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Simulation of the upper ocean thermal structure at the WHOI Arabian Sea mooring site

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We have forced an Ocean General Circulation Model (OGCM, MOM_4) with surface observations at the WHOI mooring site in the Arabian Sea blended with other data and compared the thermal and salinity structures of the resulting simulations with observations. The model is successful in reproducing observations during January-July 1995, but does poorly during the southwest monsoon season. We have analysed model simulations in detail to study the thermal structure and mixed layer variability and the performance of the model at the buoy location in the Arabian Sea.

[**Key words**: OGCM, MOM_4, Arabian Sea, WHOI buoy, mixed layer depth, thermocline variability]

Introduction

The importance of the tropical ocean in influencing global climate is well understood. The Indian Ocean, especially the Arabian Sea, is unique for many reasons. It is the only bounded ocean basin in the north. Further, the monsoon reversals and the resulting currents make it quite unlike other ocean basins. It is a region of intense air-sea interaction and plays a very significant role in climate variability.

In connection with the JGOFS campaign[1], the Woods Hole Oceanographic Institute (WHOI) established a time series at 61.5°E and 15.5°N (in Arabian Sea), (Fig. 1) which operated from October 1994-October 1995. For the first time an accurate and continuous record of near-surface meteorology were collected at the buoy site. From the recorded observations like surface parameters (wind velocities, short and long wave fluxes) and sub-surface parameters (temperature, salinity and velocities) a time series of latent and sensible heat fluxes, net shortwave radiation, net longwave radiation[1-4] were determined. The recording interval was 7.5 minutes.

Many modeling studies of Arabian Sea have used climatological forcings for the study of Arabian Sea circulation features and seasonal reversal of Somali current[5]. Young & Kindle[6], and Keen *et al*.[7] have suggested that in the Arabian Sea offshore advection of coastal upwelling is an active process, which contributes to productivity in the central basin. Simmons *et al*[8]. studied the upper layer circulation of the northwest Indian Ocean using a nonlinear reduced gravity model incorporating with realistic boundary geometry and forced with 1985 observed winds. Anderson *et al*[9]. used a 16-level general circulation model with a number of model geometries and wind forcing patterns for investigating the dynamics of the Somali current system during the SW monsoon. Bruce *et al*[10,11]. studied the eddy formation in the eastern Arabian Sea during the NE monsoon. Jensen[12] studied the equatorial variability using a wind driven layer model. Shankar & Shetye[13] investigated the dynamics of the Lakshdweep high and low using a

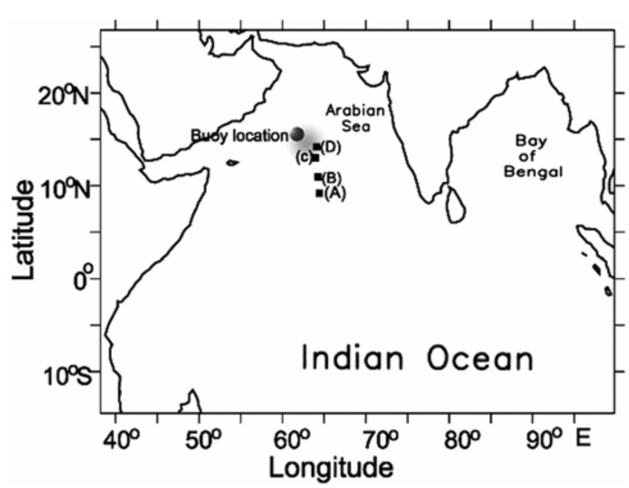

Fig. 1—Study area map

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reduced gravity model in the study of north Indian Ocean. Sengupta & Ravichandran[14], have analysed deep sea buoy data to study intraseasonal oscillations in SST and surface heat fluxes of Bay of Bengal.

Rochford *et al*[15]. used Naval Research Laboratory Layered Ocean Model (NLOM) to examine the sensitivity of the Ocean General Circulation Model (OGCM) calculations of mixed layer depth (MLD) and SST to the choice of forcing fields and compared with moored buoy observations for the period 1994-1995. Fischer[1] and McCreary *et al.*[16.] have attempted to model these observations using a reduced gravity model. Both of them were quite successful in simulating MLD and the temperature profiles during North East (NE) monsoon and spring intermonsoon period, but did not do well in July-October 1995 period. We have attempted a similar exercise, but with a full 3-D OGCM[17] and different physical parametrizations for simulating upper layer thermal structure and mixed layer variability of the buoy location in the Arabian sea.

