A “mirror layer” of temperature and salinity in the ocean

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Abstract

Using the newly available 13-year Argo float data for the period 2004–2016, a three-dimensional temperature–salinity (T – S) correlation field is constructed for the global upper ocean. It is revealed that the layer-averaged correlation between T and S time series has a significant peak (~ 0.7) at a depth of approximately 300 m, suggesting that the density-compensated thermohaline covariation may lead to a maximum T – S coupling in the vicinity of the pycnocline. This argument is supported by subsequent findings that the spatial distributions of temperature and salinity have excellent consistencies in terms of both climatology and seasonality around this depth, which we call a “ T – S mirror layer”. Since mass, heat and salt are mainly transported by dynamic events and processes, dominant currents and prevailing eddies in the pycnocline zone are found to determine the fundamental patterns of the global T/S climatologies which are characterized by a unified pattern of six well-defined warm/salty pools with collocated centroids and a clear west preference. Our results also suggest that the climatological ocean circulations transport heat/salt as a conveyor belt, meanwhile heat and salt parcels are discretely transported by numerous migrating mesoscale eddies, the combined effects of which lead to the formation of six well-defined “warm/salty pools” in the western subtropical oceans with a core depth of ~ 300 m at the “mirror layer”.

1 Introduction

The seawater density is physically determined by temperature and salinity along with pressure. Small changes of temperature–salinity (T – S) relation may result in spatial variations in pressure at a given depth, which in turn drive the horizontal circulation and vertical convection of the ocean at all scales (Riser et al. 2008). Temperature and salinity are also the two most important factors in controlling the fundamental aspects of the chemistry of seawater and of biological processes within it (Pawlowicz 2013), thus serve as connecting variables to “bridge” the geophysical and biogeochemical states of the ocean. The apparent link between ocean temperature/salinity and the global water cycle via evaporation and precipitation brings them to the center of global climate change. For all these reasons, a clear understanding

of the T – S relationship on a global scale is highly desirable for both ocean and climate researches.

Many observations show that the thermohaline structure of the horizontal fronts is largely density compensated on scales of 10–100 km (e.g., Roden 1975; Yuan and Talley 1992; Rudnick and Ferrari 1999). In other words, temperature and salinity fronts are collocated so that the resulting density contrasts are small relative to the individual contributions of heat and salt. Meanwhile, some observations also show that temperature gradient is only partially opposed by the salinity gradient across the horizontal density fronts on scales finer than 10 km due to the active subducting isopycnal which has a great deal of temperature and salinity variability (e.g., Flament et al. 1985; Rudnick and Luyten 1996; Ferrari and Rudnick 2000). Using the 15 years of best available SeaSoar data in the twentieth century, an attempt is made by Rudnick and Martin (2002) to estimate the horizontal density ratio ($R = \Delta T / \Delta S$, the change in density due to temperature divided by the change in density due to salinity) in a number of subtropical and midlatitude regions of the upper ocean. They find that the mixed layer and thermocline density ratios are generally close to 1 and 2, respectively. The transition from $R = 1$ to $R = 2$ is mainly caused by salt fingering (Schmitt 1994).

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It is apparent from the above brief review that, observations on T – S relation in the past few decades mostly concentrated on sea surface front, the mixed layer and the thermocline zone, due to a general lack of simultaneous temperature/salinity measurements in deeper oceans during the past century (e.g., Roemmich and Gilson 2009). As pointed out by Rudnick and Ferrari (1999), the questions of whether measurements at specific locations are representative of other oceans, and what sustains the large-scale density ratio in the world's oceans remain open. In this study, taking advantage of the unprecedented Argo (Array for Real-time Geostrophic Oceanography) floats with space-time collocated T – S data pairs, a systematic analysis of the global temperature-salinity relationship in the upper ocean is carried out as a first step towards revealing its truly four-dimensional (4-D, x , y , z and t) structures and profound implications. The rest of the paper is organized as follows: A brief description of the Argo data and processing method is provided in Sect. 2. The global T – S correlation coefficient is computed and its geographical distribution characterized in Sect. 3. The patterns and effects of 4-D T – S relationship are analyzed in the context of climatology and seasonality in Sects. 4 and 5, respectively. The robustness of T/S similarity and the density compensation mechanism are discussed in Sect. 6. A summary with concluding remarks is provided in Sect. 7.

