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Validation Test Report for the Tidal Open-Boundary Prediction System (TOPS)

Paul J. Martin
Scott R. Smith
Gretchen M. Dawson
Pamela G. Posey

Ocean Dynamics and Prediction Branch
Oceanography Division

Edward D. Zaron

Portland State University
Portland, Oregon

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Paul J. Martin, Scott R. Smith, Gretchen M. Dawson, Pamela G. Posey, and Edward D. Zaron*

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*College of Engineering and Computer Science, Portland State University, Portland, OR

14. ABSTRACT

This Validation Test Report presents tests of the use of the Oregon State University (OSU) Tidal Inversion Software (OTIS) to provide tidal boundary conditions (BCs) for the Navy Coastal Ocean Model (NCOM) in several regional and coastal domains. OTIS is a set of programs designed to generate optimal tidal solutions within an ocean domain by 4D variational assimilation of tidal data from various sources, including satellite altimetry and coastal tide gauges. The procedure used to generate tidal BCs is that OTIS is run on the grid used by NCOM to generate a tidal solution for that domain, and values from the OTIS solution are used to provide tidal BCs for NCOM. The tides generated by NCOM with BCs from OTIS and from existing regional and global tidal data bases (DBs) are compared. Tidal errors are computed by comparison of the tidal solutions with coastal tide-gauge and satellite altimeter data. For large ocean domains, using tidal BCs from OTIS and from existing tidal DBs gave comparable errors. For smaller domains, using tidal BCs from OTIS gave a small improvement, overall, compared to using BCs from the tidal DBs. The OTIS tidal solutions, themselves, generally provide more accurate tides than the tidal DBs in small, coastal domains.

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VALIDATION TEST REPORT FOR THE TIDAL OPEN-BOUNDARY PREDICTION SYSTEM (TOPS)

1. INTRODUCTION

Tides are generally an important part of the variability of sea-surface height (SSH) and currents in coastal and shallow-water areas and, hence, are an important component of coastal ocean models. If the boundary conditions (BCs) being used for a regional ocean model (e.g., from a larger-scale ocean model) do not include tides, tidal BCs need to be obtained from some source. Tidal BCs need to include both tidal SSH and transports (i.e., the vertical mean velocity multiplied by the water depth) to accommodate the radiation BCs generally used by regional ocean models (tidal BCs that involve just SSH tend to be less robust for applications involving more than just tidal forcing).

There are currently available both global and regional tidal data bases (DBs) that can provide both tidal SSH and transports to use for tidal BCs. Most of the tidal DBs that are currently being used by NRL were generated by Oregon State University (OSU) using their OSU Tidal Inversion Software (OTIS) (Egbert and Erofeeva, 2002). OTIS is a set of programs designed to generate optimal tidal solutions in a global or regional ocean domain by assimilation of tidal data derived from satellite altimetry, coastal tide gauges, and other sources.

The tidal DBs from OSU currently being used by NRL are listed in Table 1. Note that there are a number of regional tidal DBs available from OSU that have not been downloaded for use at NRL; however, most of these lie within the areas covered by the OSU regional DBs in Table 1. Also, note that the regional tidal DBs available from OSU are continually being expanded and updated. Hence, some of the OSU tidal DBs that were used for this study have been superseded by newer versions, which are available at OSU's OTIS web site (http://volkov.oce.orst.edu/tides).

Table 1 — OSU Tidal Data Bases Currently Being Used at NRL

database	longitude (°E)	latitude (°N)	resolution	tidal constituents
Global	0.00 to 360.00	-90.00 to 90.00	1/4°	K_1 O_1 P_1 Q_1 K_2 M_2 N_2 S_2 Mm Mf
Indonesia	95.00 to 165.00	-21.00 to 15.67	1/6°	K_1 O_1 P_1 Q_1 K_2 M_2 N_2 S_2
Mediterranean	-5.58 to 36.33	30.42 to 45.91	1/12°	K_1 O_1 M_2 S_2
North Atlantic	-100.00 to 15.00	-5.00 to 75.00	1/12°	K_1 O_1 P_1 Q_1 K_2 M_2 N_2 S_2
US West Coast	225.00 to 255.00	21.00 to 50.00	1/12°	K_1 O_1 P_1 Q_1 K_2 M_2 N_2 S_2
Yellow Sea	105.25 to 129.25	14.00 to 42.00	1/12°	K_1 O_1 M_2 S_2

Because of the large computational demands of OTIS, there are practical limits to the amount of data and the grid resolution that can be used to generate a tidal solution for a domain. For

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this reason, tidal solutions generated with OTIS for moderately large domains have been done with limited grid resolution. For example, the global tidal DB developed by OSU has a resolution of 1/4°, and the regional DBs that we have, e.g., for the Mediterranean, the North Atlantic, the eastern North Pacific, and the greater Yellow Sea, have been computed at 1/12°(Table 1).

Because of their assimilation of tidal data derived from satellite altimetry, these DBs generally have fairly accurate tides in deep water away from the coast. However, in shallow-water areas and near coasts, where altimetry data tend to be less accurate and errors in the bathymetry used by OSU for OTIS tend to be more critical, the tidal solutions can have significant errors (Martin et al., 2009). Also, note that the tidal DBs from OSU that we currently use (Table 1) were generated by OSU using data only from satellite altimetry.

Because of these limitations of the existing tidal DBs, OTIS has been adapted to directly calculate tidal BCs for a specified, regional, ocean-model domain. The procedure used to generate the tidal BCs is that OTIS is run on the grid used by the ocean model to generate a tidal solution for that domain, and values from the OTIS solution are used to provide tidal BCs for the regional ocean model.

This report discusses the use of OTIS to generate tidal BCs for a regional ocean model, and provides results from tests using OTIS to generate tidal BCs for a number of regional, ocean-model domains. The regional ocean model used here is the Navy Coastal Ocean Model (NCOM) (Martin, 2000), which is currently being used by the Naval Oceanographic Office (NAVO) in both global (Barron et al., 2004) and regional (Rowley, 2010) applications. Tidal errors for NCOM using tidal BCs from a local OTIS solution are compared with errors for NCOM using tidal BCs from our OSU tidal DBs (Table 1).

The OTIS software obtained from OSU came supplied with an altimeter data set called the Pathfinder (PF) data, and the assimilation of this altimeter data by OTIS was used for our initial work with OTIS and for most of the results described in this report. A separate altimeter data set has been developed at NRL that uses the longer time series of altimeter data that has became available since the PF data set was created. The longer length of the NRL altimeter data set should provide slightly more accurate tidal information than the PF data. To see if results from OTIS are improved by use of the NRL altimeter data, tidal errors for OTIS, and for NCOM tidal simulations using tidal BCs from OTIS, are compared for both altimeter data sets.

Errors are also computed for a few of the domains using tidal BCs for NCOM generated by the tide/surge model PCTides (Posey et al., 2008), to see how using PCTides to compute tidal BCs for a regional ocean model compares with using OTIS. The PCTides model is currently in operational use at NAVO for tidal prediction.

The sections that follow contain (2) a brief description of OTIS as it pertains to computing tidal BCs for a regional ocean model, including some limitations, (3) a discussion of the procedure used for the tests conducted in this report, (4) results from the tests of using OTIS to compute tidal BCs for NCOM, (5) comparison of some results from assimilation by OTIS of the NRL altimetry data with results from assimilation of the Pathfinder data (6) a description of PCTides and results from tests using PCTides to generate tidal BCs for NCOM, and (7) a summary.

2. OTIS

The development of OTIS is one of several efforts over the past couple of decades to use satellite altimeter data to derive accurate tidal solutions for the global ocean and for regional ocean domains. Some of the earlier efforts include Cartwright et al. (1990), Egbert et al. (1994), Mazzega et al. (1994), Kantha (1995), Matsumoto et al. (1995), and Le Provost et al. (1998).

The development of OTIS and the tidal DBs generated with OTIS by OSU brought two major advantages over most of the earlier available global and large-scale regional tidal solutions: (1) the OTIS tidal solutions were made available with both SSH and transport (velocity times depth) data, and (2) the OTIS software itself was made available to allow users to generate tidal solutions for domains of their own choosing using tidal data of their own choosing.

Previous to the OSU tidal DBs, most tidal DBs were made available with only SSH data, since the tidal SSHs that were computed were judged to be significantly more reliable than the tidal transports (there is not a lot of data available to evaluate tidal transports, and tidal transports tend to be much more sensitive to uncertainties in bathymetry than tidal SSH). However, both SSH and transport data are needed to implement robust radiation BCs for regional ocean-model simulations. SSH data alone can be used for regional simulations of just the tides, but for more general simulations that include the non-tidal ocean circulation and atmospheric forcing, Flather-type radiation BCs (Flather, 1976; Flather et al., 1983) are needed to allow disturbances generated within the domain to propagate out through the open boundaries so that the energy of these disturbances does not remain trapped within the domain and disrupt the interior ocean model solution. Hence, tidal transport data, even if of uncertain accuracy, make including tides in regional ocean-model simulations much easier.

The availability of the OTIS software and associated DBs (e.g., the global satellite altimeter data and the OSU global and regional tidal DBs), have made it possible to compute tidal solutions for any arbitrary ocean domain using almost any combination of available tidal data.

2.1 Description of OTIS

OTIS consists of a number of programs and associated DBs, and some discussion of these can be found in Martin et al. (2009) and Smith et al. (2010). The three main aspects of OTIS are: (1) a forward tidal solution, which is computed without data assimilation to obtain an initial solution for the tides in the domain, (2) the tidal data (e.g., tidal data that have been harmonically analysed from SSH altimeter and tide-gauge measurements), and (3) a final, data-assimilative, tidal solution that is computed using a Four-Dimensional, Variational (4DVAR), assimilation system to minimize the expected error of the solution with respect to (wrt) the momentum equations used by OTIS and the tidal data.

The version of OTIS referred to in this report is Version 3.2. The sequence of programs that were used to run OTIS for the tests described in this report is presented in Appendix A, and the values of the OTIS parameters that were used are listed and briefly discussed in Appendix B.

2.2 Data Assimilated by OTIS

Two types of data were assimilated within OTIS for the tests conducted in this report. The first type of data are the altimeter data that came with the OTIS software, which is referred to as the Pathfinder (PF) data set. These are data from the TOPEX altimeter that were collected over a 10-year period from 1992 to 2002. This satellite was in an approximately 10-day repeat orbit and the data were sampled about every 6 km along the track. There are 127 different tracks with about 6750 data values along each track. Hence, at a particular location along a track, there are SSH values roughly every 10 d for a period of 10 y. These 10-y time series are analysed by the OTIS software to determine the amplitude and phase of the main tidal constituents at that location. Since the altimeter data are degraded near land areas, the Pathfinder altimeter data are located at sea points that are sufficiently far from land areas to avoid degradation of the altimeter data by the land areas.

The second type of data that were assimilated within OTIS for the tests conducted in this report are the International Hydrographic Office (IHO) tide-gauge data. These tide-gauge data consist of a global set of tidal data from over 4000 tide-gauge stations collected by the IHO. The data for each tide-gauge station contains the name of the station, its latitude-longitude location, and the amplitude and phase of a number of tidal constituents that were determined from analysis of the SSH data collected at the station. The tidal constituents analysed at the different IHO stations vary significantly from station to station, but most stations contain data for the main, i.e., generally largest, tidal constituents: M_2, S_2, K_1, and O_1. Since the altimeter data are at open sea locations away from land areas, the IHO data are complementary in providing data near land.

Assimilation of the IHO coastal tide-gauge data has the potential problem that some tide gauges are located in areas, e.g., within bays, estuaries, or river mouths, where the amplitude and/or the phase of the tide is somewhat different than in the adjacent coastal ocean. For example, the tidal phase can change significantly as the tide propagates into a bay, estuary, or river mouth. If the computational grid does not adequately resolve the region near the tidal station that locally affects the tide, then using the data from that station to represent the tide in the adjacent coastal ocean (i.e., where the tide is adequately resolved) may involve significant error. OTIS attempts to reduce this problem by only assimilating data from tidal stations that lie within the sea grid cells of the computational grid being used, so that data from stations located in unresolved areas will be less likely to be used.

OTIS is capable of assimilating other kinds of tidal data, e.g., tidal currents analysed from moorings where velocity measurements have been made. However, we do not currently have a large DB of such data. The locations at which tidal currents are being measured and analysed is constantly expanding, and a global DB of tidal currents would be a useful addition to our currently available tidal data sets.

A set of altimeter data for assimilation by OTIS, different from the PF data set, has been developed at NRL, which will be referred to here as the NRL altimeter data set. This data set contains an additional six years of data from the Jason altimeter, which were added to the TOPEX data to provide a 16-y-long timeseries of altimeter data. Since the NRL altimeter data set is longer than the PF data set, it can potentially provide more accurate tidal analyses. Also, more care was taken in working up the NRL altimeter data to try to preserve altimeter data locations as near to land areas as possible. The results of some tests conducted with the NRL altimeter data to see how the assimilation of this data by OTIS compares with the assimilation by OTIS of the PF data, are presented in Section 5.

2.3 Data Used for Validation of the Tidal Solutions

The IHO tide-gauge data and the TOPEX Interleave (TIL) data are used for validation of the tidal solutions computed in this report. That the IHO data are used both for assimilation by OTIS and validation of the tidal solutions raises the question of whether this biases the results. However, the primary errors computed for this report are the errors for the NCOM tidal solutions, and NCOM itself does not assimilate any tidal data, the only external data that affect the NCOM tidal solutions are the tidal BCs that NCOM uses.

The TOPEX Interleave (TIL) data are a separate data set from the TOPEX Pathfinder data that are assimilated by OTIS. In 2002, the Jason-1 altimeter was launched into the same orbit as TOPEX/Poseidon, so that the Jason-1 altimeter could be calibrated with the TOPEX altimeter. In early 2003, the orbit of the TOPEX/Poseidon satellite was shifted to an orbit lying between its original ground tracks. Hence, after this shift of TOPEX/Poseidon's orbit, both TOPEX/Poseidon and Jason-1 were collecting data at the same time in different but "interleaving" orbits. Hence, these data are referred to as the TIL data. The TOPEX altimeter died in 2006, so the TIL data were collected for a period of 3 y. The processing of the TIL data set was done at NRL.

2.4 Using OTIS to Generate Tidal BCs

The procedure used to generate tidal BCs for a regional ocean model using OTIS is (a) OTIS is run on the grid used by the ocean model to generate an optimal tidal solution for that domain, and (b) values from the OTIS tidal solution are used to provide tidal BCs for the ocean model.

The advantages of this procedure over using the pre-computed tidal DBs that we have are that (a) OTIS is run directly on the grid used by the ocean model, and so will be run with the same (typically high) grid resolution used by the ocean model (but not on a larger domain, which would increase OTIS's run time), and (b) data from International Hydrographic Office (IHO) tide-gauge stations within the domain, which are available from a global DB of over 4000 stations, can be assimilated in OTIS, in addition to satellite altimeter data.

The adjustments used by OTIS to generate an optimal tidal solution are: (a) allowance for error in the tidal data being assimilated, (b) allowance for error in the tidal equations that are used, and (c) allowance for error in the tidal BCs being used. It is because of (c), the adjustment of its tidal BCs, that OTIS can be run on the grid of a regional ocean model and generate improved BCs (which will lie on the open, i.e., seaward, boundary of the ocean model domain).

However, the allowance by OTIS for error in the tidal equations is somewhat inconsistent with the ocean model, since the latter does not allow for such error. There is a parameter within OTIS, called the damping parameter, *sig-e*, that governs the relative amount of error allowed in the momentum equations versus (vs) that allowed in the observations. Note, however, that the continuity equation in the OTIS tidal model, which governs the continuity of transports in the OTIS tidal solution, is strictly enforced (Egbert and Erofeeva, 2002). Parameter *sig-e* is usually set to a value near one, which provides an approximate balance between the amount of error allowed in the momentum equations vs that allowed in the observations. If parameter *sig-e* is set high, the OTIS tidal solution is forced to conform more strictly to its momentum equations and the tidal solution will be more like that obtained by the ocean model. However, doing this tends to increase the error in the tidal solution wrt the assimilated observations.