Model and Forcing Fields

In this study we try to model the buoy observations using Modular Ocean Model (MOM-4), a contemporary OGCM. The domain of the model (Fig. 1) is 38°E-100°E (with 0.4° resolution), 15°S-27°N (with 0.4° resolution) and 35 levels in the vertical (10 m in the top 100 m and 17 m in the top 200 m). The domain is closed in all the sides with a sponge of 3° width and 30 day restoring applied at the northern and southern boundaries.

The physics of the model is neutral physics[18] for tracer diffusion and KPP[19] for vertical mixing. The 'Quicker' scheme is used for tracer advection. The time steps are 2700 sec for tracer, baroclinic and the "large"eta time steps and 60 sec for the free surface. A "weak" surface restoring of 30 days was imposed but as the results will show the restoring amount is very small and the thermodynamics is essentially under imposed flux control.

We have used the diagnostic monthly fluxes from a 50 year run as input to our model. These fluxes were used for the simulation of physical biological chemical model[20] simulation of the Indian Ocean, and these fluxes are in agreement with climatic atlas[21].

The surface buoy data which is at a high temporal resolution was blended with other gridded data sets at a coarser temporal resolution. For instance, the daily wind stress data from NCEP[22] was blended with the buoy data using a Gaussian weight spread over a radial distance of 4° from the buoy point. As a result, forcing data at the buoy point is identical to the measured value while those outside the blending

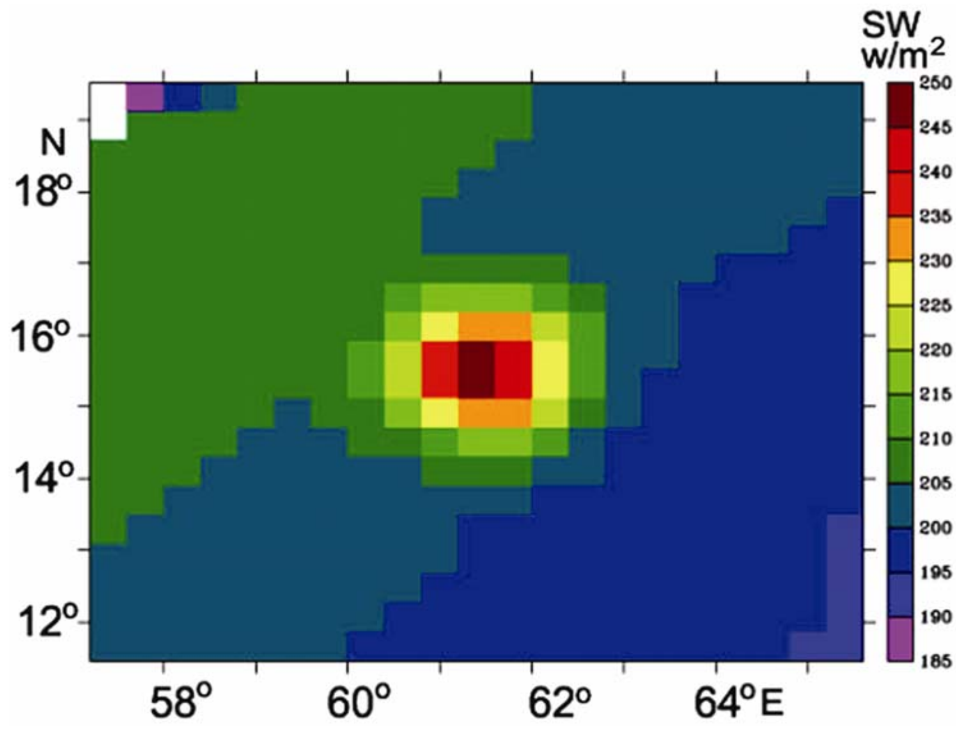

Fig. 2—Blending of WHOI measured shortwave radiation with climatic observations within a 4° radius from the buoy site (61.5°E, 15.5°N).

distance is NCEP wind stress. Within the blending region, the data is a linear combination of the two, weighted by the Gaussian distribution of the distance from the buoy point. An example of this blending is given in Fig. 2 where the effect of blending may be clearly seen. Other files which are similarly blended include heat and salt fluxes. While the model forcing for all fields is daily, we have allowed a diurnal variation of solar radiation by applying a cosine variation between 6 and 18 hours and zeroing it outside this time interval. The daily mean from this distribution is identical to the daily mean of the data[3,16].