2 Data and method

Thirteen years of Argo data spanning from 2004 to 2016 are used in this study. Argo floats are designed to observe large-scale (seasonal and longer, 1000 kilometers and larger) subsurface ocean variability globally (Roemmich et al. 2009). As the first observation system of global subsurface ocean in history and one of the main sources of in situ temperature/salinity measurements, the aim of the Argo project is to provide simultaneous T/S observations of the ~ 0 – 2000 m upper ocean in near real time, thanks to its state-of-the-art spatial-temporal sampling and coverage. By June 7, 2017, there are as many as 3883 active floats disseminated around the global ocean spacing nominally at every 3° of longitude and latitude. In this investigation, gridded Argo temperature data are obtained from the China Argo Real-Time Data Center (http://data.argo.org.cn/pub/ARGO/BOA_Argo/). The original observations used to generate the product are the so-called D-mode Argo data with pressure offsets corrected (Barker et al. 2011). There are 58 vertical layers in our dataset ranging from 0 to 1975 m with an interpolated spatial resolution of $1^\circ \times 1^\circ$ and temporal resolution of 1 month, respectively.

The accumulation of continuous time series from available Argo floats has exceeded 13 years for the first time. The two decade-long 3-D T/S climatologies can be obtained by,

$$\bar{T}(x, y, z) = 1/N \sum_{n=1}^N T(x, y, z, t_n) \quad (N = 156) \quad (1)$$

$$\bar{S}(x, y, z) = 1/N \sum_{n=1}^N S(x, y, z, t_n) \quad (N = 156). \quad (2)$$

The annual harmonics of sea temperature and salinity with a periodicity of $P = 12$ months for a given layer can also be derived through Fourier decomposition of the time series $T(x, y, z, t)$ and $S(x, y, z, t)$ at each grid point (x, y) of depth z ,

$$T(x, y, z, t) = A_T(x, y, z) \times \cos \left[(2\pi t/P + \phi_T(x, y, z)) \right] \quad (3)$$

$$S(x, y, z, t) = A_S(x, y, z) \times \cos \left[(2\pi t/P + \phi_S(x, y, z)) \right], \quad (4)$$

where A_T and A_S are the amplitudes of the annual component, ϕ_T and ϕ_S are the phase angles which determine the time when the maximum of the annual harmonic occurs, while t varies from 0 to 156 months for the present Argo dataset. The fact that the Argo array density is considered non-optimal until 2007 will not significantly affect the result of this analysis since we are focusing on the annual cycles, and according to the Nyquist criterion, the time series of over-7-year densely distributed data are long enough for resolving the T/S variability on seasonal timescales. Given a complete spatiotemporal dataset $T(x, y, z, t)$ for temperature and $S(x, y, z, t)$ for salinity, $A_T(x, y, z)$ and $\phi_T(x, y, z)$, and $A_S(x, y, z)$ and $\phi_S(x, y, z)$ can be simultaneously retrieved and are supposed to carry full information of annual T/S variability in terms of amplitude and phase for the global upper ocean.

3 The global T – S correlation

The climatology and variability of the upper ocean temperature and salinity have been respectively investigated in our recent studies (Chen and Wang 2016; Chen et al. 2017). As a quantitative measure of the temperature-salinity coherency, the point-wise correlation field is computed here using the 13-year monthly time series, and the globally averaged T/S correlation coefficient as a function of depth is shown in Fig. 1. The geographical distributions at selected depths are shown in Fig. 2a–c, representing the mixed layer zone (MLZ, 0–100 m), the pycnocline zone (PCZ, 100–1000 m), and the intermediate zone (IMZ, 1000–2000 m), respectively. As far as the vertical structure of the T/S relationship is concerned, the overall correlation increases from roughly zero at the sea surface to nearly 0.7 at the depth of 300 m