An argument for setting parameter *sig-e* large is that the tidal solution from OTIS will be more like that obtained with the ocean model, and setting *sig-e* large will force OTIS to adjust its BCs to minimize the error of the tidal solution wrt the observations. However, if this increases the error of the OTIS tidal solution, then the tidal solution is not optimal and, hence, the tidal BCs will likely not be optimal either. There is further discussion of this issue in the next section.

2.5 Limitations of the Use of OTIS to Generate Tidal BCs

Some limitations of the procedure for using OTIS to generate tidal BCs for an ocean model are: (a) OTIS can only be run on a regularly-spaced, longitude-latitude grid, (b) the tidal equations of the OTIS assimilative model are linearized, i.e., the advection terms are not included and the bottom drag is linearized, (c) the tidal model in OTIS uses a single, homogeneous layer, and (d) OTIS cannot, by itself, adjust its bottom drag to optimize the tidal solution.

OTIS is limited to using regularly-spaced, longitude-latitude grids. Such domains are only one of a number of map projections in common use in ocean modeling – other types include Mercator, Lambert-conformal, and stereographic projections. However, most ocean-model domains currently used for operational prediction by the U.S. Navy are set up as regularly-spaced, longitude-latitude grids. Hence, the limitation of OTIS to these type of grids is not currently a significant concern. Most other types of map projections could be accommodated by defining the OTIS domain to be large enough to fully include the ocean model domain, so that the tidal BCs for the ocean model could be interpolated from within the OTIS domain.

The equations used by the OTIS assimilative tidal solution are linearized to allow the equations to be solved in frequency space, rather than by integrating in time. The terms that are affected by this linearization include the advection and bottom drag terms. The advection terms are simply omitted. This omission has the largest effect in shallow water, where the tidal velocities tend to be larger and the advection term more significant. However, the effect of not including the advection term on the tidal solution and, especially, the tidal BCs in moderately-sized (e.g., 200-km) coastal ocean domains is generally small.

The OTIS forward tidal model is available in both linear and non-linear versions. The non-linear version takes longer to run, and since it did not give noticeably better results in some comparisons that were made, the linearized version of the forward model was used.

The commonly-used quadratic parameterization of the bottom drag or bottom stress, e.g., for the x-component of the momentum equation, can be written as

$$\tau_b^x = c_b u|\mathbf{v}|, \tag{1}$$

where τ_b^x is the bottom stress for the x-component of the momentum equation, c_b is the bottom drag coefficient, u is the component of velocity (at the bottom) in the x-direction, and $|\mathbf{v}|$ is the magnitude of the vector velocity. The bottom drag is linearized in OTIS by replacing the magnitude of the vector velocity in the quadratic bottom drag $|\mathbf{v}|$ by a fixed "friction velocity" v_0. This friction velocity can be specified as a spatially-constant value, or a spatially-variable value can be computed using the OTIS forward tidal solution.

OTIS computes the spatially-variable friction velocity as a temporal average of the tidal-velocity magnitude (from the previous run of the OTIS forward tidal model) at each point on the grid being used. Using a spatially-variable friction velocity in OTIS requires the forward model to be run twice, since an initial run of the forward model is used to compute an estimate of the temporal-mean velocity at each point on the grid. The forward model is then run a second time using the spatially-variable friction velocities computed from the first run. The computed, spatially-variable, friction velocity is generally a better approximation to the quadratic bottom drag used in most ocean models, but is still not the same as using a quadratic bottom drag, since the velocity magnitude in the quadratic bottom drag in Eq. (1) is not a local, temporal-mean value, but changes continually throughout the tidal cycle.

OTIS uses a single, homogeneous layer to model the barotropic tide, whereas, most coastal ocean models are multi-layer, baroclinic models that include temporally- and spatially-varying temperature, salinity, and density. However, a single-layer, homogeneous model generally provides a fairly good simulation of the barotropic tide. The main differences for a multi-layer, baroclinic model that affect the tide are that (i) the bottom drag will be computed differently, and (ii) some of the energy of the barotropic tide may be lost to the generation of baroclinic (internal) tides. However, although the energy loss to internal tides is significant globally (Kantha et al., 1997; Egbert and Ray, 2003), it tends to be small within most regional ocean domains.

OTIS cannot, by itself, adjust its bottom drag to minimize the error of its tidal solution wrt the assimilated observations. This is not very important in the deep ocean, since the tidal velocities there are small and the energy lost to bottom drag has only a very small effect on the tides. However, in shallow areas, the value of the bottom drag can significantly affect the tidal solution.

OTIS can, at least partially, compensate for its inability to adjust its bottom drag by its general allowance for error in its momentum equations as specified by input parameter *sig-e*. As long as *sig-e* is set sufficiently low, the error in the momentum equations allowed for by OTIS will include error in the bottom drag, which will allow OTIS to reduce the error of its tidal solution wrt the assimilated observations. However, we have found that if *sig-e* is set high, so that error in the momentum equations is not allowed for, a non-optimal specification of the bottom drag (among other uncertainties in the momentum equations) can result in large errors in the tidal solution. In this case, the error of the tidal solution can be reduced by manual adjustment of the specified bottom drag. This can be done by (a) adjustment of the specified, constant friction velocity, or (b) by using a spatially variable friction velocity and modifying the bottom drag coefficient, which is currently hardwired in OTIS to a fixed value of 0.003.

An approach to optimizing the tides computed in a regional ocean model might be to (a) run OTIS with a high value of *sig-e* to force OTIS's tidal solution to conform strictly to its momentum equations and manually adjust the bottom drag to minimize the error of the tidal solution. This would help tune the bottom drag in OTIS to values appropriate for the domain. Of course, it may be that adjusting the bottom drag would be helping to offset other problems, such as inadequate bathymetry and lack of representation of energy lost to the generation of internal waves (however, maybe this can't be helped). Then, (b) run OTIS with a median value of *sig-e* (i.e., a value near one) to allow for general error in the momentum equations to further minimize the error of the OTIS tidal solution. This should help to generate optimal tidal BCs.

However, a further step that would be needed would be to (c) manually adjust the bottom drag in the ocean model to minimize the error of its tidal solution wrt observations. Because of the number of differences between the treatment of tides in OTIS and in the ocean model, including the linearization used in OTIS and differences in the parameterization of the bottom drag, a separate optimization of the bottom drag in the ocean model would generally be needed to optimize its tidal solution.

It is not known if the extra work involved in steps (a) and (b) above would result in a worthwhile improvement of the BCs generated by OTIS. Hence, the current procedure for using OTIS to generate tidal BCs is to run OTIS just once with a median value of *sig-e* of one.

However, it can be said that, no matter how good the tidal BCs are, step (c), adjustment of the bottom drag used by the ocean model, is necessary to optimize the tidal solution in many coastal domains. This is strongly reflected in the coastal modeling literature and is a consequence of the fact that the bottom type and the resulting bottom friction can differ greatly from region to region, and the only means the ocean model has to account for this is adjustment of the model's bottom friction parameters.

3. TESTING THE USE OF OTIS TO GENERATE TIDAL BCS

The use of OTIS to generate tidal BCs for a regional ocean model is a general procedure that should be appropriate for any ocean model. In this report, the ocean model used is the Navy Coastal Ocean Model (NCOM). NCOM was developed by and is being used for research at NRL (Martin, 2000), and is currently being used for both global (Barron et al., 2004) and regional (Rowley, 2010) operational ocean prediction at the NAVO.

3.1 Testing Procedure

The procedure used for the testing done in this report is to (A) perform a tidal simulation with NCOM in a regional domain using tidal BCs from the available tidal DBs from Table 1 and compute errors for the tidal solution wrt the IHO stations within the domain and wrt the TOPEX Interleave (TIL) data set, (B) use OTIS to generate a tidal solution in the NCOM domain by running OTIS with the NCOM grid and bathymetry and assimilating satellite-altimeter and IHO-station tide data, and (C) perform a tidal simulation with NCOM as in (A) but using tidal BCs from the local OTIS tidal solution (B), rather than from an existing tidal DB, and compare the errors of the tidal solution with the errors from (A) to see if the tidal errors are reduced by using tidal BCs from the local OTIS tidal solution.

3.2 Specification of NCOM for Tidal Simulations

The NCOM tidal solutions computed for steps (A) and (C) in the testing procedure described above use just a single, homogeneous layer so as to simplify the simulations and reduce their run time. Hence, NCOM is run with a uniform potential temperature and salinity and is run in diagnostic mode, which means that the temperature and salinity fields are depth fixed and are not updated.

The numerical scheme used for horizontal advection in the NCOM simulations conducted here is a third-order-upwind scheme (Holland et al., 1998). Inherent in this advection scheme is a biharmonic mixing scaled by the advection velocity (however, the particular choice of numerical advection or horizontal diffusion scheme should not significantly affect the tidal solution). Because of the built-in biharmonic mixing, no additional horizontal mixing is needed. And since only a single layer is being used, no vertical mixing scheme is needed. The temporal scheme used in NCOM is leapfrog with an Asselin (1972) filter to suppress time splitting, and the free surface is solved implicitly (Martin, 2000). The timestep used for NCOM varied from 300 s for the coarsest grid resolution (3 km) to 20 s for the highest (which is 200 m for the Messina Strait domain).

The bottom stress is parameterized in NCOM by a quadratic drag law (Eq. 1). The drag coefficient c_b is calculated in terms of the bottom-layer thickness Δz_b (which is the total water depth in this case, since only a single layer is being used) and the bottom roughness z_o as

$$c_b = \max\left[\frac{\kappa^2}{\log^2(\frac{\Delta z_b}{2z_o})}, c_{b_{min}}\right], \tag{2}$$

where $\kappa = 0.4$ is von Karman's constant, and $c_{b_{min}}$ is a minimum value for c_b. This expression for c_b is derived by assuming a logarithmic boundary layer velocity profile near the bottom, which, to some extent, accounts for the effect of vertical grid resolution on the bottom drag. Values used for $c_{b_{min}}$ and z_o for these tests are 0.0025 and 0.003 m, respectively, which are fairly typical values used for coastal ocean modeling (but which may not be optimal for some areas).

The open boundary conditions used for the NCOM simulations include the Flather BC for the normal transport at the open boundary (Flather, 1976; Flather et al., 1983), which requires an externally specified tidal elevation and normal transport at the boundary, and an Orlanski (1976) radiation condition for the tangential velocity at the open boundary, which requires an externally specified tidal tangential velocity at the boundary. The use of these radiative BCs allow the tide to quickly achieve a steady solution.

The input tidal BC forcing files for NCOM contain tidal harmonic data, i.e., the tidal amplitude and phase for each included constituent, for the surface elevation and the normal and tangential transports at each grid point on the open boundary. The time-dependent tidal elevation and transports at the boundary points are computed from the harmonic tidal data during the run and are summed over all the included tidal constituents.

Tidal potential forcing is used in the interior of the model domain. This forcing is significant for large, deep ocean domains, but becomes less important as the domain becomes smaller and shallower, and is generally unimportant for small, shallow coastal domains.

3.3 Tidal Analysis of NCOM Output

The tests conducted in this report utilize mainly just the M_2 tide since this is the dominant tide in most areas of the ocean. Using a single tidal constituent has the advantage that only a short simulation is needed to analyze for the tidal amplitude and phase (which are needed to compute the tidal errors); whereas, for simulations with several tidal constituents, a fairly long simulation is needed so that the tidal analysis can separate constituents of similar frequency, like the semi-diurnal tidal constituents M_2 and S_2 and the diurnal constituents K_1 and O_1.

The tidal analyses of the output from the NCOM simulations are computed using a least-squares procedure. The NCOM tidal simulations for the tests conducted here are ten days in length. The tidal analyses are performed using time series of hourly output SSH at each model grid point over the last eight days of the NCOM simulation. Skipping the first two days allows some time for the tidal solution to spin up. Note that eight days is longer than is needed for analysis of a tidal simulation with just a single tidal constituent, and performing a tidal analysis at each model grid point is not necessary to compute errors at just the few locations needed to compare with observations. However, the least-squares tidal analysis procedure being used takes little time to compute since the time series being analysed is fairly short. Also, performing the tidal analysis at each point allows plotting the spatial variation of the tidal harmonic data over the domain for visual comparison with other solutions.

Errors for the NCOM tidal solutions in steps (A) and (C) and the OTIS tidal solution in step (B) are computed wrt the IHO stations and TIL data points that lie within the domain. The tidal analyses from (A) and (C) are taken from the sea points nearest the locations of the IHO stations and the TIL data points and mean, mean absolute, and root-mean-square (RMS) errors are computed for the SSH amplitude and phase wrt the IHO data and (separately) wrt the TIL data.

For the IHO stations, a minimum distance from the IHO station to the nearest sea point of the model grid is specified (taken here to be 10 km), so as to reduce comparison with IHO stations that might lie in bodies of water not resolved by or included in the model grid. This is not a problem for the TIL data locations, since these lie in open water.

3.4 Specification of OTIS

The OTIS analysis in step (B) of Section 3.1 is conducted using the NCOM grid and bathymetry. Tidal data that are assimilated include tidal analyses of the Pathfinder TOPEX altimeter data that were provided by OSU with the OTIS software and from IHO stations within the domain. As noted earlier, a requirement of OTIS is that IHO stations that are assimilated (a) must include all the tidal constituents that are being analysed, and (b) must be located within a sea grid cell of the grid being used.

Because of requirement (a) above and the fact that many IHO stations do not include information about some of the smaller tidal constituents such as P_1, Q_1, K_2, and N_2, the OTIS analyses are conducted only for the four generally largest tidal constituents, i.e., M_2, S_2, K_1, and O_1, for which information is available at most IHO stations.

OTIS can be run with a number of options (Egbert and Erofeeva, 2003). For the tests conducted here, OTIS is run with a maximum of 500 representers (lat_lon -M500), and with similar error for the tidal equations relative to the error for the assimilated data (*sig-e* = 1). This latter option allows the OTIS tidal solution to relax the restriction of its momentum equations so as to provide a better fit of the tidal solution to the assimilated data.

OTIS is run with a spatially variable friction velocity (which is used to compute the bottom drag), which requires two separate runs of the OTIS forward model as noted earlier. The first run of the forward model is made with a specified constant value of the friction velocity (the value used here is 1 m/s). This run is needed to generate an estimate of the mean tidal velocity at each grid point, which is then used as the friction velocity for a second OTIS forward run and for the OTIS data-assimilative run. See Appendices A and B for a description of the OTIS programs and parameters used for the tests conducted for this report.

4. RESULTS FROM TESTING OTIS

4.1 NAVO Regional Ocean Domains

NAVO currently runs NCOM for a number of regional domains, including the East and South China Seas, the Persian Gulf, and the US East and west (Southern California) coasts (Table 2). In this section, we perform tests of the ability of OTIS to improve the tidal BCs for these domains over the BCs available from our OSU Tidal DBs (Table 1). However, since these domains are fairly large, and their open boundaries generally extend across long sections of mostly open ocean where the tidal data from the OSU Tidal DBs are fairly good, it was realized before conducting these tests that the potential for OTIS to significantly improve the tidal BCs for these domains was limited. However, it was thought to be useful to run these tests, anyway, and NAVO was interested in seeing the results from OTIS for these domains.

Table 2 — NAVO Regional Ocean Model Domains

domain	longitude (°E)	latitude (°N)	resolution	dimensions
East China Sea	117.50 to 133.00	18.00 to 41.50	3 km	505 x 859
South China Sea	105.00 to 129.90	14.00 to 23.95	3 km	874 x 370
Persian Gulf	47.50 to 70.00	22.00 to 30.50	3 km	736 x 319
US East Coast	278.00 to 296.00	20.00 to 42.00	3 km	571 x 814
Southern California	235.00 to 249.00	25.00 to 40.00	3 km	436 x 556

The grid locations and dimensions for all five of these domains and the bathymetries for the US East and West Coast domains were made available to us by NAVO. However, the bathymetries used by NAVO for the East and South China Seas and the Persian Gulf domains are classified and so we computed our own bathymetries for these three domains from Version 4.0 of NRL's DBDB2, two-minute-resolution, bathymetric DB (Version 4.0 of DBDB2 includes assimilated coastal sounding data from the National Geospatial Intelligence Agency, which significantly improves the bathymetry in coastal areas). All five of these domains have approximately 3-km horizontal grid resolution (Table 2).

