

# Improving the Skill of Ocean Mixed Layer Models

Lakshmi Kantha

CB 429, University of Colorado, Boulder, CO 80309-0429

Phone: 303-492-3014 Fax: 303-492-2825 Email: [kantha@colorado.edu](mailto:kantha@colorado.edu)

Grant Numbers: N00014-03-1-0488 and N00014-05-1-0759

<http://case.colorado.edu/~kantha>

## LONG-TERM GOALS

The long-term goal of this effort is to improve the skill of modern 3-D numerical ocean circulation models used for studying the oceans, and in operational centers, for nowcasting/ forecasting the oceanic state.

## OBJECTIVES

The principal objective of this research is to improve second moment closure-based ocean mixed layer models that are in current (and potential future) use in Navy community and operational ocean circulation models.

## APPROACH

Extensive research over the past three decades has established second moment closure (SMC) as a reasonable compromise between resource-intensive techniques such as large eddy simulations (LES) and simple bulk mixed layer models (for example Large et al. 1994). The SMC approach in its most practical form reduces to a two-equation model of turbulence, with prognostic equations for the turbulent kinetic energy (TKE) and the turbulence length scale (TLS), and algebraic expressions for the mixing coefficients (Mellor and Yamada 1982; Galperin, Kantha, Hassid and Rosati 1988; Kantha and Clayson 1994 & 2000). These so-called algebraic stress closure models have become the mainstay of the US Navy operational ocean and atmosphere forecast models, for example the Shallow Water Analysis and Forecast System (SWAFS) run routinely at NAVOCEANO and Coupled Ocean Atmosphere Mesoscale Prediction System (COAMPS) run at FNMOC, as well as many civilian operational (NOAA NCEP) and research (NCAR WRF) forecast systems.

However, three decades of research and over a decade of operational use have exposed some shortcomings of the current SMC-based OML models. For example, the popular Mellor-Yamada (MY) OML models in Navy operational use, have a tendency to under predict mixing and hence overestimate upper layer currents and SST. A related problem is the underestimation of the Monin-Obukhoff similarity function  $\Phi_M$  in the surface layer of the atmospheric boundary layer (ABL) under unstable conditions (as in Mellor 1973). Advances in turbulence research using methodologies such as LES, direct numerical solutions (DNS) and renormalization group analysis (RNG) have also exposed some conceptual weaknesses. The most glaring conceptual weakness is the one related to the prescription of the turbulence length scale. MY models use an ad-hoc wall correction to their TLS equation (Mellor and Yamada 1982), whereas the K- $\epsilon$  (TKE and its dissipation rate) model used extensively by the European community (for example Rodi 1987) exhibits disturbing singular behavior in parts of the

parameter space (Burchard and Deleersnijder 2001). Another drawback is the local nature of the closure that does not work well under free convection conditions. Yet another is ignoring the very important influence of surface gravity waves on mixing in the upper ocean. None of the Navy community ocean models such as ROMS/TOMS, NCOM and HYCOM incorporate surface wave effects; neither do they account for non-local effects under convection.

Our approach to solving these problems is to examine critically the basic concepts underlying SMC models and incorporate recent advances in turbulence modeling research into second moment closure-based OML models. These advances are based on our increased understanding of turbulence in stratified fluids gained from observations, and large eddy simulations (LES), direct numerical simulations (DNS) and renormalization group (RNG) analysis of turbulence. The resulting OML model will be tested against available observational data to quantify improvements in modeling skill. We collaborate closely with LES and RNG researchers to derive benefits from their expertise and experience in dealing with turbulence, and to bring some cross-fertilization into this field.

