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Development of a tidal model for central California

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P2.10 DEVELOPMENT OF A TIDAL MODEL FOR CENTRAL CALIFORNIA

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1. MOTIVATION

The ICON model, a high-resolution, data-assimilating, model of the Monterey Bay area, was initially designed for studying mesoscale features such as eddies and upwelling filaments. Tidal forcing is now being implemented into this model to facilitate short-term particle-tracking studies, and to move towards a real-time operational forecast model.

2. BACKGROUND

Although barotropic tidal currents in this area are relatively small, they are highly spatially variable due to the complex bathymetry. The baroclinic tidal currents can be an order of magnitude larger than the barotropic, and contribute significantly to the kinetic energy, as well as producing a highly variable density field – thus producing challenges for data assimilating models that do not include tidal processes. Long-term and/or depth-averaged current records from numerous locations in and around Monterey Bay are used in an attempt to characterize the barotropic tidal currents, by minimizing the contribution from internal tides.

The intermittency of the internal tide signal has been noted on many of the world's continental shelves. It is also commonly found that the internal tide is not phase-locked to the surface tide. These properties of the internal tide may allow barotropic tidal currents to be estimated from very long records of currents at only one depth, even in areas where internal tides are known to be large. In Monterey Bay for example, previous work has shown the baroclinic tidal currents to be highly variable in both time and space. It has also been observed there that the amplitudes of the baroclinic tidal currents exceed those of the barotropic tidal currents as estimated from large-scale tide models.

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3. MODEL

The ICON model, implemented for studies of mesoscale variability during the Innovative Coastal-ocean Observing Network experiment, is a 3-D, free-surface, sigma-coordinate version of the Princeton Ocean hydrodynamic model. The orthogonal, curvilinear grid has variable resolution in the horizontal, ranging from 1 - 4 km (Shulman et al., 2002). The model has 30 vertical sigma levels.

Tidal forcing is introduced into the ICON model through specification of the open boundary conditions using the tidal constants interpolated from the Oregon State University Tidal Solution for the U.S. West Coast to the ICON grid. Eight tidal constituents (M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1) are included. These tidal constants are used to predict the tidal heights and currents using the Schwiderski (1980) scheme, which does not include a correction for the nodal factor. The model is run for 56 days starting Aug. 1, 2000 0100 GMT with the tidal forcing ramping up over the first seven inertial periods. Tidal analysis was performed on the last 34 days only, so P_1 is inferred from K_1, and K_2 is inferred from S_2. Inference parameters are based on sea level analyses.

Results from four case studies (Table 1) are discussed here. Two types of open boundary conditions were tried; the Reid and Bodine (1968) condition, which uses only sea level forcing, and the Flather (1976) condition, which requires both sea level and barotropic transport. For the latter, in addition to the interpolation, the transports (given as m^2/s) were rotated into the ICON curvilinear coordinates and the component orthogonal to each open boundary grid point was divided by the ICON bathymetry at that point to get the normal velocity used in the forcing. A homogeneous case and an initially horizontally uniform stratified case was run with each of the two boundary conditions.

Run	Density	Tidal sea level forcing	Tidal barotropic velocity forcing
8.0	stratified	yes	yes
8.1	stratified	yes	no
8.3	homogeneous	yes	no
8.4	homogeneous	yes	yes

Table 1. Attributes of the four ICON model runs with tidal forcing that are used to assess the effects of different boundary and stratification conditions on the tidal sea level and current signals. Sea level forcing only equals Reid and Bodine boundary condition. Addition of barotropic velocity forcing means the Flather boundary condition was used.

4. DATA

4.1 Sea Level and Bottom Pressure

NOAA's National Ocean Service has published tidal constants for three coastal stations on Monterey Bay: Monterey, Moss Landing and Santa Cruz. We were able to obtain bottom pressure records from three offshore stations. The tidal amplitudes for these are reported as sea level height, to be consistent with the coastal stations. There could be an error of approximately 1% associated with the conversion from bottom pressure to sea level height.