The model is spun up with climatological data for 15 years and with daily NCEP data from 1st January - 20th October 1994. At this date, forcing is switched to the blended data as described above. No adjustment of temperature and salinity profile data is made in the model at the starting date.

Model performance

We have compared vertical profiles of temperature and salinity profiles from model simulations forced with daily NCEP wind stress for the year 1994 with a few of the JGOFS observations. Figure 3 shows the comparison of temperature profiles at four locations (A) 65°E, 9°N (B) 65°E, 12.06°N, (C) 64.99°E, 13.25°N) and (D) 66.88°E, 14.91°N for the year 1994 along with root-mean-square relative error (ε_{rms}) based on Roelvink[23]. Similarly Fig. 4 shows the salinity

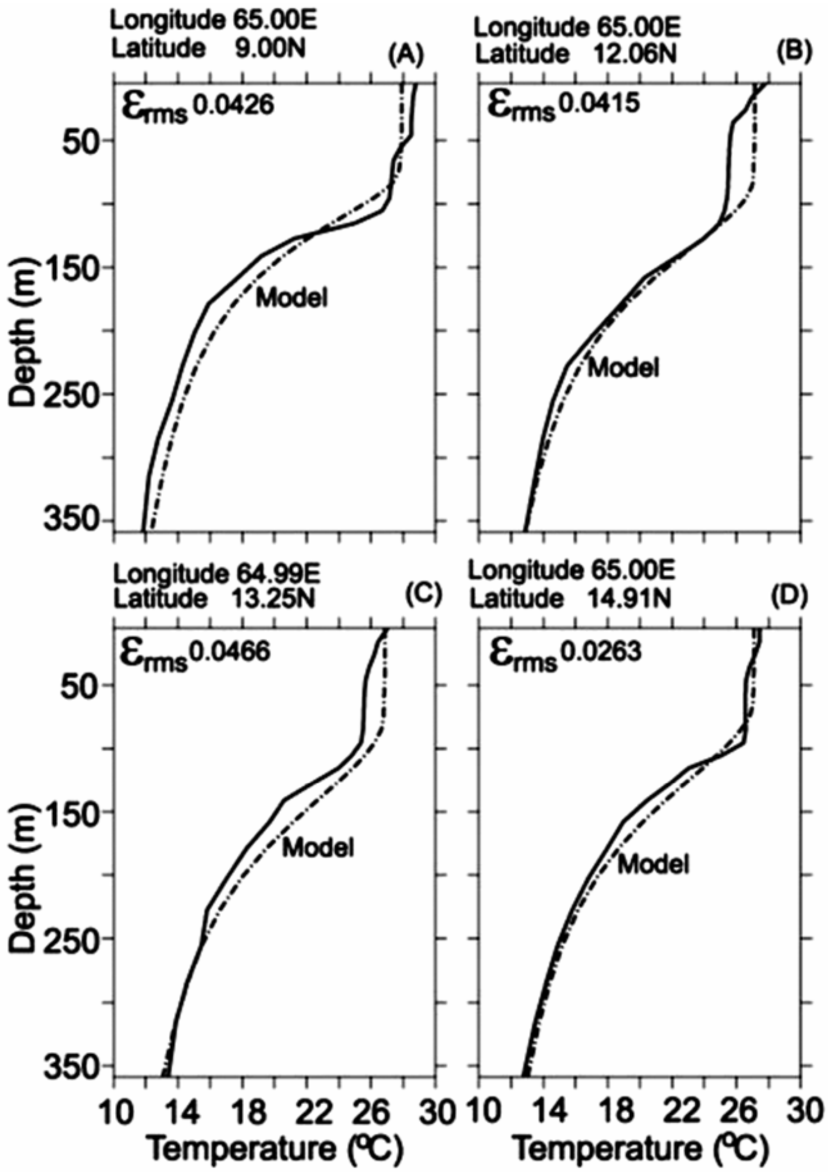

Fig. 3—Comparison of model simulated temperature profiles with U.S JGOFS observations at locations in September 1994.

profiles at the locations (Fig. 1). The inability of the model to simulate the upper ocean temperature at the locations B and C points (Fig. 3B, C) is possibly due to local forcing changes at very short time scales. The salinity section (Fig. 4) shows a reasonable agreement to data but the finer features are absent.

