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A case study on the short-term variability in the observed temperature and currents in the upper layers of the northeastern Arabian Sea during the pre-onset phase of ISMEX-73

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The observed short-term variability in the temperature records of the top 200 m water column and in the current meter records at 50 and 75 m depths was investigated with the aid of short time series measurements made at a single station (18°N, 67°E) in the NE Arabian Sea (29 May to 5 June 1973). The sea surface temperature increased by about 0.5°C and the temperature at 75 and 100 m depths did not show any perceptible changes. However, a remarkable feature was a temperature drop of 2°C at 50 m depth during this period. Both vertical and lateral advection appeared to have contributed towards cooling of 1.2°C and 0.8°C respectively in association with the readjustment conditions produced in the upper layers by a westward moving meteorological disturbance during the preceding week.

During summer (Feb-May), the surface layers in the Arabian Sea warm up due to excessive absorption of solar radiation resulting in an increase in temperature by about 2° to 4°C. However, this seasonal warming may not be monotonic and progressive throughout the summer season, but during May some short cooling events also occur due to the development and passage of transient meteorological disturbances over the warm Arabian Sea. On a climatological mode, for instance, in May, (during years 1877-1970) about 25 disturbances formed over the sea of which 16 intensified into storms[1]. Because of these meteorological disturbances which form only in some years, the thermal structure in the upper layers is expected to exhibit prominent short period variations. These disturbances not only produce localised variations but their influence could at times be noticed in the neighbouring areas too due to storm induced advection and propogating waves[2]. However, the corresponding observational evidence to describe this type of intra-seasonal variation during the premonsoon heating season in the Arabian Sea is not available due to lack of systematic data collection. The distribution of climatic mean monthly temperature fields[3-5] in the upper layers of the Arabian Sea do not reflect impression of these transient meteorological disturbances. Monitoring the physical properties of the upper layers at finer sampling interval (hours to few days) for durations 0 (1 week) probably allows the detection of short period variability caused by these transient disturbances. Occurrence of such an event was monitored during the Indo-Soviet Monsoon Experiment (ISMEX-73) during the pre-onset phase of the summer monsoon season of 1973. In the present study the possible influence of a meteorological depression (26-28 May 1973) is documented with the aid of the observations made at a nearby station (18°N, 67°E) in the NE Arabian Sea during ISMEX-73 programme.

Observations

A USSR ship *R. V. Priliv* occupied a stationary position 18°N, 67°E (Fig. 1) from 29 May to 5 June 1973 in the Arabian Sea. Time series of bathythermograph data in the upper 200 m water column were collected at slightly uneven sampling intervals (30 min to 4 h). These data were utilised to generate values at every 3 h through linear interpolation. During the same period current meter records were also collected at 50 and 75 m depths, sampled at 20 min intervals from a moored buoy. Unfortunately, very few surface marine meteorological data were reported during this period. The time series of temperature and current records were made use of in this study.

Although the weather was fair during the observational period at the station[6], disturbed weather conditions prevailed during the preceding 5 days (24-28 May 1973). A well marked low pressure developed off the southwest coast of India on 24 May. Moving westwards, this low concentrated into a depression on 26th morning near 12°N, 61°E (Fig. 1) and became deep on 27th morning near 12°30'N, 56°30'E.

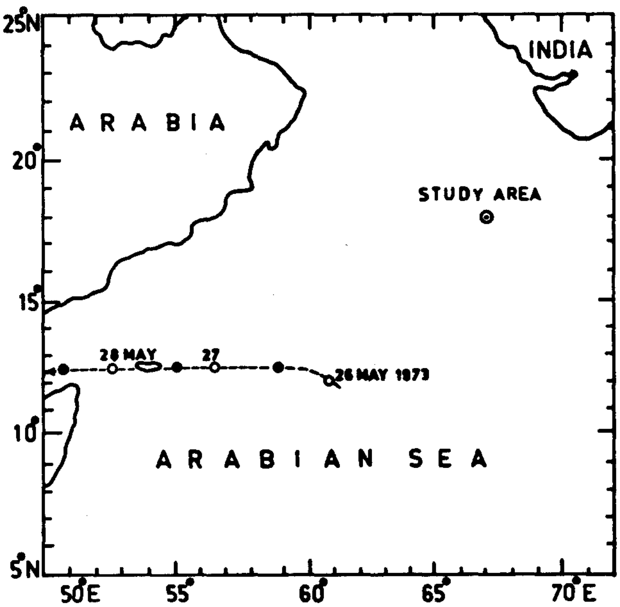

Fig. 1—Station location map (⊙) with the track of a meteorological depression (○---●---○)

