

Key Points:

- Mixed-layer cooling, despite air-to-sea heat flux, occurs in the central Arabian Sea during the boreal summer months
- Ocean processes including entrainment at the mixed layer base accounts for its summer cooling
- Upper ocean salinification, controlled partly by freshwater loss across the air-sea interface, accompanies the cooling

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Evolution of the Central Arabian Sea Summer Mixed Layer

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Abstract The northern embayments of the Indian Ocean are substantially influenced by the South Asian monsoon. An analysis utilizing Argo temperature and salinity profiles acquired between 2004 and 2021 within the central Arabian Sea (8°N–16°N, 61°E–69°E) reveals an average reduction in surface mixed layer temperature from 29.3°C in June to 27.7°C in September. The cooling coincides with a deepening of the mixed layer by approximately 35 m during the summer months. Mixed layer thickening, coupled with a deepening of the pycnocline, contributes to the development of a regional geostrophic anticyclonic gyre during the summer monsoon. Ekman convergence within the central Arabian Sea is responsible for about three-fifths of the observed mixed layer deepening. The heat content in the surface mixed layer decreases by -0.25×10^{21} J throughout the summer, despite a net heat gain of 0.51×10^{21} J from the air-to-sea heat flux. Meridional heat flux divergence and the entrainment of cooler thermocline water account for 66% of the mixed layer cooling, with the residual cooling might be partly attributed to turbulent diffusion. An increase in salinity, partly due to freshwater loss through the air-sea interface, accompanies the mixed layer cooling.

Plain Language Summary Physical processes responsible for ocean temperature variability in the surface mixed layer of the central Arabian Sea during the Southwest Monsoon period from June to September are assessed using multi-year Argo float-derived hydrographic data and ocean and atmosphere reanalysis products from 2004 to 2021. Our analysis indicates that the mixed layer loses heat by -0.25×10^{21} J despite air-sea warming of 0.51×10^{21} J during the summer monsoon. We propose that the mixed layer heat loss is attributed to entrainment of cooler deep water into shallower layers, wind-driven heat divergence, and potentially turbulent heat flux. The cooling in the upper layer is concurrent with increased salinity that is partly attributable to the sea-to-air freshwater flux, as well as ocean processes.

1. Introduction and Objectives

The Indian Ocean stands out as a distinct ocean basin, truncated in the northern hemisphere by the vast Asian continent. The resulting strong monsoonal climate induces a unique pattern of circulation and air-sea fluxes across the tropical Indian Ocean (Phillips et al., 2021; Schott et al., 2009; Schott & McCreary Jr, 2001; Shee et al., 2023), including the sharply contrasting oceanography of the two embayments on either side of India: the relatively high sea surface salinity (SSS) of the Arabian Sea and fresher SSS of the Bay of Bengal (Gordon et al., 2019; Prasad, 2004; Prasanna Kumar et al., 2002; Shenoi et al., 2002). The two embayments exchange water masses around the southern tip of India, which act to limit their SSS contrast (Rainville et al., 2022). Additionally, the Indonesian throughflow drawn from the tropical Pacific Ocean, via the varied passageways of the Maritime Continent, spreads westward across the tropical Indian Ocean thermocline within the Southern Equatorial Current near $\sim 10^{\circ}\text{S}$ – 15°S (Gordon et al., 1997), separating the two embayments from the more traditional subtropical gyre of the southern Indian Ocean.

The Arabian Sea, the northwestern Indian Ocean embayment, displays strong seasonality in circulation and stratification due to monsoonal winds (Beal et al., 2013; Düing & Leetmaa, 1980; Shenoi et al., 2002; Talley et al., 2011). During the Southwest Monsoon months from June to September, a low-pressure system is established over the South Asian continent, resulting in strong summer monsoonal winds of up to 30 ms^{-1} that bring warm and humid maritime air to the continent (Wilson-Diaz et al., 2009). The Southwest Monsoon winds directed towards the northeast produce Ekman upwelling, resulting in relatively cool sea surface temperature (SST) along the Arabian Sea's Oman and Somalia margins (Figure 1; Shi et al., 2000; Wiggert et al., 2005).

The summer monsoon winds spin up a regional clockwise, anticyclonic, circulation gyre (Schott et al., 2009), with eddies and filaments of coastal water extending eastward from the Omani coast, associated with irregularities

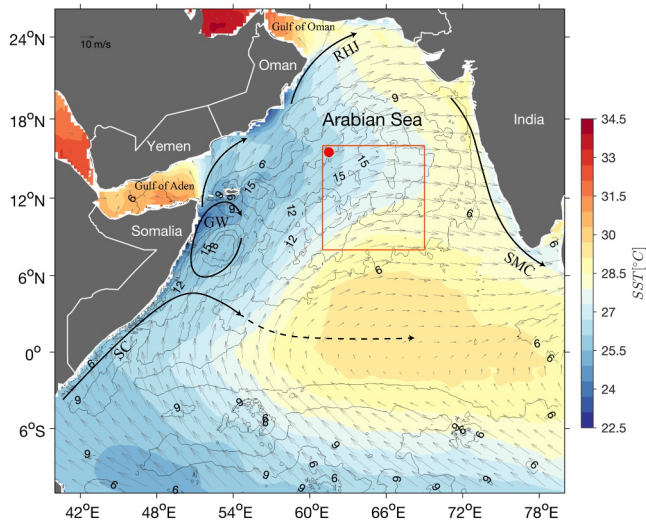


Figure 1. Average Sea Surface Temperature (SST; color pattern) and wind vectors at 10 m (gray arrows) in September, based on the SST and wind data from 2004 to 2021. The red box is the region of the Argo profiles shown in Figure 5 and the area in which the Ekman convergence and heat fluxes are calculated. The contours mark the standard deviation of the mixed layer depth. The black arrows denote major surface circulations during the Southwest Monsoon in the Arabian Sea, which include the Somali Current (SC), Great Whirl (GW), Ras al Hadd Jet (RHJ), and Southwest Monsoon Current [SMC]. The red circle marks the surface mooring operational during October 1994–October 1995, measuring near surface atmospheric parameters, including air-sea heat fluxes, and oceanic parameters, as reported by Weller et al. (2002).

of the coastline (Lee et al., 2000; Shi et al., 2000). Moreover, the Somali Current along the western boundary, the Great Whirl anticyclone, the Ras al Had Jet in the Northern Arabian Sea, and the Southwest Monsoon Current along the eastern boundary are the major Southwest Monsoon circulations in the Arabian Sea (Figure 1; Schott & McCreary Jr, 2001).