Figure 5 shows the net ocean surface heat flux for the years 1994 and 1995 at the buoy location. The northeast (NE) monsoon (November-January) was marked by a negative surface heat flux, while the SW monsoon (June-August) had a positive heat flux except for brief episodes in June and July. Also shown is the restoring flux that the model diagnoses, and is very small, suggesting that the model is responding to imposed fluxes.

Model-Buoy Inter Comparison

It is expected that the model would require a few months to adjust to the new high frequency forcing and we examine the results from January 1995 onwards.

Temperature and mixed layer depth (MLD)

Figure 6 shows the mixed layer depth which has been computed using the following definition: Mixed layer depth is the depth at which the temperature

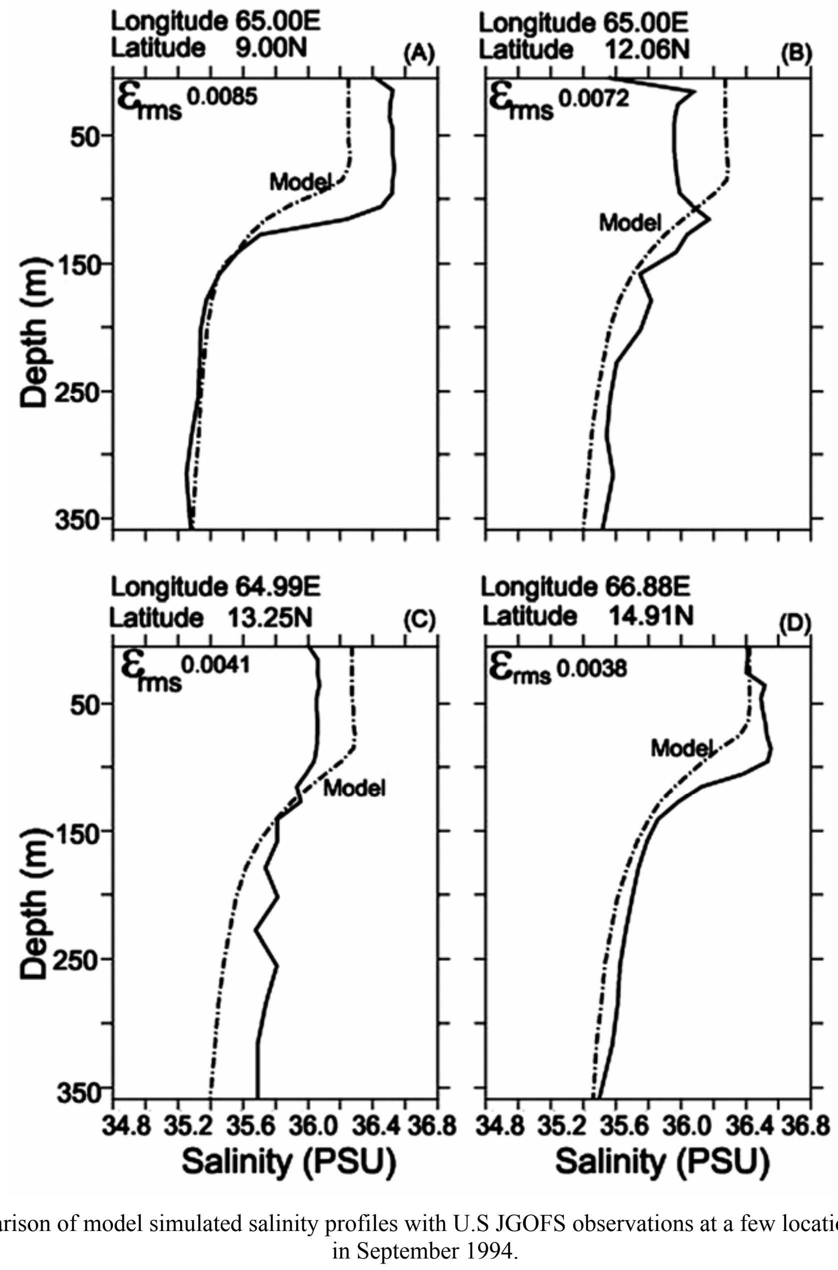

Fig. 4—Comparison of model simulated salinity profiles with U.S JGOFS observations at a few locations (transect-39) in September 1994.