Continuing to move westward at a rapid rate, it weakened into a depression on 28th evening and into a low over the Gulf of Aden on the 29th morning. This system was classified as stage B from satellite cloud imageries by National Meteorological Centre, Washington[6]. After the passage of this system, fair weather conditions prevailed over the Arabian Sea during the next 8 days. During the observational period westerly winds weakened from 4 to 2 $m.sec^{-1}$ at the stationary position (Fig. 2). The air temperature showed weak fluctuations between 29° and 30°C and cloudiness was generally around 2 octas. The sea surface temperature (SST) increased by about 0.5°C probably due to solar heating under clear skies.

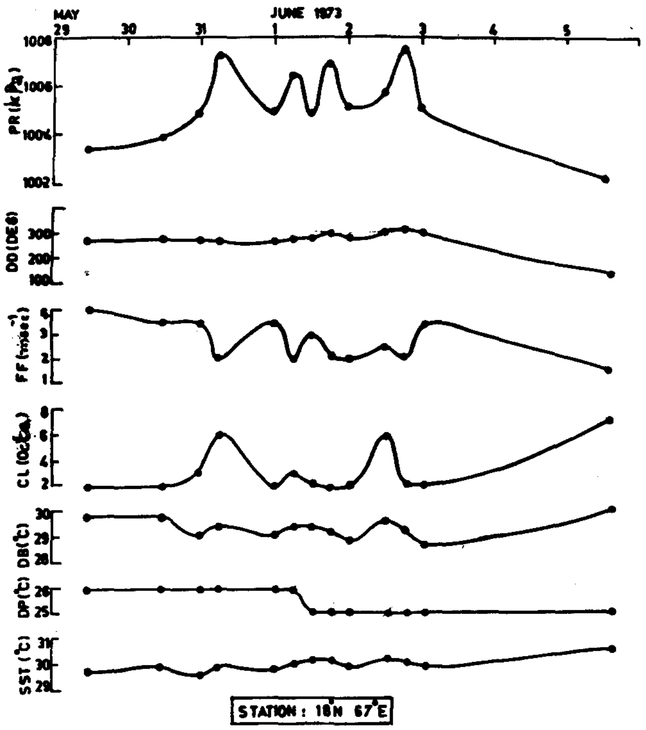

Fig. 2—Time series of surface marine meteorological elements. (PR = pressure, DD = wind direction, FF = wind speed, CL = total cloudiness, DB = dry bulb temperature, DP = dew point temperature, SST = sea surface temperature)

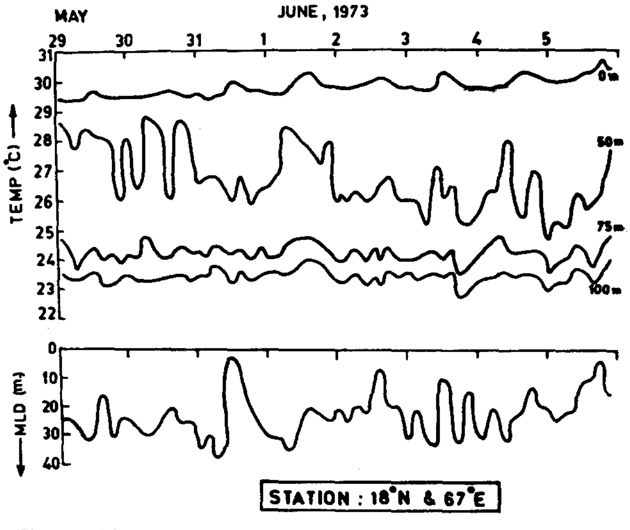

Fig. 3—Time series of temperature at surface, 50, 75 and 100 m depths and mixed layer depth (MLD)