Fig. 1 Globally averaged temperature-salinity correlations (thick black line) and their corresponding standard deviations (red dashed line) as a function of depth for 2004–2016 derived from Argo data. The SODA based correlation (green dashed line for 1980–2000, and blue dashed line for 2004–2015) is also overlaid for comparison. The horizontal line depicts a zero correlation. The grey vertical lines indicate the boundaries of the MLZ (0–100 m), the PCZ (100–1000 m) and the IMZ (1000–2000 m)

before a quick drop to a minimum value of -0.19 at 1400 m (Fig. 1), suggesting that the pycnoclines between the mixed layers and the intermediate waters are places where the most coherent T/S variations corresponding to a maximum density compensation are found. The standard deviations of the T/S correlation are overlaid on Fig. 1 (the red dashed line) where a distinct trough corresponds to the correlation peak is observed, confirming the validity of the T/S correlation maximum. This is a somewhat unexpected result which is against the common speculation that a stable temperature-salinity relationship might exist in most areas towards the ~ 2000 m Argo profiling limit—an important consideration for the validation of salinity sensor calibrations (Gould and Turton 2006).

Inspection of the geographical distributions of $T-S$ correlation coefficients reveals that each of the three characteristic zones has its own unique pattern. The MLZ appears as meridionally alternating strips of highs and lows (largely consistent with the spatial pattern of salinity climatology within this zone, see Fig. 3f below), but correlations exceeding ± 0.8 are rarely observed due to the tremendous influences of the atmosphere which decouple the original $T-S$ relations (Fig. 2a). In contrast, the PCZ is dominated by ocean-wide coherent patterns with a majority of the

correlations exceeding 0.9 (Fig. 2b). Since many dynamic events and processes (such as basin scale circulations and mesoscale eddies that will be discussed in Sect. 4) can acquire and maintain inherent density-compensated water masses in their entire lifetimes, it is not surprising to see extremely high $T-S$ correlations throughout the pycnocline layer of ~ 100 – 1000 m where ocean dynamics are most active and intense. Areas of relatively low correlations mainly exist near the edges of the Pacific subtropical gyres where the circulating currents are weakening, and in the Southern Ocean where the core of the deep water flow as part of the great ocean conveyor belt are far below 300 m (Sloyan and Rintoul 2001). In the IMZ, the correlation pattern is regionally divided: large positive correlations are found in most areas of the North Atlantic, and in the northern and southern Indian Ocean; large negative values are observed in the northwestern and southwestern parts of the Pacific Ocean, while most of its subtropical areas are basically uncorrelated (Fig. 2c). Note that the dominant dynamics at this depth is the sinking of North Atlantic Deep Water (NADW) in the Norwegian Sea, and the distributed upwellings in the North Indian and Pacific Oceans which balance the NADW generation, as well as the recooling of water along the perimeter of the Antarctic Continent. The

Fig. 2 Global distributions of ocean temperature-salinity correlation for 2004–2016 derived from Argo data at selected depths: **a** 10 m, **b** 300 m, and **c** 1400 m

three distinct patterns in Fig. 2 are found to be largely representative of their respective zones. Given the new results presented here, it is argued that the pycnocline zone around 300 m in the Atlantic Ocean between 40°S and 40°N might be one of the ideal places for the calibrations/validation of salinity sensors.

4 T–S relationship in climatology

Figure 3 shows the decadal temperature/salinity climatologies of the global ocean for 2004–2016 at selected depths from 0 to 1775 m. Such collocated climatologies with superior geographical and vertical homogeneities were simply unthinkable in the pre-Argo era until early this century. Going through all panels in the two columns, one finds a marked evolution of each climatology as a function of depth, as well as a complex relationship between the two climatologies at corresponding layers.

