Mixed-layer and Thermocline Interactions associated with the monsoonal flow over the Arabian sea

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Winter Season: Mild dry winds, clear skies, excess evaporation as compared to precipitation and net heat loss from the ocean. The negative buoyancy flux plays a major role in the convective deepening and cooling of the mixed-layer [Prasad and Ikeda, 2001; Weller et al., 2002].

Summer Monsoon: Stronger wind forcing causes deepening of the mixed-layer through shear generation of turbulence and mixing [Weller et al., 2002]
SST (°C) and currents (cms⁻¹) from OGCM simulation
Seasonal Heat Transport in the Indian Ocean

Southward ocean heat transport across equator during Boreal Summer

Northward ocean heat transport across equator during Boreal Winter
(Hastenrath and Greischar 1993; Hsuing et al., 1989)

Loschnigg and Webster (2000)

Model estimates of heat transport:
Summer (~1.5 PW)
Winter (~1.0 PW)

Wacongne and Pacanowski (1996)
(Q) Thermocline response of the Northern Indian Ocean to forcing from the Southwest Monsoon?
Analysis of multi-source datasets

- Monthly climatological temperatures from World Ocean Atlas (WOA2001) dataset [Conkright et al., 2002]
- DINDOCN dataset (ARGO + XBT)
- Monthly ocean temperatures from Joint Environmental Data Archival Center (JEDAC) - [White et al., 1995]
- Climatological heat-fluxes and wind-stress from Southampton Oceanography Centre (SOC) dataset [Josey et al., 1999]
- Surface winds from QuikSCAT for 2002-2003 [Pegion et al., 2000]
- Ocean currents from Geophysical Fluid Dynamics Laboratory (GFDL) Assimilation Dataset (GFDLAD)
Mean location of ARGO floats in the Northern Indian Ocean shown by Red Circles. The Blue Circles are measurements from XBT lines. Analysis period (January 2002 – December 2003).

Data Source: [http://www.ifremer.fr/coriolis](http://www.ifremer.fr/coriolis)  
[http://www.aoml.noaa.gov](http://www.aoml.noaa.gov)

Monthly mean number of observations

Krishnan and Ramesh (2004) IITM Research Report, RR No.102
Annual cycle of monthly climatological temperature (°C) from WOA2001 dataset averaged for the region (50 - 70 E; 0 - 20 N) at different depths (a) 10 m (b) 30 m (c) 50 m (d) 100 m (e) 150 m (f) 200 m
• **Mixed-layer cooling of the Arabian Sea during the Southwest monsoon**
  
  • Upwelling along the coasts of East Africa and Arabia [Duing and Leetmaa, 1980; Schott, 1983]
  • Surface cooling due to evaporation [Rao et al., 1986; Krishnamurti et al., 1988]
  • Horizontal advection of upwelled waters [Shetye, 1986; Rao et al., 1989]
  • Entrainment due to wind-driven mixing [McCreary et al., 1993; Lee et al., 2000; Weller et al., 2002]
  • Importance of mesoscale eddies in transporting upwelling waters far away from the coasts in the Arabian Sea [Fischer et al., 2002]
  • Role of Ekman pumping in setting up the mixed-layer structure of the Arabian Sea [Bauer et al., 1991; McCreary et al., 1993].
Temperature difference \(T_{JJAS} - T_{REST}\) at 20 m depth is shown in the top [a & b] and at 150m is shown in the bottom [c & d]. The left and right columns are based on the WOA2001 and DINDOCN datasets respectively.
(a) Vertical profile of temperature (°C) averaged for the region (50–70°E; 5-15°N) based on WOA2001 dataset. The solid line corresponds to $T_{JJAS}$ and the dashed line is for $T_{REST}$.

(b) JEDAC
(c) DINDOCN dataset.

(d) Latitude-depth section of $(T_{JJAS} - T_{REST})$ difference zonally averaged across (50-70°E) from WOA2001 dataset.

(e) JEDAC
(f) DINDOCN dataset.
(a) Climatological surface wind-stress (dynes cm⁻²) vector for June-September months based on SOC dataset. Shading denotes curl of wind-stress (dynes cm⁻³) and values are scaled by a factor of $1.0 \times 10^7$.

(b) Latitude-depth section of vertical velocity (cm s⁻¹) zonally averaged across (50–70 E) for June-September months based on GFDLAD climatology. The thick dashed line is the mixed-layer depth averaged over the same region.
Annual cycle of atmospheric and oceanic parameters averaged for the region (50-70E; 0-20N). (a) Net heat flux (red) in Wm$^{-2}$ and magnitude of surface wind-stress (blue) in dynes cm$^{-2}$. (b) Surface density in kg m$^{-3}$ (medium blue) after subtracting a reference value of 1023 kg m$^{-3}$; density difference ($\Delta \rho$) in kg m$^{-3}$ between surface and 150m reference depth (purple). (c) Mixed-layer depth (green line) and Richardson Number ($Ri = gh\Delta \rho / \rho_o u^*$) is shown by golden yellow line. (d) Heat storage in the thermocline.
Vertical velocity from Ekman pumping: Sverdrup balance

\[ W_{EP} = \frac{1}{f \rho_0} \left( \hat{k} \cdot (\nabla \times \vec{\tau}) + \frac{\beta}{f} \tau^x \right) \]

where \( \vec{\tau} = (\tau^x, \tau^y) = \) Surface windstress; \( \rho_0 = \) Surface density of water; \( f = \) Coriolis frequency; \( \beta = \) Latitudinal variation of Coriolis frequency.