Results and Discussion

The time series of temperature at the surface, 50, 75 and 100 m depths and the mixed layer depth (MLD) are shown in Fig. 3. Following Camp and Elsberry[7], the MLD was defined as the deepest depth where temperature was lower than SST by 0.2°C in the individual BT profile. During the observational period, the MLD exhibited a shoaling tendency from 30 to 15 m and the SST registered an approximate increase of 0.5°C. The mixed layer shoaling is in accordance with near surface stratification as evidenced by an increase in the SST. The temperature at 75 and 100 m depths did not show any perceptible changes. But interestingly the temperature at 50 m depth dropped over 2°C. The coherence between the temperature fluctuations at 50 and 75 or 100 m depths is apparent only in the high frequency mode but not in the low frequency mode. But the magnitudes of these high frequency fluctuations at 50 m depth are not comparable to those at 75 or 100 m depths. This conspicuous feature led to probe the reasons for the observed drop only at 50 m depth.

Surface heat budget—As the mixed layer was shallower than 50 m, the heat budget processes which regulate the mixed layer temperature cannot obviously influence the temperature at this depth in the upper thermocline. On the other hand, the SST which is analogous to the mixed layer temperature showed an increase of 0.5°C during this period. Hence, the cooling caused by the surface heat exchange processes at this depth is a remote possibility. However, no attempt could be made to parameterise heat exchange terms due to lack of sufficient surface marine meteorological data.

Mixing in the upper thermocline due to current shear—Shear instability is known to be caused by currents flowing in opposite directions, breaking of internal waves, etc. can cause mixing, thus homogenising the vertical thermal regime[8]. Colder waters from below when mixed with warmer waters above can produce cooling at the intermediate depths. This possibility was explored with the aid of available current meter records. Although it would be ideal to have one current meter record above and one below the depth under study i.e. 50 m, in the present study current meter records available only at 50 and 75 m depths were made use of. The low pass filtered current vectors (alternate 20 min observations) at these two depths (Fig. 4), suggest that the flow was steady and was mostly south-southwestward with an average speed of about 30 cm.sec^{-1}. The coherence between the flow regimes at these two depths was also quite high. The resolved zonal and meridional components are shown in Fig. 5. In general, the current components were slightly stronger at 50 m depth compared to those at 75 m depth. The westward component gradually weakened at both the depths while the southward component was relatively steady at 50 m depth. A mild strengthening tendency at least up to 4 June is evident in the southward component at 75 m depth. These components also exhibit superposed oscillatory nature (5 waves) with an approximate period of 1.6 days which shows a very good agreement with the local inertial period at the station under reference. Inertial oscillations appear always during the period of calm following a period of wind[9]. Saelen[10] recorded inertial waves at 63°N off the Norwegian coast for several days after the passing of a well defined atmospheric low. Evidence of these oscillations in the subsurface temperature and current records was shown from a buoy in the Gulf of Mexico for several days after the storm passed away[2]. Rao[11] noticed these oscillations at the base of the mixed layer in the central Arabian Sea during the following 10 days when the onset vortex traversed north westward (at an average distance of 1000 km from the observational station). The observed oscillations in the current meter records perhaps suggest the influence of the meteorological depression.

