

Insertion, validation, and application of barotropic and baroclinic tides in 1/12 and 1/25 degree global HYCOM

Brian K. Arbic

Department of Earth and Environmental Sciences, University of Michigan, Ann Arbor, MI, 48109
Phone: (734) 615-4941 Fax: (734) 763-4690 Email: arbic@umich.edu

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LONG-TERM GOALS

A partnership of institutions (academia and government) is collaborating on inserting and validating barotropic and baroclinic tides in 1/12° and 1/25° numerical simulations of the global ocean. The collaboration also has applied and will apply the results of the 1/12° and 1/25° simulations to a number of problems of scientific interest, described in further detail below. This partnership builds on the strong relationship that the lead PI of this proposal, Brian Arbic, has established since 2006 with the Naval Research Laboratory (NRL) and Florida State University (FSU). NRL and FSU have a long-standing relationship, developed during the National Oceanographic Partnership Program (NOPP)-supported HYCOM (HYbrid Coordinate Ocean Model) consortium effort, to develop and transition an eddy-resolving, real-time global and basin-scale ocean prediction system. These systems have been or are in the process of being transitioned for operational use by the U.S. Navy at the Naval Oceanographic Office (NAVOCEANO), Stennis Space Center, MS. This project builds upon work begun with Naval Research Laboratory contract N000173-06-2-C003, and reported on in Arbic et al. (2010).

OBJECTIVES

The partnership will utilize global HYCOM, run at horizontal resolutions of 1/12° and 1/25°, with barotropic and baroclinic tides inserted into an eddy-resolving (“eddy”) circulation. Thus far, most of the global NRL simulations which include tides have been forward simulations, that is, simulations without data assimilation. The NRL group has shown that the data assimilation procedure they currently use on non-tidal motions can be used in simulations with embedded tides without “breaking” either the non-tidal motions (i.e. the eddy general circulation) or the tides themselves. The next step is to perform data assimilation on the tides as well. The NRL group is currently testing two “quick-and-dirty” schemes to assimilate tides into eddy HYCOM. Ben Alterman, a student who began in the UM group in summer 2012, will participate in these efforts and is expected to write a PhD thesis on a long-term plan for data assimilation of tides into HYCOM. Since the goal of operational models is high accuracy, we have endeavored to create forward models which achieve a high level of accuracy in the tides before the data assimilation is inserted. In this way, the data-assimilative models build upon an accurate foundation laid by the forward models. Arbic and the UM team will collaborate with both NRL and FSU on the most efficient way to store HYCOM output with tides in the FSU-based data server.

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As an important first step in improving the forward tide model, the horizontal resolution of HYCOM simulations containing eddies and tides simultaneously has recently been increased to $1/25^\circ$. New simulations at this resolution are already running on DoD machines. The higher resolution simulations are in line with stated U.S. Navy goals to have a $1/25^\circ$ resolution version of the HYCOM ocean prediction system, with tides, available in the near future for Navy operational purposes. The topographic wave drag scheme utilized in the model will be improved through use of the statistical roughness field produced in a separate Office of Naval Research (ONR) grant (John Goff and Brian Arbic, N00014-07-1-0792 and N00014-09-1-1003, “Effects of small-scale bathymetric roughness on the global internal wave field”; Goff and Arbic 2010). As shown by a number of authors, topographic wave drag is critical to the accuracy of forward tide models. In addition, scientific applications of the wind-plus-tides simulations have been and will continue to be investigated during the course of this proposed research. For instance, the three-dimensional global tidal velocity and isopycnal displacement fields in HYCOM have been and will be compared to those measured by current meters. The sea surface height signatures of internal tides in HYCOM have been validated globally against satellite altimeter measurements. The temporal stability of the internal tide signals at the surface in the face of mesoscale activity will be examined. The aliasing of internal tides into the mesoscale band in satellite altimeter data, and the resulting contamination of altimetry-derived internal tide data, will be examined through sampling exercises with the model. The impact of tides on sea surface height spectra has been examined, with implications for the development of the proposed wide-swath satellite altimeter (NASA SWOT mission). Three-dimensional maps of internal-wave driven energy dissipation and mixing will be developed from the HYCOM simulations. Parametric subharmonic instability and tidal energy fluxes in HYCOM are being examined by Joseph Ansong, an NSF-funded postdoc. Interactions between tides and low-frequency motions are presently being examined. Frequency spectra of sea surface height from the model will be compared to spectra obtained from tide gauges, on timescales from hours to years. We will display some of our results on these topics below. Finally, Arbic and his team at UM will collaborate with NRL and FSU on the introduction and validation of data assimilation into the HYCOM tide simulations, and with both NRL and FSU on the FSU-based HYCOM data server. Regarding the latter point, we will specifically examine how to optimize the storage of HYCOM output on the server at high spatial resolution ($1/25^\circ$ global) when tides are included, which traditionally leads to much higher temporal sampling than is done in models which do not include tides.

APPROACH

We insert tides into HYCOM following the techniques outlined in Arbic et al. (2004), which can be consulted for extensive discussions on global tide modeling. The astronomical tidal potentials of the eight largest tidal constituents, adjusted for the effects of solid-earth body tides (e.g., Hendershott 1972) were entered into the momentum equations. For our first simulations self-attraction and loading (Hendershott 1972, Ray 1998) is parameterized using the simple scalar approximation (Ray 1998). Topographic wave drag, which represents energy loss due to breaking of internal waves generated by tidal flows over rough topography, is also inserted into the model momentum equations. This has been common practice for forward tide models since the pioneering effort of Jayne and St. Laurent (2001). With the drag scheme incorporated, HYCOM captures about 92% of the sea surface elevation variance of the eight largest tidal constituents as measured by a standard set of 102 pelagic tide gauges (Shum et al. 1997). This level of accuracy for the barotropic tides is comparable to that seen in previous carefully tuned forward tide models, e.g. Arbic et al. (2004).

