A Numerical Investigation of Mixed-layer Processes in the Arabian Sea

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LONG-TERM GOALS

My long-term research goals are to understand the dynamics, thermodynamics and mixed-layer physics that determine the coastal, equatorial and general ocean circulations.

OBJECTIVES

My objectives for this ONR project were first to develop an ocean model that can accurately simulate Arabian-Sea mixed-layer variability at diurnal through annual time scales, and then to diagnose the processes that account for this variability in its solutions. I particularly wished to be able to simulate and understand the mixed-layer-thickness record determined from the WHOI mooring data at 15.5°N, 61.5°N from October 1994 to October 1995 (Weller *et al*., 1998). Another objective was to investigate the influence of mixed-layer diurnal variability on bloom dynamics in the region using a coupled physical/biological model.

APPROACH

Most (if not all) oceanographic phenomena are too complicated to be understood with a single type of ocean model. Rather, a hierarchy of models is needed that varies in complexity from simple systems to state-of-the-art GCMs. In this study, I utilize a model of intermediate complexity, namely, a modified version of the McCreary *et al*. (1993) model that includes an extra layer to represent the diurnal thermocline.

WORK COMPLETED

Introduction: In two previous modeling projects, both partly supported by a previous ONR grant, we investigated Indian-Ocean dynamics, thermodynamics and mixed-layer processes (McCreary *et al*., 1993; MKM) and Arabian-Sea biological activity (McCreary *et al*., 1996; MKHO). The main-run solution of MKM was able to simulate prominent aspects of the climatological, upper-ocean circulation and mixed-layer thickness throughout the Indian Ocean. The MKHO main run was able to reproduce all the major Arabian-Sea phytoplankton blooms, a success certainly due in part to the MKM physical model being able to reproduce the annual cycle of mixed-layer thickness so well. In this report, I first discuss the improvements we have made to the MKM model that allow it to be able to represent diurnal variability properly, and then compare the mixed-layer-thickness field from a solution with that determined from the WHOI mooring data (Weller *et al*., 1998). Finally, I comment on preliminary results when the improved physical model is coupled to the MKHO biological model.

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Physical model: The model is a reduced-gravity system, consisting of 4 active layers with thicknesses h_i (i=1,4), overlying a quiescent, deep ocean where pressure gradients are assumed to vanish. Each of the layers represents either a specific water-mass type or a dynamically important region: the surface mixed layer (layer 1), the diurnal thermocline (layer 2), the seasonal thermocline (layer 3), and the main thermocline (layer 4). The bottom panel of Figure 1 illustrates the layer structure of the upper three layers, the interface beneath layer 4 (not shown) being located at a depth of about 350 m.

Water is also allowed to move across the interfaces between layers (that is, to entrain into or detrain from them) with velocities w_i. Velocity w_1 is crucial because it determines the model's mixed-layer physics. It is specified as in the Kraus and Turner (1967) model, in which entrainment and detrainment are related to the production of turbulent kinetic energy P by wind stirring W and the surface buoyancy flux B ($P=W–B$). It differs from the w_1 used by MKM primarily in the choice of the density jump at the base of layer 1, $\Delta\rho$: In MKM $\Delta\rho$ was set to a constant value of 0.0001 gm/cm^3 , whereas in the present model it is given realistically by the density difference between layers 1 and 2. This change is necessary so that $\Delta\rho$ can become small enough to allow h_1 to deepen rapidly at night when there is surface cooling: With MKM's choice, w_1 cannot thickens appreciably during the night, and hence h_1 always remains close to its daytime minimum.

The present model also differs from MKM by the inclusion of the diurnal thermocline layer. This additional layer allows the system to “remember”' physical and biological variables when the mixed layer thins during the day. Without it, variables are erroneously mixed down by the diurnal cycle into the seasonal-thermocline layer. Realizing the necessity for this layer, and then implementing it into the model, are the most significant advances we made on this project during the past year.

Forcing: The solution shown in Figure is forced as follows. For 5 years prior to April 1993, the model is driven by climatological FSU wind stress $\boldsymbol{\tau}$, and climatological fields of air temperature T_a, specific humidity q_a, net solar radiation Q_r, and scalar wind w_s (Rao *et al*., 1989, 1991). From April 1993 through October 1995, it is forced by FNMOC $\boldsymbol{\tau}$ and w_s fields (kindly provided by John Kindle), as well as climatological T_a, q_a, and Q_r fields. From October 1994 to October 1995 and within 500 km of the WHOI mooring (15.5°N, 61.5°E), daily-mean buoy data is blended into the forcing fields, in such a way that they are composed entirely of buoy data at the mooring site. Diurnal variability is introduced by specifying Q_r to go through a realistic daily cycle.