In contrast, cold and dense air over the Asian continent during boreal winter facilitates the monsoonal reversal (the Northeast Monsoon) that induces downwelling along the western margin and a regional counterclockwise gyre, though less of a well-defined gyre than that of the summer (Schott et al., 2009). During the Northeast Monsoon, the surface Somali Current reverses to flow southwestward along the western boundary, and the Great Whirl collapses (Beal & Donohue, 2013; Wirth et al., 2002). Likewise, the southeastward current turns to the northwestward-flowing Northeast Monsoon Current along the eastern boundary (Shankar et al., 2002).

The Arabian Sea's surface mixed layer displays seasonal and semiannual variations, particularly in the central basin where they are among the largest in the tropical Indian Ocean (Rao, 1988). The central Arabian Sea experiences mixed layer deepening during the Southwest Monsoon and, to a lesser extent, Northeast Monsoon (de Boyer Montégut et al., 2004; Levitus, 1982; Levitus & Boyer, 1994). Past studies have presented various primary causes of this mixed layer deepening in the central Arabian Sea, from air-sea heat flux to Ekman dynamics and ocean mixing.

Utilizing meteorological data and temperature [T] and salinity [S] profiles from a stationary ship in the central Arabian Sea during the onset of the Southwest monsoon in 1977 and T profiles from multi-year of conductivity-temperature-depth [CTD] and eXpendable BathyThermograph casts from 1948 to 1981 in the region, Rao (1986) and Rao et al. (1989) suggested that

the air-sea heat loss was the primary cause of the mixed layer temperature cooling and, thus, deepening in the central Arabian Sea during the monsoon onset. However, subsequent studies suggested a different mechanism. Lee et al. (2000), employing T and S profiles from a towed underwater vehicle from December 1994 to October 1995, and Weller et al. (2002), using meteorological data and T , S , and acoustic profiles from several moorings from October 1994 to October 1995, argue that the vertical velocity associated with wind-driven entrainment is the dominant driver of mixed layer deepening. A strong vertical mixing across the mixed layer base has been reported to contribute thermocline warming (Ramesh & Krishnan, 2005).

Numerical experiments underscore the significant role of turbulent mixing in influencing the surface mixed layer in the central Arabian Sea during the Southwest Monsoon. For instance, Prasad (2004) utilized a one-dimensional turbulent closure model to demonstrate that wind-driven vertical mixing is a key factor in deepening the summertime mixed layer. Singh et al. (2019) proposed that the deepening of the mixed layer in the southwest to central Arabian Sea during June–August is influenced by both wind and convective mixing, based on their use of an ocean general circulation model. In contrast, they found that the convective component is the dominant factor in the mixed layer variability observed in the central Arabian Sea from September–November.

Ekman upwelling is another mechanism, along with air-sea heat flux and ocean mixing, that contributes to the mixed layer deepening during the Southwest Monsoon in the Arabian Sea. Studies by Düing and Leetmaa (1980) and Shenoi et al. (2002) generally conclude that Ekman transport perpendicular to the coasts of Somalia and Arabia during the Southwest Monsoon drives the upwelling of the thermocline water across the entire Arabian Sea. The upwelling drives substantial cooling of the upper 50 m of the water column. Furthermore, Kumar and Narvekar (2005) proposed that Ekman dynamics are the primary cause of the summer mixed layer deepening specifically in the central Arabian Sea, within the latitude band of 0°N–25°N and the longitude band of 62°E–66°E.

A better understanding of the underlying physical processes governing surface mixed layer temperature changes in the central Arabian Sea is needed (Ghosh et al., 1978; Mishra et al., 2020).

Utilizing the extensive spatial and temporal coverage of the Argo data (Shee et al., 2023; Wong et al., 2020) as well as relatively high-resolution ocean and atmosphere reanalysis products, we aim to reevaluate the primary processes that alter the surface mixed layer temperature variability in the Arabian Sea during the Southwest Monsoon. The focus is on distinguishing the relative contribution of oceanic processes, such as Ekman dynamics and entrainment, and air-sea exchanges in controlling mainly the heat content [HC] of the surface mixed layer within the central Arabian Sea. The study area, indicated by the red box in Figure 1, is chosen due to its relatively significant mixed layer depth variations. Unlike prior research by Düing and Leetmaa (1980) and Shenoi et al. (2002) encompassing the entire semi-enclosed Arabian Sea, our focus on the central basin utilizes four open boundaries. This approach allows us to quantify heat transport across each boundary, facilitating an assessment of how zonal and meridional advective heat fluxes modulate mixed layer HC variability during the Southwest Monsoon. Section 2 describes the Argo and supporting data, as well as the data analysis. In Section 3, using Argo T and S profiles, we investigate the evolution of the mixed layer thickness and HC and, to a lesser extent, freshwater content [FWC] within the central Arabian Sea within the red box in Figure 1, from its onset of the Southwest Monsoon in June to the mature phase in September. The red box was selected for this study as it shows large surface mixed layer variations. Section 4 discusses the contribution of Ekman transports across the side walls of the box to determine the net Ekman convergences and downwelling within the surface layer. A heat budget analysis is presented in Section 5, followed by conclusions in Section 6.