The depth of pycnocline below the mixed layer is geographically dependent in the global ocean, varying

diurnally and seasonally from tens of meters to hundreds of meters (Talley et al. 2011). The pycnocline zone defined as ~100–1000 m for our purpose is likely to penetrate the thickest seasonal mixed layer in the global oceans (Chen and Yu 2015). The most striking feature in the PCZ is the “unification” of *T/S* climatological patterns in form of six warm/salty pools with a clear west preference (Fig. 3c, h). The evolution of the temperature climatology with depth appears as a splitting process: each of the three warm pools under the MLZ mode breaks into two parts and relocates at subtropical latitudes of the two hemispheres in the three ocean basins (Fig. 3a–c), while that of the salinity climatology appears as a straightforward migration of its six salty pools towards the west (Fig. 3f–h). The strengths of the gradually collocating *T/S* maxima show a tendency of decrease with respect to depth, especially in the Pacific Ocean. It should be stressed that the spatial patterns of *T/S* climatologies reach an excellent similarity when the correlation of their time series peaks at ~300 m, and we thus call this depth a “mirror layer” where ocean temperature and salinity have an extremely high correspondence

Fig. 3 Global distributions of ocean temperature (left column) and salinity (right column) climatologies for 2004–2016 derived from Argo data at selected depths: **a, f** 5 m, **b, g** 100 m, **c, h** 300 m, **d, i** 1000 m, and **e, j** 1975 m. Note the “mirror” effect between (c) and (h)

in terms of their distribution and variation. As listed in Table 1, the corresponding centroids of the six pairs of unified warm and salty pools are in good agreement with each other: four of them are deviated within 3° of longitude/latitude, and the other two are displaced by 5° and 7° in longitude while 2° and 1° in latitude, respectively.

Next, we explore the possible mechanism for the observed T/S climatology “unification”. It is understood that direct atmospheric forcing is vanishing near the upper boundary of the pycnocline. Instead, dominant driving factors are replaced by large-scale ocean circulations and mesoscale eddies for both temperature and salinity distributions

Table 1 Centroids of the six pairs of unified warm and salty pools at the “mirror layer” of 300 m depth

Pool type	N. Atlantic	S. Atlantic	N. Pacific	S. Pacific	N. Indian	S. Indian
Warm	(289°E, 31°N)	(312°E, 30°S)	(135°E, 30°N)	(153°E, 20°S)	(60°E, 24°N)	(67°E, 21°S)
Salty	(292°E, 34°N)	(310°E, 32°S)	(135°E, 30°N)	(158°E, 22°S)	(60°E, 24°N)	(75°E, 20°S)
Deviation	(-3° E, -3° N)	(2° E, -2° S)	(0° E, 0° N)	(-5° E, -2° S)	(0° E, 0° N)	(-7° E, 1° S)

within the 100–1000 m zone. Under the long-term persistent actions of these unified forcings, it is natural to see a closely coupled pattern of the T/S climatologies given their density compensation effect. Apparently, the six warm/salty pools in the PCZ coincides well with the six subtropical gyres led by the energetic western boundary currents of the Gulf Stream and the Brazil Current in the Atlantic, the Kuroshio and the East Australia Current in the Pacific, and the Agulhas and Mozambique Currents in the Indian Ocean as represented by the surface dynamic topography derived from a combination of satellite and drifter data in Fig. 4a (reproduced from Fig. 1c of Maximenko et al. 2009). The westward intensifications of both the driving gyres and the responding T/S climatological pools are in good agreement, suggesting that global circulation is the determinant factor for shaping the spatial patterns of T/S climatologies in the PCZ. The general features in Fig. 3b, c are also in qualitative agreement with the heat transport distributions estimated using hydrographic data [see, e.g., Fig. 2 of Macdonald and Wunsch (1996), and Fig. 1 of Ganachaud and Wunsch (2000)].