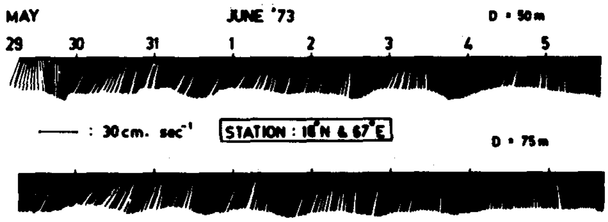

Fig. 4—Time series of low pass filtered current vectors at 50 and 75 m depths

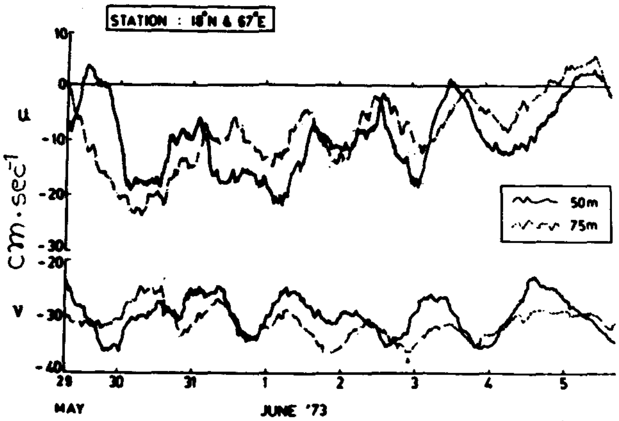

Fig. 5—Time series of zonal (u) and meridional (v) components of currents at 50 and 75 m depths

The temporal march of the derived vertical shear across the water column between 50 and 75 m depths is presented in Fig. 6. The corresponding variation in the dynamic stability (D)

$$D=\sqrt{\left(\frac{\partial u}{\partial z}\right)^2+\left(\frac{\partial v}{\partial z}\right)^2}$$

is also shown in this figure. The zonal shear was mostly positive (with the exception during the first 2 days) implying stronger westward flow at 50 m than at 75 m depth. Similarly the meridional shear was in general negative (again with the exception of the first 2 days) suggesting stronger southward flow at 75 m over that at 50 m depth. The resultant dynamic stability showed a progressive decrease with time. This reduction suggests suppression of the turbulence or strengthening of stratification between the depths under reference.

Munk and Anderson[12] reported that the effective vertical diffusivity in a turbulent, stratified fluid should depend strongly upon the Richardson number (Ri)

$$Ri=\left(\frac{g}{\rho}\frac{\partial\rho}{\partial z}\right)\Big/D^2$$

where g—the acceleration due to gravity, ρ—the density of the fluid, z—the vertical co-ordinate, u,v—the zonal and meridional components.

The Ri is a measure of the degree of balance between the stabilising effect of the density gradient and the destabilising effect of the mean velocity shear, and is an indicator of the degree to which mixing is suppressed by the density stratification[13]. In a stable stratified shear flow, the intensity of vertical mixing, represented by the vertical eddy viscosity coefficient (A_γ), is dependent upon the stratification and the shear represented by Ri. Halpern[8] presented a functional relationship between A_γ near-surface wind speed (V_{10}) and Ri as

$$A_\gamma = \frac{4.3\times10^{-4}\,V_{10}^2}{\sqrt{[1.0+10\,Ri]}}$$

The distributions of A_γ and Ri for the layer between 50 and 75 m depths are shown in Fig. 7. The progressive increase in Ri and decrease in A_γ clearly illustrate the reduction in the mixing caused by current shear instability. Hence the possibility of enhanced mixing caused by current shear also appears to be an unlikely candidate. Lateral eddy mixing is assumed to be of less importance as the station is not located in any of the known current boundary regions as the observed currents were also steady.

Advection of heat—Horizontal advection of cold (warm) waters produce cooling (warming) at a given depth. Upwelling produces cooling and downwelling results in warming. To parameterize these terms, simultaneous measurements of temperature gradients and the velocity components along three dimensions are required. Although such a data base is not available, an attempt is made to parameterize these lateral and vertical heat advection terms with the available limited data sets. The zonal thermal gradient at 50 m depth was estimated from BT casts made from an Indian research ship *INS Delhi* along 20°N (nearest available zonal leg) during the period 21 to 24 May 1973. This term $\partial T/\partial x$ at 50 m depth was approximately 1°C in 10° longitude (60°-70°E) with temperature increasing westward. The meridional thermal gradient at 50 m depth was estimated from Nansen casts made from the ship *R.V. Priliv* along 65°E (nearest available meridional leg) during 24-26 May 1973. This term $\partial T/\partial y$ at 50 m depth

