent, seasonal progression, and possible origins are characterized more fully by the Argo data. The extent of such a feature is well reproduced by both POP-LR and POP-HR, but it is too weak in POP-LR and too saline and too deep (300–500 m) in POP-HR, such that the stabilizing salinity gradient is too strong. Thus, despite biases, it appears that both models have at least most of the large-scale model physics necessary to create a subsurface salinity maximum.

The familiar MLD of de Boyer Montégut (2004) is a convenient diagnostic of vertical mixing and readily computed from the Argo data and model output, but it has short-comings. For example, its constant $\Delta B$ criteria are markedly different than the variable $\Delta B$ associated with the extent of strong boundary layer mixing. Also, in Southern Ocean winter MLD often does not coincide with a stratification feature and salinity is neither observed nor modeled to be well mixed as deep as the MLD (e.g., June values for Figures 6a, 6c, 14d, and 14f). Therefore, MLD biases may not be the only model mixing problem and the concerns about how well MLD, as opposed to BLD, represents mixing in the Southern Ocean remains.

A DMB emerges from the September Argo data. It extends nearly continuously from about 55°E in the Indian Ocean sector eastward across the Pacific to Drake Passage at 300°E. The width of the DMB is typically only 5° of latitude, but there is no robust correlation with any one of several possible contributing factors, including the wind stress and resulting Ekman suction, the surface buoyancy flux, and mesoscale eddy activity. Therefore, a conclusion is that these factors combine in just the right way to mix through the stratification, especially that associated with the subsurface salinity maximum, only in the DMB. Farther north or south in the Indian or Pacific sectors, or across the Atlantic sector to 55°E, they are either too weak or counteract too much for deep mixing. In POP-LR a DMB does not emerge so clearly, indicating that these factors appear to be too weak or too compensating. While POP-HR does have a DMB in the correct location, a more confused picture emerges with too deep mixing occurring in the Pacific and eastern Australian sectors but not in the Indian.

By using values of $Tu$ at the MLD we are able to characterize the progression of mixing from April through September in the DMB. There is a seasonal shift from temperature and salinity both contributing significantly to the stability in April, to salinity becoming more important in June, and then to temperature dominating stability in September. Physically, these shifts in $Tu$ over the months indicate that the MLD deepens slowly from April through June as it works against a stabilizing salinity gradient. However, once mixing has been sufficient to reach beyond the subsurface salinity maximum the sign of the salt gradient changes and works to deepen the MLD rather than inhibit deepening. Thus, the salt maxima is mixed out by September and the rate of deepening at the end of the season increases and the temperature gradient becomes the stabilizing factor at the MLD. Given the September biases, it is not surprising that neither simulation is able to correctly replicate the April through September behavior of $Tu$ at the MLD. Instead, both models tend to become strongly salt stabilized in June and too few points break through the salinity maximum by September. This means that neither POP-LR, despite its weak subsurface salinity maximum, nor POP-HR, perhaps because...
of its too deep and too salty subsurface salinity maximum, simulations mix through the subsurface salinity layer as is seen in Argo data.

In the Indian and Australian sectors, the Argo data suggest that the characteristic peaked salinity maximum is the result of a combination of Agulhas retroflexion of very salty water, Ekman transport of fresh water from the south, Ekman pumping immediately north of the wind stress maxima, and southward subsurface transport of high-salinity water from regions north of the Southern Ocean. Thus, simulation of this feature presents a modeling challenge. POP-LR tends to have too fresh of a subsurface salinity maximum, which is consistent with findings that there is too much leakage of the salty Agulhas current into the Atlantic basin at the expense of the Southern Ocean in low-resolution models, thereby leading to overly fresh water in the Indian sector of the Southern Ocean (Weijer et al., 2012). The resulting salinity gradient from the surface to the salt maximum is too weak, yet POP-LR is not able to mix through this feature. This inability may be related to missing vertical physics or perhaps the eddy parameterization is overly active in stabilizing the water column (Gent, 2011). POP-HR, on the other hand, is able to simulate a strong subsurface salinity maximum, perhaps because mesoscale eddies are not parameterized. However, the very negative values of Tu in through September reflect the continuing importance of salinity stratification throughout winter. Therefore, in POP-HR the deep MLDs are a result of the ability of the POP-HR simulation to mix down to this salt feature, which itself is too deep, but the mixing does not penetrate through the salinity maximum as is seen in the Argo data. While POP-HR has improved surface fluxes and currents (R. J. Small, personal communication, 12 June 2018), it appears that the improvement in MLD compared to Argo may be related to the deeper and stronger salinity maximum, rather than better mixing and eddies.

The dependence of the salinity feature structure on Ekman transport is supported by reported high correlations between SAMW properties and Ekman transport (Rintoul & England, 2002). If the magnitude of the salinity maxima is set remotely at the surface to the north of the Southern Ocean, there is a further modeling challenge, with the possibility that interannual variability in the precipitation and evaporation in these locations could impact subsequent maximum MLD in the Southern Ocean. Additionally, this salinity maximum may impact biological activity and carbon uptake during autumn and winter.

A conclusion of this work reveals that the POP models require further development to better replicate the deep mixing and uptake in the Southern Ocean. Increasing horizontal resolution may improve the general circulation and some features of subsurface stratification, but it appears that there are additional fundamental physics required to penetrate the salinity maximum for either model configuration, as is seen in the Argo observations. Possibilities include surface wave driving and nonlocal momentum transport in the KPP for vertical mixing. Additional investigation into the POP-LR and POP-HR simulations is also underway to better understand the impact of circulation on the salinity feature and hence on MLD.

References