Furthermore, according to existing literature, the PCZ is supposed to dominate by thousands of nonlinear eddies (Chelton et al. 2011), since the typical vertical range of a mesoscale eddy can reach ~1000–1500 m (Zhang et al. 2013) with a core depth of ~200–400 m (corresponding to the maximum salinity anomaly which represents the core depths of the trapped eddies, see Fig. 2 in Dong et al. 2014). The propagation directions of the observed eddies by satellite altimetry are nearly due west. In fact, of the eddies that

propagated zonally by more than 10° of longitude, only 16% had azimuths that deviated by more than 15° from due west (Chelton et al. 2011). Climatologically, the accumulating effect is evidenced in Fig. 4b where the mean amplitude of mesoscale eddies exhibits a nice correspondence to the “pool” dominated pattern in Fig. 3c, h. As systematic eddy propagation can transport water parcels and their associated physical, chemical and biological properties, the resulting westward intensification of the T/S climatologies can thus be well expected. This argument is further supported by the recent finding of Zhang et al. (2014) that the eddy-induced zonal mass transport can reach a total meridionally integrated value of up to 30–40 Sv, and it occurs mainly in subtropical regions. This transport of heat and salt is comparable in magnitude to that of the large-scale wind- and thermohaline-driven circulation. As a result, the joint effects of the climatological ocean circulations which transport salt as a conveyor belt with westward intensification, and numerous migrating mesoscale eddies which transport salt parcels discretely towards due west are likely to be responsible together for the unified pattern of T/S climatologies at the “mirror layer” in the PCZ (Fig. 3c, h).

5 T–S relationship in seasonality

We first try to examine the penetrative behavior of seasonal signals into the upper ocean. Figure 5 shows the layer-averaged period-depth diagrams of recovered amplitude of

Fig. 4 **a** Gyre-related dynamic topography (sea level anomaly), and **b** eddy-induced surface elevation (mean amplitude) in the global ocean. **a** is reproduced from Fig. 1c in Maximenko et al. (2009); **b** is derived from Argo data for the period 2004–2016 using the methodology described in Liu et al. (2016)

Fig. 5 Period-depth diagram of layer-integrated spectrum of **a** ocean temperature and **b** salinity variabilities for the broad seasonal band derived from Argo data of 2004–2016. The color scales depict the

globally averaged harmonic amplitudes of each depth layer for the corresponding variables

temperature and salinity variabilities for the broad annual band. It is obvious that a three-mode structure centered at 4, 6 and 12 months can be identified for both variables throughout the upper global ocean, confirming previous findings that significant temperature variations exist below the thermocline on timescales ranging from intraseasonal (Matthews et al. 2007) to annual (Hosoda et al. 2006). As expected, the seasonal variations of temperature and salinity are dominated by the annual component, followed by the semiannual and intraseasonal components. The annual amplitudes of both variables decrease exponentially as a function of depth. Surprisingly to some extent, not only the annual signals but also the semiannual and even the intraseasonal signals can effectively reach a depth of ~ 2000 m.

The geographical distributions of annual temperature and salinity amplitudes at selected depths are shown in the left and right columns of Fig. 6, respectively. A gradual downward decrease in the strength of both variables is clearly evident (note the specific color bars for different panels in Fig. 6), which is in general agreement with Fig. 5. The dissimilarity of major features at different depths within each column suggests that the transformation of seasonality from the sea surface to the intermediate water is also highly nonlinear and inhomogeneous. In other words, the causes of the seasonal variability in the ocean are also layer dependent, there is no single dominant factor which controls the oceanic annual cycles, especially for temperature. However, the eminent spatial coherence between temperature and salinity reappears in the annual amplitudes at the “mirror layer” (Fig. 6c, h) as we have seen in the climatology maps (see

Fig. 3c, h), implying that density compensation occurs systematically not only in the space domain, but also in the time domain, at least on seasonal timescales.

The overall influence of the solar penetration is seen to almost terminate at 100 m depth (Fig. 6b). In fact, the most significant signatures of seasonal variability are shifted to the tropical oceans as well as the Kuroshio, the Gulf Stream and the Antarctic Circumpolar Current (ACC) regions for the depths between 80 m and 300 m. In Fig. 6b, c, a three-strip zonal feature centered respectively around 13°N , 5°N and 7°S exists in the equatorial Pacific, climbing from a 200 to an 80 m depth while migrating from western to eastern Pacific. Judging from their spatial trajectories, the origins of these features are likely to be linked to the equatorial current system. As labelled in Fig. 6b, c, possible contributors are the South Equatorial Current/North Equatorial Current and their branches, and the Equatorial Countercurrent and Equatorial Undercurrent of the three ocean basins whose pathway cores are mostly located between 100 and 400 m (e.g., Meyers 1975; Wyrski and Kilonsky 1984; Richardson and Walsh 1986; Izumo 2005; Urbano et al. 2008), as well as the Indian Monsoon Current and the Equatorial Jet unique to the Indian Ocean (e.g., Reppin et al. 1999).