Negative (Positive) wind-stress curl in Northern Hemisphere

Convergence (Divergence) of ocean currents; so that the vertical velocity due to Ekman pumping is Downward (Upward)

The vertical velocity due to Ekman pumping, computed for the central and southern Arabian Sea (60-70E; 5-15N) for June-Sept months is found to be \( W_{EP} = -0.32 \times 10^{-3} \text{ cm s}^{-1} \)
Vertical velocity due to wind-driven mixing and entrainment at the base of the mixed-layer (Kraus and Turner, 1967)

\[
P = m u_*^3 - \frac{1}{2} \left( \frac{\alpha g h Q}{\rho_0 C_p} \right)
\]

\[
W_{KT} = \frac{2P}{\alpha g h \Delta T} \quad P > 0
\]

\[
W_{KT} = \frac{h_{MO} - h}{2 \Delta t} \quad P \leq 0
\]

\[
h_{MO} = \frac{2m u_*^3 \rho_0 C_p}{\alpha g Q}
\]

where \( Q \) = Net surface heat flux; \( h \) = Mixed-layer depth; \( u_* = \sqrt{\frac{F}{\rho_0}} \) = Friction velocity

\( \alpha = 0.00025^\circ K^{-1} \) = Coefficient of thermal expansion;

\( g = 9.8 \text{ m s}^{-2} \) = Acceleration due to gravity;

\( \rho_0 = 1025 \text{ kg m}^{-3} \) = Surface density of water;

\( C_p = 3994 \text{ J kg}^{-1} \text{ K}^{-1} \) = Specific heat capacity of water;

\( m = 0.5 \) = Wind-stirring coefficient; \( \Delta T = 2^\circ C \) = Temperature jump across the mixed-layer base

Net Rate of Production of Turbulent Kinetic Energy (McCreary et al., 1993; Lee et al., 2000).

The value of \( W_{KT} \) in the central and southern Arabian Sea (60-70E; 5-15N) for the June - Sept months is found to be \(-1.2 \times 10^{-3} \text{ cm s}^{-1}\)
Horizontal advection of Heat

MLD

(a)

Temperature from WOA2001 and currents from GFDL assimilation

Thermocline

(b)

Zonal component

\( u_x \partial T/\partial x \)

(c)

Meridional component

\( u_y \partial T/\partial y \)

(d)
Monthly surface forcing parameters for KPP Diffusivity Profiles
(50 E – 70E ; 0 - 20N)

<table>
<thead>
<tr>
<th></th>
<th>$T^x$ (N/m²)</th>
<th>$T^y$ (N/m²)</th>
<th>Shortwave Flux (W/m²)</th>
<th>Longwave Flux (W/m²)</th>
<th>Sensible Heat Flux (W/m²)</th>
<th>Evaporation Rate (kg m⁻²s⁻¹)</th>
<th>Rainfall Rate (kg m⁻²s⁻¹)</th>
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</table>
Diffusion of heat into thermocline

KPP vertical mixing parameterization (Large et. al., 1994)

Diffusivity of heat ($m^2s^{-1}$)

JJAS

REST
Upper-ocean response to monsoon interannual variability

Southwest Monsoon 2002: WEAK
Southwest Monsoon 2003: NORMAL

(a) Surface wind difference (July 2003 minus July 2002) in ms\(^{-1}\) from QuikSCAT dataset  (b) Latitude-depth section of temperature difference (July 2003 – July 2002) zonally averaged across (50-70E) from DINDOCN dataset.
Climatological surface winds (ms⁻¹) and MLD (m) for July.

Anomaly composite based on strong minus weak monsoons: MLD and surface wind anomalies during July composited from 5 strong and 5 weak monsoons.

Latitude-depth section of temperature anomaly composite - zonally averaged across (50-70E). The strong minus weak monsoon composite is based on 5 strong and 5 weak monsoons.

Data source: JEDAC

Ramesh and Krishnan (JGR revision)
Summary:

• Seasonal surface cooling of the Arabian Sea, during the Southwest monsoon season, is accompanied by distinct warming of the thermocline by as much as 1.2 °C.

• Downward transfer of warm waters from the surface into the thermocline. Strong and deep vertical diffusivity of heat during the Southwest monsoon season is a combined effect of strong wind-driven mixing; Ekman pumping, horizontal advection and shear instability (weak density stratification and strong wind forcing) in the upper ocean.

• The temperature variability between strong and weak Southwest monsoons consistently bring out the response of the Arabian Sea to forcing associated with the monsoon interannual variability. Stronger monsoons give rise to enhanced cooling of the mixed-layer and warming of the thermocline. Conversely, weaker monsoons induce weaker responses of the mixed-layer and the thermocline.
Thank You