2. Data and Methods

To elucidate the T and S stratification changes during the Southwest Monsoon in the Arabian Sea, we analyzed 17,979 Argo T and S profiles in the basin from 2004 to 2021, obtained and archived by the International Argo Program, part of the Global Ocean Observing System (Argo, 2000). We focus on conservative T , absolute S , and density [ρ] changes from the monsoon onset month in June to the termination month in September. In addition to the Argo data, we also examined the T and S profiles obtained from R/V Knorr along the I01 W section of the World Ocean Circulation Experiment [WOCE] from August 1995 to October 1995 (Talley, 2013).

We determine changes in the heat and freshwater contents during the Southwest Monsoon. The HC is quantified from multiplying the depth-integrated T from the surface to a specified depth (z), $\langle T \rangle = \int T(x, y, z) dz$, with ρ_0 ($1,022.4 \text{ kg m}^{-3}$) and specific heat capacity c_p ($3,985 \text{ J kg}^{-1} \text{ K}^{-1}$), with x and y denoting respectively the longitude and latitude. Likewise, the FWC in 1 kg of seawater is defined as $\text{FWC} = 1 - S/1000$. We are mainly interested in evaluating the HC and FWC changes within the upper 200 m.

To explore the role of air-sea exchanges and ocean processes in regulating changes mainly in the HC during the Southwest Monsoon, we evaluated a simplified version of surface heat budget within the red box (Figure 1). The simplified surface heat budget terms are as follows:

$$\rho_0 C_p h \frac{\partial T}{\partial t} = (J_0^q - I_{-h}) - \rho_0 C_p h \left(U \nabla \cdot T + \frac{w_e \Delta T}{h} \right) + R, \quad (1)$$

where T and U are respectively vertically averaged temperature and horizontal velocity vector within layer h , ρ_0 is the background seawater density value taken to be $1,022 \text{ kg m}^{-3}$, C_p is the specific seawater heat capacity given as $4,218 \text{ J kg}^{-1} \text{ }^\circ\text{C}^{-1}$, w_e is the entrainment velocity, J_0^q is surface net heat flux, I_{-h} is the fraction of shortwave heat flux penetrating at h , ΔT is the temperature gradient across h (defined here as the difference between the mixed layer T and the depth-averaged T 10 m below h), and t is time. The entrainment velocity is determined using $w_e = \frac{\partial h}{\partial t} + \nabla \times \frac{\tau}{\rho_0 f}$ (Carranza & Gille, 2015; De Szoeke, 1980), where τ is wind stress and f is the Coriolis parameter. R is the residual representing the terms unaccounted for in Equation 1 and the observational and model biases.

As for salinity (freshwater content), we assess the contribution of the air-sea freshwater flux to the FWC change in the mixed layer thickness, h . We examined a simplified version of the salinity budget for the vertically integrated salinity balance within h , which can be expressed as:

$$\int_{-h}^0 \frac{\partial S}{\partial t} dz = -S_0(P - E) + R, \quad (2)$$

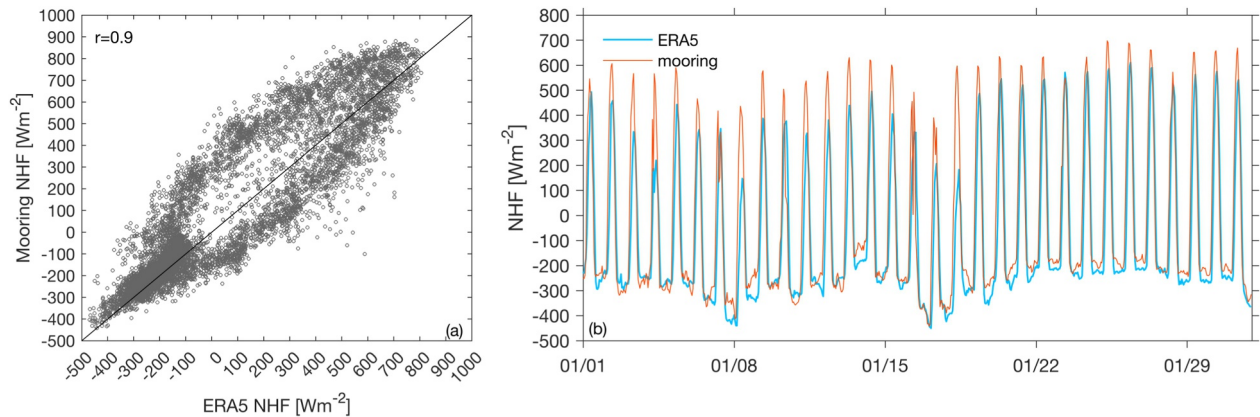


Figure 2. (a) The hourly ERA5 NHF data versus the hourly mooring NHF data at 15°N and 61°E at the central Arabian Sea during 16 October 1994–19 October 1995. (b) Time series of a subset of the ERA5 and mooring NHF data in January 1995.

where the first term on the right-hand side indicates air-sea freshwater flux, with S_0 , p and E denoting sea surface salinity, precipitation, and evaporation, respectively. Like for (Equation 1), R is the residual term. The salinity budget within the red box in Figure 1 was investigated. Results from a salinity budget analysis, which takes into account the horizontal advective salinity flux, the divergence of stratified shear eddy flux, and the entrainment terms, will be reported in a separate study.

To estimate air-sea heat exchange, we used surface latent heat flux [LHF], sensible heat flux [SHF], shortwave radiation [SWR], longwave radiation [LWR], data sets from the European Center for Medium-range Weather Forecast reanalysis v5 [ERA5] product (Hersbach et al., 2020). The net heat flux [NHF] is the summation of radiative heat fluxes (SWR and LWR) and turbulent heat fluxes (LHF and SHF). Relative to the observed NHF values from the surface mooring at 15°N and 61°E operational during, the hourly ERA5 values compare reasonably with a correlation coefficient $r = 0.9$ (Figure 2).