differs by 0.1° C from the surface temperature. Notice that model has picked up the diurnal deepening and shallowing in the NE and SW monsoons quite well though there are other qualitative differences. During the southwest monsoon season, the mixed layer depth deepens with the onset of strong southwest monsoon, whereas during January to March mixed layer deepening is an account of negative buoyancy flux and the corresponding wind components are very weak. We have compared our model derived MLD which is saved at every six hourly intervals with buoy

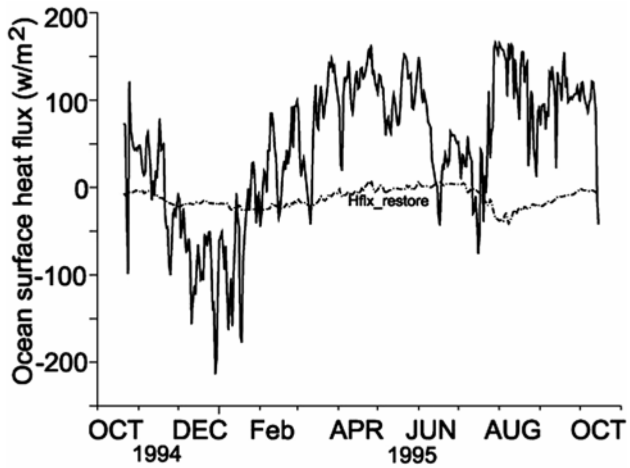

Fig. 5—Net surface heat flux derived from the model at WHOI buoy site for the period 1994 October-1995 October along with the restore term in W/m^2.

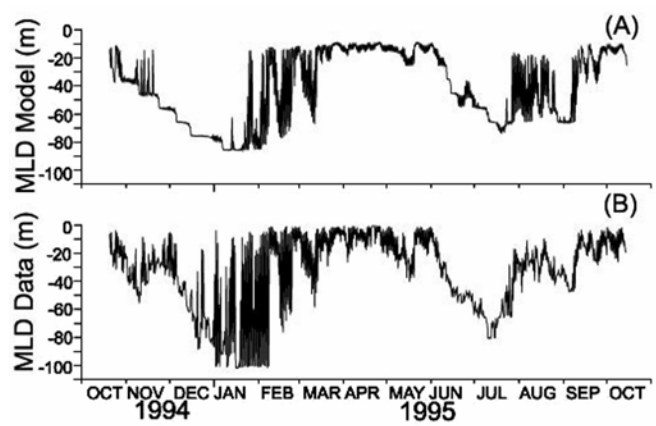

Fig. 6—Comparison of mixed layer depth (MLD) computed from the model derived temperature(A) at the WHOI buoy site with the observed (B) MLD for the period 1994 October-1995 October.