Results: Figure 1 plots mixed-layer thickness from the buoy data h_m (top panel) and from the solution h_1 (thick curve, bottom panel). The two thicknesses are strikingly similar. Note, for example, that their maximum values are large during the two monsoons (winter and summer) and thin during the transition seasons (spring and fall), and that their diurnal cycles are large during winter and small during the summer. The most prominent differences between the two thicknesses are that maximum h_m deepens (thins) at the beginning (end) of November 1994 and shallows during August 1995 but maximum h_1 does not, differences likely due to the passage of eddies through the mooring area (Weller, priv. comm.).

In the solution, and likely the observations as well, the difference in diurnal amplitudes between the two monsoons is due to the amplitude of wind stirring W. During the Northeast Monsoon, the winds and hence W are weak, so that P is dominated by $–B$, which changes sign daily (positive during the day due to Q_r and negative during the night due to latent heat loss); as a consequence, w_1 also changes

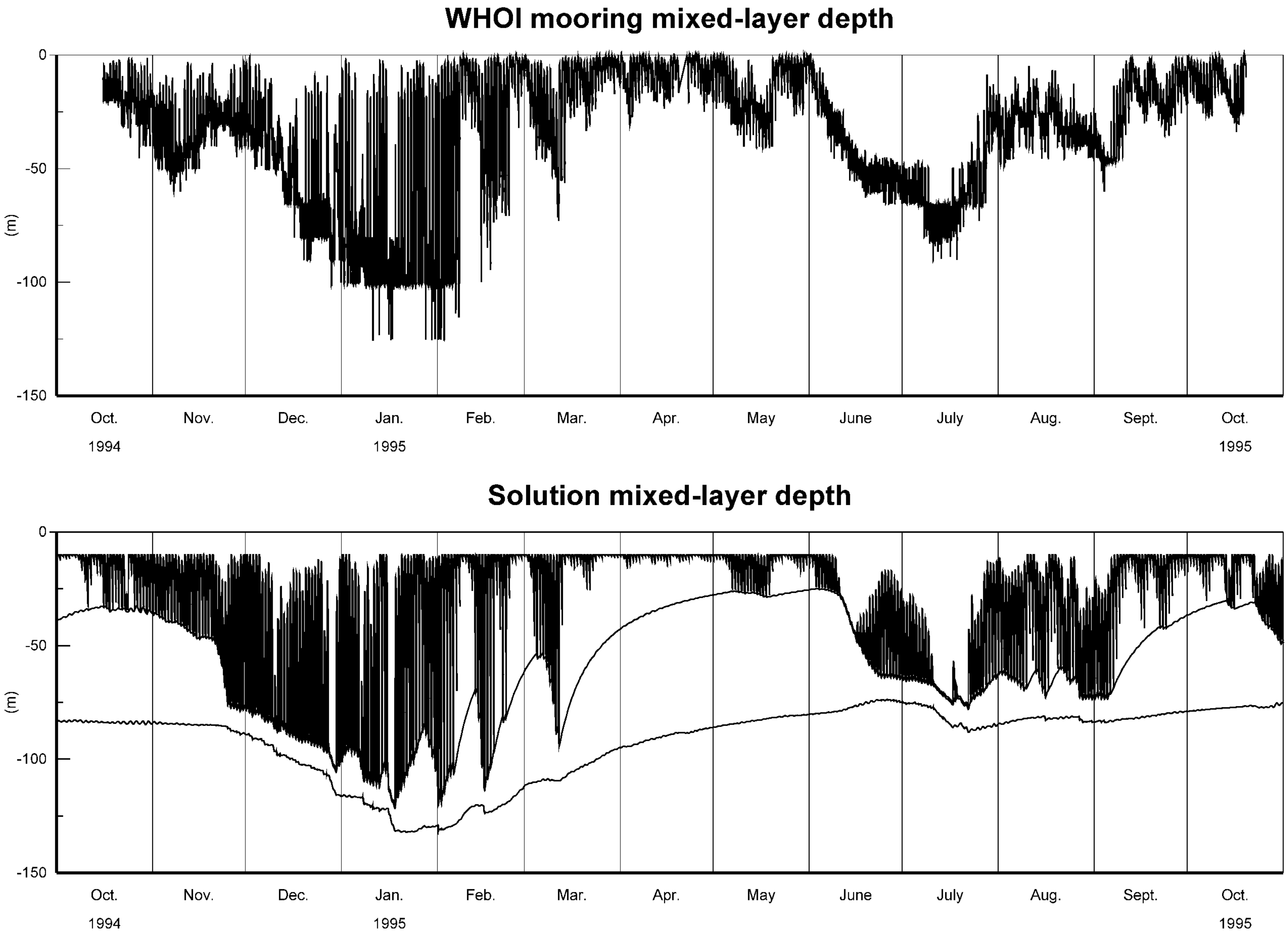

Figure 1: Time plots of mixed-layer thickness in the central Arabian Sea from the WHOI mooring h_m (top panel), as estimated by the depth at which ocean temperature is 0.1°C less than SST, and from the solution h_1 (bottom panel). The thin curves in the bottom panel are $h_1 + h_2$ and $h_1 + h_2 + h_3$. To ensure model stability, h_1 and h_3 are not allowed to become thinner than 10 m.