The key individuals involved in this research are:

--Brian K. Arbic, University of Michigan, PI of this grant: Arbic is in frequent contact with the individuals listed below as we continue to research tides in HYCOM, and is a critical actor in coordination of the overall HYCOM tides effort. In addition, Arbic is also currently working with Alan Wallcraft to improve several aspects of the HYCOM tides simulations, including self-attraction and loading, topographic wave drag, implementation of the first few “quick and dirty” schemes for tidal data assimilation, and examination of the impact of stratification on the barotropic tidal field. We have been using the same HYCOM tide simulation for the last few years, for the analyses and papers reported on below. This simulation represents a significant improvement over the first HYCOM tide simulations reported on in Arbic et al. (2010), but it is time for a new simulation to be run, and we plan to do one that incorporates the above improvements over the next year.

--Patrick G. Timko, former University of Michigan postdoc supported by this grant, currently at University of Bangor in the United Kingdom: Timko is validating the three-dimensional structure of tidal currents and displacements in HYCOM (Timko et al. 2012a, 2012b, Arbic et al. 2012a) with respect to the current meter observation archive of Scott et al. (2010).

--Malte Mueller, postdoctoral scientist subcontractor, University of Victoria, Canada: Mueller has been supported by a subcontract from this grant since April 2012 and will work with us for approximately one year, thus helping us to expend funds left over by Timko’s earlier-than-anticipated departure for permanent employment in the United Kingdom. Mueller has worked on two projects with us. First, he utilized the methods of Maik Thomas to improve the astronomical tidal forcing in HYCOM. Specifically, he developed a full luni-solar tidal potential, analyzed it harmonically to come up with tidal constituents, and adjusted the constituents by frequency-dependent Love numbers to account for solid earth body tide effects. This increases the number of constituents in HYCOM from 8 to 430. This new potential is currently being tested for implementation in HYCOM tides runs by Alan Wallcraft and Arbic in consultation with Mueller. Mueller’s second and main project with us has been to compute spectra, spectral transfers, and spectral fluxes in frequency-wavenumber space, as a method of diagnosing nonlinear interactions between oceanic motions. He is currently working with Arbic to extend the results reported on in Arbic et al. (2012b), which reported on nonlinear interactions of geostrophic eddies in the frequency domain, to the frequency-wavenumber domain. This work is already well underway and is expected to be completed quickly, after which Mueller will extend the work to nonlinear frequency-wavenumber interactions in the full model velocity field, which includes near-inertial and tidal motions as well as geostrophic eddies.

--Joseph Ansong, postdoctoral scientist, University of Michigan: Ansong, an NSF-funded postdoc, is examining parametric subharmonic instability (PSI) and tidal energy fluxes in the HYCOM tides simulations.

--Ben Alterman, graduate student in the Applied Physics Program, University of Michigan: Alterman will collaborate with Arbic, NRL researchers, and Chassignet on a long-term plan for incorporation of data assimilation of tidal motions into HYCOM.

--Conrad Luecke, graduate student in the Department of Earth and Environmental Sciences, University of Michigan: Luecke is working with Arbic, Bassette (see below), NRL collaborators, and Rob Scott of the University of Brest, to compare low-frequency temperature and isopycnal fluctuations in HYCOM with those in current meters.

--Steve Bassette, undergraduate math/physics student, University of Michigan: Bassette is working with Arbic, Luecke, NRL collaborators, and Rob Scott of the University of Brest, to compare tidal frequency temperature and isopycnal fluctuations in HYCOM with those in current meters. Once Luecke and Bassette have developed a methodology for model/current meter comparisons of temperature and isopycnal fluctuations (essentially, potential energy), global three-dimensional maps of potential and kinetic energy in different frequency bands (geostrophic/mesoscale, near-inertial, and tidal) will be constructed from our HYCOM simulations.

--Eric P. Chassignet, Florida State University, head of HYCOM consortium and keeper of the HYCOM data server: As discussed above and below, we will work with Chassignet on the storage strategy for the server, and on data assimilation of tides into HYCOM.

--Alan J. Wallcraft, NRL Stennis Space Center, lead PI of related tides grant at NRL: Wallcraft and Arbic collaborated to insert tides into the HYCOM code and continue to consult each other about numerous technical aspects of the tide coding.

--E. Joseph Metzger, NRL Stennis Space Center: Metzger has been the NRL go-to person for running the HYCOM simulations, and has been extremely helpful to David Trossman, who is conducting NSF-funded HYCOM simulations of the eddying general circulation (more below).

--Jay F. Shriver, NRL Stennis Space Center: Shriver is conducting global comparisons of HYCOM to the satellite altimeter data of Richard Ray, and an examination of the temporal stationarity of internal tides. These are both topics of great interest to NASA as it prepares for the wide-swath satellite altimeter.

--James G. Richman, NRL Stennis Space Center: Richman has been an active contributor to Timko's and Shriver's projects, and has taken the lead on examining the impact of internal tides on the wavenumber spectra of sea surface height, a subject also of great interest to NASA. Richman has also begun to examine the frequency spectra of sea surface height, on time scales from hours to years, in the model and in tide gauge data.

WORK COMPLETED

HYCOM has been run globally with tides at $1/12^\circ$ and $1/25^\circ$ resolution. Numerous analyses have been performed on the $1/12^\circ$ simulations; the $1/25^\circ$ results are just starting to be looked at. A selection of the most significant results obtained during the last year are described in the following section.

RESULTS

Below we report on results from this past year obtained by Shriver and Richman, Arbic's NRL collaborators, and by Timko and Joseph Ansong, Arbic's postdocs. Shriver has harmonically analyzed one year of output from the HYCOM-with-tides simulations and high-passed the resulting tidal amplitudes to reveal the signature of internal tides at the sea surface. Figure 1 below, taken from Shriver et al. (2012), displays the amplitude of the M_2 signature in both altimeter data (top panel; Ray and Mitchum 1996, 1997; Ray and Byrne 2010) and HYCOM (bottom panel). The figures demonstrate that HYCOM is capturing the hotspots of internal tide generation well. Shriver et al. (2012) confirms this by showing that the HYCOM RMS amplitudes over the hotspot boxes shown in Figure 1 are within about 20% of those in altimeter data for the most important constituents (results not shown here for the sake of brevity). In the HYCOM K_1 results (not shown), there are no internal waves poleward of 30° , as expected from theoretical considerations. The altimeter results contain substantial K_1 activity in western boundary currents poleward of 30° . We interpret this as mesoscale contamination brought about by the relatively poor temporal sampling of the altimeter; the 10 day repeat time of the altimeter aliases tides into the mesoscale band. The K_1 comparison shows that the hourly sampling possible in HYCOM can reveal important limitations in the altimeter data.

