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Mixed Layer Budget Terms on Acoustic Propagation: A Study-based on the Butterfly Track Experiment in the South-Eastern Arabian Sea

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ABSTRACT

A butterfly type of repeat track cruise was carried out in the South Eastern Arabian Sea (off Minicoy) onboard *INS Sagardhwani* during July 2016 to Aug 2016. We have also made use of the data from OMNI buoy, AD09, which is about 6 km close to the centre station of butterfly track. Air sea flux, the horizontal current data from AD09 and the time series data collected from the butterfly experiment were analysed to compute the mixed layer heat and salt budget. The short-term thermo-haline variability off Minicoy, relative contribution of heat/salt budget terms in MLD and its effects on acoustic propagation are addressed in this paper. In this study, most dominating term in the mixed layer heat budget estimation is net surface heat flux followed by the advective terms has been found. However the salinity in the mixed layer is dominated by the contribution of buoyancy mixing due to night time evaporative cooling. During the calm, sunny day, the so-called afternoon effect due to the diurnal heating restricts the sonar range. But during the windy day, the wind/wave mixing prevents the warming of the surface layer which in turn enhances the sonar range. Similarly, the night time cooling also enhance the acoustic propagation range. The presence of Arabian Sea High Salinity Watermass in the surface layer also enhances the acoustic propagation.

Keywords: Heat and salt budget; Advective terms; Surface flux; South-Eastern Arabian Sea; Butterfly type experiment

1. INTRODUCTION

The upper layer of ocean with nearly uniform hydrographic properties is defined as surface mixed layer and it plays an important role in the air- sea heat, moisture and momentum exchange. Mixed layer depth (MLD) is an essential parameter for the weather prediction, biological production, tropical cyclone formation studies and is also an important input for all biogeochemical studies. MLD is chiefly controlled by the surface stress (due to momentum transfer by wind), buoyancy fluxes (due to change in density by heat and fresh water fluxes) and dissipation. Hence, variability in the mixed layer depth can be related to the contribution of these processes. Under water acoustics are mainly dependent on sound speed profiles, which are purely dependent on thermo-haline properties, depth and behaviour of MLD. Similar to MLD, there exists a surface layer of interest, viz., sonic layer depth (SLD), which characterises acoustic ducts in the ocean. SLD is the vertical distance from ocean surface to the depth of a sound speed maximum. The processes in the mixed layer determines the sonic layer depth (SLD), often SLD and MLD coincides. When sound travels in a duct, it is prevented from spreading in depth and remains confined between the boundaries of the sonic layer and can be transmitted for great distances[1]. Depending on the SLD, there exists a 'cut off frequency' above which sound tends to be 'trapped' near the surface[2]. Hence SLD and the associated 'cut off frequency' are the key characteristics of the ducted propagation in the upper ocean.

To understand the upper oceanic physical processes, many have studied the seasonal variability of mixed layer budget terms in the SEAS by analysing the observational and model simulated data sets[3-8]. But it is well evident that salinity is also playing a significant role in the upper ocean dynamics in the SEAS[9-11]. In view of the significance of salinity, Salinity Processes in the Upper-ocean regional study (SPURS)[12] have been carried in the North Atlantic (SPURS-1) and Pacific (SPURS-2) to improve understanding of the physical processes influencing upper-ocean salinity. So we also designed a scientific program to understand the short term variability of heat and salt budget terms in the mixed layer. It is well-known that the MLD varies on diurnal to inter-decadal time scales, but high frequency fluctuation (diurnal) in MLD is poorly understood due to the insufficient data. Hence to study the various physical process of the MLD we designed an experiment to collect data at 3 hour interval to estimate the heat and salt budgets of the mixed layer. A heat (salt) budget, as the name suggests, is a process of accounting for all of the heat (salt) entering or leaving a control volume (or box) in the ocean[12]. Budget studies usually require continuous observations of CTD casts and surface met observations, hence require multiple ships and mooring platforms. Recently National Institute of Ocean Technology (NIOT) has deployed Ocean moored buoy network for northern Indian Ocean (OMNI) buoys along the seas around India, which transmit met–ocean data to the shore

