Astronomical Tides and Turbulent Mixing in ROMS/TOMS

Lakshmi Kantha
CB 429, University of Colorado, Boulder, CO 80309-0429
Phone: 303-492-3014   Fax: 303-492-2825   Email: kantha@colorado.edu

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http://ocean.colorado.edu/kantha

LONG-TERM GOALS

The long-term goal of this effort is to improve the Navy community ocean circulation model ROMS/TOMS by incorporating astronomical tidal forcing and the latest developments in turbulent mixing.

OBJECTIVES

The principal objective of this research is to improve subgrid-scale parameterization in Navy community and operational ocean circulation models. This is to be accomplished by assessing and refining turbulent mixing parameterization as well as including comprehensive direct astronomical tidal forcing of importance to many semi-enclosed marginal seas.

APPROACH

The approach is to incorporate latest developments in turbulence and tidal research and modeling into ROMS. This project complements well, the AESOP program, the ONR DRI on subgrid-scale parameterization and skill assessment of numerical ocean models as well as the new Characterization and Modeling of Archipelago Strait Dynamics (CMASD) DRI. Using the Adriatic Sea (and North Indian Ocean) ROMS/TOMS as the test bed, we are incorporating direct astronomical forcing of the 11 major tides in the global ocean: semidiurnal M_2, S_2. N_2, K_2; diurnal K_1, O_1, P_1 and Q_1; long period Mf, Mm and Ssa. The co-oscillating barotropic tides are prescribed from Kantha's tidal model. Note that many global ocean models such as the ones resulting from NASA initiatives do not perform well in some marginal seas and it is essential that a regional model be used. Note also that compound tides such as M_4 will be generated by the nonlinear model itself and is an indirect result of the principal astronomical tidal forcing.

The latest Kantha and Clayson (2004) turbulent mixing model based on second moment closure is being incorporated into ROMS/TOMS. This model includes the effect of surface waves. No other turbulence model does at present. The inclusion of surface wave effects especially Stokes production of turbulence should greatly improve the simulation of the state of the upper ocean and hence drifter trajectories in the Adriatic.

Nonlocal mixing effects due to large eddies in the mixed layer are particularly important when free convection dominates mixing. However, a rigorous incorporation of nonlocal effects is a daunting task that is not easily amenable to simplification. Nevertheless, this approach is being explored since parameterizations in the past have been rather ad-hoc. It is also important to include double diffusive mixing, which is important in some regions of the global oceans.

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14. ABSTRACT
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15. SUBJECT TERMS

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WORK COMPLETED

Mixed layer models incorporated into ocean circulation models such as ROMS are either bulk models (e.g. Large et al. 1994) or based on simplified second moment closure of turbulence (e.g. Mellor and Yamada 1982, Kantha and Clayson 1994). While the bulk models appear to yield reasonable results, with appropriate tuning, for first moment quantities such as the mixed layer temperature, they are quite ad-hoc and lack the ability to provide information on second moment parameters such as the TKE and its dissipation rate, which can be verified against microstructure measurements. Second moment closure models do and hence provide an additional measure of model skill. However, most second moment closure formulations to-date have ignored non-local effects, which are clearly important under free convection dominated mixing scenarios. Under stably stratified conditions, double diffusion can be an important source of mixing but is not included currently. Stokes production of TKE is also ignored. Including these neglected effects has been the primary focus of this project. Acquiring the means to assess any improvements resulting from the inclusion of Stokes production of TKE has been a secondary focus.

Observational data to compare with ocean models, especially on turbulence, are scarce. Microstructure measurements have not become a routine staple of oceanographic measurements as CTD casts have been for decades. Therefore, in collaboration with Dr. Sandro Carniel of ISMAR, Italy, who had a related NICOP grant from ONR, we participated in NATO Undersea Research Center/Naval Research Laboratory (NURC/NRL) DART 06A and 06B cruises in March and August of 2006, and collected turbulence data using a microstructure profiler constructed and operated by Dr. Prandke. The NURC also undertook an air-sea interaction study called Lasie07 in the Ligurian Sea in June 2007. We participated in the week-long cruise on board the Italian CNR RV Urania. Unfortunately, nature did not cooperate and while strong winds and high sea state existed on the way to and back from the moored buoy site where, the intensive observations took place, the winds were weak and the sea state calm over the entire week we were on station! Also because the water column was deep at the site, we were unable to make microstructure measurements with an upward-traversing probe so that the wave-affected upper few meters of the water column could not be sampled.