4.1.1 East China Sea

The tidal errors for the East China Sea (ECS) domain (Fig. 1) wrt the IHO data are listed in Table 3. The NCOM root-mean-square (RMS) error for the M_2 amplitude is slightly improved using BCs from the local OTIS solution rather than the OSU Global DB (0.351 vs 0.395 m), but the RMS phase error is slightly worse (23.9°vs 21.5°). The mean amplitude error for the NCOM tidal solutions suggests that the NCOM amplitude errors could be reduced a bit by adjusting the bottom drag.

The errors for the local-OTIS-computed tide are significantly lower than the errors for the NCOM tidal solutions, which is the case for most of the regions tested. This is expected, since

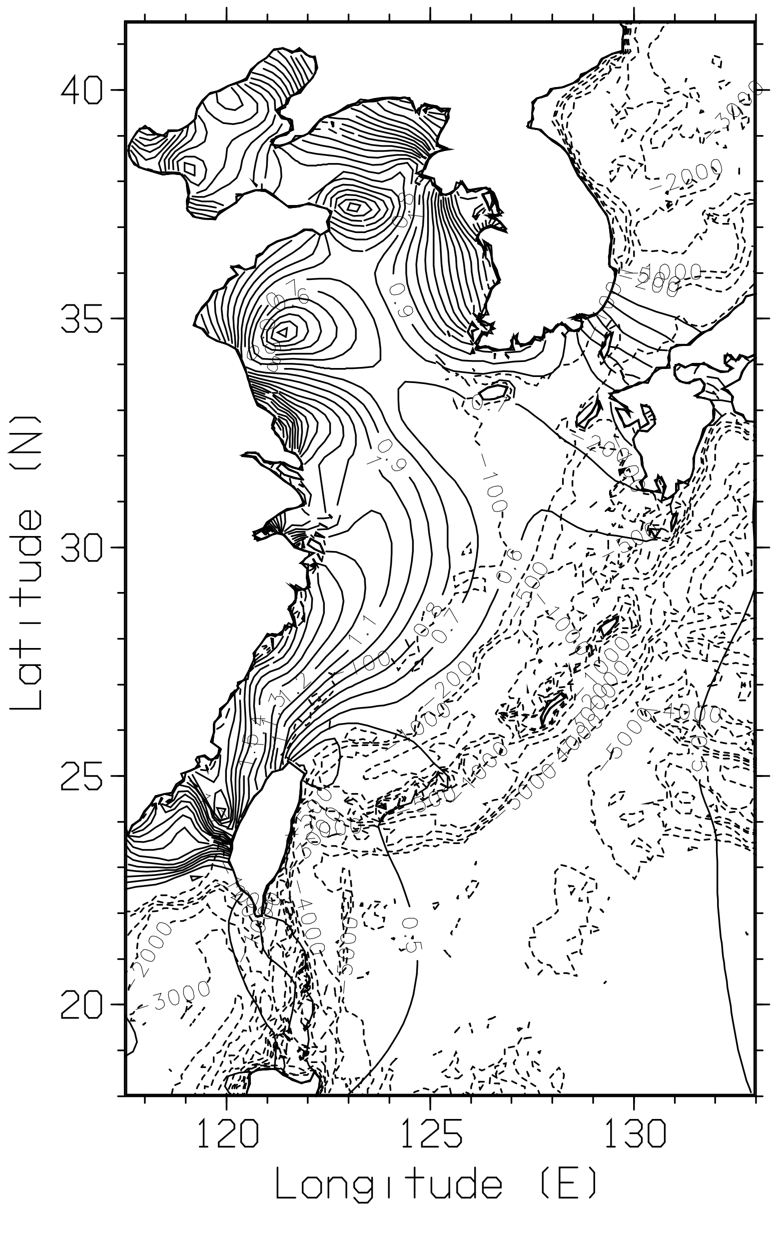

Fig. 1 — NAVO East China Sea domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line).

OTIS is assimilating some of the IHO data and is allowing for error in its momentum equations to improve the fit of its tidal solution to this data.

The RMS errors for the OSU and FES 2004 Global DBs are also provided for reference and are 0.483 and 0.255 m, respectively, for the M_2 amplitude, and 29.2°and 40.9°, respectively, for the M_2 phase. The OSU DB is significantly worse than the FES 2004 DB for the M_2 amplitude but significantly better for the phase. Note that the FES tidal DB provides only tidal SSH and not transport, and so cannot be used for tidal BCs when using a Flather-type BC.

Table 3 — Tidal Errors for East China Sea relative to IHO data

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	IHO stations
errors for local OTIS solution							
M_2	0.010	0.079	0.162	-1.3	8.8	16.2	425
errors for OSU Global DB							
M_2	-0.258	0.294	0.483	-3.4	18.3	29.2	425
errors for FES 2004 Global DB							
M_2	-0.052	0.156	0.255	-1.8	19.5	40.9	425
errors for NCOM with BCs from local OTIS							
M_2	0.130	0.224	0.351	-1.7	16.0	23.9	425
errors for NCOM with BCs from OSU Global DB							
M_2	0.152	0.245	0.395	-1.5	13.9	21.5	425

The tidal errors for the ECS domain wrt the TIL data are listed in Table 4. These data, like the TOPEX data assimilated by OTIS, are located along altimeter ground tracks. These errors are significantly smaller than the errors relative to the IHO data. This is in part due to the fact that the TIL data are generally located in deeper water further from the coast, where the tidal amplitude tends to be smaller and the tidal spatial scales tend to be larger and, hence, the tides tend to be easier to predict than at the IHO stations near the coast.

The smallest TIL data errors are for the local OTIS solution, which is able to draw fairly closely to the TOPEX altimeter data that it assimilates, with RMS errors of 0.018 m for the M_2 amplitude and 5.4°for the phase. The RMS errors for the NCOM simulations with BCs from the OSU Global DB and the local OTIS solution are similar at about 0.1 m and 9–10°for the M_2 amplitude and phase, respectively.

Figures 2 and 3 show the spatial distribution of the NCOM M_2 amplitude error wrt the IHO and TIL data, respectively, for the East China Sea domain. The shading of the circles shows the absolute value of the errors at the locations of the circles.

The plot of the IHO errors (Fig. 2) generally shows smaller errors along the island chains in the deep, southern part of the domain, and larger errors along the Chinese coast and within the Yellow Sea where there is more tidal amplification by the shallow coastal shelves and the tides tend to be larger.

The plot of the TIL errors (Fig. 3) shows the extensive coverage of the TIL data. The errors tend to be smaller in the southern part of the domain and increase within the Yellow Sea. The

Table 4 — Tidal Errors for East China Sea relative to TIL data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of locations
errors for local OTIS solution							
M_2	-0.002	0.011	0.018	0.0	2.2	5.4	3748
errors for OSU Global DB							
M_2	-0.017	0.029	0.071	-0.6	3.4	7.5	3748
errors for FES 2004 Global DB							
M_2	-0.003	0.036	0.084	0.4	4.5	9.5	3748
errors for NCOM with BCs from local OTIS							
M_2	0.002	0.062	0.103	1.3	6.3	9.0	3748
errors for NCOM with BCs from OSU Global DB							
M_2	0.006	0.061	0.103	-1.7	6.1	10.1	3748

errors are small within the Sea of Japan because the tides there are small (the tides are choked off by the small, shallow passages into the Sea of Japan).

Note that in the comparisons to follow, the errors wrt the tidal DBs will be included in the tables for reference, but will usually not be commented upon in the text. In the plots that are provided to show the locations of the test domains, the tide that is plotted is the OTIS assimilative (i.e., final) tidal solution.

4.1.2 South China Sea

The NCOM RMS M_2 tidal errors for the South China Sea (SCS) (Fig. 4) wrt the IHO data using BCs from the local OTIS tidal solution (Table 5) are lower than when using BCs from the OSU Global DB for the amplitude (0.116 vs 0.135 m) and are similar for the phase (21.0°vs 20.7°) and, as for the ECS, the NCOM errors are significantly higher than the errors for the local OTIS tidal solution.

Table 5 — Tidal Errors for South China Sea relative to IHO data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of IHO stations
errors for local OTIS solution							
M_2	0.007	0.030	0.039	-5.6	9.6	16.9	86
errors for OSU Global DB							
M_2	-0.041	0.077	0.106	-3.0	12.9	19.5	86
errors for FES 2004 Global DB							
M_2	-0.010	0.071	0.105	1.1	15.4	24.1	86
errors for NCOM with BCs from local OTIS							
M_2	0.047	0.091	0.116	-6.5	12.8	21.0	86
errors for NCOM with BCs from OSU Global DB							
M_2	0.058	0.109	0.135	-4.9	13.1	20.7	86

The RMS errors for NCOM wrt the TIL data for the M_2 tide (Table 6) are slightly lower for the local OTIS BCs than for the OSU Global BCs for the amplitude (0.061 vs 0.071 m) and are similar for the phase (6.8°vs 6.7°).

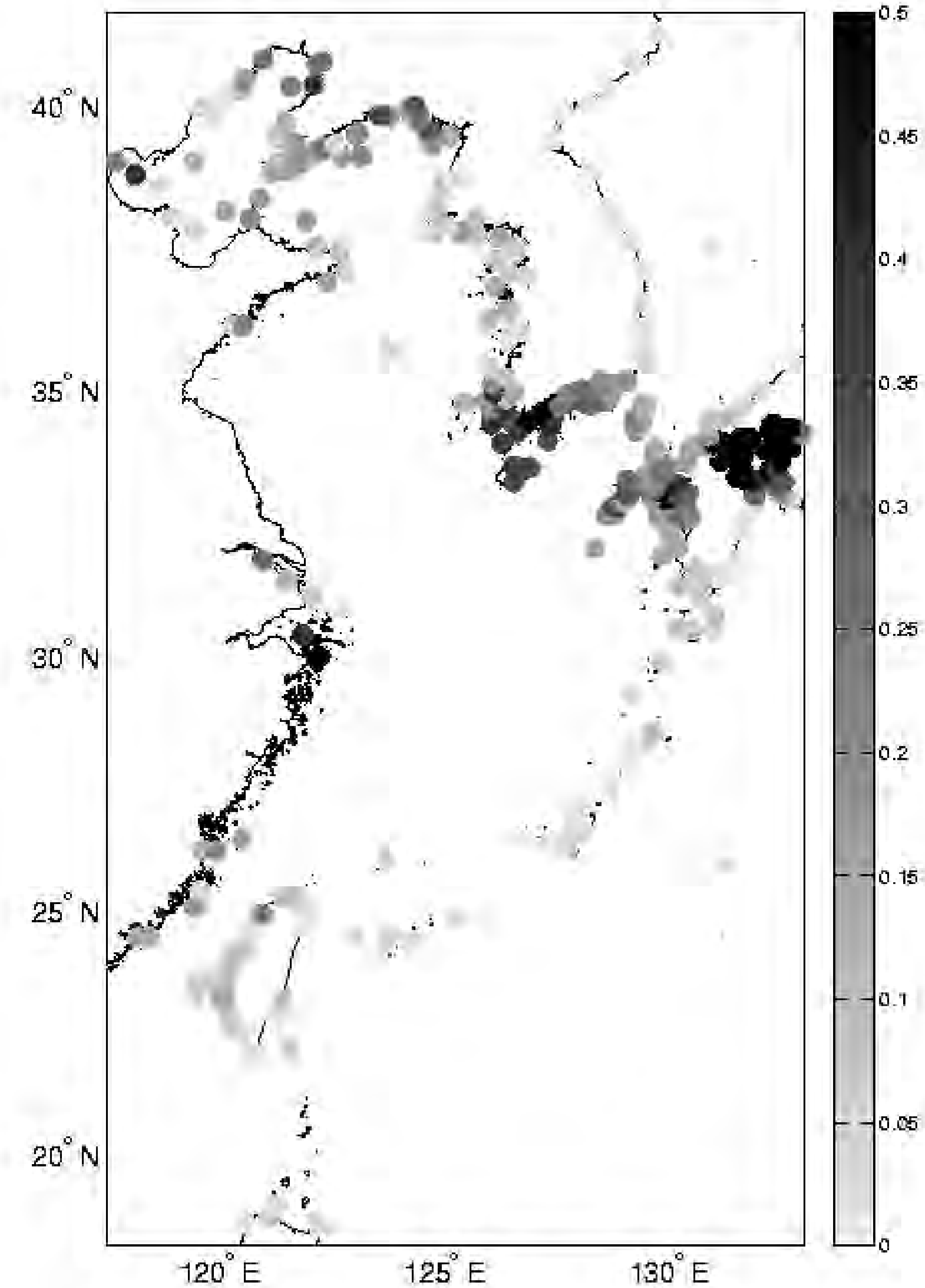

Fig. 2 — Spatial distribution of NCOM M_2 amplitude error wrt IHO station s for East China Sea domain.

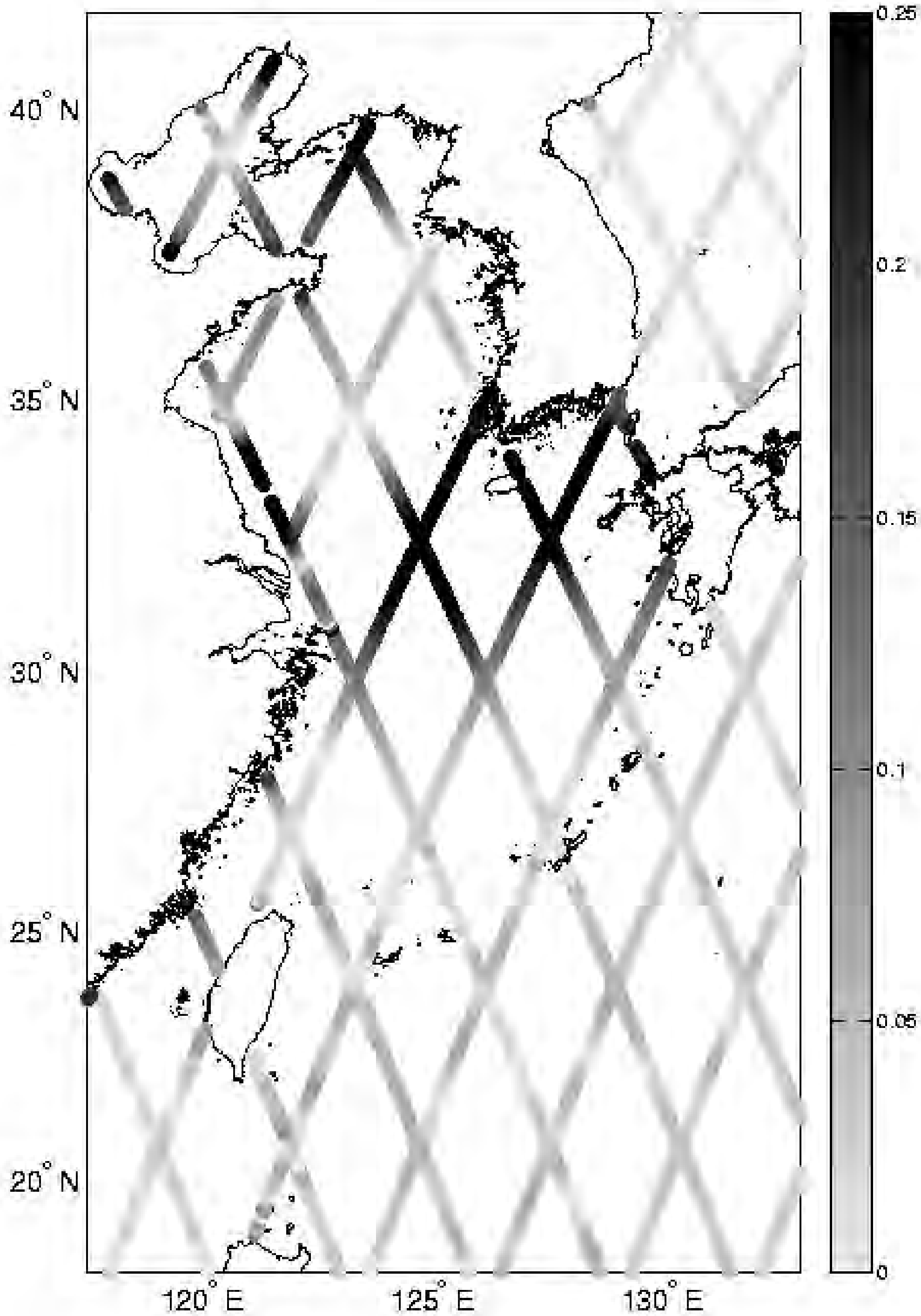

Fig. 3 — Spatial distribution of NCOM M_2 amplitude error wrt TIL data fo r East China Sea domain.