In addition to the heat fluxes, we use P and E rates from ERA5 to estimate the air-sea freshwater flux. Moreover, we also analyzed the ERA5 wind velocities at 10 m above the surface, with u_w and v_w denoting the zonal and meridional winds, respectively. Based on u_w and v_w , we determined the zonal wind stress (τ^x) and meridional wind stress (τ^y) by using $\tau^x = \rho_a C_d u_w \sqrt{(u_w^2 + v_w^2)}$ and $\tau^y = \rho_a C_d v_w \sqrt{(u_w^2 + v_w^2)}$, with ρ_a and C_d denoting the air density ($\rho_a = 1.2 \text{ kg/m}^3$) and the drag coefficient ($C_d = 0.0013$). The ERA5 reanalysis data are available on a $0.25^\circ \times 0.25^\circ$ grid, hourly interval, and span the period 1979-present. For the rest of the analysis, we analyzed monthly averages of the data, to correspond with the ocean reanalysis data described below, from 2004 to 2021, concurrent with the timeframe of the Argo data.

The advective heat flux associated with ocean processes across each side of the red box (Figure 1) is calculated from ocean currents and T and S profiles for the upper 300 m from the Global Ocean Physics Reanalysis [GLORYS] reanalysis data available at $1/12^\circ$ horizontal and daily temporal resolutions from 1993 to present (Jean-Michel et al., 2021). The GLORYS reanalysis data are at discrete depths, with the vertical resolution of the data being higher in the upper 100 m than below. For the present study, we analyzed the monthly averages of the reanalysis data from 2004 to 2021 to match the timeframe of the Argo data. The T and S data from GLORYS and Argo are in reasonable agreement in the central Arabian Sea, which is discussed in Section 3.

3. Contrasting June and September Stratification

Argo profiles within the central Arabian Sea demonstrate a shift in the spatial pattern of the surface mixed layer base from the onset of the summer monsoon in June to the mature phase at the end of September. The upper layer T exceeding 26°C is more centralized within the Arabian Sea in September compared to June, reflecting the evolution of the summer monsoon's influence (Figure 3; left panels). In June, 147 Argo profiles recorded temperatures at 80 m warmer than 26°C within the defined red box shown in Figure 3. This number decreased to 131 profiles in September. Air-sea heat flux-induced ocean warming accompanies the upper layer T throughout most

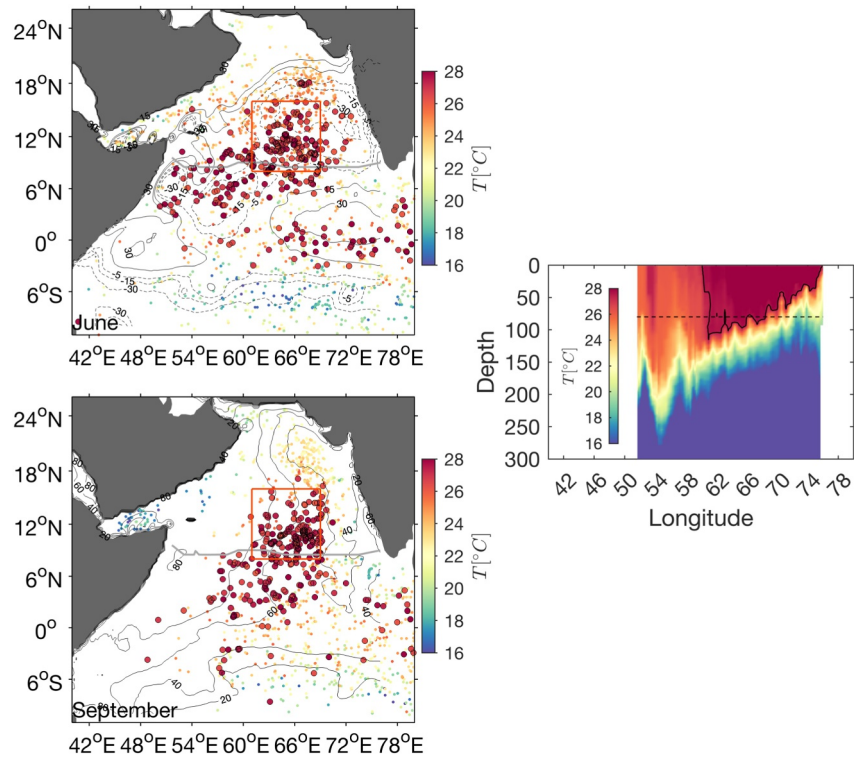


Figure 3. (Left) The temperature [T] at 80 m, as observed by Argo floats, within the central Arabian Sea in June (top left) and September (bottom left). (Right) The WOCE T along the 101°W section (marked by the gray lines in the left panels) was obtained from 12 September 1995 to 13 October 1995. The black circled symbols and the contours in the left panels indicate the T above 26°C and the surface net heat flux (solid contours for positive values and dashed contours for negative values). The contour and horizontal dashed line on the right panel marks the isotherm of 26°C and the 80 m depth, respectively. The red box is the region of the Argo profiles shown in Figure 5.

of the summer monsoon. Whereas the central Arabian Sea experiences a net heat loss to the atmosphere, averaging 18 W m^{-2} , in June (within the red box in Figure 3), it gains heat from the surface by 48 W m^{-2} in September.

Upwelling is most intense along the Yemen and Oman coasts in July and August (Wilson-Diaz et al., 2009), reducing upper layer temperatures to below 18°C. The relatively cool summer coastal surface water persists in September and is well resolved by Argo floats (Figure 3; bottom left panel). The two-dimensional spatial structure of the T obtained from the WOCE hydrographic survey in September–October 1995 along the 101°W line (gray line in the left panels of Figure 3) captured the warm layer in the upper 100 m within the central Arabian Sea, consistent with the Argo T profiles (Figure 3; right panel).

The distribution of the relative salty surface water values tends to spread southward in September relative to June (Figure 4, left panels), which may be induced by the spin-up of the clockwise circulation during the summer monsoon. High-salinity water ($S > 36.4 \text{ PSU}$) in the upper 100 m, concurrent with the warm layer shown in Figure 3, characterizes the central Arabian Sea, as evidenced in the data from the Argo floats and the WOCE cruise (Figure 4). The central Arabian Sea salinification is consistent with net air-sea freshwater loss, as the evaporation rate exceeds the precipitation rate. The $P-E$ rate averaged within the red box shown in Figure 4 (left panel) and averaged throughout the monsoon is about -2.4 mm day^{-1} .