6 Discussion

It is desirable to examine the robustness of the identified “mirror layer” using an independent oceanic climatological dataset. One such possibility is the SODA (Simple Ocean

Fig. 6 Global distributions of annual amplitude of ocean temperature (left column) and salinity (right column) variabilities for 2004–2016 derived from Argo data at selected depths: **a, f** 5 m, **b, g** 100 m,

c, h 300 m, **d, i** 1000 m, and **e, j** 1975 m. Note the “mirror” effect between (c) and (h)

Data Assimilation) reanalysis data which is basically a model forecast produced by an ocean general circulation model with an average resolution of $0.25^\circ \times 0.4^\circ \times 40$ levels, and is continuously corrected by contemporaneous observations every 10 days (Carton and Giese 2008). Since Argo data have been assimilated into SODA product after 2001, the SODA layer-averaged T/S correlations for pre-Argo (1980–2000, the green dashed line) and Argo (2004–2015, the blue dashed line) periods are overlaid on Fig. 1 for comparison. Note that the green curve and blue curve are considered as fully and partially independent of the black one, respectively. Obviously, the SODA- and Argo-based

correlation patterns are in good agreement with a slight shift in their peaking depths (330 and 285 versus 300 m), confirming that the “mirror layer” of temperature and salinity is a robust finding near the pycnocline of the subsurface ocean.

Furthermore, an empirical orthogonal function (EOF) analysis is performed for both temperature and salinity of the “mirror layer” at 300 m depth, the spatial and temporal patterns of which are shown in Figs. 7 and 8, respectively. Note that a monthly mean is first subtracted from the detrended temperature and salinity data so that the seasonal variations have been removed. Since the first three modes explain respectively 54.0 and 52.6% of the total

Fig. 7 Spatial patterns of EOF Modes 1–3 (top to bottom) at 300 m depth derived from Argo based temperature (left column) and salinity (right column) data for 2004–2016. Fractions of variances explained by each mode are indicated on respective panels

variances for temperature and salinity, the corresponding degree of spatiotemporal coherency determines to a large extent the T/S similarity in general. In the space domain, a general similarity can be found between corresponding modes of T and S . Relative large values (both positive and negative) are observed in the western tropical Pacific and the Brazil Current/Malvinas Current region (Fig. 7b, e). In the time domain, the T/S time series are found to be highly consistent: All three modes display a large interannual variability on top of irregular yet significant seasonal cycles (Fig. 8). Moreover, the geographical distributions of T/S correlation between corresponding principle modes are shown in Fig. 9. It confirms that the “mirror effect” generally holds for the three principle modes (except for a few small areas in blue) given the overall correlation of 0.838, 0.726, and 0.823 for EOF-1, 2, and 3, respectively. As a combined result, it can be concluded that temperature and salinity vary coherently within the “mirror layer” on major spatiotemporal scales.

At this point, it should be emphasized that the globally averaged T - S correlations for the 13-year time series as well as the spatial similarities of climatology and annual amplitude all peak around 300 m depth (Figs. 1, 3c, h, 5c, h), implying that this might be the zone where most intensive density-based thermohaline compensation takes place in the upper ocean. The basic concept is straightforward: temperature and salinity are dynamically active because they contribute to density gradients, i.e., temperature and salinity gradients tend to be parallel and to cancel each other in their effect on density via stirring and diffusion (Ferrari and Paparella 2003). Because density compensation requires the equality $\Delta T/\Delta S = \beta_s/\alpha$ to hold along mean trajectories, the ratio $\Delta T/\Delta S$ may potentially undergo large amplitude variations if the ratio β_s/α does, where α and β_s are the thermal expansion and haline contraction coefficients, respectively (Tailleux et al. 2005). Most of the previous observations on T - S relations are limited to the mixed layer in the context of oceanic fronts with horizontal scales of tens to hundreds of kilometers (e.g., Rudnick and Ferrari 1999;