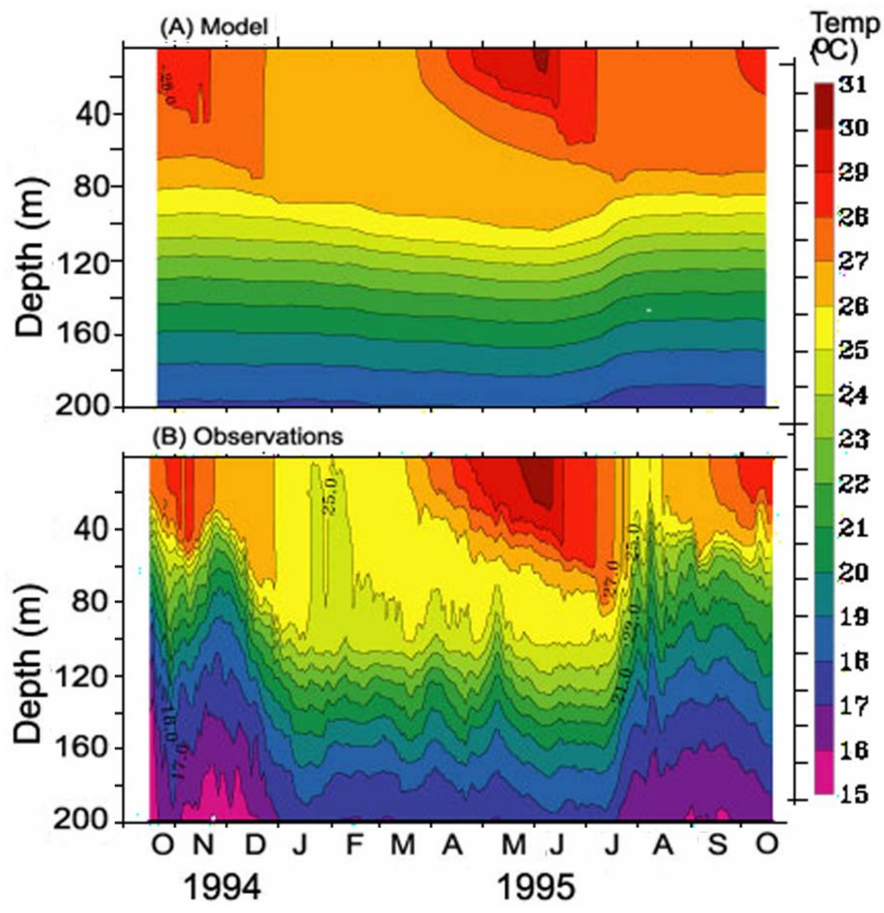

Fig. 7—Comparison of model temperature (A) at the WHOI buoy site with observations (B) for the period 1994 October-1995 October.

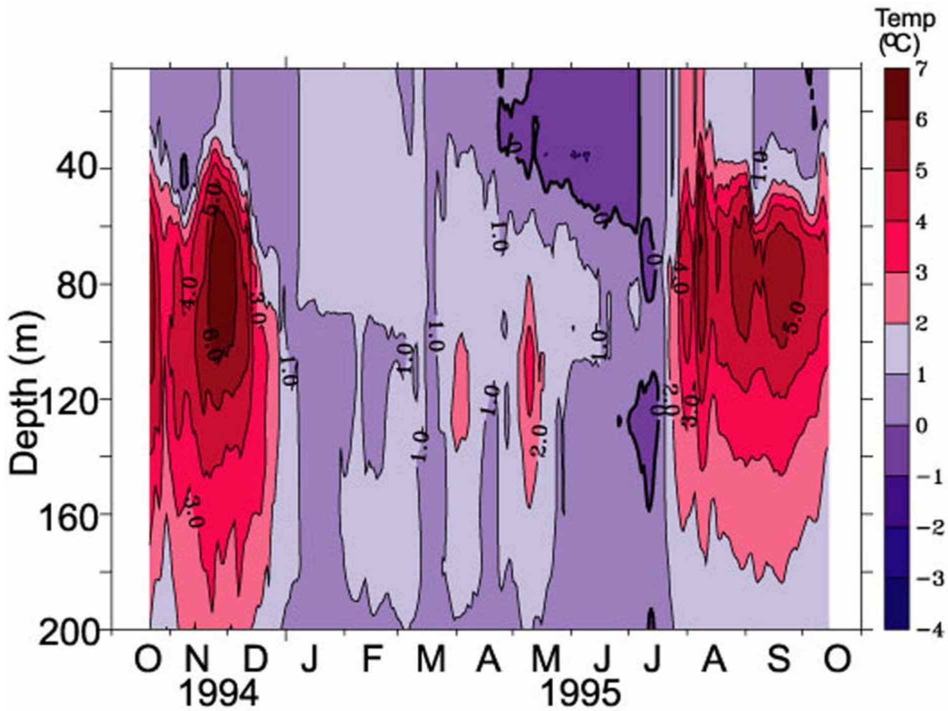

Fig. 8—Difference between model derived and observed WHOI buoy temperature (°C) for the period 1994 October-1995 October.

observations. The deepening and cooling of the mixed layer during NE monsoon is attributed to local forcing and primarily by the negative heat flux[2] and the changes observed during SW monsoon are mainly due to wind stress.

Figure 7 is the model-derived (A) vertical temperature section at the buoy location and Fig. 7B from buoy observations. We can see the evolution of temperature from cooling of the upper layer water in NE, warming during the spring intermonsoon and cooling again in SW. The small scale features which are seen in the observations are absent in the model simulations.