We know of only one set of measurements made by Lass and Prandke (2003) with an upward-traversing microstructure probe at a 50m deep station in the Baltic Sea in 2001. Observations made consisted of CTD and ADCP measurements in the water column, microstructure measurements of TKE dissipation rate in the water column, flux-related measurements at the air-sea interface AND simultaneous wave rider measurements of the wave spectrum needed to extract Stokes drift velocity profile. Fortunately, we have been able to get hold of these data and were able to test the Kantha and Clayson (2004) model against this dataset to assess the impact of Stokes production (see below).

We have requested a one-year no-cost extension of the contract so that we can complete the remaining tasks of including improved subgrid scale parameterization and tidal forcing in ROMS/TOMS.
We will incorporate astronomical tidal forcing into ROMS/TOMS in the final year of this project. Using the Adriatic Sea (or North Indian Ocean) ROMS/TOMS as the test bed, we will incorporate direct astronomical forcing of the 11 major tides in the global ocean: semidiurnal M_2, S_2. N_2, K_2; diurnal K_1, O_1, P_1 and Q_1; long period Mf, Mm and Ssa. The co-oscillating barotropic tides will be prescribed from Kantha’s tidal models.

RESULTS

We will first describe the inclusion of double diffusive mixing in Kantha and Clayson (2004) second moment closure (SMC) based oceanic mixed layer model.The approach follows that of Canuto et al. (2002), who attempted to improve the depiction of the vertical structure of water masses in a 3-D ocean model through inclusion of an SMC model that accounted for both double-diffusive and shear mixing. Canuto et al. (2008a) have modified this model recently by insisting that shear-driven turbulence exist at all gradient Richardson numbers. In traditional closure models, turbulence is extinguished beyond a finite critical value of *Ri*, for example, about 0.2 in Kantha and Clayson (1994) and 0.9 in Kantha (2003). However, based on some sparse experimental and numerical data as well as a recent theoretical model (Galperin et al. 2007), Canuto et al. (2008b) have modified their SMC model to assure $Ri_{cr} = \infty$. Canuto et al. (2008a) follows the same philosophy and models the time scales $\tau_\theta, \tau_s, \tau_{p\theta}, \tau_{ps}, \tau_{\theta s}$ involved in the dissipation terms in the equations for second moment quantities $\overline{\theta^2}, \overline{s^2}, \overline{p\theta}, \overline{ps}, \overline{\theta s}$ as

$$\pi_1 = \frac{\tau_{ps}}{\tau} = \pi_1^0 \left[1 + \frac{Ri}{1 + aR_\rho^{-1}} \right]^{-1}; \ \pi_2 = \frac{\tau_{s\theta}}{\tau} = 2\pi_2^0 \left[R_\rho + R_\rho^{-1} \right]^{-1}$$

$$\pi_3 = \frac{\tau_s}{\tau} = \pi_3^0; \ \pi_4 = \frac{\tau_{p\theta}}{\tau} = \pi_4^0 \left[1 + \frac{Ri}{1 + aR_\rho} \right]^{-1}; \ \pi_5 = \frac{\tau_\theta}{\tau} = \pi_5^0 \qquad (1)$$

where $Ri = \frac{N^2}{\Sigma^2}; \ N^2 = -\frac{g}{\rho_0}\frac{\partial \rho}{\partial z}, \ \Sigma^2 = \left(\frac{\partial U}{\partial z}\right)^2 + \left(\frac{\partial V}{\partial z}\right)^2$ and $R_\rho = \frac{\alpha_s \frac{\partial S}{\partial z}}{\alpha_T \frac{\partial T}{\partial z}}$. $\tau = \frac{q^2}{\varepsilon}$ is the time scale associated with the dissipation term in the TKE equation. Ri is the gradient Richardson number and R_ρ is the density ratio. *T* is temperature, *S* is salinity, *U* and *V* are horizontal velocity components, and *z* is the vertical coordinate, positive upwards. q^2 is twice the TKE and ε is its dissipation rate. α_T, α_s are molecular diffusion coefficients of temperature and salinity. $\pi_1^0, \ \pi_2^0, \ \pi_3^0, \ \pi_4^0, \ \pi_5^0$ are closure constants equal to 0.08372, 1/3, 0.72, 0.08372, 0.72; *a* = 10.0. Thus, this model combines both shear and DD mixing and provides expressions (not shown here) for the stability functions S_M, S_H and S_S in the expressions:

$$\overline{uw} = -\frac{q^2}{B_1}\tau S_M \frac{\partial U}{\partial z}; \ \overline{w\theta} = -\frac{q^2}{B_1}\tau S_H \frac{\partial T}{\partial z}; \ \overline{ws} = -\frac{q^2}{B_1}\tau S_H \frac{\partial S}{\partial z}$$