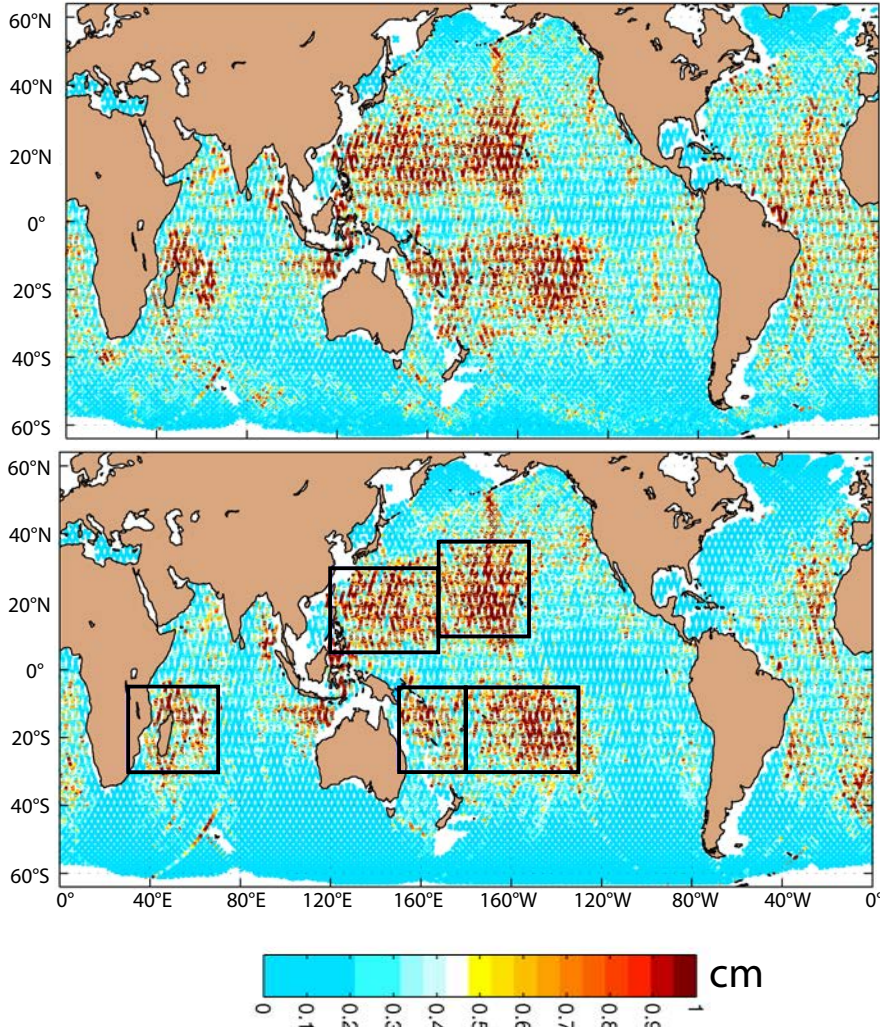
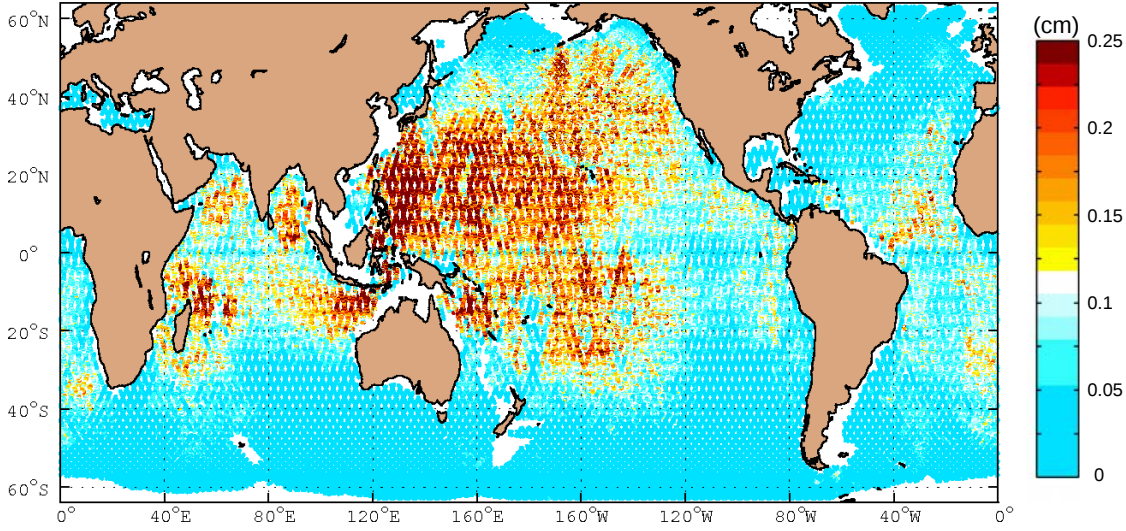


Figure 1: Amplitude (cm) of M_2 internal tide signature in sea surface height, obtained from high-passing the M_2 amplitudes of the full sea surface height. Upper panel: results from satellite altimetry. Lower panel: results from HYCOM.

After showing that the basic structure of the internal tide field in HYCOM compares well with altimetry, Shriver has moved on to examine the stationarity of HYCOM internal tides (Shriver et al., paper in preparation). Internal tide stationarity in HYCOM and in the ocean is impacted by seasonal effects which alter the oceanic stratification, and by mesoscale motions which scatter internal tides. Internal tide stationarity is not only a problem of great scientific interest, but is also important for NASA's planning for the wide-swath satellite altimeter. If internal tide signatures at the sea surface are mostly stationary, then they are removable via standard tidal harmonic analysis. If instead they are mostly non-stationary, then harmonic analysis will not suffice. In Figure 2 we display the non-stationarity by means of absolute and normalized standard deviations of HYCOM M_2 amplitudes, computed from overlapping 183-day windows of HYCOM output. The absolute standard deviations are generally largest in the hotspot regions. However, in those same regions the normalized standard deviations (standard deviations divided by the mean) are generally fairly small, indicating a large degree of stationarity in agreement with the altimetric analysis of Ray and Zaron (2011).