4.2 Surface Currents from HF Radar

Two year-long (or nearly so) records of hourly surface current vectors from Monterey Bay were chosen for tidal analysis from a multi-year, though gappy, set of data derived from HF surface radars. The most recent data makes use of the newer CODAR systems, so has much better domain coverage. We have also converted model velocities for comparison with the radar-measured radial velocities, but the interpretation of these is problematic so they are not included here.

4.3 Moored Currents

Nearly full water column velocity profiles for 29 days or longer were available from three locations within the model domain: P1, AOSN2, and Davenport. Multi-year current records at multiple depths were available for another four locations: M1, M2/S2, P2, and P3. Velocity data from the surface moorings, M1 and M2, have been corrected for horizontal mooring motion using information from a GPS mounted on the surface buoy.

5. METHODS

Tidal analysis was performed using T_TIDE (Pawlowicz et al., 2002), the Matlab version of Foreman's (1977, 1978) tidal analysis programs. T_TIDE is recommended for use with time series no longer than one year since the nodal correction factor is applied to the center of the time series. For the multi-year records, albeit with large gaps in some cases, we averaged results from multiple pieces of one year or less. These averaged tidal constants compared favorably with those calculated from a beta version of T_TIDE designed for use with very long records.

Although tidal constants were calculated for all constituents resolved with a Rayleigh factor of 1 (0.94 in the case of the most recent surface current data), results will be shown here only for the two largest, the M_2 (period = 12.42 h) and the K_1 (period = 23.93 h). For time series too short to resolve all eight of the forcing constituents, P_1 was inferred from K_1 and K_2 from S_2.

Using the OSU tidal prediction software, which does include the nodal correction factor, we created a predicted sea level time series at each of the sea level and bottom pressure stations for the time coincident with the last 34 days of the model run. The comparison between sea level from the ICON model and that predicted from tidal constants at the coastal locations is shown in Figure 1.

The tidal current ellipses calculated from the moored velocity data are compared with model ellipses calculated from the velocities at the closest model grid points, choosing the sigma levels closest to the measurement depths for that location.

6. RESULTS

All four model runs are quite successful in reproducing the measured bottom pressure and sea level tidal signals (Figure 1). The model slightly under-predicts both the M_2 and K_1 sea level amplitudes. The phase of the M_2 constituent is well-predicted, but the K_1 phase is off by about 14°, which equals 0.9 h for this frequency. The model does a slightly better job using the Reid and Bodine boundary condition, which forces only with sea level at the open boundary, rather than the Flather boundary condition. The inclusion of stratification does very little to change the results. This is evidenced by the fact that the M_2 amplitude and phase for sea level are essentially the same for model runs 8.0 and 8.4, while the results from run 8.1 are essentially the same as for run 8.3. So the differences in the M_2 tidal constants for sea level between runs 8.0 and 8.3 are more due to the different boundary conditions, than the addition of stratification. The same is true for the K_1 constituent. The K_1 sea level amplitude from runs 8.1 and 8.4 are essentially the same as from run 8.3, which differs slightly from run 8.0, particularly in the southern part of Monterey Bay. The phases from runs 8.1 and 8.3 are nearly equal, while the same is true for runs 8.4 and 8.0.

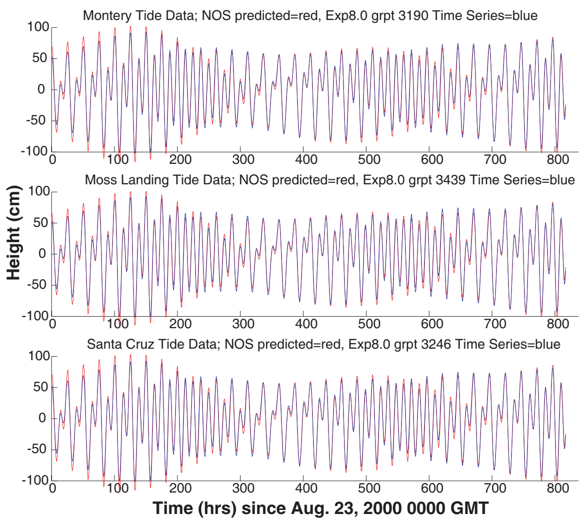

Figure 1. Sea level predicted using the OSU tidal prediction software with the NOS-published tidal constants for the 8 constituents used in the ICON model forcing (red), versus the ICON model sea level from the closest grid points to the coastal tide stations (blue).