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at 3 h interval via International Maritime Satellite Organisation communication system[13]. The OMNI buoys are equipped with additional meteorological measurements for radiation, rainfall and subsurface measurements on conductivity, temperature and currents. These buoy data has given a unique opportunity to study the heat/salt balance in the nearby locations. Hence we planned a butterfly type experiment very close to the OMNI buoy, AD09, off Minicoy. The main oceanographic objective of the study is to investigate processes that control temperature, salinity, and thickness of the oceanic mixed layer depth (MLD). Similar experiment was conducted during spring under Armex project[14] but they were not addressed the salt budget terms. Hence, the *in situ* observation for the budget analysis for heat and salt terms in the mixed layer is first of its kind in Arabian Sea. The analysis of heat and salt water budgets in the mixed layer have significant role in air-sea heat flux, evaluation of ocean models and performance of sonar range prediction. The short-term thermo-haline variability off Minicoy, relative contribution of heat/salt budget terms in MLD and its effects on acoustic propagation are addressed in this paper.

2. MATERIAL AND METHODS

2.1 Materials

In order to estimate lateral heat and salt advection, a butterfly type of repeat track cruise (Fig. 1) was carried out in the SEAS (off Minicoy) onboard *INS Sagardhwani* during 27 Jul 2016 to 2 Aug 2016. The centre of the butterfly survey, C is chosen close to the OMNI buoy, AD09 located at 73.302°E: 8.261 °N in the south eastern Arabian Sea. The distance between C and any of the four vertices E, W, N or S is about 7 Nm. The distance from W to N and S to E is approximately 10 Nm. During this mission, we occupied 141 CTD stations by repeating 23 butterfly tracks: consisting of 24 zonal tracks (E-C-W) and 23 meridional tracks (N-C-S). Station C occupied at 47 time approximately at 3 h interval. Similarly, stations E W, S, N were occupied at 6 h interval. In addition to this, to estimate the light attenuation coefficient for heat budget study we also collected 33 water samples for chlorophyll-*a* estimation. All CTD data have been quality controlled and interpolated as per the standard procedures to make all profiles at 1m intervals. We define and compute the MLD as the depth where the water density is higher by 0.125 kgm^{-3} than the density at 5 m. Similarly, the isothermal layer depth (ILD) is defined as the depth at which the temperature changes by 0.5°C from the temperature at 5 m. Sonic layer depth (SLD) is defined as the depth at which sound speed maxima occurs in the upper layers.

2.2 Methods

In this study we simplified the the mixed layer heat budget terms[15-16] into:

$$\frac{\partial T}{\partial t} = \frac{Q_0}{\rho_0 C_p h} - U\frac{\partial T}{\partial x} - V\frac{\partial T}{\partial y} + D \tag{1}$$

Similarly the mixed layer salt budget terms[10,17-18] are simplified into:

$$\frac{\partial S}{\partial t} = \frac{(E-P)S_0}{h} - U\frac{\partial S}{\partial x} - V\frac{\partial S}{\partial y} + R \tag{2}$$

where T is the vertically averaged temperature over the MLD, h ; Q_0 is the near-surface net heat flux; ρ_0 is the density of seawater (1,024 kg m^{-3}); Cp is the specific heat capacity of sea water (4,000 J kg^{-1}K^{-1}); t is time (3 h); U and V are zonal