**M₂ 1/12° Global HYCOM amplitude
standard deviation, using 183-day
windows**



**M₂ 1/12° Global HYCOM normalized
amplitude standard deviation**

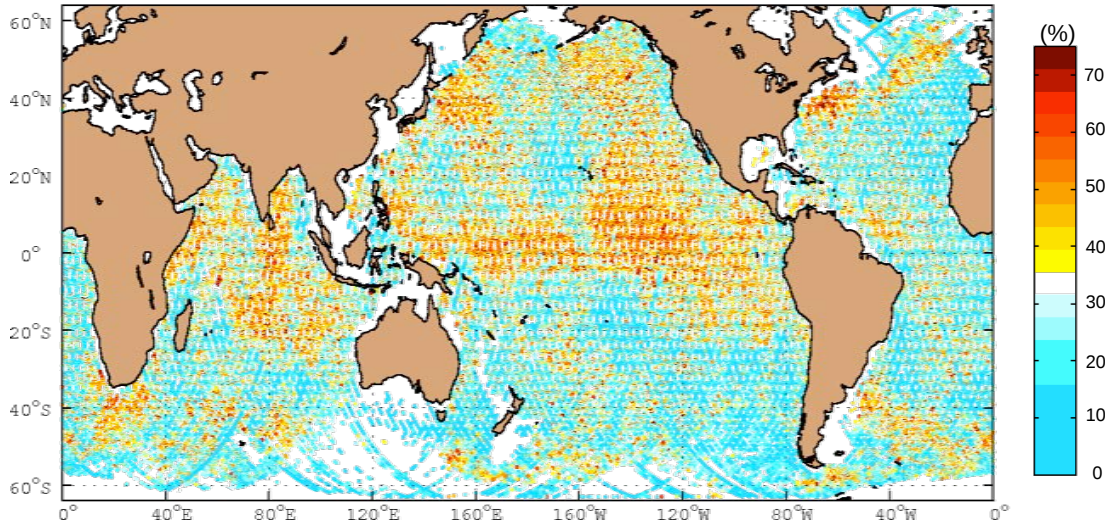


Figure 2: Standard deviation of M₂ internal tide signature in sea surface height, computed from overlapping 183-day windows of HYCOM output put onto altimeter tracks. (Top) absolute value (cm)

of standard deviation. (Bottom) Normalized standard deviation, i.e. standard deviation divided by mean amplitudes.

Richman has also taken advantage of the hourly output of HYCOM, to separate the contributions of low and high frequencies to the wavenumber spectrum of sea surface height (Richman et al. 2012). In regions of low internal tide activity, the low frequencies dominate the spectrum (not shown).

However, in regions of high internal tide activity, the high frequencies dominate the spectrum, as shown in Figure 3. The implications are that the low-frequency spectrum, which is predicted by surface quasi-geostrophic theory to have a slope of $-11/3$ (Le Traon et al., 2008), will be buried underneath the high frequency spectrum in regions of high internal tide activity. Therefore, the internal tide corrections to the wide-swath satellite altimeter data will have to be very accurate to reveal submesoscale dynamics in regions of high internal tide activity.

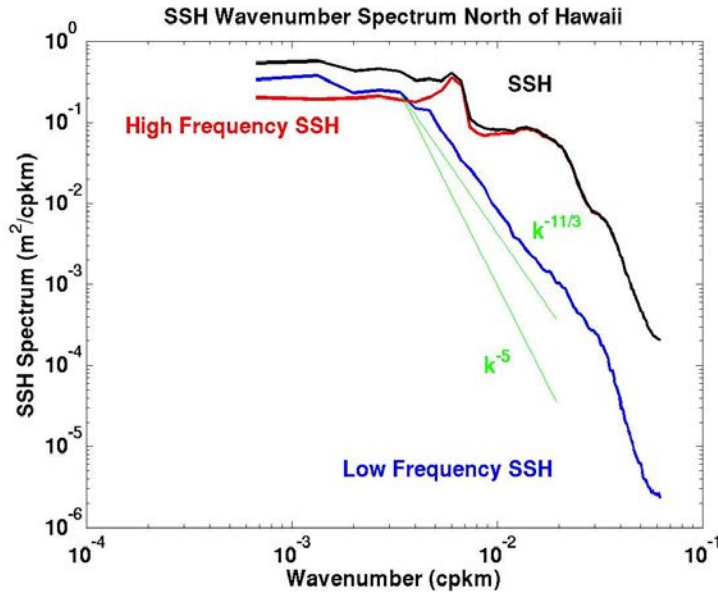


Figure 3: Wavenumber spectrum of steric sea surface height in region of high internal tide activity near Hawai'i. Black/blue/red curves represent spectra of steric height, low frequency steric height, and high frequency steric height, respectively. Extra slanted lines are at theoretically predicted slopes of $-11/3$ and -5 .

Timko has compared the global three-dimensional tidal velocity field in HYCOM with available current meter data (Timko et al. 2012a, 2012b, Arbic et al. 2012a). Timko et al. (2012a) develops rigorous criteria for model/data comparisons at individual current meter locations. In general, the diurnal currents in HYCOM are too weak in comparison to observations. This result inspired us to revisit our topographic wave drag. The drag is tuned for M_2 , which results in a drag that is probably too strong for K_1 . We are currently engineering the wave drag so that it is weaker for K_1 than it is for M_2 , in accordance with theoretical considerations (Bell 1975). Figure 4 shows a model/data comparison in a North Pacific location where the model performs particularly well. Timko et al. (2012b; see also Arbic et al. 2012a) finds that the semi-diurnal tidal currents in HYCOM match up with those in current meter data reasonably well, as long as substantial averaging is done over both time and space. This can be seen in Figure 5, which displays the locations of the current meters used to compare to HYCOM output, and the vertically averaged kinetic energy over depth bins, in both HYCOM and current meter data.