Canuto et al. (2008a) approach to include DD is philosophically different than traditional approaches, where the shear-generated turbulence and DD-generated turbulence are assumed to be simply additive, for example, $S_M = S_M^{SH} + S_M^{DD}$. Inoue et al. (2007) present observational justification for this approach. The thinking here is that DD mixing becomes prominent only when the shear mixing is nonexistent, i.e. beyond Ri_{cr}. Below Ri_{cr}, shear mixing dominates and traditional expressions (Kantha 2003 and Kantha and Clayson 1994, 2004) can be used for S_M, S_H and S_S. Above Ri_{cr}, DD mixing takes over. We have followed this approach and have derived the expressions for S_M, S_H and S_S for double-diffusive mixing by a simple modification of (1), which does not involve *Ri* and hence holds for purely double-diffusive mixing:

$$\pi_1 = \pi_1^0 \left[1 + aR_\rho \right]^{-1}; \ \pi_4 = \pi_4^0 \left[1 + aR_\rho^{-1} \right]^{-1} \qquad (2)$$

Many experiments have been conducted on double-diffusive mixing over the past four decades and there exist data on the ratio of the heat flux to salt flux as a function of R_ρ, so that it is possible to compare the model results to laboratory data. Canuto et al. (2008a) have done so and shown reasonable, if not perfect agreement. Figure 1 shows the variation of γ and Rf with R_ρ, where $\gamma = \frac{\alpha_T \overline{w\theta}}{\alpha_s \overline{ws}} = \frac{1}{Rf}$. The red line shows results from Canuto et al. (2008b) for $Ri = 10^4$ (and hence nearly shearless case) and the black line is from the above model (Eq. 2) with closure constants from Kantha (2003): $\pi_1^0,\ \pi_2^0,\ \pi_3^0,\ \pi_4^0,\ \pi_5^0$ are 0.112, 0.27, 0.58, 0.112, 0.27 respectively. See Canuto et al. (2008a) for experimental data (not shown here). The model agreement with data is comparable to that of Canuto et al. (2008a). Incidentally, we observed double-diffusive layering in the Adriatic during DART06 campaign, which we publisheded in Carniel et al. (2007).

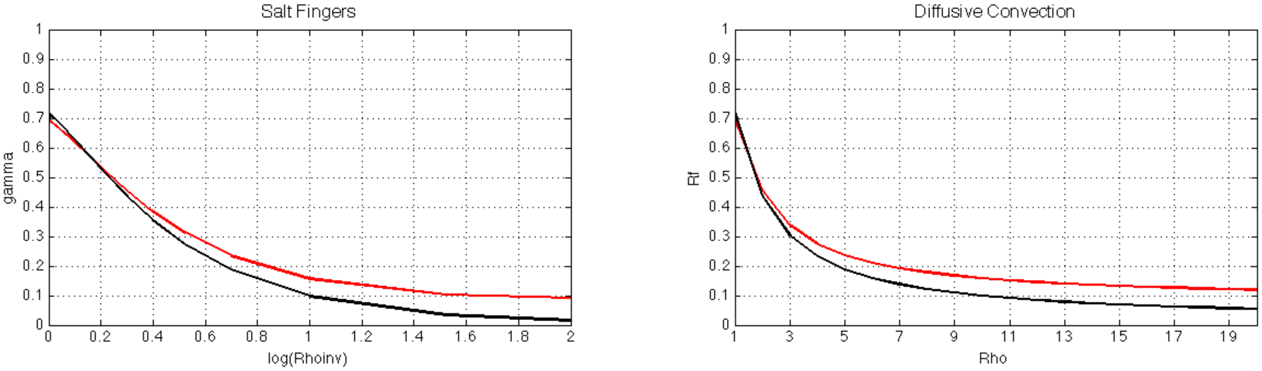

Figure 1: Left panel: Plot of γ vs. R_ρ^{-1} for salt fingers; Right panel: Rf vs. R_ρ for diffusive convection, The red lines are from Canuto et al. (2008a) model for Ri = 10^4 and the black lines are from the model described above with Kantha (2003) closure constants.