The T , S , and σ_0 profiles, averaged within the red box in Figure 1, from the sea surface to 200 m in the central Arabian Sea indicate surface mixed layer thickening from June through September (Figures 5a–5c and 5f–h). Following Holte and Talley (2009), we determined the surface mixed layer base, hereafter referred to as the mixed layer depth [MLD], as the depth at which

$$\frac{\sigma_{0i} - \sigma_{0i+1}}{p_i - p_{i+1}} > 5 \times 10^{-3} \text{ kg m}^{-3} \text{ dbar}^{-1}, \quad (3)$$

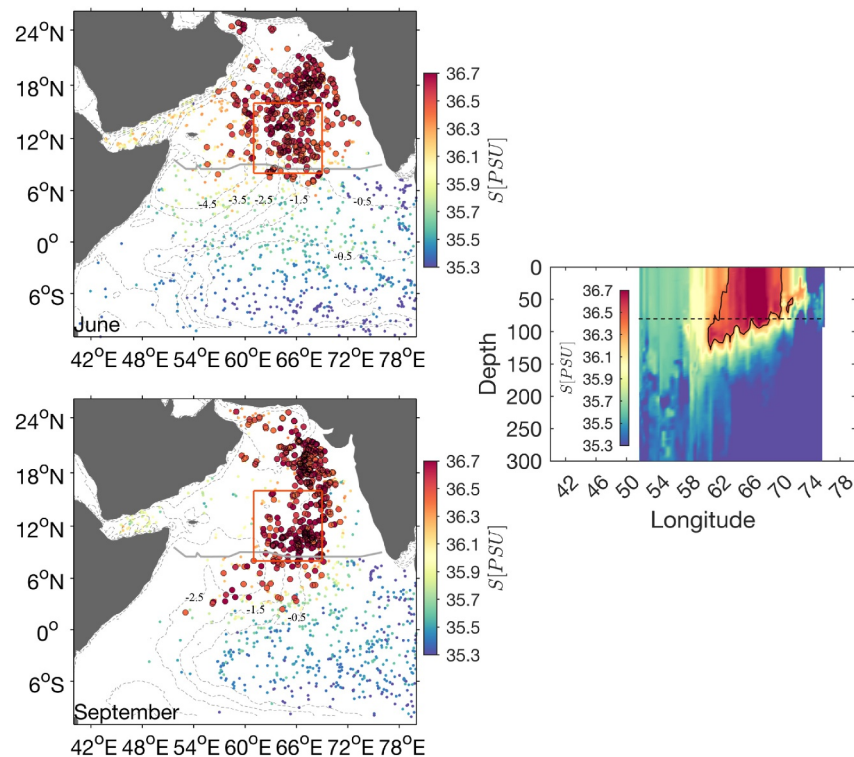


Figure 4. As in Figure 3, but for Salinity [S]. The black circles in the left panels and the black contour on the right mark the S values above 36.4 PSU. The dashed contours and the gray lines in the left panels indicate the difference between precipitation (P) and evaporation (E) [P-E] rates and the WOCE I01 W section. The unit of P-E is mm/day. The red box is the region of the Argo profiles shown in Figure 5.

where p is pressure and i is the depth of measurement index from the surface to one level above the maximum observational depth.

Based on the MLD criterion given above, we find that the average MLD in the central Arabian Sea in June is ~ 20 m (Figure 5c), with a wide range of salinity values, whereas it is ~ 55 m in September (Figure 5h). During the summer monsoon the surface mixed layer thickens by ~ 35 m, which is within the error limits of the mixed layer progressive thickening throughout the summer monsoon months in the central Arabian Sea, inferred from historical XBT and Nansen data and reported by Rao (1988). The central Arabian Sea MLD is deepest in August (Figure 6a).

As the summer monsoon progresses, the surface mixed layer loses heat and becomes saltier (Figures 6b and 6c), likely due to evaporative cooling and as evaporation exceeding precipitation, respectively and due to the entrainment of colder and more saline upper pycnocline water into the mixed layer. Evaporative freshwater loss may also explain the increase in the mixed layer salinity (Prasad & Ikeda, 2002). The mean mixed layer T and S values change from 29.3°C to 36.3 PSU in June to 27.7°C and 36.6 PSU in September, respectively. The mixed layer overlies a weak salinity maximum near 100 m (Figure 5) in the upper pycnocline in June, which is derived from the Arabian Sea High-Salinity Water (Kumar & Prasad, 1999; Prasad & Ikeda, 2002). The summer monsoon forcing thickens the mixed layer, altering its T and S , by entraining the upper pycnocline S -maximum into the mixed layer.

To further explore the T and S changes, we computed the HC and FWC associated with the mean T and S profiles in May and October, across the upper layer from the surface to the lower thermocline at around 200 m deep. The profiles in these 2 months represent the pre- and post-monsoon periods, respectively. Differencing the HC and FWC between the two periods yields the accumulated heat and freshwater gain or loss for a 4-month period of the summer monsoon from June to September. Figures 5e and 5j demonstrate changes in the vertically integrated HC and FWC for the upper 200 m in the central Arabian Sea during the summer monsoon. Notable HC changes occur