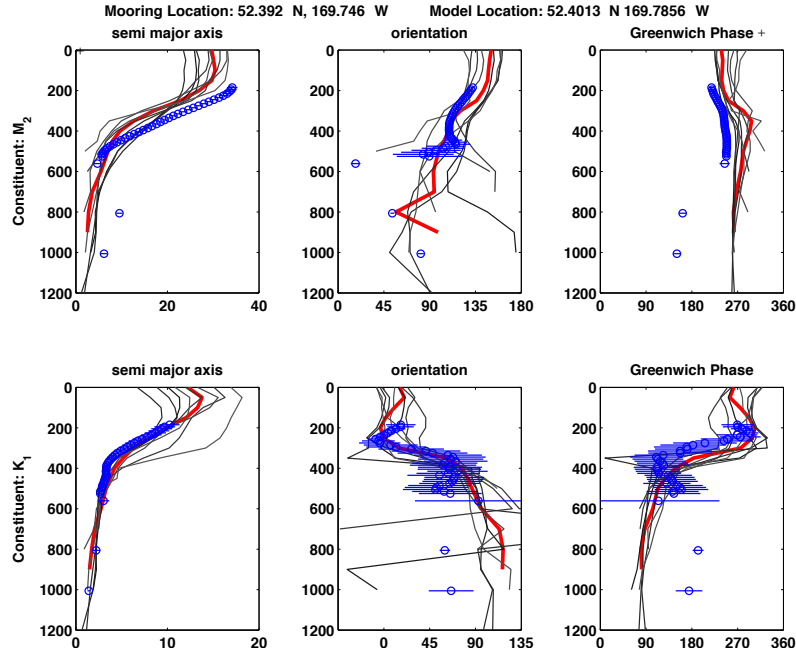


Figure 4: Vertical structure of tidal currents in ADCP data at a particular North Pacific location (blue curves), nearest model gridpoint in HYCOM (red curves), and in eight surrounding model gridpoints (black curves). Top/bottom panels are for M_2 / K_1 , respectively. Left/middle/right panels show semi-major axis, orientation, and Greenwich phase, respectively.

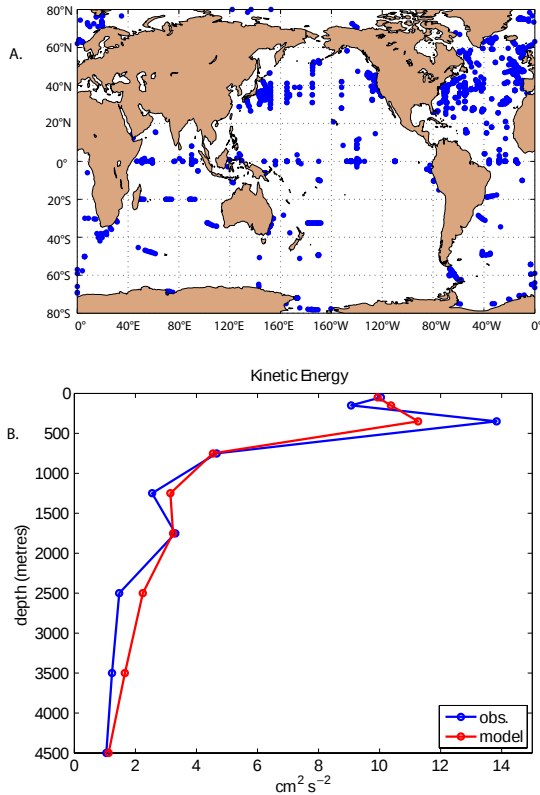


Figure 5: (a) Horizontal locations of current meters used to validate the tidal currents in the HYCOM simulations. Units of x- and y-axes are degrees. (b) Vertical distributions of the M_2 tidal

kinetic energy, spatially averaged over depth-binned instruments, for current meter observations and HYCOM simulations.

Richman has begun to compute frequency spectra of sea surface height, with the goal of comparison to spectra computed from tide gauges. In Figure 6 we show our preliminary results, from four different locations. The tides are easily seen as spikes at the high frequency end. The slopes at lower frequencies, given by the red lines, are in reasonable agreement with those found in Arbic et al. (2012b).

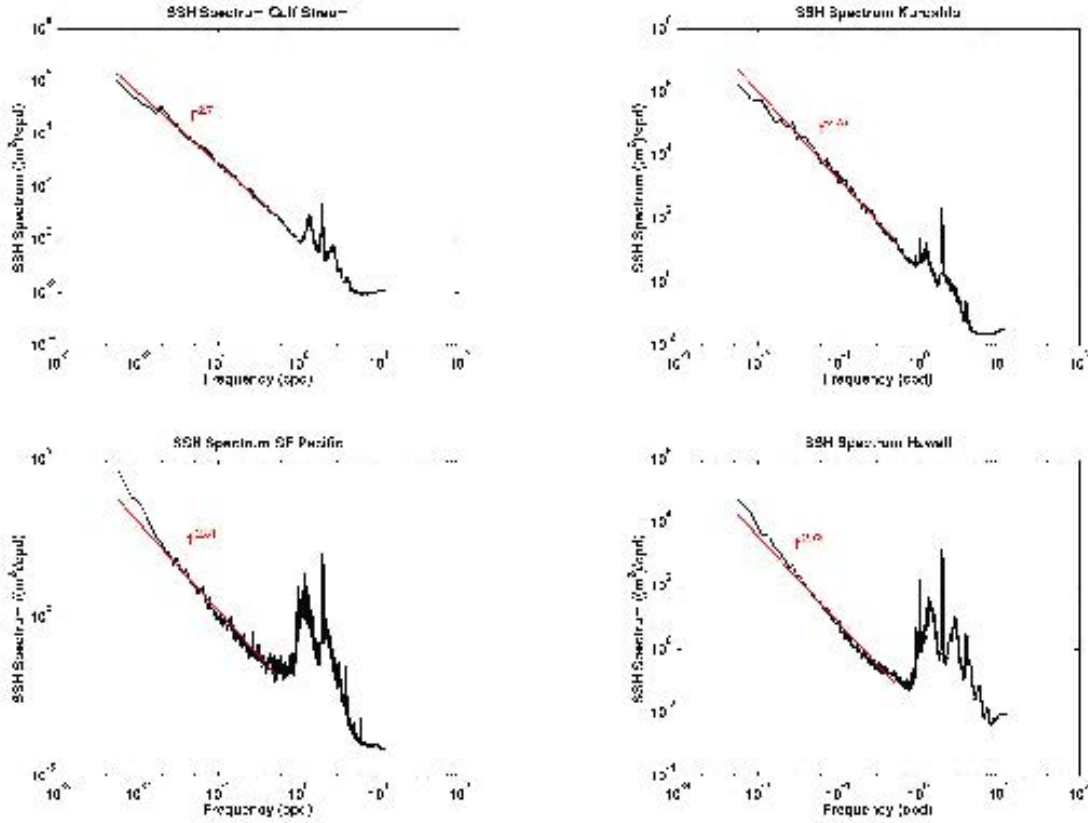
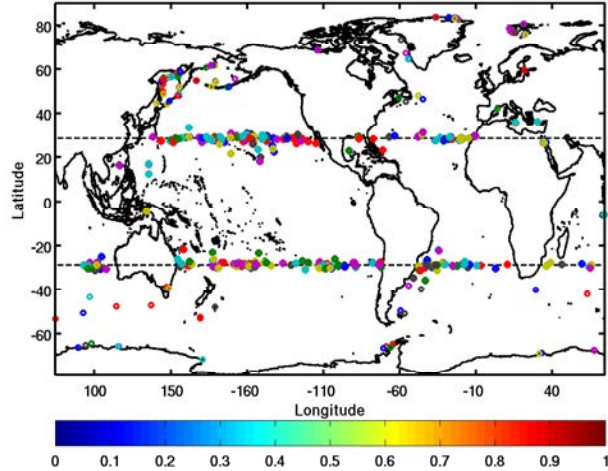