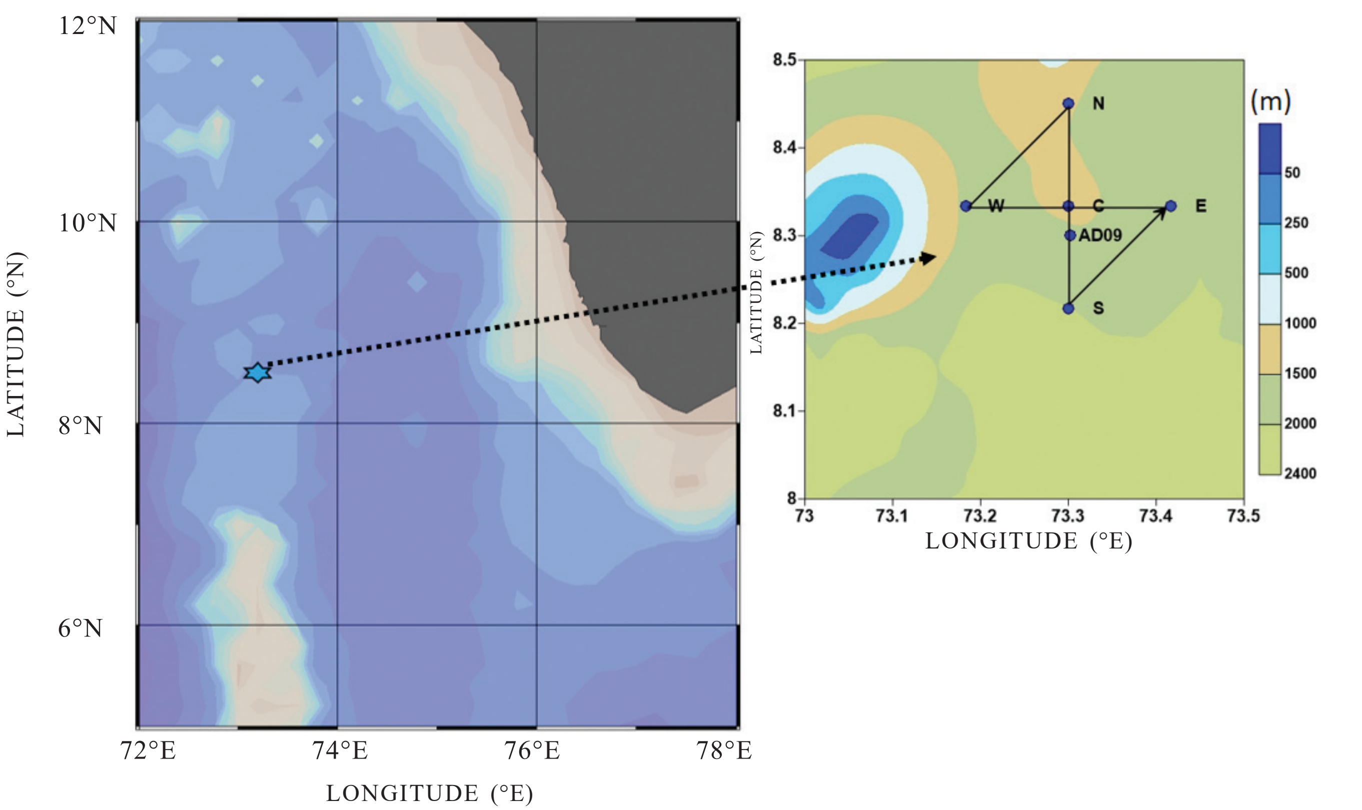

Figure 1. Survey area and station locations. AD09 is the OMNI buoy. Color scale is the bathymetry of the region in meters.

and meridional components of velocity respectively. S_0 in Eqn. (2) represents mixed layer salinity; E is evaporation; P is precipitation. Ideally, current, temperature and salinity averaged over the mixed layer are used to estimate the horizontal advection terms in the budget studies. Due to the lack of ADCP data, we use 10 m current data of AD09 is a proxy for ML averaged current. D and R represents the residual terms includes the physical processes we are not accounted and errors related to instrumental accuracy, temporal, spatial accuracy.

The net surface heat flux (Q_0)[14] is calculated as

$$Q_0 = Q_s - (Q_p + Q_b + Qe + Q_h) \quad (3)$$

Q_s = net shortwave radiation, Q_p = shortwave radiation that penetrates below the ML,

Q_b = net long wave radiation, Q_e = latent heat flux, and Q_h = sensible heat flux.

$$Q_p = Q_s * (1 - \alpha) - h/\zeta \quad (4)$$

(Sengupta[4], *et al.*; Parampil[19], *et al.*)

where α = 0.58 is the fraction of red and infrared part of shortwave radiation, which is generally absorbed within the upper 2 m of the water column. ζ is the attenuation depth.