We will now turn to Stokes production of TKE in the upper ocean. Until recently, wind generated waves were assumed to propagate in an inviscid ocean, conveniently ignoring the fact that the upper layer is highly turbulent and vortical. A proper treatment of the combined mean flow, turbulence and wave motions (e.g. Mellor 2003, Ardhuin et al. 2008) indicates that the interaction of wave and turbulence motions transfers energy from waves to turbulence enhancing the TKE in the mixed layer. Kantha and Clayson (2004) are the only ones to include this effect in SMC models. This interaction also constitutes a dissipation mechanism for oceanic gravity waves. The dissipation rate can be written as:

$$\frac{dE}{dt} = -\int_{-\infty}^{0}\left(\vec{\tau}\cdot\frac{d\vec{V}_S}{dz}\right)dz = -\int_{-\infty}^{0}\frac{4\sigma k^2}{\rho g}E\exp(2kz)\left(\vec{\tau}\cdot\vec{k}\right)dz \qquad (3)$$

where E is the wave energy, $\vec{\tau}$ is the shear stress, $\vec{V}_S$ is the Stokes drift velocity, k is the wave number and σ is the wave frequency. It is the working of the turbulent Reynolds stress in the upper layers against the vertical shear of the Stokes drift velocity that extracts energy from waves (akin to extraction from mean flow) and transfers it to turbulence. This Stokes dissipation of wind waves is about 2.5 TW on the average in the global ocean, is more than the 2.4 TW dissipation rate of waves in the surf zones around the ocean margins, and hence too important to be ignored (Kantha et al. 2008).

Figure 2 shows the time series of energy in wave motions and their Stokes dissipation rate determined from 1/2^o WAVEWATCH III global wave model run for the year 2007. More details, including the spatial distribution of Stokes dissipation in the global ocean, can be found in Kantha et al. (2008).

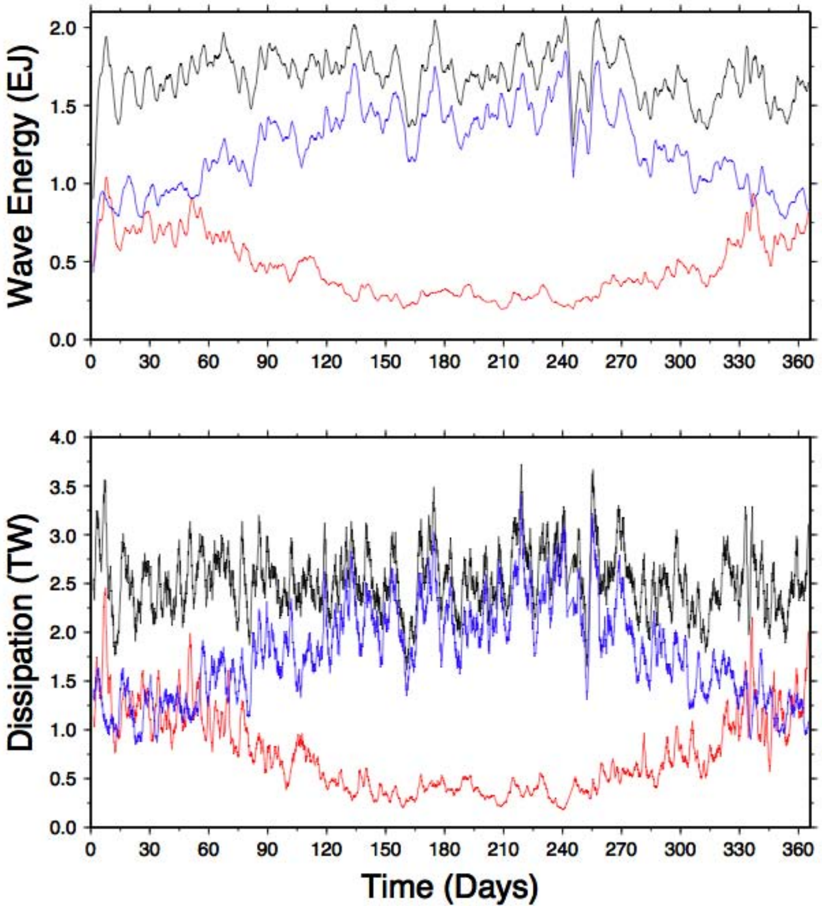

Figure 2. Time series of the energy in the global surface gravity wave field (in EJ) and the rate of dissipation of that energy by Stokes dissipation (in TW): Global average (black), Northern hemisphere (red), Southern hemisphere (blue). Note the large dissipation rates in the southern hemisphere.