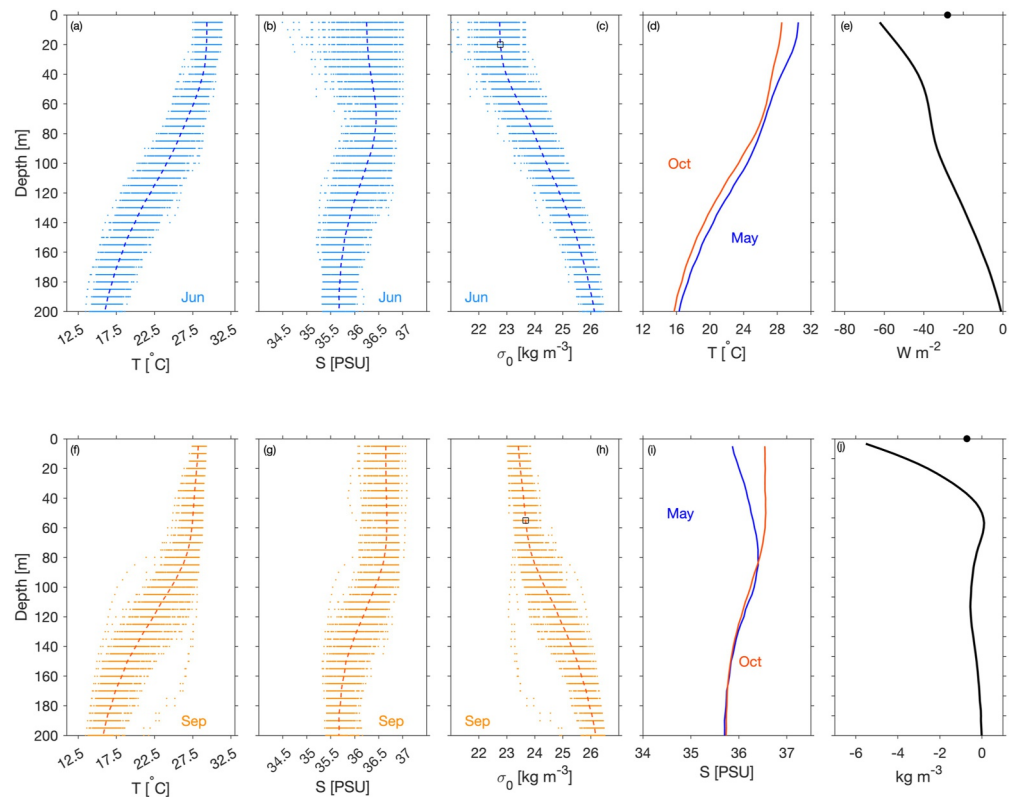


Figure 5. Argo profiles from the sea surface to 200 m of T, S, and σ_0 in the central Arabian Sea, within the red box shown in Figure 1, in June (a–c) and in September (f–h). The color-coded dashed lines indicate the average values. The square markers in (c) and (h) denote the average values of the surface Mixed Layer Depth [MLD]. The difference in the mean T (d) and S (i) in May versus October (before and after the summer monsoon). The change in heat (e) and freshwater (j) contents associated with the difference in the mean T (d) and S (i) respectively. The circle markers in (e, j) indicate the average values.

throughout the water column, with an integrated heat loss of 62 W m^{-2} or $62 \text{ J s}^{-1} \text{ m}^{-2}$. The integrated heat loss within a mixed layer of 55 m, the average MLD in September, is 25 W m^{-2} , commensurate with the mixed layer cooling by approximately 0.5°C . Interestingly, the mixed layer experiences heat loss through the summer despite an average net air-to-sea heat flux of 48 W m^{-2} .

The upper ocean heat loss during the Southwest Monsoon in the central Arabian Sea is accompanied by a freshwater removal, with an average FWC change per meter depth of -2.3 kg m^{-3} in the upper 55 m (Figure 5j). The average value translates to a freshwater removal rate of about -0.2 mm day^{-1} over the course of the summer monsoon. The freshwater removal rate is consistent with a 0.4 PSU increase in mixed layer salinity.

4. Ekman Convergence

As discussed in the previous section, the upper water column in the central Arabian Sea cools and becomes saltier during the Southwest Monsoon. In this and the subsequent sections, we will assess the relative contributions of oceanic processes and air-sea exchanges in regulating heat and freshwater loss during the summer monsoon.

Here, we quantify the contribution of Ekman dynamics in modulating the upper ocean variability. Figure 1 shows near surface winds during boreal summer, potentially driving Ekman transport convergence in the central Arabian Sea. To estimate the transport convergence, we computed Ekman transports across the four sides of the red box in Figure 1 in the central Arabian Sea. The Ekman transport in the x and y direction along each side of the rectangle is estimated as follows,

$$M^x = \int_0^y \frac{\tau^y}{\rho_0 f} dy, \quad (4)$$

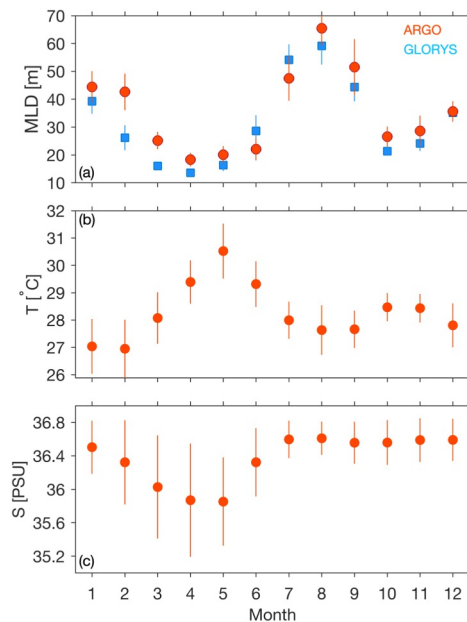


Figure 6. Monthly averages of the surface mixed layer depth [MLD] (a) and the mixed layer T (b) and S (c), inferred from the Argo data observed within the red box shown in Figure 1. The error limits are based on the standard deviation values of the monthly averages.

5. Heat Flux

To further explore the processes driving mixed layer cooling in the central Arabian Sea during the Southwest Monsoon, we analyzed the heat budget in the upper 55 m within the red box area shown in Figure 1. This depth was selected based on the deepest limit of the mean MLD in the area during the monsoon (Figure 5a). GLORYS reanalysis products were utilized to estimate the averages of the mixed layer's zonal and meridional velocities, as well as the mixed layer temperature. The air-sea heat flux was determined from the ERA5 NHF data set.