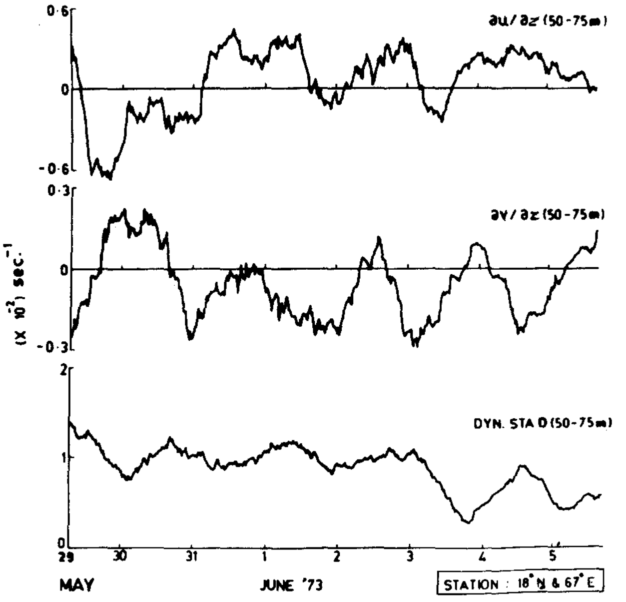

Fig. 6—Time series of zonal ($\partial u/\partial z$), meridional ($\partial v/\partial z$) current shears and dynamic stability (D) across 50 and 75 m depths

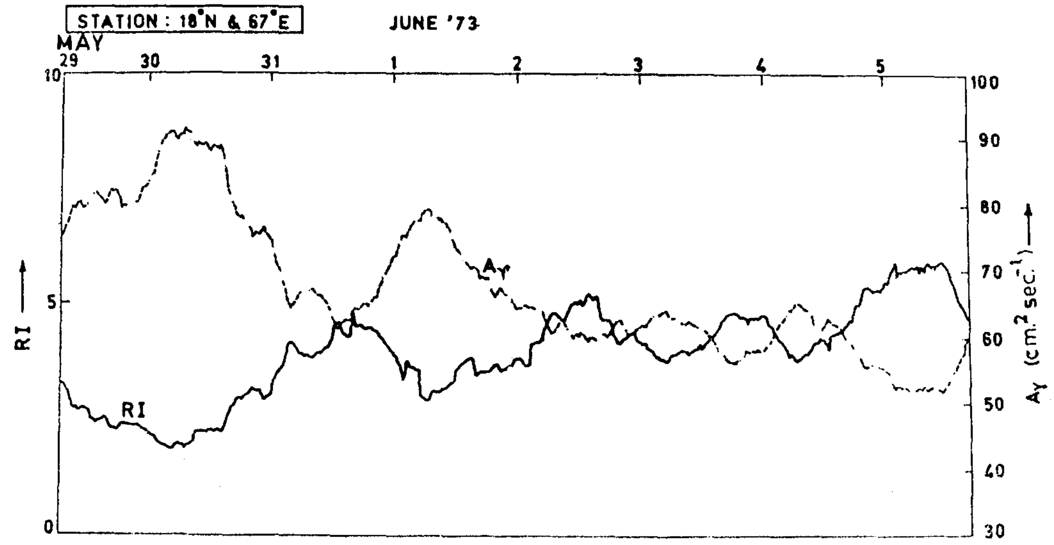

Fig. 7—Time series of Richardson Number (Ri) and vertical eddy viscosity coefficients (A_γ) across 50 and 75 m depths

was approximately 4°C in 10° latitude (12°-22°N) with temperature increasing southward. These estimates imply that meridional thermal gradient at 50 m depth in this area was 4 times stronger than the zonal thermal gradient. The vectorially averaged zonal and meridional currents at 50 m depth for the period 29 May to 5 June 1973 were -9.3 cm. sec^{-1} and -29.8 cm.sec^{-1} respectively. The observed flow in both the directions favour advection of colder waters at the station under study. But the southward transport term was stronger than the westward transport term by more than one order of magnitude. The estimated cooling $[(u\partial T/\partial x)+(v\partial T/\partial y)]$ with the aforementioned values works out to be 0.8°C during the 8 d period.