Fig. 8 Time series of EOF Modes 1–3 (top to bottom) at 300 m depth derived from Argo based temperature (red) and salinity (blue) data for 2004–2016

Rudnick and Martin 2002). In fact, all processes that depend on density gradients are potentially capable of creating T – S relations by acting only on fluctuations of temperature and salinity that reinforce their joint effect on salinity. Our investigation extends previous findings from the mixed layer to the entire upper ocean, and from the space domain to the time domain, i.e., the temporal evolution of density-compensated T – S relation is also a commonplace at given locations. More importantly, we identify that it is in the pycnocline zone rather

than the previously thought mixed layer where the best thermohaline compensation is maintained.

7 Summary and concluding remarks

The climatological patterns of the T/S distributions in the MLZ are primarily controlled by atmospheric forcings, although some secondary modulations from the subsurface

Fig. 9 Global distributions of ocean temperature-salinity correlation for respective principle modes at 300 m depth derived from Argo data of 2004–2016. **a** EOF-1, **b** EOF-2, and **c** EOF-3

ocean are also evident. Given the fundamentally different forcing mechanisms (solar radiation versus net water flux), the temperature and salinity climatologies appear to be entirely dissimilar in their geographical patterns within the seasonal mixed layer: three equatorial warm pools versus six subtropical salty pools (see Fig. 3a, f). For the same reasons, the T/S annual amplitudes are also geographically uncorrelated with a midlatitude and tropical dominance, respectively (Fig. 6a, f).

In the PCZ below the MLZ, the T/S climatologies become geographically correlated, having a unified pattern of six well-defined subtropical warm/salty pools with collocated centroids and a clear west preference. The dramatic transformation from a total dissimilarity in the MIZ to a gradual resemblance in the PCZ is attributable to the shifts of major forcings from the atmosphere to the ocean. The spatial patterns of both temperature and salinity climatologies in the PCZ are jointly determined by the large-scale ocean circulations and mesoscale eddies sharing the same prominent characteristic of westward intensification (Fig. 3c, h). Similarly, the subtropical gyres, equatorial currents, as well as the

ACC are responsible for the covariations of T/S on seasonal time scales (Fig. 6c, h). As a combined result, an ocean-wide “mirror layer” of temperature and salinity is formed near the upper boundary of the pycnocline which may serve as an ideal location for salinity sensor calibration/validation. The robustness of this finding is confirmed by an independent SODA dataset, and is supported by an EOF analysis of their spatiotemporal variabilities.

Further downward in the IMZ, the influences of mesoscale eddies and western boundary currents are largely blocked by the pycnocline, and the governing dynamic process is found to be the meridional overturning circulation (MOC). The North Atlantic is known to be the most intensive part of the MOC system, which is confirmed in our result as a collocated single marked warm/salty pool with an eastern intensification (Fig. 3d, e, i and j). In addition, the β -refracted annual Rossby waves are thought to play an important role in the tropical dynamics of this zone, but whose signatures are only identifiable on the phase maps due to the absence of heat and salt transport for wave propagation [see Fig. 4 of Chen and Wang (2016) and Fig. 9 of Chen

et al. (2017)]. Instead, regions of active density compensation are detected in both northern Atlantic and the Southern Ocean below the ACC which support the MOC dominance within this zone.

In the complex cascades of the *T/S* climatologies from the MLZ to the PCZ and the IMZ, the layered geographical patterns are always characterized by various distinct warm/salty pools regulated by a number of persistent atmospheric and oceanic forcings, notably evaporation, precipitation, mesoscale eddy, western boundary current, and meridional overturning circulation. As a combined effect of these dynamics processes, our results demonstrate that the density compensation of temperature and salinity in the joint spatiotemporal domain is in fact a global feature which is best held as a maximum *T-S* coupling in the “mirror layer” of the pycnocline zone.

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