sign daily and the diurnal cycle is large. In contrast, W is large during the Southwest Monsoon, and it can become so large that P *never* changes sign so that there is no diurnal cycle at all. This situation happens for h_1 during the first half of July, and apparently (almost) occurs for h_m during most of the summer.

Coupled model: A deficiency of the MKHO solution is that its spring and fall blooms are too intense and short-lived in comparison with the observations, a limitation also shared by most other coupled systems. We hypothesized that the cause of this discrepancy is the lack of a diurnally varying mixed layer in the MKHO model as follows: In the MKHO solution, h_1 is thick enough during the winter and summer to suppress phytoplankton growth (by lowering the depth-averaged light intensity), and so the onset of blooms is delayed until the mixed layer thins at the end of each season; with diurnal variability h_1 could thin enough each day to allow phytoplankton growth, even though its daily-averaged value was too large to allow blooms to develop.

We have obtained a few initial solutions to an ecosystem model consisting of the MKHO biological model coupled to the improved physical model discussed above. They confirm that diurnal variability does broaden and weaken the spring and fall blooms, but not as much as much as we had expected. We are now exploring other ideas for overcoming this problem.

RESULTS

The primary result of this ONR project is the development of an ocean model of intermediate complexity (*i.e.*, one considerably simpler than a state-of-the-art GCM) that is able to reproduce mixed-layer-thickness variability at diurnal through annual time scales throughout the Indian Ocean, and in particular at the WHOI site. A key part of this development is the inclusion of a diurnal thermocline layer, which is essential for preventing spurious mixing of near-surface variables down into the seasonal-thermocline layer. Initial solutions to a coupled biological/physical model indicates that mixed-layer diurnal variability can influence Arabian-Sea blooms.

IMPACT/APPLICATIONS

The modeling techniques developed here have a general applicability in any modeling study of upper-ocean circulation or biology, particularly in regions where mixed-layer diurnal variability is important.

TRANSITIONS

The improved ocean model is being used in our NSF-sponsored research that investigates circulations throughout the Indian Ocean. As noted next in Related Projects, several other scientists are also utilizing versions of the model.

RELATED PROJECTS

Weiqing Han (my graduate student) and I are using the improved model to investigate effects of salinity variations throughout the Indian Ocean. Peter Webster (Univ. of Colorado) and Swadhin Behera (Frontier Research Group in Tokyo) are using it in their studies of the Indian-Ocean heat budget. Zuojun Yu (PMEL) has modified the code to be applicable to the Pacific Ocean, and is studying the 1997 ENSO as well as salinity effects in the tropical Pacific. Albert Fisher (WHOI) plans to use the model to continue his analyses of the WHOI Arabian-Sea mooring data.

REFERENCES

Kraus, E. B. and J. S. Turner, 1967: A one-dimensional model of the seasonal thermocline. II: The general theory and its consequences. *Tellus,* **119**, 98-106.

McCreary, J. P., P. K. Kundu and R. L. Molinari, 1992: A numerical investigation of the dynamics, thermodynamics and mixed-layer physics in the Indian Ocean. *Prog. Oceanogr.*, **31**, 181-244.

McCreary, J. P., K. E. Kohler, R. R. Hood and D. B. Olson, 1996: A four-component ecosystem model of biological activity in the Arabian Sea. *Prog. Oceanogr.*, **37**, 117-165.

Rao, R. R., R. L. Molinari, and J. F. Festa, 1989: Evolution of the climatological near-surface thermal structure of the tropical Indian Ocean, 1, Description of mean monthly mixed-layer depth and sea-surface temperature, surface-current, and surface meteorological fields. *J. Geophys. Res.*}, **94**, 10,801-19,815.

Rao, R. R., R. L. Molinari and J. F. Festa, 1991: *Surface meteorological and near surface oceanographic atlas of the tropical Indian Ocean*, NOAA Tech. Memo. ERL AOML-69, 59 pp.

Weller, R. A., M. F. Baumgartner, S. A. Josey, A. S. Fischer and J. C. Kindle, 1998: A one-year record of atmospheric forcing from the Arabian Sea. *Deep-Sea Res.* (In press.)