The measured surface tidal currents exhibit considerable spatial variation, but are remarkably consistent year to year. The M_2 surface currents from the homogeneous runs (8.3 and 8.4) are very similar and very weak. Adding stratification produces somewhat larger semidiurnal tidal currents, while the further addition of velocity forcing (run 8.0, Figure 2) results in current speeds similar to what are observed (Figure 3). The model currents show spatial variability comparable to that observed and the model captures some of the details quite well (such as the velocity minima over the canyon and in the northern bight), but misses others (such as the phase just north of the canyon inside the Bay). It would appear that even with a year-long time series, the measured surface semidiurnal tidal currents may not be representative of the barotropic velocity field. The depth-averaged currents off Pt. Sur (moorings P1, P2, and P3 in Figure 4) compare favorably with the currents from the homogeneous model (Figure 5).

Without velocity forcing, the model's K_1 currents are very small. Even with velocity forcing, the model K_1 surface currents in Monterey Bay (Figure 6) are considerably weaker than the measured ones (Figure 7). This is not thought to be due to effects of diurnal wind forcing on the real ocean, which is known to be quite large in this area, since the tidal analysis separates the K_1 from the S_1 response in the observed time series. It is possible that an erroneous amount of the model's energy at the K_1 frequency may be put into the P_1 constituent that is inferred from it. We have also seen that the phase of the K_1 constituent in sea level is off by about an hour, and that may contribute to errors in the velocity field. The model does capture the offshore decay in depth-averaged K_1 kinetic energy measured by moorings P1, P2, and P3 on the Sur Ridge.

The horizontal current ellipses versus depth represent averages over long periods of time. Analyses over shorter periods indicate that, as with the surface currents, the picture is pretty consistent year to year. Stratification must be included in the model to even approach the measured M_2 velocities. This, together with the vertical variations in the observed horizontal currents, demonstrates again that tidal analysis of even a multi-year time series does not isolate the barotropic component of the semidiurnal tidal currents in some geographic areas. As expected, the difference between the homogeneous and stratified modeled sub-inertial K_1 currents are much less than for the super-inertial M_2 currents. The differences between the measured and modeled currents shows how difficult it will be to accurately reproduce, and ultimately predict, the tidal currents at a given location and depth.

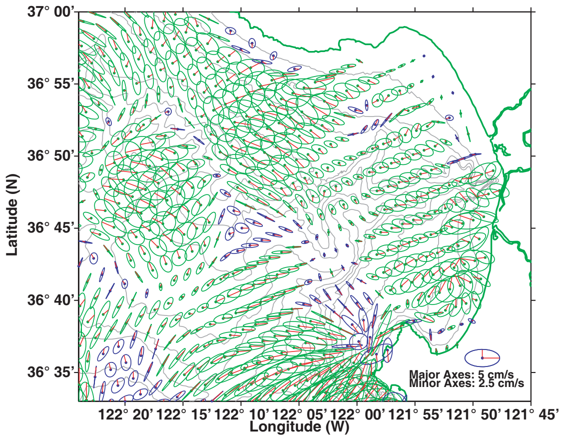

Figure 2. M_2 surface current tidal ellipses from model run 8.0, which is stratified and uses the Flather boundary condition. Only the portion of the model domain which is usually covered by the HF radar array is shown. Blue ellipses mean the current vector rotates counter-clockwise, green ellipses mean clockwise rotation. The red line in each ellipse indicates the direction toward which current flows at the time of high M_2 sea level at Monterey. The 25, 50, 75, 100, 250, 500, 750, 1000, 1500, 2000, and 2500 m isobaths are shown.