Figure 6: Frequency spectra of sea surface height at four locations, in HYCOM simulations with embedded tides.

Finally, we display some results from Joseph Ansong, an NSF-funded postdoc who was been analyzing the HYCOM results for evidence of parametric subharmonic instability (PSI), a potential mechanism for the breakdown of low-mode internal tides. In Figure 7 we display the bicoherence values at each grid location from the baroclinic velocities obtained from layer 14 (lying at about 500 m depth over much of the ocean) from HYCOM. Both semidiurnal and diurnal results are shown; in each case we show only subharmonic signals having energy at least 1% of that of the primary waves. The results clearly show that PSI is happening primarily at the critical latitudes, as expected. A paper on these results, and another on the computed tidal energy fluxes from HYCOM, are currently being prepared by Ansong.

(a) Semi-diurnal



(b) Diurnal

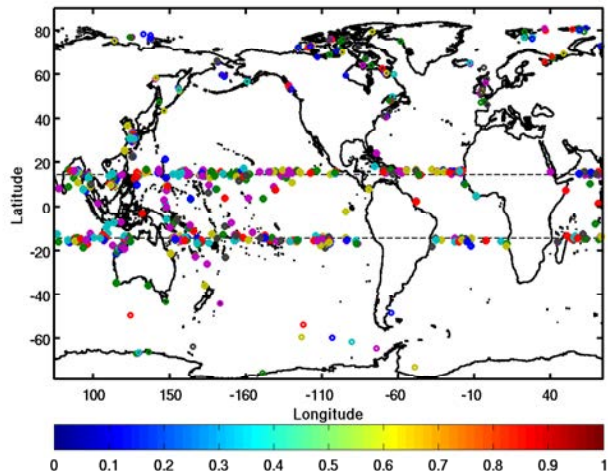


Figure 7: Significant bicoherence values at each grid location from the baroclinic velocities in layer 14 (laying at about 500 m over much of the ocean) from HYCOM. Only locations at which the subharmonic energy is at least 1% of the primary waves are shown.

IMPACT/APPLICATIONS

The tidal research is driven by the stated need for NAVOCEANO to have tides and data assimilation in 1/25° HYCOM, for operational purposes.

The wavenumber spectrum calculation done by Richman was done at the request of the wide-swath satellite altimeter PIs (Lee-Lueng Fu, Rosemary Morrow, Ernesto Rodriguez), who have invited Arbic to several planning meetings for the wide-swath altimeter. Richman's results were used in the planning of the locations for the AirSWOT test mission (Ernesto Rodriguez, personal communication 2011). Shriver's results have been shown at these planning meetings and have garnered great interest.

TRANSITIONS

The work reported on here is an important part of a planned transition by the Stennis Space Center ocean modeling group from forecasts that are based on NLOM (Naval Research Laboratory Layered Ocean Model) to HYCOM. Tides are among a number of improvements in the HYCOM simulations compared to the NLOM simulations.

RELATED PROJECTS

The work reported on here is strongly tied to the HYCOM tides grants currently in place at Florida State University (led by Eric Chassignet) and at Naval Research Laboratory (led by Alan Wallcraft). Arbic has been working closely with Wallcraft and other NRL Stennis personnel (Metzger, Richman, Shriver) since 2006 to implement and validate tides in HYCOM. Arbic has continued to work closely with Stennis personnel as the papers listed below under “Publications thus far, resulting from current grant” and “Publications from previous NRL subcontract to PI” are submitted. More studies and papers are planned, and the close collaborations will continue. Arbic will work closely with NRL collaborators and with Chassignet to decide how best to store simulations with tides included on Florida State’s data server. Tidal data is traditionally stored hourly, but hourly three-dimensional global output from HYCOM will likely overwhelm any server at Florida State. As we have been doing with the simulations thus far, we will decide on sampling strategies to best handle this problem. Thus far, for instance, we have been saving 1) daily averages of three-dimensional global output, 2) three-dimensional global output at hourly intervals over the timespan of one month, 3) selected variables, such as sea surface height and surface velocities, at hourly intervals over several years, 4) selected regions of interest, such as Hawai’i and the Philippines, at hourly intervals and at full three-dimensional spatial resolution. We will discuss similar strategies for the Florida State data server.