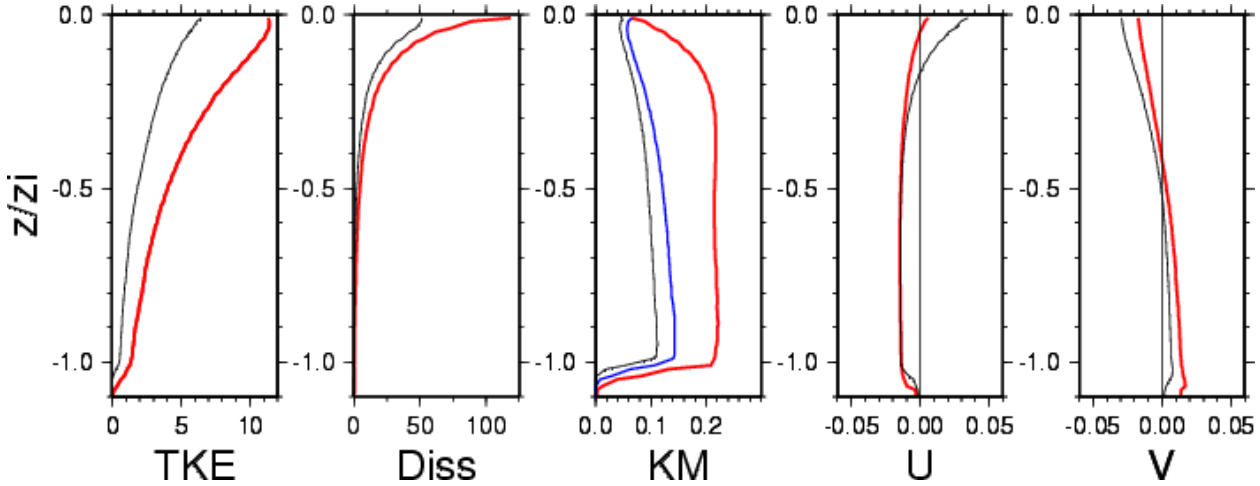
Observational data to compare with turbulence models are scarce. Microstructure measurements have not become a routine staple of oceanographic measurements as CTD casts have been for decades. This has led us to propose making microstructure measurements during NRL/NURC 2006 DART cruises in the Adriatic Sea. Under a related NICOP funding to Dr. Sandro Carniel of ISMAR, Italy, we have begun a collaborative effort to take part in the winter and fall 2006 DART cruises, collect turbulence data using a microstructure profiler, and along with other complementary oceanographic data collected during the cruises, assess the skill of the mixed layer model in ROMS run for the Adriatic Sea.

## **WORK COMPLETED**

We have refined the closure constants in SMC models for better performance under free convection. We have reexamined the entire question of the turbulence length scale prescription and demonstrated that all the different approaches proposed since Kolmogoroff (1942) are equivalent, and a general equation for the quantity  $q^m L^n$  can be derived, from which the various approaches proposed over the past five decades can be derived as subsets, provided proper attention is paid to the modeling of the diffusion terms and the values of various turbulent Prandtl numbers. We have also incorporated the effect of surface waves including wave breaking and Langmuir turbulence into OML models. We have explored the consequences of incorporating Langmuir turbulence on the velocity structure in the mixed layer. We have shown that surface gravity waves transfer energy to turbulence in the mixed layer by the action of the Reynolds stress against the vertical shear due to the wave-induced Stokes drift. We have also shown that this transfer constitutes an important loss mechanism for swell propagating across ocean basins. We have formulated a universal two-equation turbulence model that can simulate any existing two-equation model such as the *k-epsilon*, *k-omega*, *k-kL*, *k-ktau*, *k-tau*, and *k-L* model. We have examined the efficacy of non-local models and demonstrated the importance of proper parameterization of the diffusion terms (third order moments). We have reexamined the classic experiments by Dickey and Mellor (1980) on turbulence decay and demonstrated that these observations can be explained without invoking a drain of TKE into internal waves. We have also applied SMC to explain the difference between mixing produced by plunging and that produced by spilling waves in the surf zone. We have started working with the turbulence module of the ONR-supported ROMS/TOMS model. The Adriatic Sea version of the model will be run during the DART cruises.

## RESULTS

Proper formulation of TLS equation enables any existing 2-equation model such as the *k-epsilon*, *k-omega*, *k-kL*, *k-ktau*, *k-tau*, and *k-L* model to be simulated. Including the transfer of energy from surface waves to turbulence via the interaction of the Reynolds stress and wave-induced Stokes drift intensifies mixing throughout the ML and changes the velocity structure in the oceanic mixed layer (see Figure 1). Wave breaking also enhances mixing but only in layers adjacent to the free surface. The refinement of second moment closure constants eliminates the long-standing problem in Mellor-Yamada type closure models of underestimation of the Monin-Obukhoff similarity function  $\Phi_M$  in the surface layer of the atmospheric boundary layer (ABL) under unstable conditions. The popular Kantha and Clayson (1994) mixed layer model is being updated to incorporate these latest advances. A generic closure model is also being constructed. The question of improved performance under unstably stratified flow conditions is being addressed via non-local closure models. The down-the-gradient model for diffusion terms has been reexamined, based on the work of Dr. Vittorio Canuto's group at NASA Goddard Institute for Space Studies (GISS), which has used RNG methodology to advance our understanding of turbulence over the past decade (Canuto et al. 2002). Their most recent work (Cheng et al. 2004) involves a complex model for convective turbulence and we are examining ways to simplify it and bring it within the framework of 2-equation closure models. An alternative explanation for the decay of turbulence in stably stratified fluid in the classic experiments of Dickey and Mellor (1980) has been offered, in which the internal wave field seen in the experiment is postulated to have been generated in the beginning during the passage of the grid. Several papers have been published; more are in the works (see the publication list).