Figure 8 shows the difference between the model and buoy temperature profiles in the top 200 m. Note that they match within a degree at most depth until mid-July. Between July-October there are major differences between the two especially between the depths of 40-120 m. This is a region of intense cooling in the buoy data under a positive heat flux regime at the surface. We examine the terms in the energy equation to locate the source of this cooling.

Figure 9 shows the various terms of the energy equation, for the two monsoon seasons separately. Under the influence of the positive buoyancy flux, the two mechanisms capable of removing heat are enhanced mixing due to velocity shear at high winds and advection. Of the two it appears that advection is

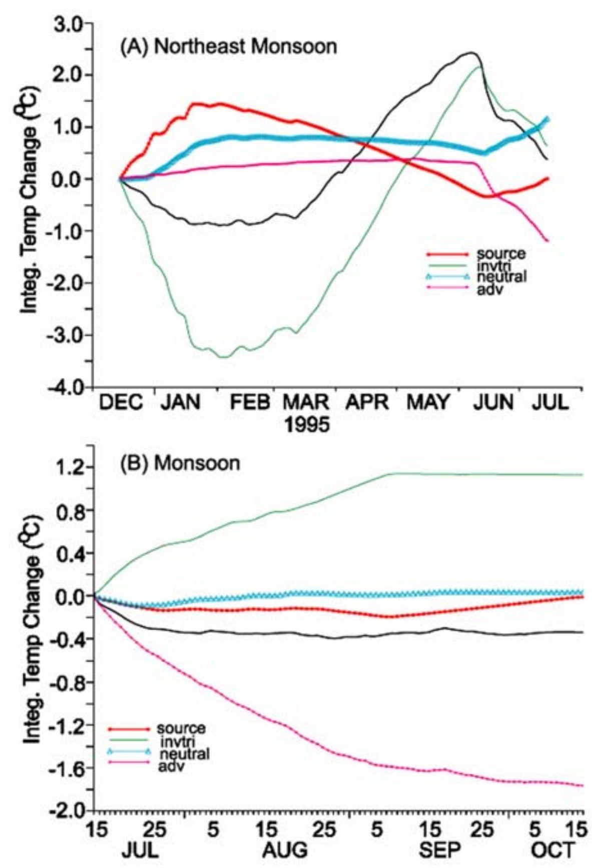

Fig. 9—Term balances of the temperature equation at the buoy site for northeast monsoon (A) and monsoon (B) seasons for period the 1994 December-1995 October.