$$\zeta = 1/(0.027 + (0.0518 * \text{chlorophyll } a))^{20}$$

3. RESULTS AND DISCUSSIONS

The surface heat flux terms, such as shortwave radiation (Q_s), long wave radiation (Q_b), latent heat flux (Q_e) and sensible heat flux (Q_h) derived from AD09 are presented in Fig. 2. The radiative flux observed in the AD09 and flux values derived from tropflux shows relatively better agreement except for long wave radiation. So in this study we used long wave radiation from tropflux and rest of the terms from AD09 to compute surface flux. The penetrative radiated flux is always observed less than 14 W/m^2 with an average of 6 W/m^2 possibly due to deep MLD. Satellite derived surface winds and currents are plotted in the Fig. 3. Relatively strong winds are blowing during the initial phase of the survey. However the current plot did not show any noticeable change during the survey.

To understand thermo-haline variability off Minicoy, Depth-Time sections of temperature, salinity, SST and SSS for the buoy AD09 and the station C were plotted (Fig. 4). In general, very deep isothermal layers were seen during the period and SST was relatively cooler, however warmer waters (>28.5 °C) are occupied till 28 July 2016. During the early phase of our observation, thermal structure showed more fluctuations than that observed in the remaining period. Diurnal oscillations in thermal structure were clearly seen from 30 Jul onwards. In the salinity structure, it can be inferred that the relatively very low saline waters were observed at the surface layers during 27-29 July 2016 and the influence of the surface freshening is visible up to 60 m depth. Although the rainfall extends only few hours its manifestations at the surface layers remained for several hours. Similarly ASHSW was clearly seen in the sub-surface layers and it oscillated from 50 m to 100 m at C, but its signatures are weakened from 31 July 2016 onwards. In general, AD09 data showed good agreement with the observations. However, the surface salinity and hence the MLD showed marked discrepancies between the buoy and ship observations. SLD we computed from the data showed more variability