In the calculation of vertical advection of heat, determination of vertical velocity (w) is usually a difficult task as its order of magnitude is much smaller. The vertical velocity can be indirectly estimated from the slope of the subsurface isotherms from a depth-time temperature section after filtering out the influence of internal waves. In the present study, w was estimated from the depth-time section of temperature constructed from BT casts (Fig. 8). This figure clearly portrays the upsloping of a bunch of tightly packed isotherms with time, around 50 m depth. The average ascent rate of these isotherms (26° to 28°C) in the vicinity of 50 m depth was estimated to be ~ 1 m.d^{-1} (7.5 m from 29 May to 5 June). The average (29 May-5 June) vertical thermal gradient observed at 50 m depth was 1.5°C. 10 m^{-1}. This type of upwelling might have produced a cooling $(w\partial T/\partial z)$ of 1.2°C during the observed 8 d period. If these estimates are reasonably accurate, the observed drop in temperature at 50 m depth of 2°C can be accounted to cooling of 0.8°C due to lateral advection and 1.2°C due to vertical advection.

It would be rather difficult to explain the factors responsible for the observed horizontal currents and the inferred upwelling tendency from single point measurements alone due to non-availability of other complementary data sets (on the distributions of large scale surface wind stress and its curl over the Arabian Sea, the density structure in the upper layers of the surrounding areas, etc.) for the observational period.

When a meteorological disturbance passes over the ocean, the anticlockwise surface wind stress curl within the eyewall (radius of maximum winds) produces upwelling tendency in the upper layers below. Outside the eyewall, the clockwise curl produces downwelling tendency. The meteorological disturbance which traversed westward along 12.5°N must have produced such upwelling/downwelling tendencies in the upper layers of the sea. The station under study was located at an approximate distance of 1300 km to the centre of the system when the disturbance was most intense (27 May 1973). It is difficult to ascertain whether this system could have had its influence in producing such a downwelling tendency at this distant station. If such a proposition can be accepted, under its influence the mixed layer depth must have been depressed due to Ekman type of convergence. After the passage of the system, once the wind field relaxed, a retreat might had set in and accordingly the mixed layer and a bunch of isotherms just below the mixed layer might have shoaled to their pre-storm position. Such a retreat after the passage of a strom was noticed[14] in the upper layers of the Bay of Bengal during MONEX-79.

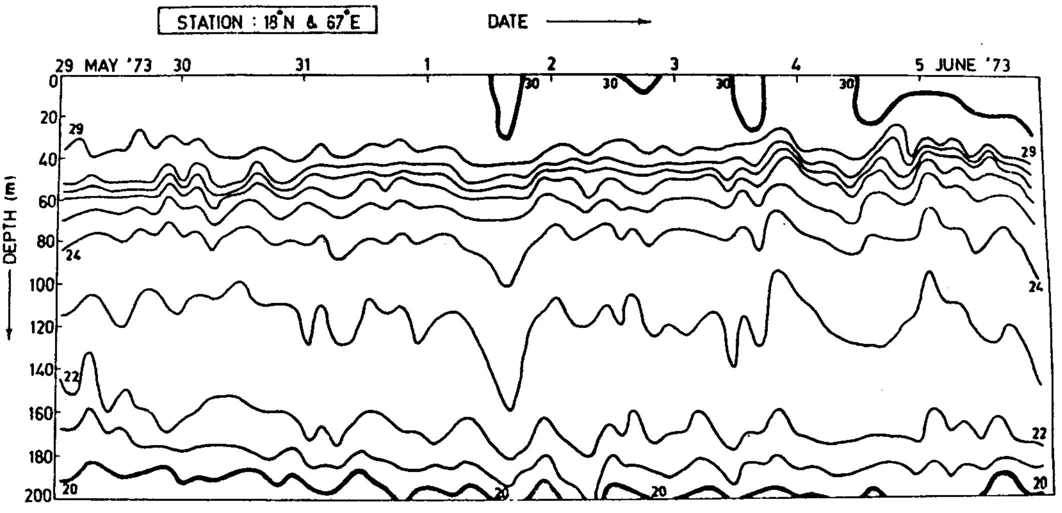

Fig. 8—Depth-time section of temperature in the upper 200 m water column

The large magnitude of w (1 $m.d^{-1}$) also suggests the probable influence of strong meteorological forcing regime that prevailed earlier.

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