Finally, we will describe the influence of Stokes production of TKE on the oceanic mixed layer. Dr. Ulli Lass of the Baltic Research Institute, Germany has kindly provided us with data collected during the three Reynolds 2001 observational campaigns in the Baltic Sea (Lass and Prandke 2003). The uniqueness of this dataset results from the fact that hourly dissipation rates were obtained using an upward traversing microstructure profiler deployed from RV Prof. A. Penck anchored in 50 m deep water column at a heavily instrumented station in the Baltic Sea, which enabled TKE dissipation rates to be measured all the way to the air-sea interface. This is important since the wave influence on TKE can be expected to be more significant in the upper few meters of the water column. Concurrent wave, flux and ADCP measurements permit model simulations to be made and Stokes production rate to be estimated. Figure 3 shows the observed and modeled TKE dissipation rates. The results will be published in a paper under preparation.

There remains the task of completing the inclusion of a mixed layer model that incorporates all our findings over the last 3 years into ROMS. This is the reason we have requested one-year no-cost extension of this contract. We could not attend and present our findings at the October 2008 ROMS workshop in Grenoble, but we do plan to attend the next one.

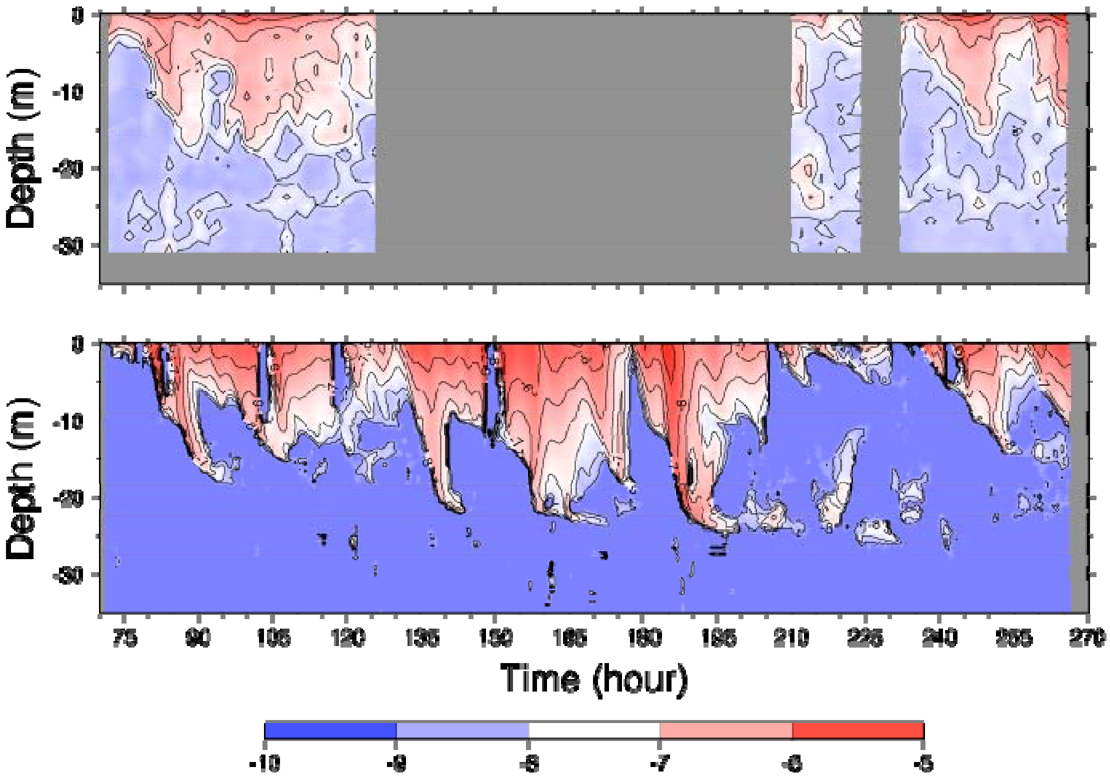

Figure 3. TKE dissipation rate in (W/kg) the water column as a function of time during the 2001 Reynolds 1 campaign (August 27 – September 8). Top panel: Microstructure measurements. Bottom panel: From Kantha and Clayson (2004) model run. The measurements have 1.0 m resolution while the model resolution is 0.1 m.

IMPACT/APPLICATIONS

Accurate depiction of many quantities of interest to worldwide naval operations, such as the upper layer temperature and currents, requires accurate simulation of turbulent mixing in the water column and accurate tidal forcing. 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.

RELATED PROJECTS

None.

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