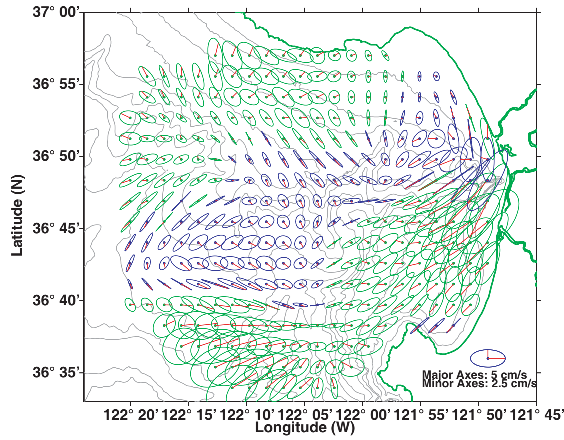

Figure 3. M_2 surface current tidal ellipses, derived from velocities measured by the HF radar array. Ellipses are shown only for locations where there was data coverage at least 50% of the time during July 2003 – June 2004. Blue ellipses mean the current vector rotates counter-clockwise, green ellipses mean clockwise rotation. The red line in each ellipse indicates the direction toward which current flows at the time of high M_2 sea level at Monterey.

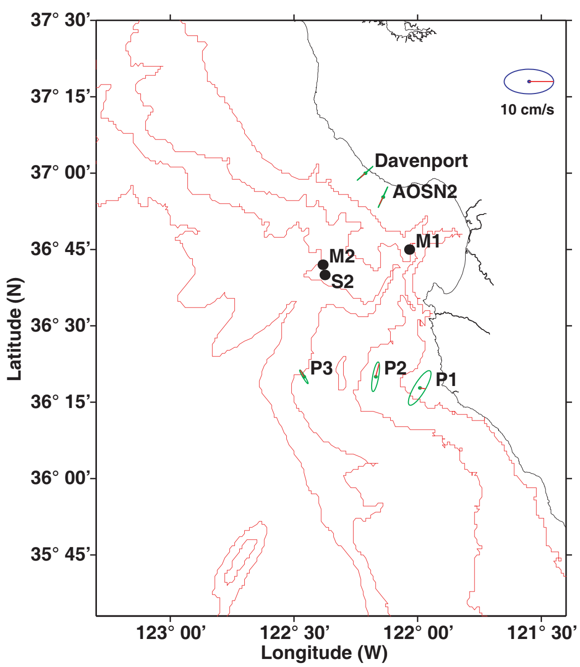

Figure 4. The depth-averaged M_2 tidal current ellipses for Davenport, AOSN2, P1, P2, and P3 are shown, as well as the locations of moorings M1, M2 and S2. Bottom-mounted upward-looking ADCPs were deployed at the first 3 of these locations, and velocity measurements covered nearly the whole water column. The 200, 1000, 2000, 3000, and 4000 m isobaths are shown.