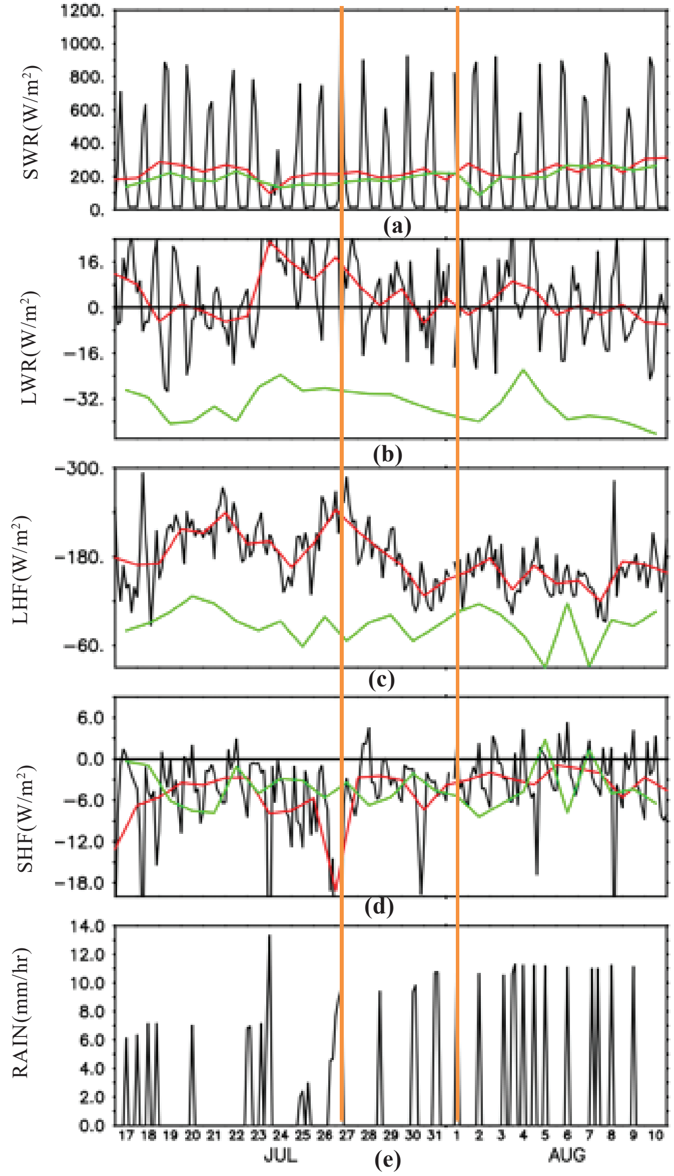

Figure 2. Distribution of (a) short wave radiation, (b) longwave radiation, (c) latent heat flux, (d) sensible heat flux, and (e) rain rate at AD09. Red and green lines in (a) - (d) represents daily average of AD09 and tropflux data, respectively.

during the initial period of survey thereafter it follows the temperature section. Relative importance of each term in Eqns. (1) and (2) are estimated at every 3 h interval and is presented in Fig. 5. Temporal contribution of surface flux, horizontal advection and the resultant contribution (surface flux + H. advection) on heat (salt) terms of the MLD are showed in the top, middle and bottom panels respectively. The net surface heat flux in the MLD is mainly dominated by the incoming solar radiation during day and the latent heat of evaporation during night. Though the contribution of horizontal advection is very little in the ML budget, the contribution of meridional advection is slightly higher than the zonal advection. Hence in this study we can clearly perceive that surface flux is the dominating term in the mixed layer temperature estimation, followed by advective terms. The surface and horizontal flux

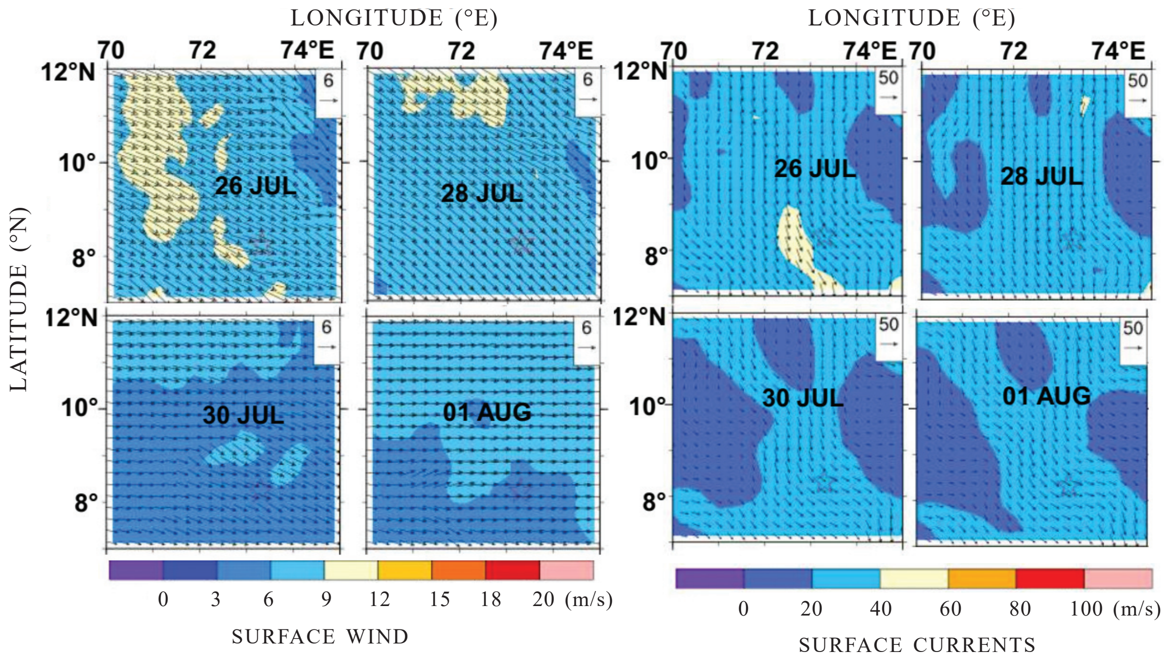

Figure 3. Satellite derived surface winds (ASCAT) and surface currents (GECKO) during the survey period. Red star in the plot represents the centre point, C, of the butterfly track.