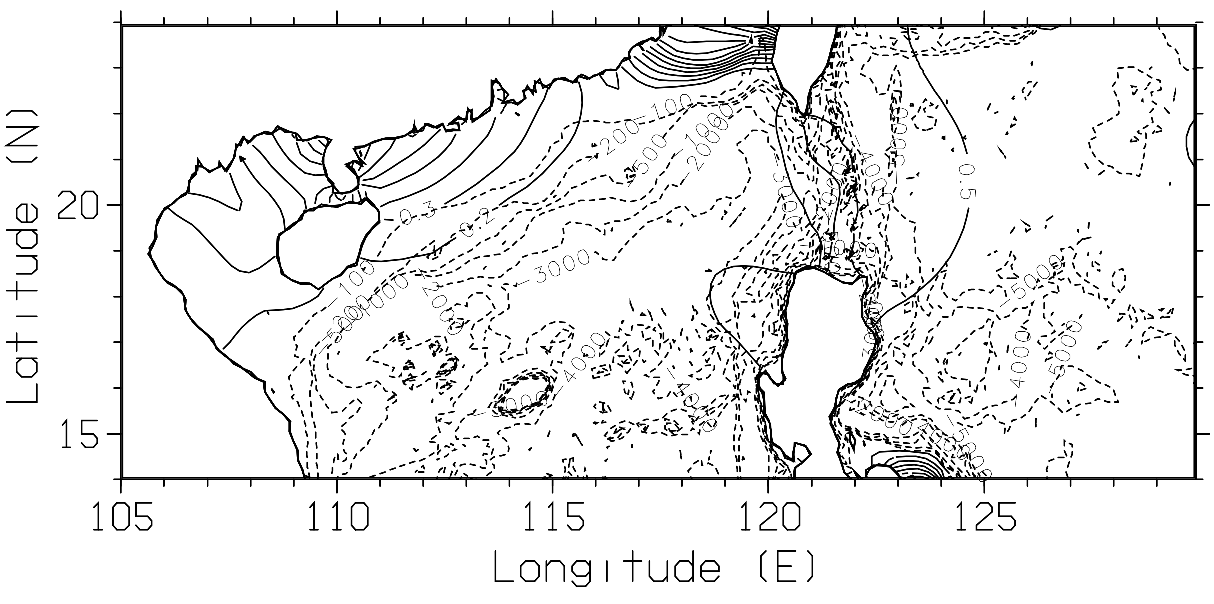

Fig. 4 — NAVO South China Sea domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line).

Table 6 — Tidal Errors for South China Sea relative to TIL data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of locations
errors for local OTIS solution							
M_2	-0.001	0.010	0.018	0.2	2.5	3.8	2616
errors for OSU Global DB							
M_2	-0.002	0.015	0.028	0.3	3.2	5.4	2616
errors for FES 2004 Global DB							
M_2	0.007	0.017	0.026	-1.2	3.9	5.9	2616
errors for NCOM with BCs from local OTIS							
M_2	0.022	0.041	0.061	0.0	3.9	6.8	2616
errors for NCOM with BCs from OSU Global DB							
M_2	0.034	0.053	0.071	1.4	3.8	6.7	2616

4.1.3 Persian Gulf

The NCOM RMS M_2 tidal errors for the Persian Gulf (Fig. 5) wrt the IHO data using BCs from the local OTIS tidal solution vs BCs from the OSU Global DB (Table 7) are the same for the amplitude (0.264 m) and similar for the phase (23.2°vs 22.5°). The RMS amplitude and phase errors for the local OTIS tidal solution (0.223 m and 20.1°, respectively) are, as usual, lower than the NCOM errors.

Table 7 — Tidal Errors for Persian Gulf relative to IHO data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of IHO stations
errors for local OTIS solution							
M_2	-0.018	0.062	0.223	-4.0	10.2	20.1	100
errors for OSU Global DB							
M_2	-0.134	0.193	0.346	-25.3	28.5	44.0	100
errors for FES 2004 Global DB							
M_2	-0.057	0.118	0.277	-5.5	11.7	21.3	100
errors for NCOM with BCs from local OTIS							
M_2	-0.050	0.123	0.264	2.1	15.8	23.2	100
errors for NCOM with BCs from OSU Global DB							
M_2	-0.049	0.122	0.264	1.2	15.3	22.5	100

The RMS M_2 tidal errors for NCOM for the Persian Gulf wrt the TIL data (Table 8) are qualitatively similar to the errors for the IHO data, i.e., similar for the M_2 amplitude (0.051 m) and slightly worse with BCs from local OTIS than from the OSU Global DB for the phase (9.0°vs 8.4°, respectively).

4.1.4 US East Coast

For the NAVO US East Coast (USEC) domain (Fig. 6), the M_2 tidal errors were computed using BCs from two available OSU tidal DBs that cover this area, the Global and the North Atlantic (NA) DBs. The NA DB has significantly higher resolution than the Global DB, i.e., 1/12°vs 1/4°(Table 1).

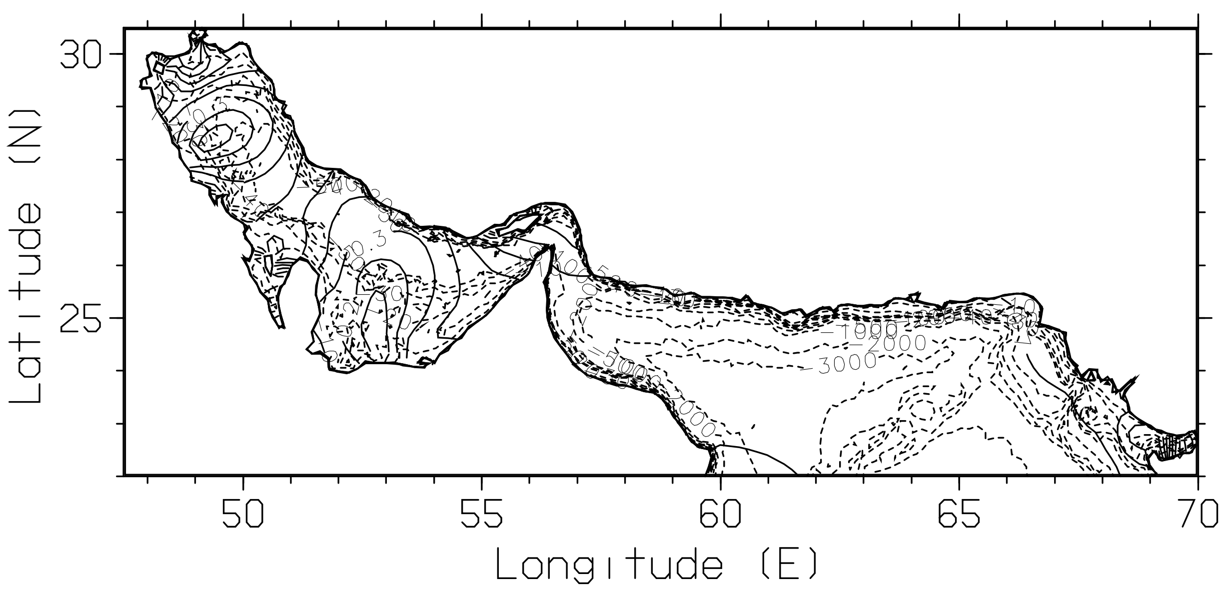

Fig. 5 — NAVO Persian Gulf domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line).

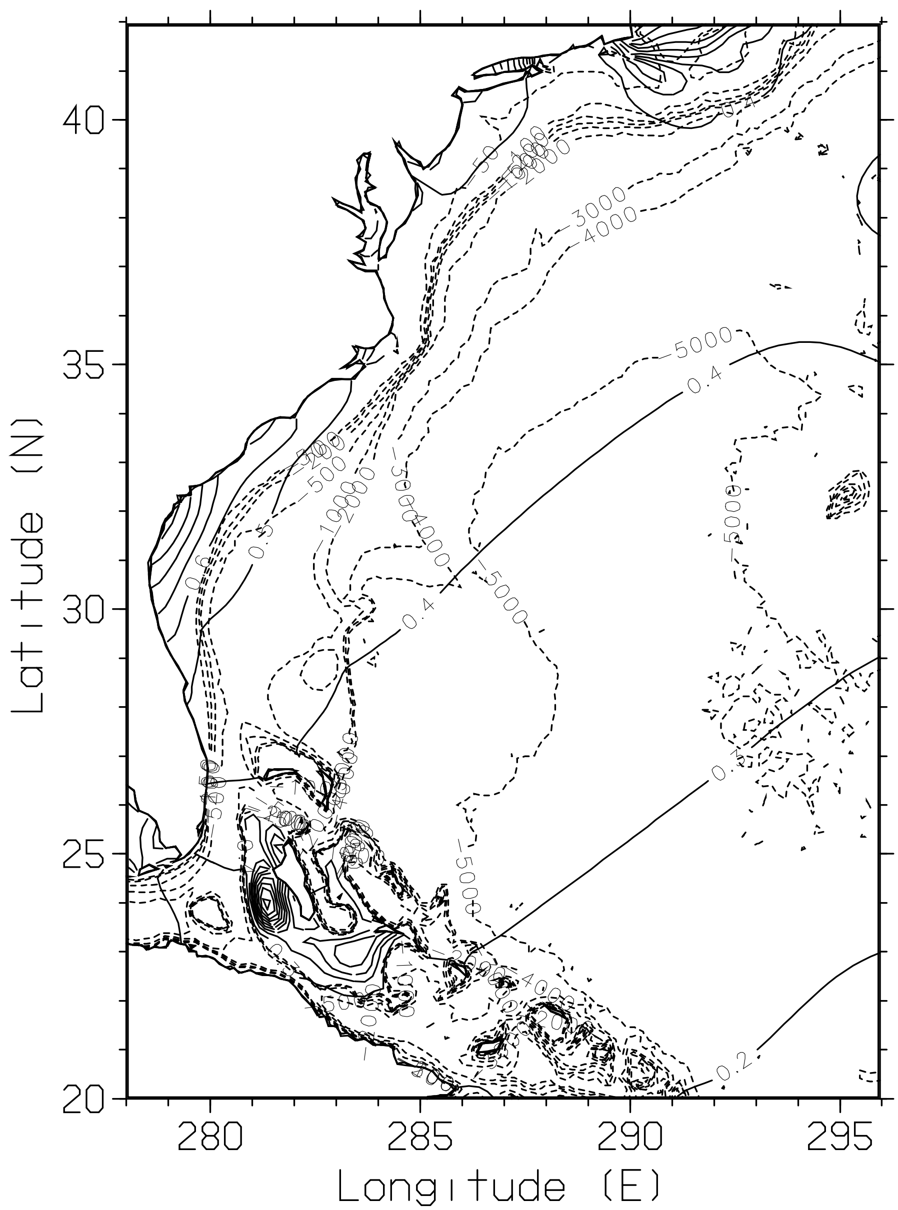

Fig. 6 — NAVO US East Coast domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line).

Table 8 — Tidal Errors for Persian Gulf relative to TIL data

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	locations
errors for local OTIS solution							
M_2	0.001	0.008	0.014	0.4	1.2	6.6	752
errors for OSU Global DB							
M_2	-0.005	0.020	0.039	-2.3	5.0	16.0	752
errors for FES 2004 Global DB							
M_2	0.002	0.017	0.027	-0.3	2.4	6.4	752
errors for NCOM with BCs from local OTIS							
M_2	-0.005	0.028	0.051	5.2	5.9	9.0	752
errors for NCOM with BCs from OSU Global DB							
M_2	-0.002	0.029	0.051	4.2	5.0	8.4	752

The NCOM RMS M_2 amplitude error wrt the IHO data is slightly lower using the North Atlantic DB than the Global DB (0.092 vs 0.100 m), but the RMS phase error is slightly higher (27.0°vs 24.6°) (Table 9). The RMS amplitude and phase errors for NCOM wrt the IHO data using BCs from the local OTIS solution (0.101 m and 28.0°) are slightly higher than the amplitude and phase errors using BCs from the two OSU DBs.

The RMS M_2 amplitude error for the local OTIS tidal solution wrt the IHO data (0.172 m) is, unusually, significantly higher than that for the NCOM-computed tides (Table 9). Why is this? The error for the local OTIS tidal solution is lower, i.e., 0.116 m (not shown in the table), when a constant friction velocity of 1 m/s is used instead of the spatially-variable friction velocity. The positive mean amplitude error of the OTIS tidal solution of 0.045 m (Table 9) suggests that, with the spatially variable friction velocity, the bottom drag is too small (a larger bottom drag tends to reduce the tidal amplitude near the coast).

Table 9 — Tidal Errors for U.S. East Coast relative to IHO data

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	IHO stations
errors for local OTIS solution							
M_2	0.045	0.079	0.172	-8.4	16.8	29.5	115
errors for OSU N Atlantic DB							
M_2	-0.033	0.095	0.170	-2.5	28.8	44.0	115
errors for OSU Global DB							
M_2	0.014	0.121	0.181	-13.6	39.4	63.1	115
errors for FES 2004 Global DB							
M_2	-0.011	0.084	0.156	-7.2	16.9	31.6	115
errors for NCOM with BCs from local OTIS							
M_2	0.040	0.065	0.101	-9.6	17.2	28.0	115
errors for NCOM with BCs from OSU N Atlantic DB							
M_2	0.023	0.064	0.092	-7.8	17.0	27.0	115
errors for NCOM with BCs from OSU Global DB							
M_2	0.039	0.064	0.100	-9.6	14.7	24.6	115

The RMS M_2 tidal errors for NCOM for the US East Coast wrt the TIL data (Table 10) are similar to the OSU tidal DB errors for the M_2 amplitude (0.022 m vs 0.025 and 0.022 m for the NA and Global DBs, respectively) and are slightly better than and similar to the OSU DB errors for the phase (4.8°vs 7.8°and 4.9°).

Table 10 — Tidal Errors for U.S. East Coast relative to TIL data

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	locations
errors for local OTIS solution							
M_2	0.001	0.008	0.018	0.0	1.3	2.9	4468
errors for OSU N Atlantic DB							
M_2	0.002	0.012	0.030	-0.3	2.9	9.3	4468
errors for OSU Global DB							
M_2	-0.003	0.012	0.027	-0.1	1.8	5.2	4468
errors for FES 2004 Global DB							
M_2	-0.003	0.011	0.023	-0.4	2.7	9.4	4468
errors for NCOM with BCs from local OTIS							
M_2	0.003	0.012	0.022	1.9	3.1	4.8	4468
errors for NCOM with BCs from OSU N Alantic DB							
M_2	-0.010	0.017	0.025	6.1	6.9	7.8	4468
errors for NCOM with BCs from OSU Global DB							
M_2	0.002	0.011	0.022	1.6	2.8	4.9	4468

4.1.5 Southern California

For the NAVO Southern California (SOCAL) domain, the M_2 tidal errors were computed using BCs from the OSU Global and US West Coast (WC) tidal DBs. The OSU WC DB, like the NA DB, is computed at significantly higher resolution than the Global DB, i.e., 1/12°vs 1/4°resolution (Table 1).

The NCOM RMS M_2 amplitude and phase errors wrt the IHO data are the same using BCs from the Global and WC DBs, i.e., 0.119 m and 17.2°(Table 11). The similarity of the NCOM errors with BCs from these two DBs is probably because of the deep water and narrow continental shelf along this coast, which results in little amplification of the tide near the coast (Fig. 7). As a result, the spatial scale of the tidal variation along this coast is relatively large and the additional resolution of the West Coast DB does not provide much change in the structure of the tide near the open boundary of the SOCAL domain.