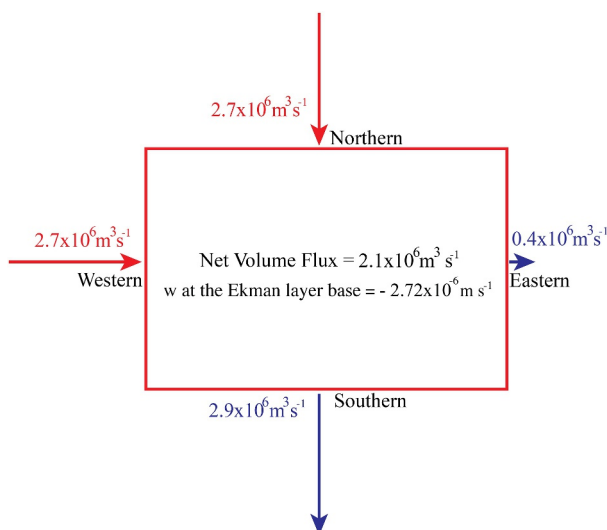


Figure 7. Ekman layer transports across the side walls of the red box shown on Figure 1. Red (blue) fonts and arrows indicate Ekman transports entering (leaving) the box. The net convergence and associated downwelling velocity are shown within the red rectangle.

$$M^y = \int_0^x \frac{-\tau^x}{\rho_0 f} dx. \quad (5)$$

Inferred from the average wind stresses for June through September, the Ekman transports across the four sides indicate the inflow across the northern and western walls are greater than the export Ekman transports across the eastern and southern walls (Figure 7), yielding a net volumetric convergence of $2.1 \times 10^6 \text{ m}^3 \text{ s}^{-1}$, or $\sim 2.1 \text{ Sv}$.

Due to the net horizontal convergence in the surface Ekman layer, downwelling is induced across the layer's base. Since the area demarcated by the red box (Figure 1) in the central Arabian Sea is $7.8 \times 10^{11} \text{ m}^2$, the average downwelling (Ekman pumping) velocity at the Ekman layer base during the summer monsoon is approximately $-2.72 \times 10^{-6} \text{ m s}^{-1}$ or -0.23 m day^{-1} .

Given the average downwelling velocity, we estimated that Ekman convergence would deepen the surface mixed layer by about 21 m over the course of the summer monsoon, which is roughly 60% of the mixed layer deepening, $\sim 35 \text{ m}$, observed during the monsoon. Based on the trends in mixed layer temperature and salinity, the rest of the mixed layer deepening involves entrainment of pycnocline water, which is enabled by wind-driven surface layer turbulence, as found by Lee et al., 2000, using climatology wind data and mixed layer data along with observations made during the 1994–1995 monsoon cycle.

Over the summer monsoon months, the water column in the upper 55 m in the central Arabian Sea experiences a net heat loss of $-0.25 \times 10^{21} \text{ J}$. This loss occurs despite air-to-sea heat flux of $0.51 \times 10^{21} \text{ J}$ (Figure 8). Unlike past studies (e.g., Rao, 1986), suggesting air-sea heat fluxes as the predominant driver for the mixed layer temperature in the central Arabian Sea, we argue that the surface mixed layer cooling during the summer monsoon appears to be primarily accounted for by the heat flux divergence between the northern and southern walls and the heat loss across the base of the water column, which together exceed the heat convergence from the western and eastern walls.

During the Southwest Monsoon, the central Arabian Sea experiences a zonal heat convergence within the mixed layer, primarily because the heat flux across the western boundary is greater than across the eastern boundary (Figure 8). This dynamic leads to an average heat gain of $2.18 \times 10^{21} \text{ J}$. Conversely, a meridional heat divergence leads to a net heat loss of $-2.47 \times 10^{21} \text{ J}$ occurs. However, the net heat loss of $-0.29 \times 10^{21} \text{ J}$ attributable to the heat fluxes from the sidewalls is insufficient to counteract the net heat gain of $0.51 \times 10^{21} \text{ J}$ from the air-to-sea heat flux in the context of the observed heat loss of $-0.25 \times 10^{21} \text{ J}$ heat loss in the water column. An additional heat loss of $-0.47 \times 10^{21} \text{ J}$ is required to achieve the heat budget closure for the mixed layer during the summer monsoon. We postulate that

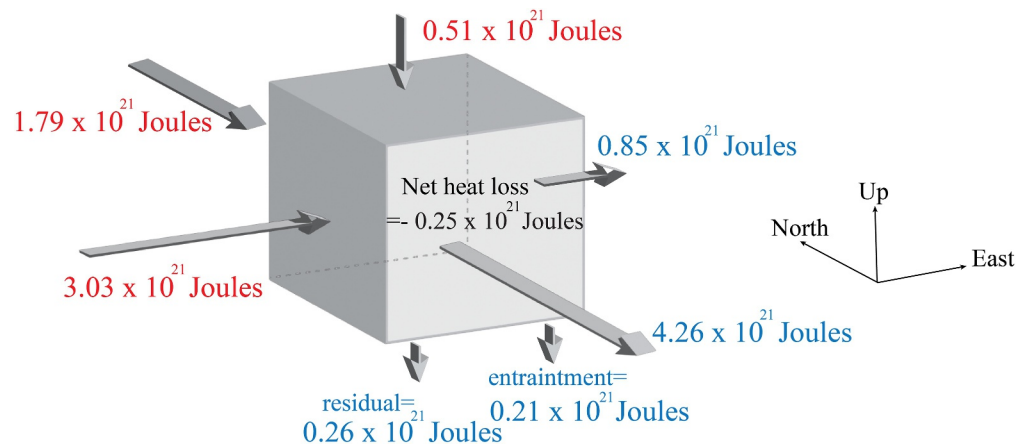


Figure 8. Heat flux into the surface mixed layer within the central Arabian Sea. Red font indicates heat entering the box; Blue font indicates heat leaving the box. Values are for June–September total.