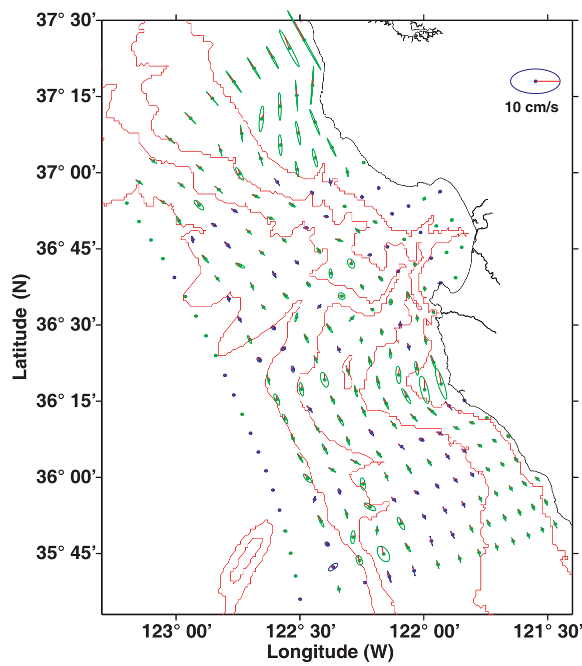

Figure 5. M_2 surface current tidal ellipses at every 4^{th} grid point from model run 8.4, which is homogeneous and uses the Flather boundary condition. Blue ellipses mean the current vector rotates counter-clockwise, green ellipses mean clockwise rotation. The red line in each ellipse indicates the direction toward which current flows at the time of high M_2 sea level at Monterey.

7. WHAT'S NEXT?

Now that we've determined that stratification and the Flather boundary condition are needed to achieve realistic semidiurnal currents, we will do a long model run (> 205 days) so that the time series after the ramp-up period will be long enough to resolve all eight of the forcing constituents. This will let us avoid having to infer P_1 from K_1, which may be causing unrealistic K_1 constants.

In order to correct for the long period nodal factor, we will switch to a different tidal prediction scheme for the model forcing.

In order to see if we can do a better job at isolating the barotropic tidal currents, we will perform tidal analyses for shorter periods of time when the water column is well mixed.

Given that the real ocean stratification changes over time, we will test how sensitive the model tidal currents are to changes in stratification more subtle than the stratified – homogeneous comparisons explored to date.

Tidal forcing is now being added to a number of other models, including NCOM, ROMS, and HOPS, that are being run in domains including the Monterey Bay area, so it is hoped that these analyses will be useful to those efforts as well.

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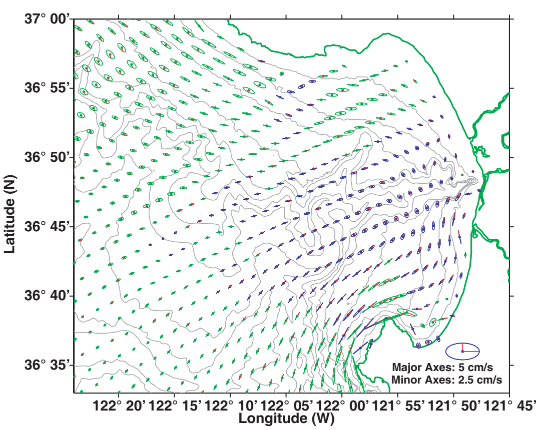

Figure 6. K_1 surface current tidal ellipses from model run 8.0, which is stratified and uses the Flather boundary condition. Only the portion of the model domain which is usually covered by the HF radar array is shown. Blue ellipses mean the current vector rotates CCW, green ellipses mean CW rotation. The red line in each ellipse indicates the direction toward which current flows at the time of high K_1 sea level at Monterey.

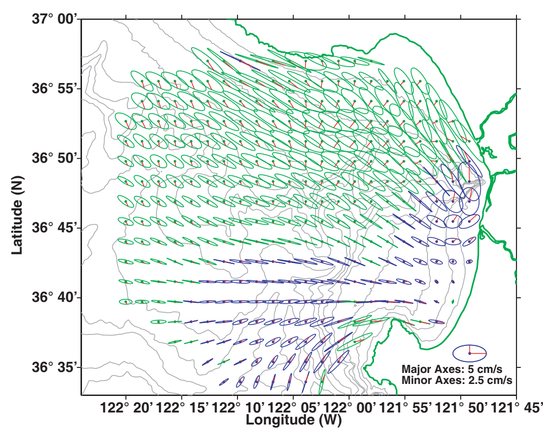

Figure 7. K_1 surface current tidal ellipses, derived from velocities measured by the HF radar array. Ellipses are shown only for locations where there was data coverage at least 50% of the time during July 2003 – June 2004. Blue ellipses mean the current vector rotates CCW, green ellipses mean CW rotation. The red line in each ellipse indicates the direction toward which current flows at the time of high K_1 sea level at Monterey.