**Fig. 1. The influence of a monochromatic surface gravity wave (wavelength of 60 m,  $kD = 3.47$ , Langmuir number  $Ln = 2.24$ ) on properties in the mixed layer (depth  $D = 33\text{m}$ ). From left to right: turbulence kinetic energy, its dissipation rate, mixing coefficient for momentum, the velocity components in the direction of the wind and perpendicular to the wind, with (red line) and without (black line) the inclusion of Langmuir turbulence. Note the significant enhancement of turbulence throughout the mixed layer.**

## IMPACT/APPLICATIONS

Accurate depiction of many quantities of interest to worldwide naval operations, such as the upper layer temperature and currents, requires the use of skillful ocean mixed layer (OML) models. Operationally, this contributes to better counter mine warfare capabilities through better and more accurate tracking of drifting objects such as floating mines. Other drifting materials such as spilled oil are also better tracked and counter measures made more effective. Other applications include search and rescue. The improved mixed layer model code will be transitioned to Navy modelers for possible use in their community and operational models.

## RELATED PROJECTS

NICOP with Dr. Sandro Carniel of ISMAR, Venice, Italy

## REFERENCES

- Burchard, H. and E. Deleersnijder, 2001: Investigating the stability of algebraic non-equilibrium second-moment turbulence closure models. *Ocean Modeling*, 3, 33-50.
- Canuto, V. M., A. Howard, Y. Cheng, and M. S. Dubovikov, 2002: Ocean turbulence. Part II: Vertical diffusivities of momentum, heat, salt, mass and passive scalars. *J. Phys. Oceanogr.*, 32, 240-264.
- Cheng, Y., V. M. Canuto, and A. M. Howard, 2002: An improved model for the turbulent PBL. *J. Atmos. Sci.*, 59, 1550-1565.
- Cheng, Y., V. M. Canuto, and A. M. Howard, 2004: Non-local convective PBL model based on new third and fourth order moments. *J. Atmos. Sci.*, (submitted).
- Galperin, B., L. H. Kantha, S. Hassid, and A. Rosati, 1988: A quasi-equilibrium turbulent energy model for geophysical flows. *J. Atmos. Sci.*, 45, 55-62.
- Kantha, L. H., and C.A. Clayson, 1994. An improved mixed layer model for geophysical applications. *J. Geophys. Res.*, 99, 25,235-25,266.
- Kantha, L. H., and C. A. Clayson 2000. *Small Scale Processes in Geophysical Flows*. Academic Press, pp 888.
- Kolmogoroff, A. N., 1942: Equations of turbulent motion of an incompressible fluid. *Izvest. Akad. Nauk. USSR, Ser. Phys.*, 6, 56-58.
- Langmuir, I., 1938: Surface motion of water induced by wind, *Science*, 87, 119-123.
- Large, W. G., J. C. McWilliams, and S. C. Doney, 1994: Oceanic mixing: A review and a model with a nonlocal boundary layer parameterization, *Rev. Geophys.*, 32, 363-403.
- Mellor, G. L., 1973: Analytical prediction of the properties of stratified planetary surface layers. *J. Atmos. Sci.*, 30, 1061-1069.

- Mellor, G. L., and T. Yamada, 1982: Development of a turbulence closure model for geophysical fluid problems, *Rev. Geophys. Space Phys.*, 20, 851-875.
- Mironov, D. V., V. M. Gryanik, C. H. Moeng, D. J. Olbers, and T. Warncke, 2000. Vertical turbulence structure and second moment budgets in convection with rotation: A large eddy simulation study. *Q. J. Roy. Meteorol. Soc.*, 126, 477-515.
- Rodi, W., 1987: Examples of calculation methods for flow and mixing in stratified fluids. *J. Geophys. Res.*, 92, 5305-5328.