The RMS M_2 amplitude error wrt the IHO data for NCOM using the BCs from the local OTIS tidal solution (Table 11) is similar to that for the NCOM tides using BCs from the OSU DBs (0.120 vs 0.119 m). The RMS M_2 phase error is also similar (17.6°vs 17.2°). This is consistent with the local OTIS tidal solution and the OSU WC and Global DBs having similar tides near the open boundary of the SOCAL domain.

The RMS ampltitude and phase errors wrt the IHO data (Table 11) for the local OTIS tidal solution (0.054 m and 7.0°) are lower than the errors for the OSU WC DB (0.070 m and 9.5°), which are both lower than the errors for the OSU Global DB (0.090 m and 25.5°). This is consistent with

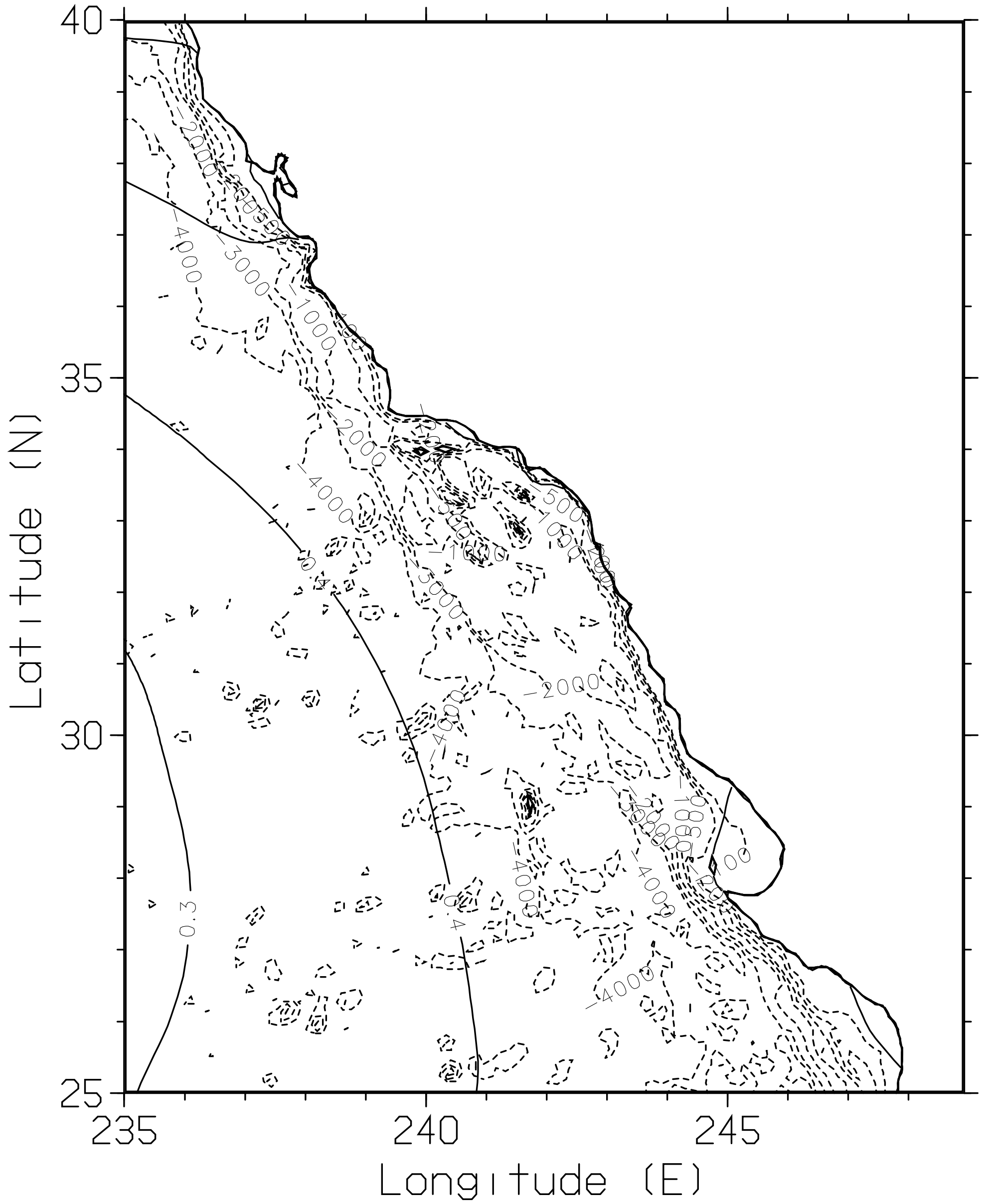

Fig. 7 — NAVO Southern California domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line).

the higher resolution tidal solutions being better able to resolve and compute the tidal solution at the coast where the IHO stations are located.

Table 11 — Tidal Errors for Southern California relative to IHO data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of IHO stations
errors for local OTIS solution							
M_2	-0.006	0.032	0.054	-2.4	4.3	7.0	29
errors for OSU US W Coast DB							
M_2	-0.008	0.038	0.070	-5.5	6.0	9.5	29
errors for OSU Global DB							
M_2	-0.035	0.048	0.090	-16.1	16.5	25.5	29
errors for FES 2004 Global DB							
M_2	-0.030	0.047	0.088	-3.7	4.6	6.9	29
errors for NCOM with BCs from local OTIS							
M_2	-0.057	0.079	0.120	7.5	11.6	17.6	29
errors for NCOM with BCs from OSU US W Coast DB							
M_2	-0.057	0.078	0.119	7.1	11.5	17.2	29
errors for NCOM with BCs from OSU Global DB							
M_2	-0.058	0.078	0.119	7.0	11.4	17.2	29

The RMS M_2 tidal errors wrt the TIL data for the SOCAL domain (Table 12) for the local OTIS solution, the OSU DBs, and the NCOM tidal solutions are all similar, ranging from 0.009 to 0.012 m for the amplitude and from 1.0 to 2.3°for the phase. This is additional indication of the large spatial scale of the tide here, except very near the coast. The errors wrt the TIL data are less affected by the resolution of the tidal solutions than the errors wrt the IHO data in Table 11 since the TIL data, unlike the IHO data, are mostly located away from the coast.

Table 12 — Tidal Errors for Southern California relative to TIL data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of locations
errors for local OTIS solution							
M_2	0.000	0.005	0.009	0.2	0.7	1.0	1458
errors for OSU US W Coast DB							
M_2	0.000	0.005	0.009	0.1	0.8	1.1	1458
errors for OSU Global DB							
M_2	-0.001	0.006	0.009	0.4	0.8	1.1	1458
errors for FES 2004 Global DB							
M_2	-0.002	0.006	0.009	0.2	0.8	1.1	1458
errors for NCOM with BCs from local OTIS							
M_2	-0.003	0.008	0.011	1.9	2.0	2.3	1458
errors for NCOM with BCs from OSU US W Coast DB							
M_2	-0.003	0.008	0.011	1.7	1.8	2.1	1458
errors for NCOM with BCs from OSU Global DB							
M_2	-0.005	0.009	0.012	1.6	1.7	2.0	1458

4.1.6 Summary of NAVO regional domains

Figure 8 shows a comparison of the M_2 RMS amplitude and phase errors for NCOM using tidal BCs from a local OTIS tidal analysis and from the OSU regional and global DBs for the five NAVO regional domains that were tested. Overall, the errors are fairly similar. On average, the domains show a slight decrease in the M_2 RMS amplitude error and a slight increase in the RMS phase error for the use of BCs from the local OTIS tidal solution. As was noted earlier, because of the large size of these domains, and the fact that most of the open boundaries of these domains lie in the open ocean where the OSU tidal DBs are fairly accurate, this result was not unexpected. There should be more potential for improvement in smaller, coastal domains where the OSU DBs are less accurate.

4.2 Additional Regional Ocean Domains

Since the potential for improving tidal BCs in relatively large domains, such as those discussed in the previous section, is limited, we wanted to do some tests of improving tidal BCs in some smaller domains. A list of the additional, generally smaller domains that were used for testing in this report is given in Table 13. The motivation for the selection of these domains was varied. Some were chosen because of the interesting tides present in the domain. Some of the domains are, or were, being studied in other projects at NRL. The remainder of the domains were chosen somewhat at random. Bathymetry for these domains was taken from NRL's DBDB2 Version 4.0 DB.

Table 13 — Additional Regional Ocean Model Domains

domain	longitude (°E)	latitude (°N)	resolution	dimensions
Incheon, Korea	125.0 to 127.0	36.0 to 38.1	1 km	178 x 233
Adriatic Sea	12.1 to 19.8	40.0 to 45.9	1 km	627 x 657
Taiwan Strait	117.0 to 121.0	22.0 to 25.0	2 km	204 x 167
Liaodong Bay	118.3 to 122.3	39.0 to 41.0	2 km	170 x 111
Guangdong, China	113.0 to 120.0	20.0 to 25.0	2 km	360 x 278
Gulf of Tonkin	106.5 to 108.5	20.5 to 22.0	1 km	208 x 167
Messina Strait	15.35 to 15.95	38.0 to 38.6	0.2 km	262 x 334

4.2.1 Incheon, Korea

A small, approximately 2°-square region near Incheon, Korea (Fig. 9) was selected for testing since (a) there are a relatively large number of IHO tide stations along this part of the Korean coast and (b) the tides here are very high because of large amplification by the local bathymetry, e.g., the M_2 tide has an amplitude at Incheon of almost 3 m. A 1-km resolution grid was used with dimensions of 178 x 233 (Table 13). Fig. 9 shows the location of the IHO stations and TIL data used to compute the errors for the tidal solutions.

The errors for the M_2 tide for the Incheon domain wrt the IHO data are listed in Table 14. The NCOM RMS error for the M_2 amplitude using BCs from the local OTIS tidal solution (0.557 m) is lower than the errors using BCs from the OSU YS (0.635 m) and Global (0.716 m) DBs, and the RMS phase error is also significantly lower (25.8°for the local OTIS tidal solution vs 34.1°and 33.4°for the OSU YS and Global DBs, respectively).

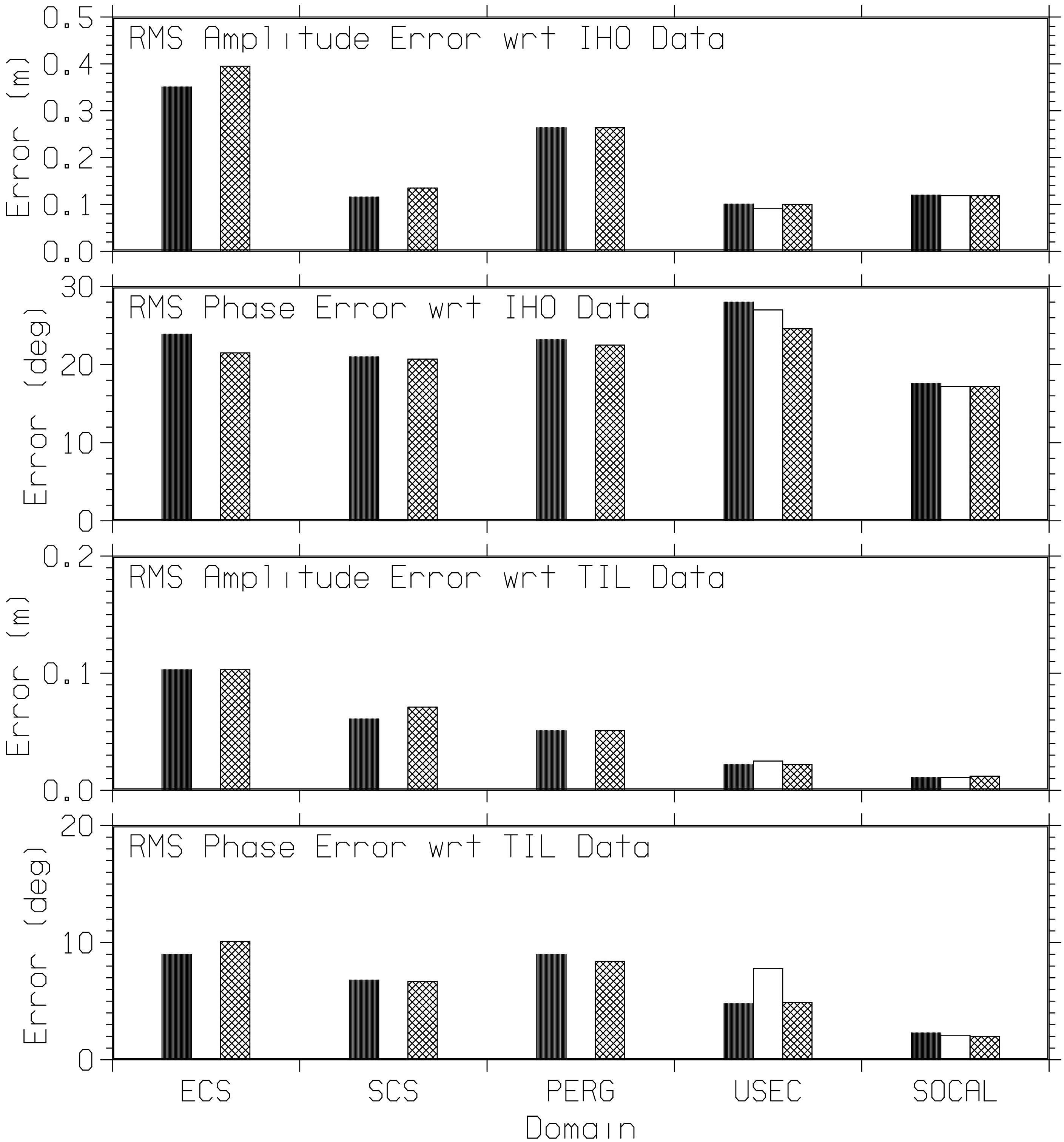

Fig. 8 — Comparison of M_2 RMS tidal errors for NCOM with BCs from a local OTIS analysis (black bars), an OSU regional tidal DB (white bars), and the OSU Global tidal DB (cross-hatched bars) for the five NAVO regional domains.

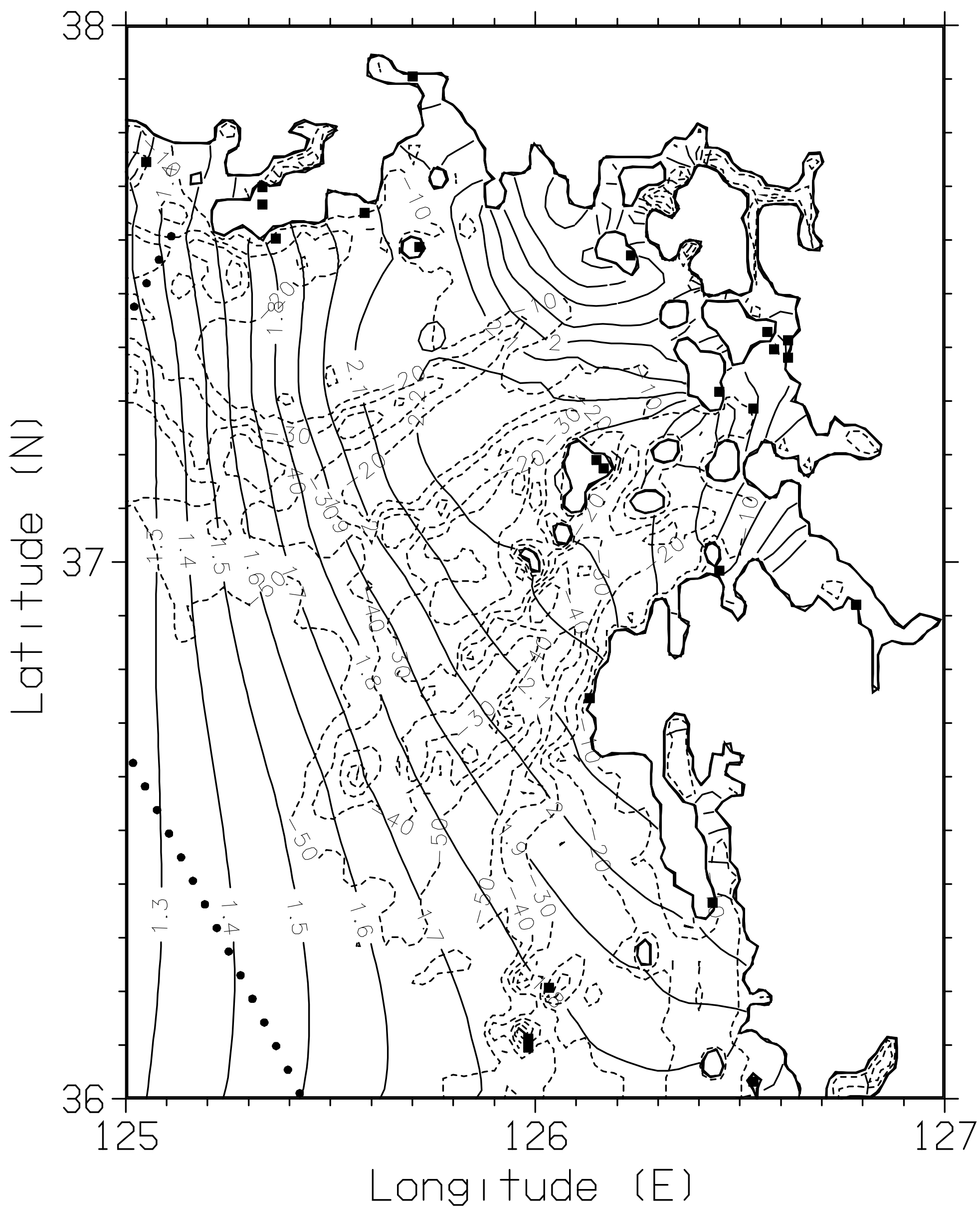

Fig. 9 — Incheon, Korea domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line), and locations of IHO stations (squares), and TIL data (dots) used for computing errors.