The work reported on here was leveraged to obtain two grants from NSF, both involving multiple institutions. The focus of one NSF grant is to examine the impact of bottom boundary layer drag and topographic wave drag on low-frequency motions such as mesoscale eddies and western boundary currents. The postdoc employed on this grant, David Trossman, has obtained computer accounts on NAVO and ERDC machines, as well as 10,000,000 core hours on the new Yellowstone NCAR machine, and is working closely with Joe Metzger and Alan Wallcraft. As expected, the wave drag impacts the model energy budgets significantly. This work should therefore be beneficial for overall HYCOM development. The other NSF grant is a Climate Process Team (CPT) grant led by Jennifer MacKinnon and focused on developing better parameterizations of internal-wave driven mixing for ocean models. This project involves many internal wave experts (Polzin, St. Laurent, Alford, Simmons, Kunze, Gregg, MacKinnon, Legg, Klymak, Pinkel), most of whom work on Navy-funded internal wave projects. One of the four postdocs funded by this CPT, Joseph Ansong, is based at UM and is analyzing the HYCOM with tides simulations reported on here for the NSF work. Specifically he is examining parametric subharmonic instability in the model (Simmons 2008), and has been computing barotropic-to-baroclinic energy conversions as in Simmons et al. (2004), but under more realistic conditions such as the presence of eddies and of horizontally varying stratification. Ansong has already visited Simmons, Alford, and Gregg in order to facilitate better communication. The results of

Ansong's NSF-funded research, like those of Trossman's, are anticipated to be beneficial to overall HYCOM development, and to the HYCOM-with-tides project reported on here.

In addition, Arbic has utilized his connections to NRL investigators to investigate eddy dynamics in NRL models (NLOM and HYCOM), leading to papers on the bottom boundary layer drag dissipation of the low-frequency general circulation (Arbic et al. 2009), a paper on comparison of HYCOM vs current meter kinetic energies at low frequencies (Scott et al 2010), and three papers motivated by present-day and planned wide-swath altimeter missions—Arbic et al. (2012c), which investigates the effect of stencil width on computations of geostrophic velocities from altimeter data, Arbic et al. (2012b), which investigates nonlinear interactions in the frequency domain, and Arbic et al. (2012d), which investigates the impacts of eddy viscosity and horizontal resolution on the forward energy cascades to high wavenumbers computed from models and altimeter data.

Four additional brief notes of interest: First, as anticipated, Patrick Timko, who was funded by this ONR grant, was instrumental in helping to get Trossman and Ansong up to speed on their NSF-funded HYCOM projects. Second, Timko has moved on to permanent employment, as a project scientist for the SEACAMS project based out of the University of Bangor, United Kingdom. Third, since Ansong is from sub-Saharan Africa, he represents a member of an under-represented group working on HYCOM. However, since he is funded by an NSF grant, I did not count him as a minority postdoc working on this ONR grant. Fourth, Steve Bassette, an undergraduate performing Navy-related (but NSF-funded) research on HYCOM, is a Navy veteran.

REFERENCES

- Arbic, B.K., Garner, S.T., Hallberg, R.W., Simmons, H.L., 2004. The accuracy of surface elevations in forward global barotropic and baroclinic tide models. *Deep-Sea Research II* 51, 3069-3101.
- Arbic, B.K., J.F. Shriver, P.J. Hogan, H.E. Hurlburt, J.L. McClean, E.J. Metzger, R.B. Scott, A. Sen, O.M. Smedstad, and A.J. Wallcraft, 2009. Estimates of bottom flows and bottom boundary layer dissipation of the oceanic general circulation from global high-resolution models. *Journal of Geophysical Research* 114, C02024, doi:10.1029/2008JC005072.
- Arbic, B.K., Wallcraft, A.J., Metzger, E.J., 2010. Concurrent simulation of the eddying general circulation and tides in a global ocean model. *Ocean Modelling* 32, doi:10.1016/j.ocemod.2010.01.007, 175-187.
- Arbic, B.K., J.G. Richman, J.F. Shriver, P.G. Timko, E.J. Metzger, and A.J. Wallcraft, 2012a. Global modeling of internal tides within an eddying ocean general circulation model. *Oceanography* 25, 20-29, <http://dx.doi.org/10.5670/oceanog.2012.38>.
- Arbic, B.K., R.B. Scott, G.R. Flierl, A.J. Morten, J.G. Richman, and J.F. Shriver, 2012b. Nonlinear cascades of surface oceanic geostrophic kinetic energy in the frequency domain. *Journal of Physical Oceanography*, in press.
- Arbic, B.K., R.B. Scott, D.B. Chelton, J.G. Richman, and J.F. Shriver, 2012c. Effects of stencil width on surface ocean geostrophic velocity and vorticity estimation from gridded satellite altimeter data. *Journal of Geophysical Research* 117, C03029, doi:10.1029/2011JC007367.
- Arbic, B.K., K.L. Polzin, R.B. Scott, J.G. Richman, and J.F. Shriver, 2012d. On eddy viscosity, energy cascades, and the horizontal resolution of gridded satellite altimeter products. *Journal of Physical Oceanography*, in press.
- Bell, T.H., 1975. Lee waves in stratified flows with simple harmonic time dependence. *Journal of Fluid Dynamics* 67, 705-722.