## **PUBLICATIONS (REFEREED) RESULTING FROM THIS GRANT**

1. Kantha, L. H., 2003a. On an improved model for the turbulent PBL, *J. Atmos. Sci.*, 60, 2239-2246.
2. Kantha, L. H., 2003b. Reply to Comments on "On an improved model for the turbulent PBL," by Canuto et al., *J. Atmos. Sci.*, 60, 3047-3049.
3. Kantha, L. H. and S. Carniel, 2003. Comments on "A generic length-scale equation for geophysical turbulence models," by L. Umlauf and H. Burchard, *J. Mar. Res.*, 61, 693-702.
4. Kantha, L. H., 2004a, A general ecosystem model for applications to carbon cycling and primary productivity studies in the global oceans, *Ocean Modelling*, 6, 285-334.
5. Kantha, L. H., 2004b. The length scale equation in turbulence models. *Nonlin. Processes Geophys.*, 11, 83-97.
6. Kantha, L. and C. A. Clayson, 2004. On the effect of surface gravity waves on mixing in an oceanic mixed layer, *Ocean Modelling*, 6, 101-124.
7. Kantha, L. H., 2005a. Comments on "Turbulence Closure, Steady State, and Collapse into Waves" by H. Baumert and H. Peters, *J. Phys. Oceanogr.*, 35, 131-134.
8. Kantha, L. H., 2005b. Oceanic mixed layer. In *Marine turbulence*, eds. H. Baumert, J. Simpson and J. Sundermann, Cambridge University Press, 244-249.
9. Kantha, L. H., 2005, Comments on "Oscillatory bottom boundary layers", *J. Phys. Oceanogr.*, 35, 1297-1300.
10. Kantha, L., J.-W. Bao and S. Carniel, 2005, A note on Tennekes hypothesis in second moment closure models, *Ocean Modelling*, 9, 23-29.
11. Onken, R., A. R. Robinson, L. H. Kantha C. J. Lozano, J. P. Haley, and S. Carniel, 2005, Inter-model nesting and rapid data exchange in distributed systems, *J. Marine Syst.*, 56, 45-66.
12. Nagai, T., H. Yamazaki, H. Nagashima and L. H. Kantha, 2005, Field and numerical study of entrainment laws for surface mixed layer. *Deep-Sea Res. II*, 52, 1109-1132.
13. Kantha, L. H., 2006. A note on the decay rate of swell, *Ocean Modelling*, 11, 167-173.

## PAPERS IN EUROPEAN JOURNALS

1. Carniel, S., L. Kantha, and M. Sclavo, 2004. Influence of Langmuir cells on the velocity structure in the mixed layer, *Annalen Hydrographiques*, Shom ed., 6e serie, Vol. 3, 8-1/8-5.
2. Carniel, S., M. Sclavo, L. Kantha and C. A. Clayson, 2005, Langmuir cells and mixing in the upper ocean, *Il Nuovo Cimento*, 3, 8/1-8/5.

## CONFERENCE PRESENTATIONS

1. Carniel, S., L. Kantha, and M. Sclavo, 2003, The influence of Langmuir cells on the velocity structure in the mixed layer, *Workshop on Waves and Operational Oceanography*, Brest, France, June 23-24, 2003.
2. Clayson, C. A., L. Kantha and S. Carniel, 2004. A non-local second moment closure model applied to convective boundary layers. Extended Abstract (P5.3), *16<sup>th</sup> AMS Symposium on Boundary Layers and Turbulence*, Portland, Maine, Aug 9-14, 2004.
3. Clayson, C. A., S. Carniel, and L. Kantha, 2004. A generic two-equation turbulence model for geophysical applications. Extended Abstract Abstract (5.3), *16<sup>th</sup> AMS Symposium on Boundary Layers and Turbulence*, Portland, Maine, Aug 9-14, 2004.

## PAPERS IN THE PIPELINE

1. Kantha, L. H., 2006. Comments on “Second-order turbulence closure, models for geophysical boundary layers. A review of recent work,” *Continental Shelf Research* (under review).
2. Kantha, L. H., 2006, Modeling grid-generated turbulence in a stably stratified fluid, *Phys. Fluids* (rejected but being resubmitted elsewhere).
3. Kantha, L. H., 2006, A note on modeling the turbulence generated by spilling and plunging waves in the surf zone, *J. Coastal Res.* (rejected but being resubmitted elsewhere).