Table 14 — Tidal Errors for Incheon, Korea Domain relative to IHO data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of IHO stations
errors for local OTIS solution							
M_2	-0.018	0.140	0.244	1.9	6.3	9.5	26
errors for OSU Yellow Sea DB							
M_2	-1.335	1.335	1.624	61.3	61.3	81.9	26
errors for OSU Global DB							
M_2	-1.248	1.248	1.391	12.8	16.3	20.3	26
errors for FES 2004 Global DB							
M_2	-0.284	0.300	0.409	1.2	5.8	8.0	26
errors for NCOM with BCs from local OTIS							
M_2	-0.467	0.479	0.557	16.7	18.7	25.8	26
errors for NCOM with BCs from OSU Yellow Sea DB							
M_2	-0.548	0.555	0.635	27.9	27.9	34.1	26
errors for NCOM with BCs from OSU Global DB							
M_2	-0.664	0.664	0.716	27.4	27.8	33.4	26

The RMS M_2 amplitude tidal error wrt the TIL data for NCOM for the Incheon domain (Table 15) using BCs from the local OTIS solution (0.119 m) are lower than when using BCs from the OSU YS (0.204 m) and Global (0.291 m) DBs, and are also lower for the phase (4.8°for local OTIS vs 8.5°and 9.1°for the OSU YS and Global DBs, respectively).

Table 15 — Tidal Errors for Incheon, Korea Domain relative to TIL data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of locations
errors for local OTIS solution							
M_2	-0.002	0.015	0.018	0.1	0.4	0.6	19
errors for OSU Yellow Sea DB							
M_2	-0.042	0.044	0.050	2.0	2.0	2.4	19
errors for OSU Global DB							
M_2	-0.124	0.124	0.128	-0.3	5.4	6.9	19
errors for FES 2004 Global DB							
M_2	-0.087	0.087	0.091	-5.1	5.1	6.0	19
errors for NCOM with BCs from local OTIS							
M_2	-0.022	0.086	0.119	-3.2	3.2	4.8	19
errors for NCOM with BCs from OSU Yellow Sea DB							
M_2	-0.191	0.191	0.204	8.2	8.2	8.5	19
errors for NCOM with BCs from OSU Global DB							
M_2	-0.285	0.285	0.291	8.2	8.3	9.1	19

In Table 14, the errors for the NCOM-computed tides with BCs from the local OTIS tidal solution are much higher than the RMS errors for the local OTIS tidal solution itself, which are 0.244 m for the amplitude and 9.5°for the phase. The main contribution to the high error of the NCOM-computed tides in this domain is the large, mean error in both the amplitude (-0.467 m) and phase (16.7°). We were able to signficantly reduce these bias errors by reducing the bottom drag in NCOM (see Eq. 1 and 2), which reduces the drag on the tidal currents, which, in turn, increases the amplitude of the tide near the coast and reduces the phase lag.

Table 16 lists errors for the NCOM-computed tide wrt the IHO data with tidal BCs from the local OTIS tidal solution for different values of the minimum drag coefficient ($c_{b_{min}}$) and bottom roughness (z_0). As the minimum bottom drag coefficient and bottom roughness are reduced from their standard values of 0.0025 and 0.003 m, respectively, the mean and RMS errors are significantly reduced. The lowest errors were obtained with very low values of the minimum bottom drag and bottom roughness of 0.0002 and 0.00002 m, respectively. The low value of the bottom drag required may be a reflection of the fine bottom sediment that is found in this area.

Table 16 — Tidal Errors for NCOM for Incheon, Korea Domain Relative to IHO Data With BC from Local OTIS for Different Values of Bottom Drag Parameters

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	IHO stations
errors with $c_{bmin} = 0.0025$, $z_0 = 0.003$ m							
M_2	-0.467	0.479	0.557	16.7	18.7	25.8	26
errors with $c_{bmin} = 0.0025$, $z_0 = 0.001$ m							
M_2	-0.427	0.438	0.499	16.3	18.1	24.9	26
errors with $c_{bmin} = 0.0015$, $z_0 = 0.001$ m							
M_2	-0.352	0.362	0.422	14.9	16.7	23.2	26
errors with $c_{bmin} = 0.0010$, $z_0 = 0.0003$ m							
M_2	-0.259	0.269	0.314	13.5	15.1	21.1	26
errors with $c_{bmin} = 0.0010$, $z_0 = 0.0001$ m							
M_2	-0.185	0.200	0.237	12.5	14.1	19.5	26
errors with $c_{bmin} = 0.0005$, $z_0 = 0.00005$ m							
M_2	-0.144	0.161	0.199	11.9	13.5	18.7	26
errors with $c_{bmin} = 0.0002$, $z_0 = 0.00002$ m							
M_2	-0.093	0.125	0.166	11.3	12.8	17.7	26

4.2.2 Adriatic Sea

The M_2 tide was simulated in an Adriatic Sea domain that included the entire Adriatic Sea (Fig. 10), with a grid resolution of about 1 km (Table 13). Errors for the M_2 tide wrt the IHO data are shown in Table 17. Note that the IHO stations in Venice Lagoon in the northwest Adriatic were not used for assimilation in OTIS or to compute errors since this area is not properly resolved by the grid. The RMS error of the NCOM-computed M_2 tidal amplitude with BCs from the local OTIS tidal solution (0.018 m) is similar to the RMS error using BCs from the OSU Mediterranean (Med) tidal DB (0.019 m) and is significantly less than the RMS error using BCs from the OSU Global DB (0.046 m). The RMS M_2 phase error for the NCOM tidal simulation with BCs from OTIS (7.5°) is less than that with BCs from the OSU Med DB (8.7°) and is similar to that with BCs from the OSU Global DB (7.6°).

Errors for the M_2 tide wrt the TIL data are shown in Table 18. The RMS amplitude errors for NCOM using tidal BCs from local OTIS (0.011 m) and the OSU Med tidal DB (0.011 m) are similar; the RMS error using BCs from the OSU Global DB (0.027 m) is significantly larger. The corresponding phase errors are all fairly similar, i.e., about 10°.

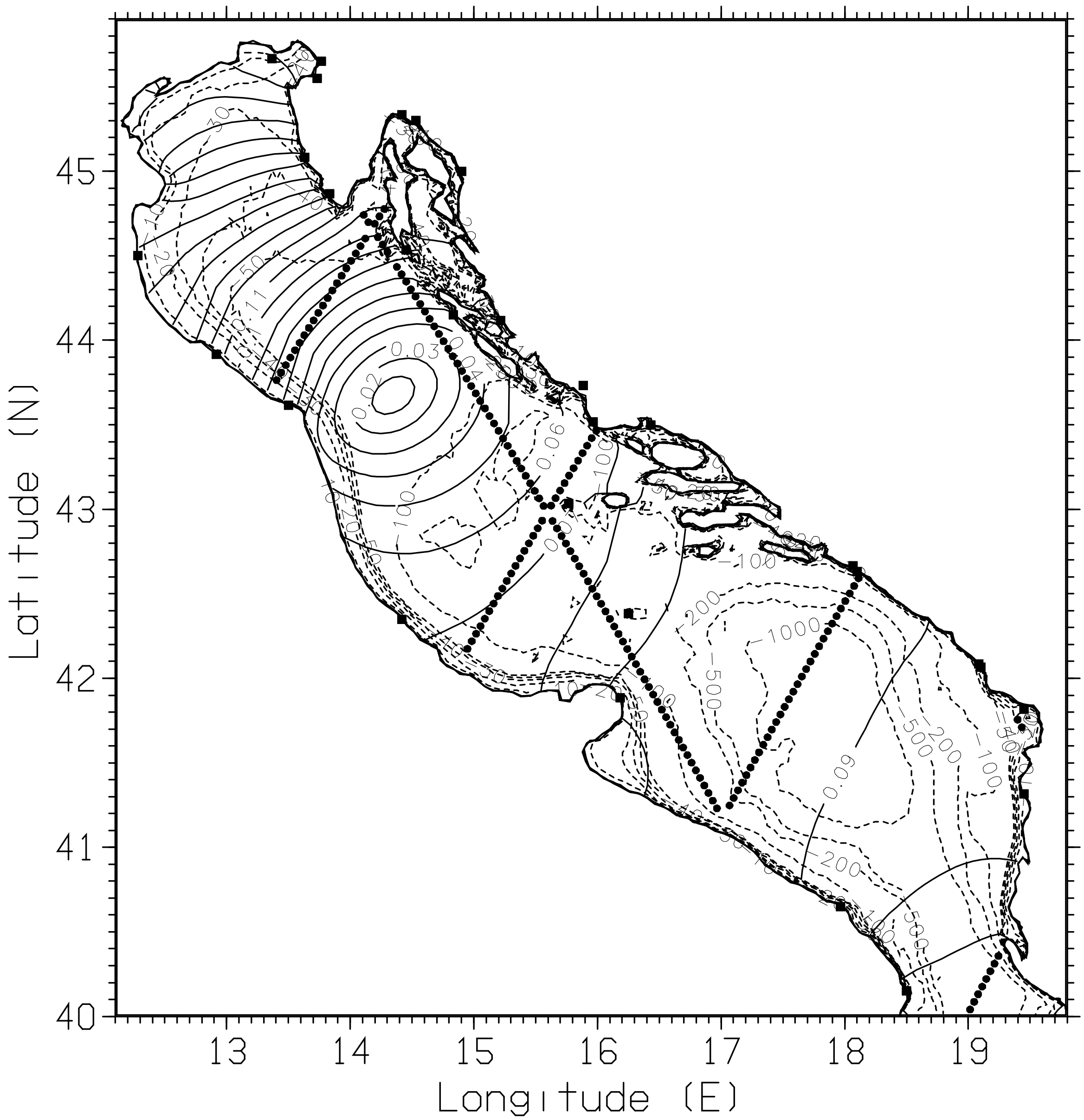

Fig. 10 — Adriatic Sea domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line), and locations of IHO stations (squares), and TIL data (dots) used for computing errors.

Table 17 — Tidal Errors for Adriatic Sea Domain relative to IHO data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of IHO stations
errors for local OTIS solution							
M_2	-0.004	0.010	0.019	-0.6	5.9	8.0	29
errors for OSU Mediterranean DB							
M_2	-0.011	0.014	0.022	-6.2	7.9	13.8	29
errors for OSU Global DB							
M_2	-0.013	0.029	0.039	1.1	10.9	15.6	29
errors for FES 2004 Global DB							
M_2	-0.008	0.013	0.022	3.6	17.8	30.7	29
errors for NCOM with BCs from local OTIS							
M_2	-0.002	0.009	0.018	0.4	5.5	7.5	29
errors for NCOM with BCs from OSU Mediterranean DB							
M_2	0.004	0.011	0.019	-4.4	6.3	8.7	29
errors for NCOM with BCs from OSU Global DB							
M_2	0.038	0.042	0.046	-1.7	5.3	7.6	29

Table 18 — Tidal Errors for Adriatic Sea Domain relative to TIL data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of locations
errors for local OTIS solution							
M_2	-0.004	0.006	0.011	0.8	5.3	9.6	170
errors for OSU Mediterranean DB							
M_2	-0.007	0.010	0.015	-1.3	6.1	10.8	170
errors for OSU Global DB							
M_2	-0.004	0.012	0.019	3.4	8.3	11.4	170
errors for FES 2004 Global DB							
M_2	-0.004	0.008	0.014	-1.9	10.6	14.8	170
errors for NCOM with BCs from local OTIS							
M_2	-0.004	0.007	0.011	1.5	5.7	9.9	170
errors for NCOM with BCs from OSU Mediterranean DB							
M_2	0.000	0.007	0.011	-3.3	5.8	10.3	170
errors for NCOM with BCs from OSU Global DB							
M_2	0.025	0.026	0.027	-0.3	5.2	9.7	170

4.2.3 Taiwan Strait

The M_2 tide was simulated in the area of Taiwan Strait (Table 13), which lies between the island of Taiwan and the Chinese coast (Fig. 11). Errors for the M_2 tide wrt the IHO data are shown in Table 19. The RMS amplitude errors for NCOM using tidal BCs from local OTIS and from the OSU Yellow Sea (YS) tidal DB are similar (0.112 and 0.110 m, respectively); the RMS error for NCOM using BCs from the OSU Global DB is slightly larger (0.130 m). The corresponding M_2 RMS phase error is slightly larger using the local OTIS BCs (30.0°), than using the OSU YS (28.0°) or the OSU Global DBs (27.9°) for BCs.

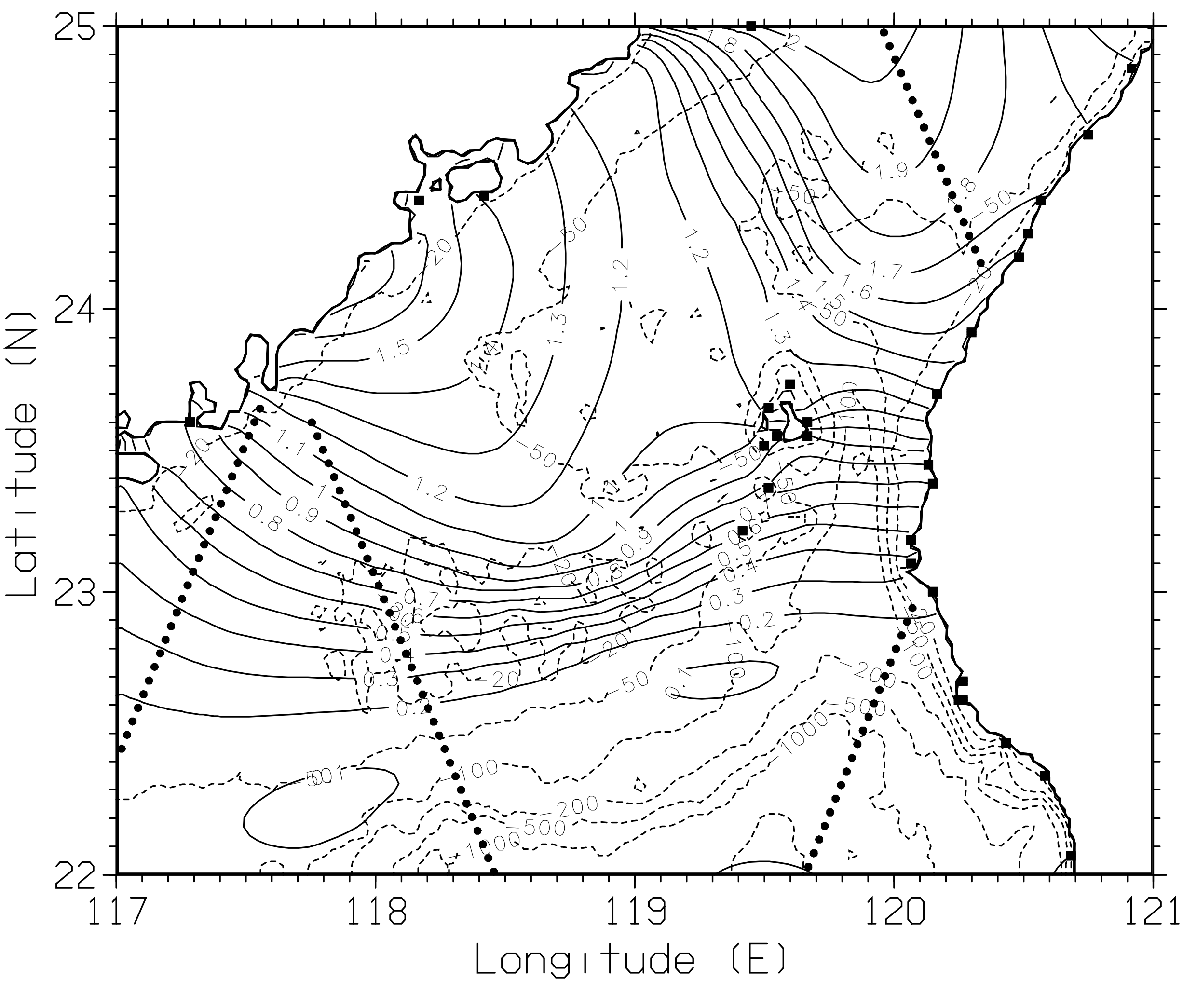

Fig. 11 — Taiwan Strait domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line), and locations of IHO stations (squares), and TIL data (dots) used for computing errors.