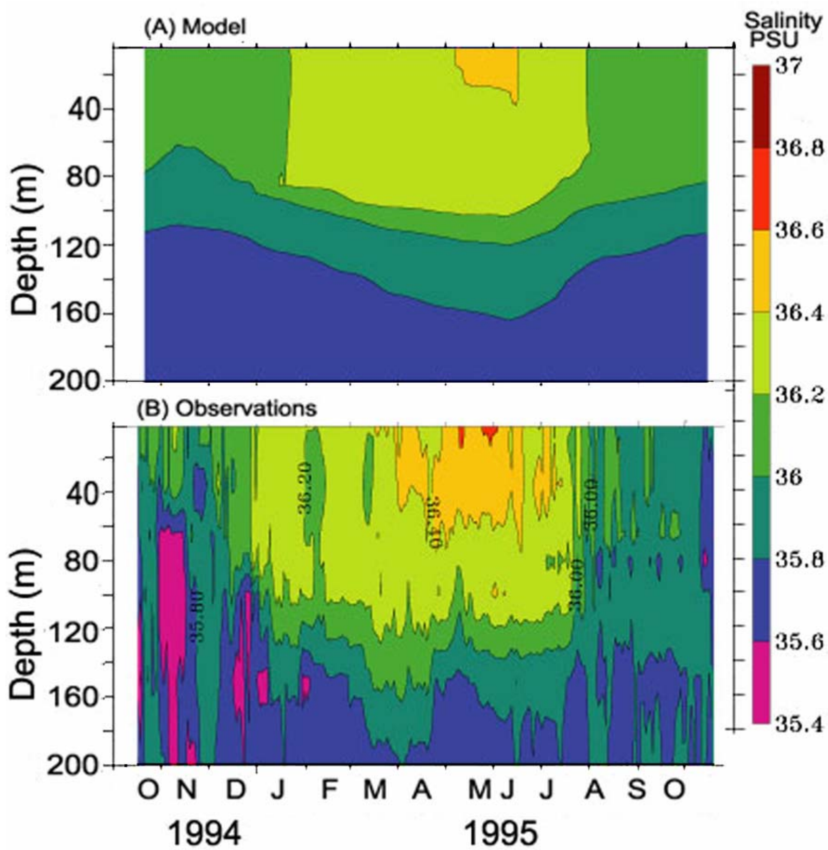

Fig. 10—Comparison of model salinity (A) at the WHOI buoy site with observations (B) for the period 1994 October-1995 October.

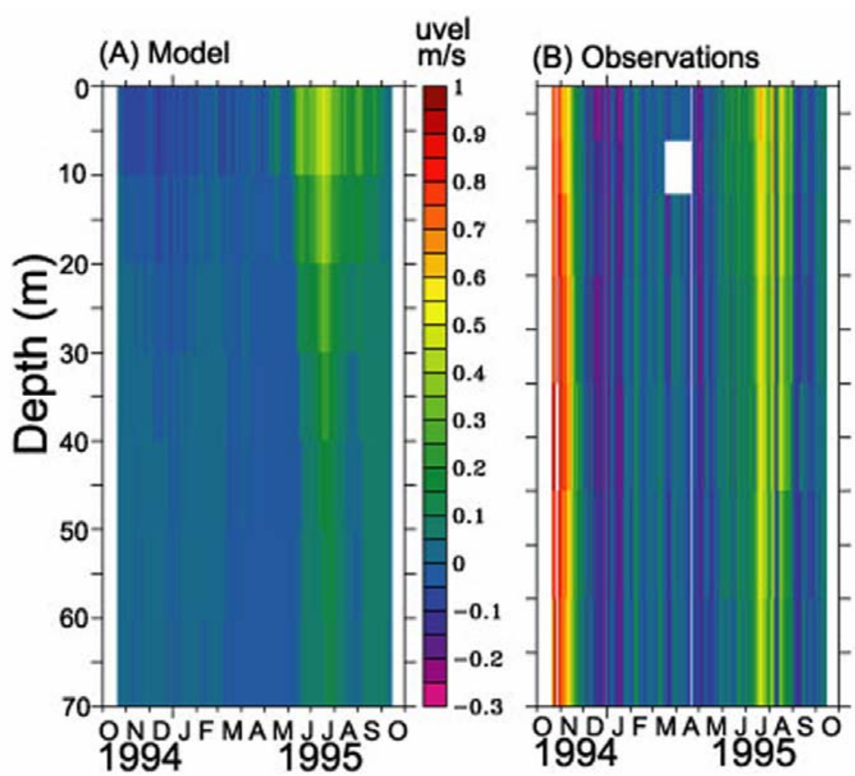

Fig. 11—Comparison of model zonal velocity (A) with observed velocity (B) at the buoy site for the period 1994 October-1995 October.

underestimated by a significant amount in the model at depths. This difference is attributed to offshore advection of cool coastal water filaments which the model is unable to capture with the current resolution[3].

Salinity from the model (Fig. 10A) has been compared with observations (Fig. 10B). Salinity in the top 200 m, is in good agreement with observations, although finer scale features are absent in the model. The salinity during the southwest monsoon of 1995 is almost uniform in the top 80 m both in observations and model simulations.

Figure 11 shows the comparison between modeled and measured zonal velocities. Note that the agreement between the two is far less than the one seen for temperature in Fig. 7. Many of the current reversals seen in the observations are missing in the model. We expect the simulations to improve when we add high frequency wind forcing and sea surface height changes to the model in future.

Conclusion

In this paper we have for the first time forced the Modular Ocean Model (MOM_4) with actual surface forcings of the WHOI Arabian Sea moored buoy and tried to simulate the thermal and salinity structure of the ocean. The model simulated thermal structure and salinity comparable well with observations in the top 200 m. The model is also able to simulate the diurnal variation of the mixed layer depth, especially the response to negative buoyancy fluxes during NE monsoon and increased winds in the SW monsoon. The reason for the disagreement between model and data during July-October period is attributed to local high frequency forcing which is not included in the model.

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