- Goff, J.A., Arbic, B.K., 2010. Global prediction of abyssal hill roughness statistics for use in ocean models from digital maps of paleo-spreading rate, paleo-ridge orientation, and sediment thickness. *Ocean Modelling* 32, doi:10.1016/j.ocemod.2009.10.001, 36-43.
- Hendershott, M.C., 1972. The effects of solid earth deformation on global ocean tides. *Geophysical Journal of the Royal Astronomical Society* 29, 389-402.
- Jayne, S.R., St. Laurent, L.C., 2001. Parameterizing tidal dissipation over rough topography. *Geophysical Research Letters* 28, 811-814.
- Le Traon, P.Y., Klein, P., Hua, B.L., Dibarboure, G., 2008. Do altimeter wavenumber spectra agree with the interior of surface quasigeostrophic theory? *Journal of Physical Oceanography* 38, 1137-1142.
- Ray, R.D., 1998. Ocean self-attraction and loading in numerical tidal models. *Marine Geodesy* 21, 181-192.
- Ray, R.D., Byrne, D.A., 2010. Bottom pressure tides along a line in the southeast Atlantic Ocean and comparisons with satellite altimetry. *Ocean Dynamics* 60, 1167-1176.
- Ray, R.D., Mitchum, G.T., 1996. Surface manifestation of internal tides generated near Hawai'i. *Geophysical Research Letters* 23, 2101-2104.
- Ray, R.D., Mitchum, G.T., 1997. Surface manifestation of internal tides in the deep ocean: Observations from altimetry and tide gauges. *Progress in Oceanography* 40, 135-162.
- Ray, R.D., Zaron, E.D., 2011. Non-stationary internal tides observed with satellite altimetry. *Geophysical Research Letters* 38, L17609, doi:10.1029/2011GL048617.
- Richman, J.G., B.K. Arbic, J.F. Shriver, E.J. Metzger, and A.J. Wallcraft, 2012. Inferring dynamics from the wavenumber spectra of an eddying global ocean model with embedded tides, in revision.
- Scott, R.B., Arbic, B.K., Chassignet, E.P., Coward, A.C., Maltrud, M., Merryfield, W.J., Srinivasan, A., Varghese, A., 2010. Total kinetic energy in four global eddying ocean circulation models and over 5000 current meter records. *Ocean Modelling* 32, doi:10.1016/j.ocemod.2010.01.005, 157-169.
- Shriver, J.F., B.K. Arbic, J.G. Richman, R.D. Ray, E.J. Metzger, A.J. Wallcraft, and P.G. Timko, 2012. An evaluation of the barotropic and internal tides in a high resolution global ocean circulation model, in revision.
- Shum, C.K., Woodworth, P.L., Andersen, O.B., Egbert, G.D., Francis, O., King, C., Klosko, S.M., Le Provost, C., Li, X., Molines, J.-M., Parke, M.E., Ray, R.D., Schlax, M.G., Stammer, D., Tierney, C.C., Vincent, P., Wunsch, C.I., 1997. Accuracy assessment of recent ocean tide models. *Journal of Geophysical Research* 102, 25173-25194.
- Simmons, H.L., Hallberg, R.W., Arbic, B.K., 2004. Internal wave generation in a global baroclinic tide model. *Deep-Sea Research II* 51, 3043-3068.
- Simmons, H.L., 2008. Spectral modification and geographic redistribution of the semi-diurnal internal tide. *Ocean Modelling* 21, 126-138, doi:10.1016/j.ocemod.2008.01.002.
- Timko, P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E.J. Metzger, and A.J. Wallcraft, 2012a. Skill tests of three-dimensional tidal currents in a global ocean model: A look at the North Atlantic. *Journal of Geophysical Research* 117, C08014, doi:10.1029/2011JC007617.
- Timko, P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E.J. Metzger, and A.J. Wallcraft, 2012b. Comparison of tidal kinetic energy in a global three-dimensional circulation model, historical current meter observations, and a global barotropic model, in revision.

PUBLICATIONS FROM PREVIOUS NRL SUBCONTRACT TO PI

Arbic, B.K., Wallcraft, A.J., Metzger, E.J., 2010. Concurrent simulation of the eddy general circulation and tides in a global ocean model. *Ocean Modelling* 32, doi:10.1016/j.ocemod.2010.01.007, 175-187.

Scott, R.B., Arbic, B.K., Chassignet, E.P., Coward, A.C., Maltrud, M., Merryfield, W.J., Srinivasan, A., Varghese, A., 2010. Total kinetic energy in four global eddy ocean circulation models and over 5000 current meter records. *Ocean Modelling* 32, doi:10.1016/j.ocemod.2010.01.005, 157-169.

Arbic, B.K., J.F. Shriver, P.J. Hogan, H.E. Hurlburt, J.L. McClean, E.J. Metzger, R.B. Scott, A. Sen, O.M. Smedstad, and A.J. Wallcraft, 2009. Estimates of bottom flows and bottom boundary layer dissipation of the oceanic general circulation from global high-resolution models. *Journal of Geophysical Research* 114, C02024, doi:/10.1029/2008JC005072.

PUBLICATIONS THUS FAR, RESULTING FROM CURRENT GRANT

Arbic, B.K., R.B. Scott, D.B. Chelton, J.G. Richman, and J.F. Shriver, 2012. Effects of stencil width on surface ocean geostrophic velocity and vorticity estimation from gridded satellite altimeter data. *Journal of Geophysical Research* 117, C03029, doi:/10.1029/2011JC007367.

Arbic, B.K., J.G. Richman, J.F. Shriver, P.G. Timko, E.J. Metzger, and A.J. Wallcraft, 2012. Global modeling of internal tides within an eddy ocean general circulation model. *Oceanography* 25, 20-29, <http://dx.doi.org/10.5670/oceanog.2012.38>.

Timko, P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E.J. Metzger, and A.J. Wallcraft, 2012. Skill tests of three-dimensional tidal currents in a global ocean model: A look at the North Atlantic. *Journal of Geophysical Research* 117, C08014, doi:10.1029/2011JC007617.

Arbic, B.K., R.B. Scott, G.R. Flierl, A.J. Morten, J.G. Richman, and J.F. Shriver, 2012. Nonlinear cascades of surface oceanic geostrophic kinetic energy in the frequency domain. *Journal of Physical Oceanography*, in press.

Arbic, B.K., K.L. Polzin, R.B. Scott, J.G. Richman, and J.F. Shriver, 2012. On eddy viscosity, energy cascades, and the horizontal resolution of gridded satellite altimeter products. *Journal of Physical Oceanography*, in press.

Shriver, J.F., B.K. Arbic, J.G. Richman, R.D. Ray, E.J. Metzger, A.J. Wallcraft, and P.G. Timko, 2012. An evaluation of the barotropic and internal tides in a high resolution global ocean circulation model, in revision.

Timko, P.G., B.K. Arbic, J.G. Richman, R.B. Scott, E.J. Metzger, and A.J. Wallcraft, 2012. Comparison of tidal kinetic energy in a global three-dimensional circulation model, historical current meter observations, and a global barotropic model, in revision.

Richman, J.G., B.K. Arbic, J.F. Shriver, E.J. Metzger, and A.J. Wallcraft, 2012. Inferring dynamics from the wavenumber spectra of an eddy global ocean model with embedded tides, in revision.