Table 19 — Tidal Errors for Taiwan Strait Domain relative to IHO data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of IHO stations
errors for local OTIS solution							
M_2	0.047	0.098	0.128	2.3	14.9	22.5	31
errors for OSU Yellow Sea DB							
M_2	-0.064	0.177	0.325	-5.4	15.7	25.8	31
errors for OSU Global DB							
M_2	-0.058	0.159	0.251	-9.1	16.8	27.4	31
errors for FES 2004 Global DB							
M_2	0.055	0.090	0.122	-10.5	16.2	28.1	31
errors for NCOM with BCs from local OTIS							
M_2	0.079	0.083	0.112	6.0	20.2	30.0	31
errors for NCOM with BCs from OSU Yellow Sea DB							
M_2	-0.029	0.077	0.110	-9.6	15.8	28.0	31
errors for NCOM with BCs from OSU Global DB							
M_2	-0.067	0.094	0.130	-8.3	14.9	27.9	31

Errors for the M_2 tide wrt the TIL data are shown in Table 20. The RMS M_2 amplitude errors for NCOM using tidal BCs from local OTIS (0.070 m) is lower than when using tidal BCs from the OSU YS (0.106 m) or Global (0.134 m) DBs. The corresponding phase errors are 16.0°for local OTIS BCs, 22.8°for the OSU YS BCs, and 6.7°for the OSU Global BCs.

Table 20 — Tidal Errors for Taiwan Strait Domain relative to TIL data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of locations
errors for local OTIS solution							
M_2	0.049	0.060	0.082	4.9	5.2	5.7	98
errors for OSU Yellow Sea DB							
M_2	-0.006	0.038	0.052	-1.2	4.4	7.2	98
errors for OSU Global DB							
M_2	-0.003	0.065	0.087	9.2	10.4	16.9	98
errors for FES 2004 Global DB							
M_2	-0.004	0.048	0.055	-4.2	7.0	11.9	98
errors for NCOM with BCs from local OTIS							
M_2	0.038	0.047	0.070	9.5	13.2	16.0	98
errors for NCOM with BCs from OSU Yellow Sea DB							
M_2	-0.054	0.070	0.106	12.1	12.7	22.8	98
errors for NCOM with BCs from OSU Global DB							
M_2	-0.084	0.093	0.134	2.9	5.4	6.7	98

4.2.4 Liaodong Bay

The M_2 tide was simulated in the area of Liaodong Bay (Fig. 12), which is located in the most northern part of the Yellow Sea (Table 13). Errors for the M_2 tide wrt the IHO data are shown in Table 21. The RMS amplitude error for NCOM using tidal BCs from local OTIS (0.129 m) is significantly lower than the errors using tidal BCs from the OSU YS or Global DB (0.245 and 0.220 m, respectively). However, the RMS phase error for NCOM using tidal BCs from local OTIS (50.0°) is much higher than when using tidal BCs from the OSU YS and Global DBs (21.0°and 22.5°, respectively). The large differences in these errors are due to the fact that the tides in this area are difficult to model.

Table 21 — Tidal Errors for Liaodong Bay Domain relative to IHO data

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	IHO stations
errors for local OTIS solution							
M_2	-0.005	0.047	0.066	-3.1	7.8	11.5	17
errors for OSU Yellow Sea DB							
M_2	-0.188	0.273	0.386	9.7	45.1	74.8	17
errors for OSU Global DB							
M_2	-0.445	0.461	0.557	-22.1	71.0	85.3	17
errors for FES 2004 Global DB							
M_2	0.317	0.448	0.497	20.5	49.0	69.7	17
errors for NCOM with BCs from local OTIS							
M_2	-0.098	0.099	0.129	13.4	25.6	50.0	17
errors for NCOM with BCs from OSU Yellow Sea DB							
M_2	-0.209	0.209	0.245	5.1	12.5	21.0	17
errors for NCOM with BCs from OSU Global DB							
M_2	-0.185	0.185	0.220	7.5	13.2	22.5	17

Errors for the M_2 tide wrt the TIL data are shown in Table 22. The RMS M_2 amplitude error for NCOM using tidal BCs from local OTIS (0.085 m) is lower than when using tidal BCs from the OSU YS (0.146 m) or Global (0.136 m) DB. The RMS phase error for NCOM using BCs from local OTIS (13.6°), is also lower than the errors using BCs from the YS (20.5°) or Global (20.3°) DB.

4.2.5 Guangdong, China

The M_2 tide was simulated in an area off the coast of Guangdong Province, China (Table 13, (Fig. 13)), which is located in the South China Sea southwest of Taiwan Strait. Errors for the M_2 tide wrt the IHO data are shown in Table 23. The RMS amplitude error for NCOM using tidal BCs from local OTIS (0.077 m) is lower than the RMS errors using tidal BCs from the OSU YS DB (0.123 m) or the OSU Global DB (0.100 m). However, the RMS phase error for NCOM using tidal BCs from local OTIS (34.2°) is higher than when using tidal BCs from the OSU YS or Global DB (27.0°and 28.4°, respectively).

Errors for the M_2 tide wrt the TIL data are shown in Table 24. The RMS M_2 amplitude error for NCOM using tidal BCs from local OTIS (0.060 m) is higher than when using tidal BCs from the OSU YS DB (0.041 m) and higher than when using tidal BCs from the OSU Global DB (0.031 m). Similarly, the RMS phase error for NCOM using BCs from local OTIS (17.2°) is higher than when using tidal BCs from the OSU YS DB (8.5°) and higher than when using BCs from the OSU Global DB (10.1°).

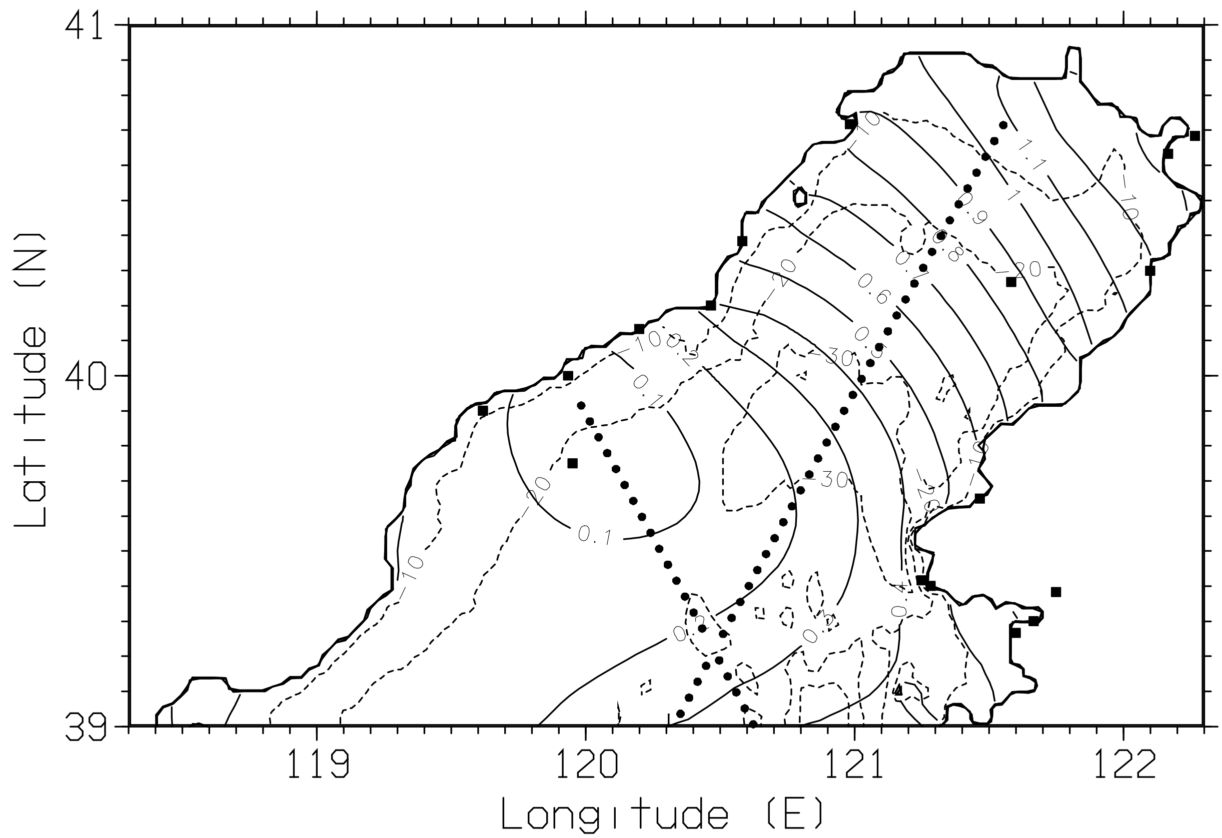

Fig. 12 — Liaodong Bay domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line), and locations of IHO stations (squares), and TIL data (dots) used for computing errors.

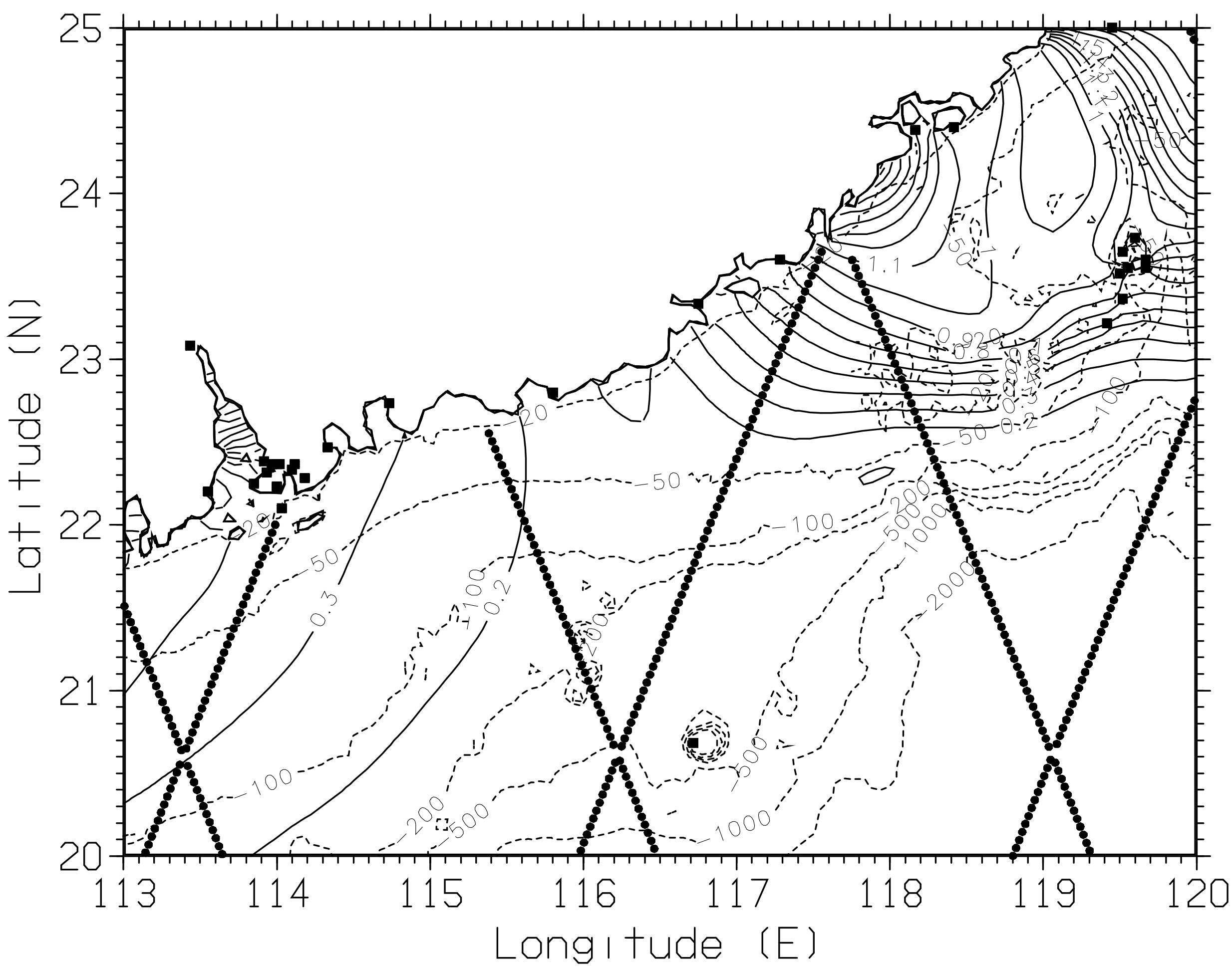

Fig. 13 — Guangdong, China domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line), and locations of IHO stations (squares), and TIL data (dots) used for computing errors.

Table 22 — Tidal Errors for Liaodong Bay Domain relative to TIL data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of locations
errors for local OTIS solution							
M_2	-0.004	0.015	0.028	-9.4	10.4	32.8	57
errors for OSU Yellow Sea DB							
M_2	0.010	0.022	0.034	1.2	5.5	10.4	57
errors for OSU Global DB							
M_2	-0.121	0.150	0.262	-12.2	12.6	25.6	57
errors for FES 2004 Global DB							
M_2	0.326	0.410	0.443	8.0	27.2	29.1	57
errors for NCOM with BCs from local OTIS							
M_2	-0.014	0.068	0.085	5.2	9.5	13.6	57
errors for NCOM with BCs from OSU Yellow Sea DB							
M_2	-0.087	0.096	0.146	-1.8	11.4	20.5	57
errors for NCOM with BCs from OSU Global DB							
M_2	-0.081	0.091	0.136	1.3	13.0	20.3	57

Table 23 — Tidal Errors for Guangdong, China Domain relative to IHO data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of IHO stations
errors for local OTIS solution							
M_2	0.036	0.171	0.405	10.3	21.8	33.9	32
errors for OSU Yellow Sea DB							
M_2	-0.276	0.282	0.385	19.7	31.7	41.1	32
errors for OSU Global DB							
M_2	-0.158	0.168	0.254	-12.0	17.8	31.8	32
errors for FES 2004 Global DB							
M_2	-0.084	0.116	0.151	3.3	21.4	34.9	32
errors for NCOM with BCs from local OTIS							
M_2	0.021	0.053	0.077	13.8	26.2	34.2	32
errors for NCOM with BCs from OSU Yellow Sea DB							
M_2	-0.086	0.093	0.123	-8.1	14.1	27.0	32
errors for NCOM with BCs from OSU Global DB							
M_2	-0.058	0.064	0.100	-4.9	17.4	28.4	32

4.2.6 Gulf of Tonkin

The M_2 tide is the largest tidal constituent in most areas of the world's oceans and in most areas of southeast Asia. However in the Gulf of Tonkin (Table 13, Fig. 14), which is located in the northwest South China Sea and boarders both China and Vietnam, the M_2 tide is small. The main tides in this area are the diurnal K_1 and O_1 tides, which have a similar magnitude. Hence, results in the Gulf of Tonkin are shown for the O_1 tide. Errors for the O_1 tide wrt the IHO data are shown in Table 25. The RMS errors for NCOM using tidal BCs from local OTIS (0.088 m and 6.0°) are simliar to or smaller than the RMS errors using tidal BCs from the OSU YS (0.100 m

Table 24 — Tidal Errors for Guangdong, China Domain relative to TIL data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of locations
errors for local OTIS solution							
M_2	0.001	0.018	0.027	3.2	5.1	6.9	332
errors for OSU Yellow Sea DB							
M_2	-0.002	0.018	0.033	-1.7	4.9	8.0	332
errors for OSU Global DB							
M_2	0.004	0.026	0.048	2.4	7.0	11.2	332
errors for FES 2004 Global DB							
M_2	0.018	0.028	0.035	-1.6	6.5	9.6	332
errors for NCOM with BCs from local OTIS							
M_2	0.036	0.053	0.060	5.3	12.0	17.2	332
errors for NCOM with BCs from OSU Yellow Sea DB							
M_2	-0.020	0.027	0.041	0.0	6.6	8.5	332
errors for NCOM with BCs from OSU Global DB							
M_2	0.010	0.021	0.031	3.3	8.4	10.1	332

and 5.5°) or Global (0.155 m and 9.4°) DB.