this heat loss arises from processes at the base of the mixed layer, specifically the entrainment of cool upper-thermocline water into the surface layer and likely vertical turbulent mixing. Entrainment contributes a heat loss of -0.21×10^{21} J, which supports the findings of Lee et al. (2000) regarding the importance of entrainment in regulating mixed-layer variability in the central Arabian Sea during the monsoon. The remaining heat loss, -0.26×10^{21} J, constitutes the residual term in Equation 1, suggesting the potential influence of turbulent eddy diffusion across the mixed layer base. A turbulent diffusivity (K_z) of $1.5 \times 10^{-2} \text{ m}^2 \text{ s}^{-1}$ would be required to account for the residual heat flux, a value falls within the range of K_z estimates derived from the K-Profile parameterization scheme for the upper 100 m of the Arabian Sea by Ramesh and Krishnan (2005). Their finding further noted a thermocline approximately 1.2°C warmer in the south-central Arabian Sea during the summer monsoon, attributed to strong vertical diffusivity and downwelling. However, the absence of direct K_z observations in the central Arabian Sea complicates the verification of whether the K_z estimate accurately reflects actual turbulent diffusivity at the mixed layer base at around 55 m depth. When compared to long-term turbulent diffusivity observations in the eastern equatorial Indian Ocean (Pujiana et al., 2015; Pujiana & McPhaden, 2018) and the Bay of Bengal (Thakur et al., 2019; Warner et al., 2016), the estimated K_z value is roughly four times higher than expected. Therefore, it is probable that the residual heat flux reflects not only turbulent heat transfer across the mixed layer base but also other physical processes not explicitly accounted in the mixed-layer heat budget equation.

6. Conclusions

The northern embayments of the Indian Ocean, the Bay of Bengal and the Arabian Sea, are strongly affected by the South Asian Monsoon. Using multi-year Argo float and ocean and atmosphere reanalysis data, we investigate the mechanisms governing the evolution of the surface layer within the Arabian Sea during the Southwest Monsoon (summer monsoon).

Clockwise near-surface winds prevail in the marine boundary layer over the Arabian Sea during the summer. The wind-driven Ekman dynamics deepens the surface mixed layer and the pycnocline, particularly in the central basin. The Argo temperature profiles in the central Arabian Sea, centered at 12°N and 65°E , indicate that the mixed layer deepens from ~ 20 m in June to ~ 55 m in September. Concurrently, the mixed layer temperature cools from 29.3°C to 27.7°C water. Thickening of the surface mixed layer and deepening of the pycnocline leads to a geostrophic anticyclonic gyre circulation.

The wind-driven Ekman convergence into the central Arabian Sea accounts for about three-fifths of the surface mixed layer deepening. The remaining mixed layer deepening is likely attributed to the downward heat transfer from warmer surface to thermocline. The heat content in the mixed layer in the central Arabian Sea (the red box shown in Figure 1: 8°N – 16°N ; 61°E – 69°E) during the summer decreases by -0.25×10^{21} J. The heat loss is concurrent with freshwater removal in the mixed layer, corresponding to a 0.4 PSU increase in the mixed layer salinity. A net sea-to-air freshwater flux partly accounts for the salinification of the upper layer.

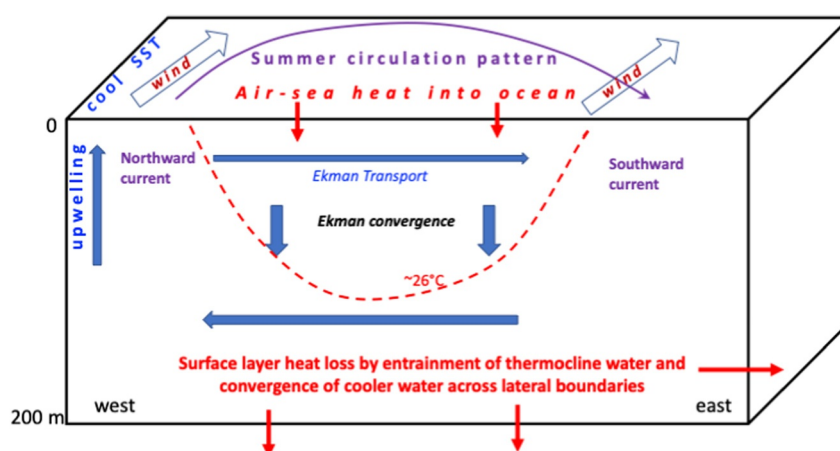


Figure 9. A schematic illustrating the physical processes characterizing the mean state of the upper ocean heat content in the central region of the Arabian Sea during the summer monsoon.

The decreased heat content is not solely a response to the air-sea heat flux, which adds 0.51×10^{21} J to the ocean. It also reflects a net horizontal heat divergence-driven heat loss across the side walls, amounting to -0.29×10^{21} J, the heat loss across the base of the surface mixed layer, amounting to -0.21×10^{21} J a consequence of entrainment of cooler subsurface water upward, and potentially turbulent diffusivity-driven cooling. Figure 9 summarizes the physical processes attributable to the mean state of the upper ocean heat content in the Arabian Sea.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The T and S profiles obtained from R/V Knorr along the I01 W section are available from <https://www.ncei.noaa.gov/data/oceans/ncei/ocads/data/0115009/i01.dat> (Johnson et al., 2002).

The ERA5 reanalysis products can be obtained from <https://cds.climate.copernicus.eu/datasets/reanalysis-era5-single-levels-monthly-means?tab=download> (Hersbach et al., 2023). The GLORYS reanalysis products can be downloaded from https://data.marine.copernicus.eu/product/GLOBAL_MULTIYEAR_PHY_001_030/services (Jean-Michel et al., 2021). The Argo data is available for download from <https://www.ncei.noaa.gov/data/oceans/argo/gadr/data/indian/> (International Argo Program, 2003).

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