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NOVA UNIVERSITY
OCEANOGRAPHIC CENTER

September 18, 1992

Dr. Robert Peloquin
Office of the Chief of Naval Research
800 N. Quincy Street
Code 1242
Arlington, VA 22217-5000

Re: Final Report for ONR Grant..
N-00014-91-J-4008

Dear Dr. Peloquin:

The following letter is the final report for my ONR Grant No. N-00014-91-J-4008, entitled "Mixed-layer parameterizations in models of the Indian Ocean". I enclose two additional copies for your use. I have also sent copies to the Director of the Naval Research Laboratory in Washington D.C., the Director of the Naval Research Laboratory at the Stennis Space Center, our Administrative Contracting Officer, and 2 copies to the Defense Technical Information Center.

During the course of this research we have completed our initial Indian-Ocean study, and have submitted a paper describing that work to *Progress in Oceanography*. The paper is long and comprehensive, discussing dynamical, thermodynamical and mixed-layer processes in all regions of the Indian Ocean. One success of our "main-run" solution is that it is able to simulate the annual cycle of observed SST patterns everywhere in the Indian Ocean remarkably well. Another pleasing aspect is that the currents along the east and west coasts of India agree with the recent observations of Shetye and coworkers; this success suggests among other things that remote forcing by winds in the Bay of Bengal is an important driving mechanism for the west-coast currents throughout the year.

In spite of its successes, the model has limitations that point toward deficiencies in its mixed-layer physics. We hope to eliminate these deficiencies during the current research-year of our ongoing ONR grant. One goal of our present research is to include current shear within the upper layer of the model: the lack of this shear is the likely reason for discrepancies between model currents and ship-drift data at various locations in the tropical Indian Ocean, particularly in the southern Arabian Sea.

I believe I have already sent you a preprint of our paper. For your convenience, I conclude this report with the abstract from the paper, which outlines the research we have accomplished in a bit more detail:

ABSTRACT

A $2\frac{1}{2}$-layer, thermodynamic numerical model is used to study the dynamics, thermodynamics and mixed-layer physics of Indian-Ocean circulation. A surface mixed layer of temperature T_m is imbedded in the upper layer of the model, and entrainment and detrainment in the mixed layer are determined by wind stirring and surface cooling. There is also detrainment w_d through the base of the upper layer that models subduction. Monthly climatological data, including air temperature T_a and specific humidity q_a, are used to force the

model, but model sea surface temperature (SST), T_m, is used to determine the sensible and latent heat fluxes. With a few notable exceptions, our main-run solution compares well with observed current and SST data; this is particularly true for T_m, which typically differs from observed SST by less than 0.5 - 1.0°C. Our analysis focuses on three topics: the relative importance of *remote versus local forcing*, the *thermodynamic processes* that determine the model SST field, and the development of *meridional circulation cells.*

There are a number of examples of remotely forced circulations in our main run. During the spring a northeastward countercurrent flows against the prevailing winds along the Somali coast north of 4°N, and from October through February a southwestward Somali Undercurrent is present from the tip of Somalia to 3°N; both of these flows result in part from forcing during the previous Southwest Monsoon. From March through May there is another southwestward Somali Undercurrent south of 7°N, generated primarily by the propagation of a Rossby wave from the west coast of India. The currents along the west coast of India are either strongly influenced or dominated by remote forcing from the Bay of Bengal throughout the year. A northeastward flow is well established along the east coast of India in March, long before the onset of the Southwest Monsoon; it is remotely forced either by upwelling-favorable, alongshore winds elsewhere within the Bay of Bengal or by negative wind curl in the western Bay. Finally, the Agulhas Current is strengthened considerably in a solution that includes throughflow from the Pacific Ocean.

To investigate the relative importance of thermodynamic processes, we carried out a series of test calculations with various terms dropped from the T_m-equation. There is little effect on T_m when the sensible heat flux is set to zero, when temperature advection is deleted, or when the solar radiation field is replaced by a spatially smoothed version. Without entrainment cooling, T_m never cools during the summer in the intense upwelling regions in the northern ocean, and the annual-mean heat gain through the ocean surface reverses to become a net heat loss. In individual tests without entrainment cooling, with $T_a = T_m$ and with q_a set to 80% of its saturated value q_s, model SST warms near the northern and southern boundaries during their respective winters by about 1°C, indicating that several processes contribute to wintertime cooling. The T_m field degrades considerably in a single test run with both $T_a = T_m$ and $q_a = .8q_s$, so that one or the other of these external forcing fields is required to be able to simulate SST accurately.

The annual-mean circulation has two meridional circulation cells. In the Tropical Cell water subducts in the southern ocean, flows equatorward in the lower layer of the western-boundary current, and is entrained back into the upper layer in the open-ocean upwelling regions in the southern ocean. In the Cross-Equatorial Cell the subducted water crosses the equator near the western boundary, where it is entrained in the regions of intense coastal upwelling in the northern ocean. The strength of the cells is directly related to the assumed magnitude of the subduction rate w_d, but their structure is not sensitive to the particular parameterization of w_d used.

Sincerely,

Julian P. McCreary, Jr.

jpm:km

cc: Director Naval Research Laboratory, Washington
Director Naval Research Laboratory, Stennis Space Center
Mr. Matt Mietala, Administrative Contracting Officer
Defense Technical Information Center