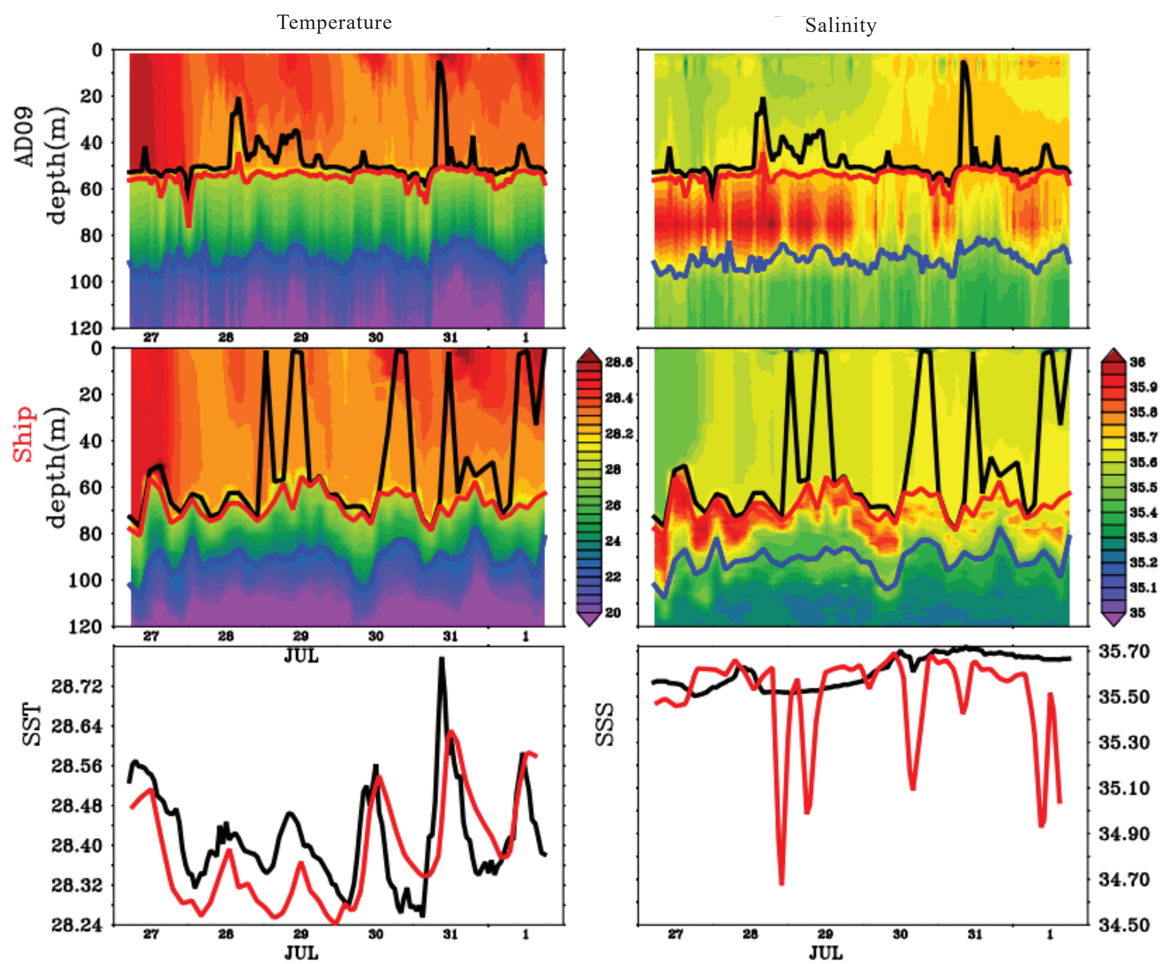

Figure 4. Temporal evolution of temperature (left panel) and salinity (right panel), SST and SSS of AD09 buoy and the ship location at C. ((a), (d)) AD09 ((b),(e)) stn C (c) SST and (f) SSS. Mixed layer depth is indicated by the thick black line, isothermal layer depth by the dashed black line, and depth of the 23 °C by blue lines, respectively. Black line indicates the buoy and red line represents ship data ((c) & (f)).

terms in the mixed layer salt budget did not show any significant contribution of ML salinity hence the residual term is dominated in the mixed salt budget. It can be clearly seen that salinity tendency showed an increasing trend during the night time and the residual terms exactly follows the salinity trend. Hence residual term may be attributed to the buoyancy mixing due to night time cooling, which dominates in the salt budget terms.

To understand the significance of the T-S variability on acoustic propagation, transmission loss modelling[21] (Kraken RQ) has been done for the frequency of 1500 Hz, source at 10 m and 50 m for three selected profiles. The results are presented in Fig. 6. Among the three profiles, two profiles corresponds to the diurnal warming time (during a strong windy day and weak windy day) and one profile corresponds to a night time cooling period. The transmission mosaic corresponds to the source at 10 m clearly depicts that the night time cooling period and strong windy after noon showed better ducted propagation range. The results clearly shows that so called afternoon effect is prominent only during the calm wind conditions. The source depth at 50 m (Fig. 5. Bottom panel) reveals that the presence of dominant ASHSW clearly enhances the acoustic propagation.

4. SUMMARY AND CONCLUSIONS

We have addressed the short-term thermo-haline variability off Minicoy and resolved the mixed budget terms reasonably well. The most prominent feature in the salinity structure is the presence of low saline waters during the rainy day and the spatio-temporal variability of ASHSW. ASHSW was observed throughout the period at W, but its intensity is not evident after 30 Jul, especially at

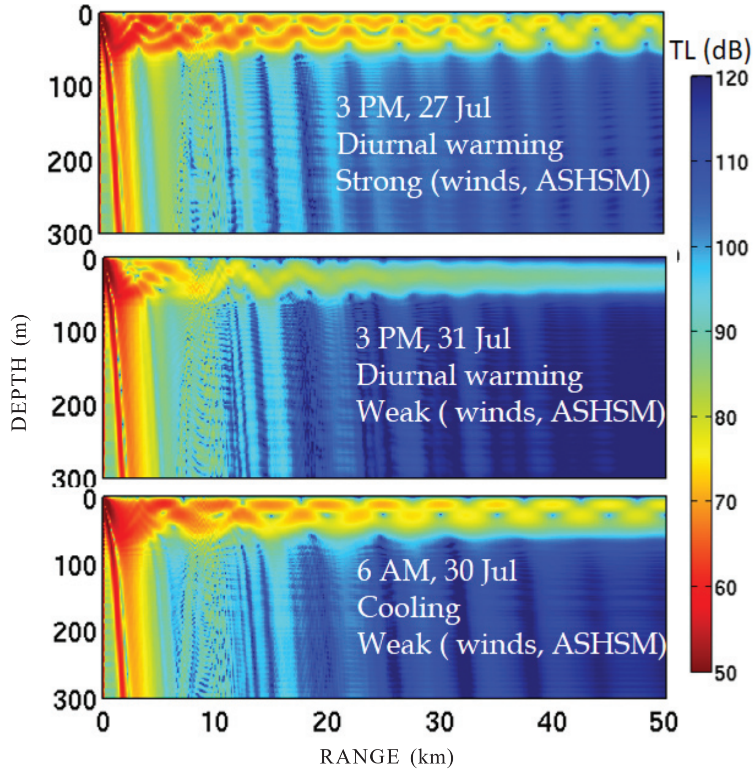

Figure 6. Transmission loss mosaic of 1500 Hz for the source at 10 m (top panel) and at 50 m (bottom panel) for the three selected profiles viz., a) diurnal warming period -3 PM, 27 Jul 2016 (strong winds & ASHSW was significant), b) diurnal warming period -3PM, 31 Jul (Weak winds & ASHSW was less prominent), c) nighttime cooling period - 2 AM, 30 Jul 2016 (Weak winds & ASHSW was less prominent) . X – axis is Range in km and Y-axis is depth in m.

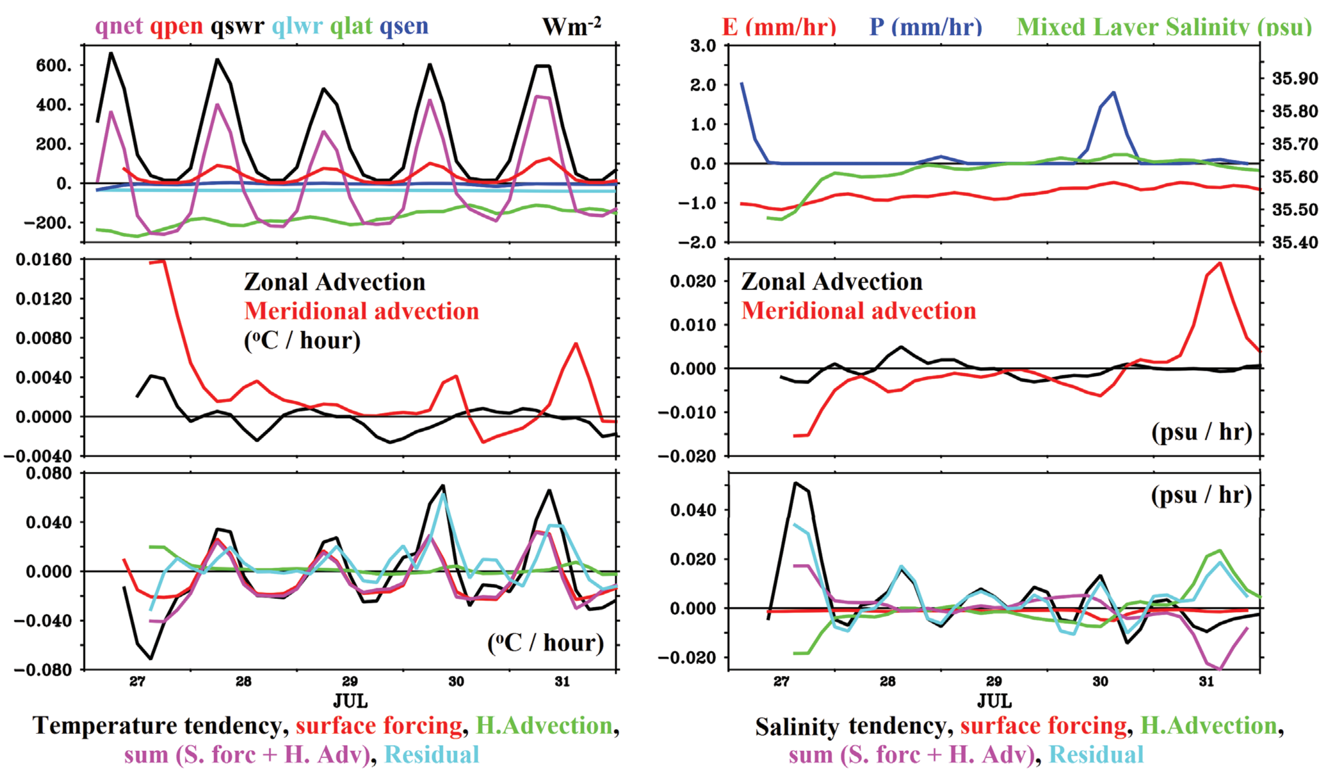

Figure 5. Temporal evolution of relative contribution of heat (left) and salt (right) budget terms in the mixed layer.

N & E stations. The dominating term in the ML heat budget estimation is net surface heat flux followed by advective terms. While the salinity in ML is dominated by the residual term, which might be the contribution of buoyancy mixing due to the night time cooling. Transmission loss modelling results clearly suggests the significance of these budget terms in the acoustic propagation. During the calm, sunny day, the so-called afternoon effect due to the diurnal heating restricts the sonar range. But during the windy day, the wind/wave mixing prevents the warming of the surface layer which in turn enhances the sonar range. Similarly, the night time cooling also enhance the acoustic propagation range. The presence of ASHSW in the surface layer also enhances the acoustic propagation. Hence this study suggests that surface forcing and horizontal advection terms have significant role in acoustic propagation. Similar experiments can be extended for longer duration and different seasons for better understanding of the dynamics of the upper Ocean.

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