Table 25 — Tidal Errors for Gulf of Tonkin Domain relative to IHO data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of IHO stations
errors for local OTIS solution							
O_1	0.050	0.058	0.072	3.5	6.1	7.5	7
errors for OSU Yellow Sea DB							
O_1	-0.041	0.061	0.072	12.2	12.2	13.8	7
errors for OSU Global DB							
O_1	-0.084	0.084	0.103	-2.7	7.0	9.0	7
errors for FES 2004 Global DB							
O_1	0.006	0.045	0.060	3.6	8.5	9.7	7
errors for NCOM with BCs from local OTIS							
O_1	-0.061	0.074	0.088	3.5	4.6	6.0	7
errors for NCOM with BCs from OSU Yellow Sea DB							
O_1	-0.067	0.078	0.100	1.5	4.4	5.5	7
errors for NCOM with BCs from OSU Global DB							
O_1	-0.144	0.144	0.155	-5.5	7.4	9.4	7

Errors for the O_1 tide wrt the TIL data are shown in Table 26. The RMS O_1 amplitude error for NCOM using tidal BCs from local OTIS (0.139 m) is smaller than the RMS error when using tidal BCs from the OSU YS (0.215 m) or Global (0.259 m) DB. The RMS phase error for NCOM using BCs from local OTIS (2.8°) is higher than when using tidal BCs from the OSU YS DB (1.6°) or the OSU Global DB (2.3 deg), but all these phase errors are small.

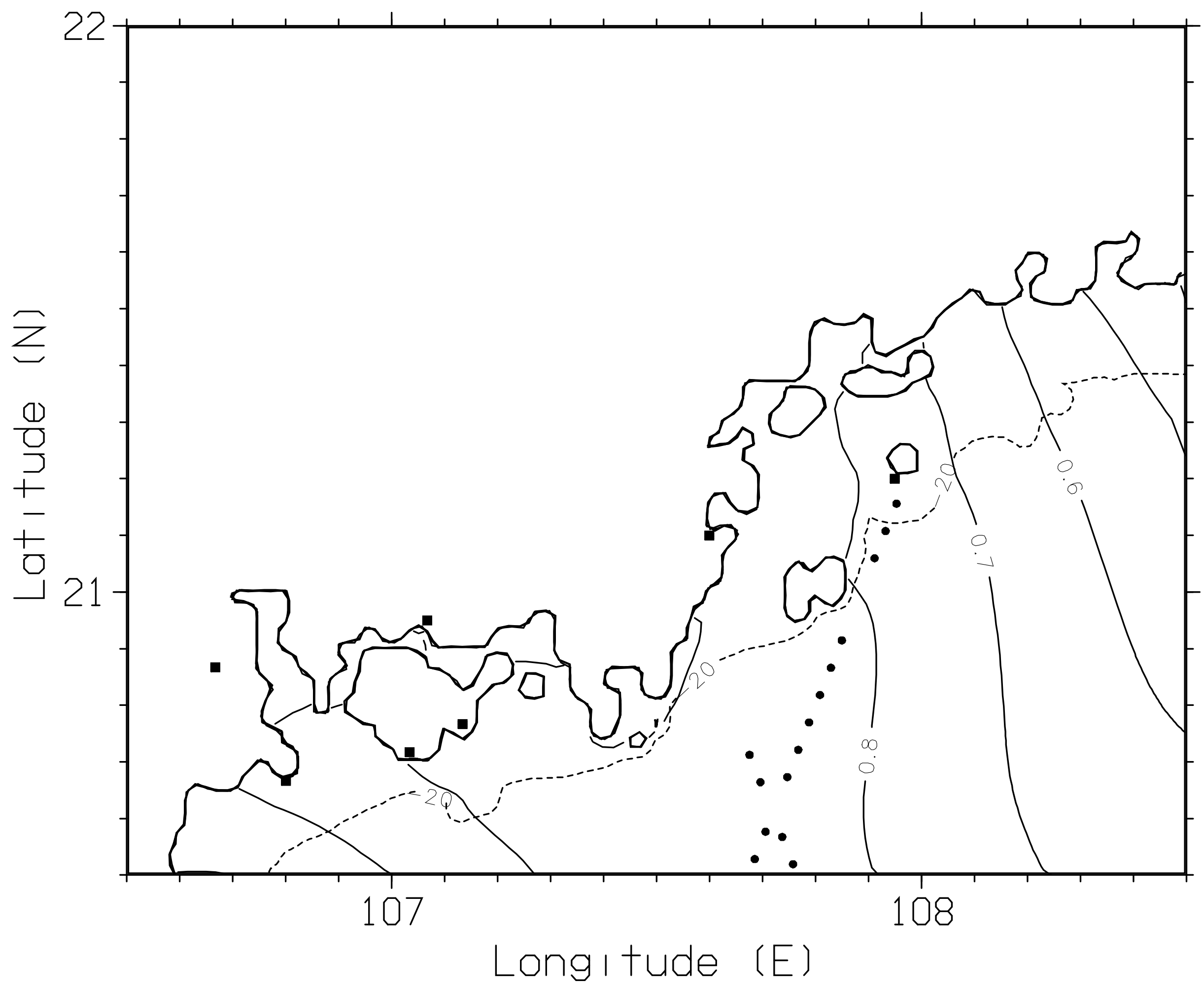

Fig. 14 — Gulf of Tonkin domain, bathymetry in m (dashed line), O_1 tidal amplitude from OTIS in m (solid line), and locations of IHO stations (squares), and TIL data (dots) used for computing errors.

Table 26 — Tidal Errors for Gulf of Tonkin Domain relative to TIL data

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	locations
errors for local OTIS solution							
O_1	-0.036	0.043	0.068	-0.7	1.2	1.6	15
errors for OSU Yellow Sea DB							
O_1	-0.044	0.050	0.079	1.4	1.7	2.6	15
errors for OSU Global DB							
O_1	-0.177	0.177	0.183	-1.3	1.4	1.8	15
errors for FES 2004 Global DB							
O_1	-0.060	0.060	0.064	4.4	4.4	4.7	15
errors for NCOM with BCs from local OTIS							
O_1	-0.109	0.109	0.139	-1.6	2.3	2.8	15
errors for NCOM with BCs from OSU Yellow Sea DB							
O_1	-0.212	0.212	0.215	1.0	1.2	1.6	15
errors for NCOM with BCs from OSU Global DB							
O_1	-0.257	0.257	0.259	-1.9	2.1	2.3	15

4.2.7 Messina Strait

The M_2 tide was simulated in the area of the Messina Strait between Sicily and Italy in the Mediterannean Sea (Table 13, Fig. 15). This was set up as a small domain with high grid resolution since Messina Strait is only a couple of km across at its narrowest point. Because of the small size of the domain, there were only a few IHO stations within the domain, and no TOPEX data. Hence, the local OTIS analysis assimilated only IHO data and only IHO data are available for computing errors.

Errors for the M_2 tide wrt the IHO data are shown in Table 27. The RMS amplitude error for NCOM using tidal BCs from local OTIS (0.031 m) is smaller than the RMS errors using tidal BCs from the OSU Mediterranean DB (0.064 m) or the OSU Global DB (0.056 m). The RMS phase error for NCOM using tidal BCs from local OTIS (59.2°) is also lower than when using tidal BCs from the OSU Med DB (64.9°) or the OSU Global DB (132.2°). The large phase errors are due to the large change in phase of the tide as it passes though the strait. Also, the tidal analysis of the NCOM output was complicated by the presence of eddies in the strait caused by the strong tidal currents.

4.2.8 Summary of additional regional domains

Figure 16 shows a comparison of RMS tidal amplitude and phase errors for NCOM using tidal BCs from a local OTIS tidal analysis and from the OSU regional and global DBs for the smaller domains that were tested. These domains were typically 200 to 500 km in lateral extent, which is still not all that small for a coastal simulation. The one domain significantly smaller than the rest is the Messina St. domain, which is about 52 by 67 km in size with 200-m resolution (Table 13. High resolution was used for this domain because the strait is so narrow.

The RMS amplitude error for NCOM with tidal BCs from the local OTIS analysis is similar to or smaller than the error with tidal BCs from the OSU DBs, except for the error wrt the TIL

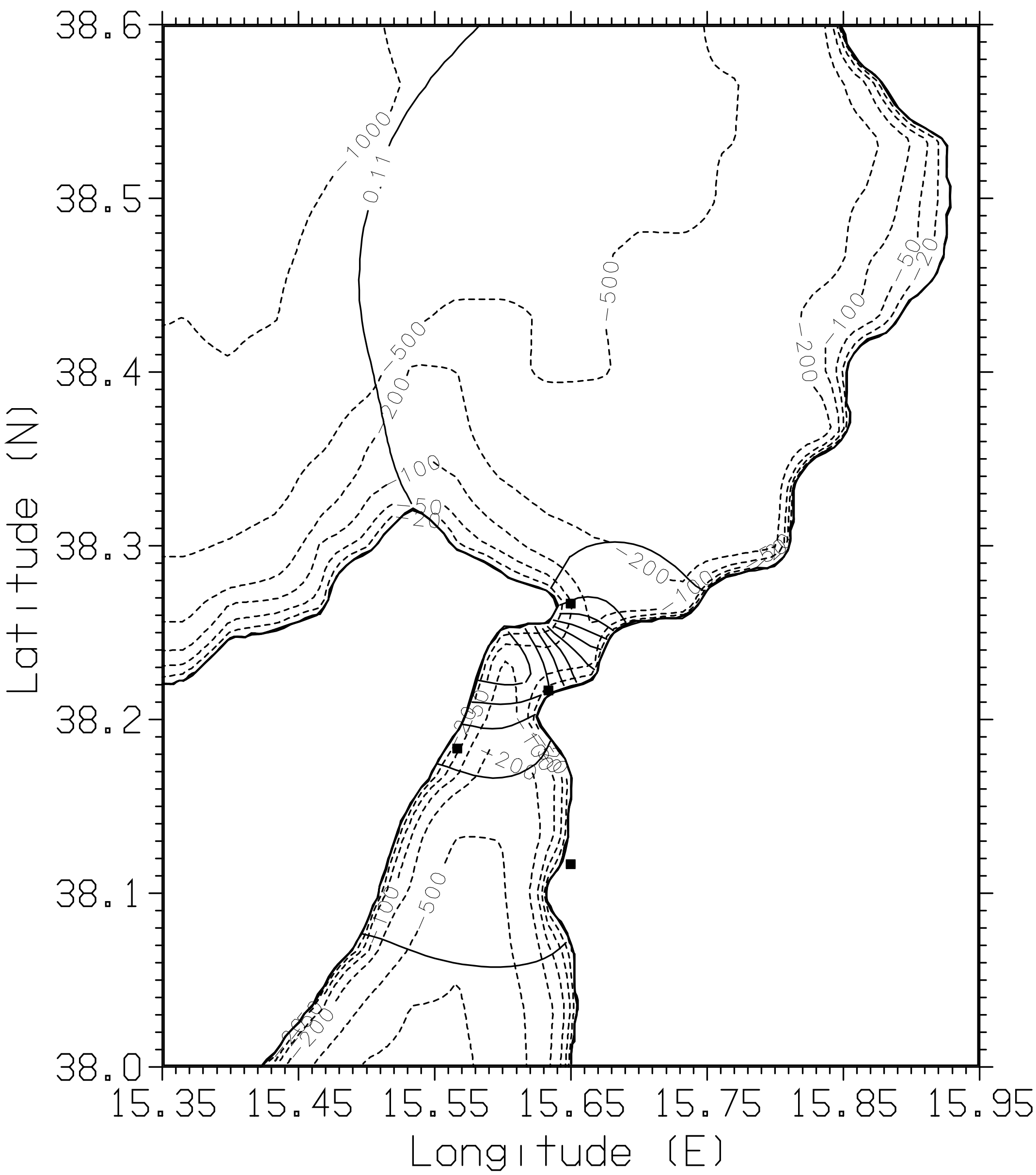

Fig. 15 — Messina Strait domain, bathymetry in m (dashed line), M_2 tidal amplitude from OTIS in m (solid line), and locations of IHO stations (squares), and TIL data (dots) used for computing errors.

Table 27 — Tidal Errors for Messina Strait Domain relative to IHO data

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of IHO stations
errors for local OTIS solution							
M_2	-0.003	0.019	0.021	29.1	29.9	40.9	4
errors for OSU Mediterranean DB							
M_2	-0.024	0.024	0.028	4.9	22.6	31.0	4
errors for OSU Global DB							
M_2	0.058	0.058	0.061	49.8	113.2	131.5	4
errors for FES 2004 Global DB							
M_2	-0.018	0.018	0.023	13.1	31.1	44.9	4
errors for NCOM with BCs from local OTIS							
M_2	-0.006	0.027	0.031	49.5	49.5	59.2	4
errors for NCOM with BCs from OSU Mediterranean DB							
M_2	0.063	0.063	0.064	55.8	55.8	64.9	4
errors for NCOM with BCs from OSU Global DB							
M_2	0.054	0.054	0.056	53.4	114.1	132.2	4

data for the Guangdong, China domain. The RMS phase errors are more mixed, with a few cases where the error is lower with BCs from the local OTIS analysis and a few cases where the error is lower with BCs from the OSU tidal DBs. On average, the RMS errors show a small improvement using BCs from the local OTIS analysis.

Regardless of the tidal BCs used, for some domains, the bottom drag used by the ocean model needs to be adjusted to optimize the tidal solution. For the Incheon, Korea domain, there was a large amplitude and phase bias in the NCOM tidal solutions that could only be reduced by reducing the bottom drag used by NCOM. This may reflect the fine bottom sediments that occur in this area.

5. TESTING OTIS WITH NRL ALTIMETRY DATA SET

For the results with OTIS described in the previous sections, the altimeter data assimilated into OTIS were the Pathfinder (PF) data that came with the OTIS software. In this section, some of the same tests are conducted with OTIS with an altimetry data set developed at NRL, which is referred to as the NRL altimetry data set. This is potentially a better data set than the PF data, since it contains a longer time period of altimeter data, i.e., 16 years of data instead of 10. The longer time series of data should allow a more accurate tidal analysis and, hence, provide more accurate tidal data for assimilation.

5.1 NAVO Regional Ocean Domains

Figure 17 shows a comparison of the OTIS RMS errors for the five NAVO domains with assimilation by OTIS of (i) the PF altimeter data and (ii) the NRL altimeter data, and Fig. 18 shows a comparison of the RMS errors for the NCOM tidal simulations conducted in the NAVO domains using the two different OTIS tidal solutions for tidal BCs.

The RMS errors using the PF and NRL altimeter data are generally very similar. The only

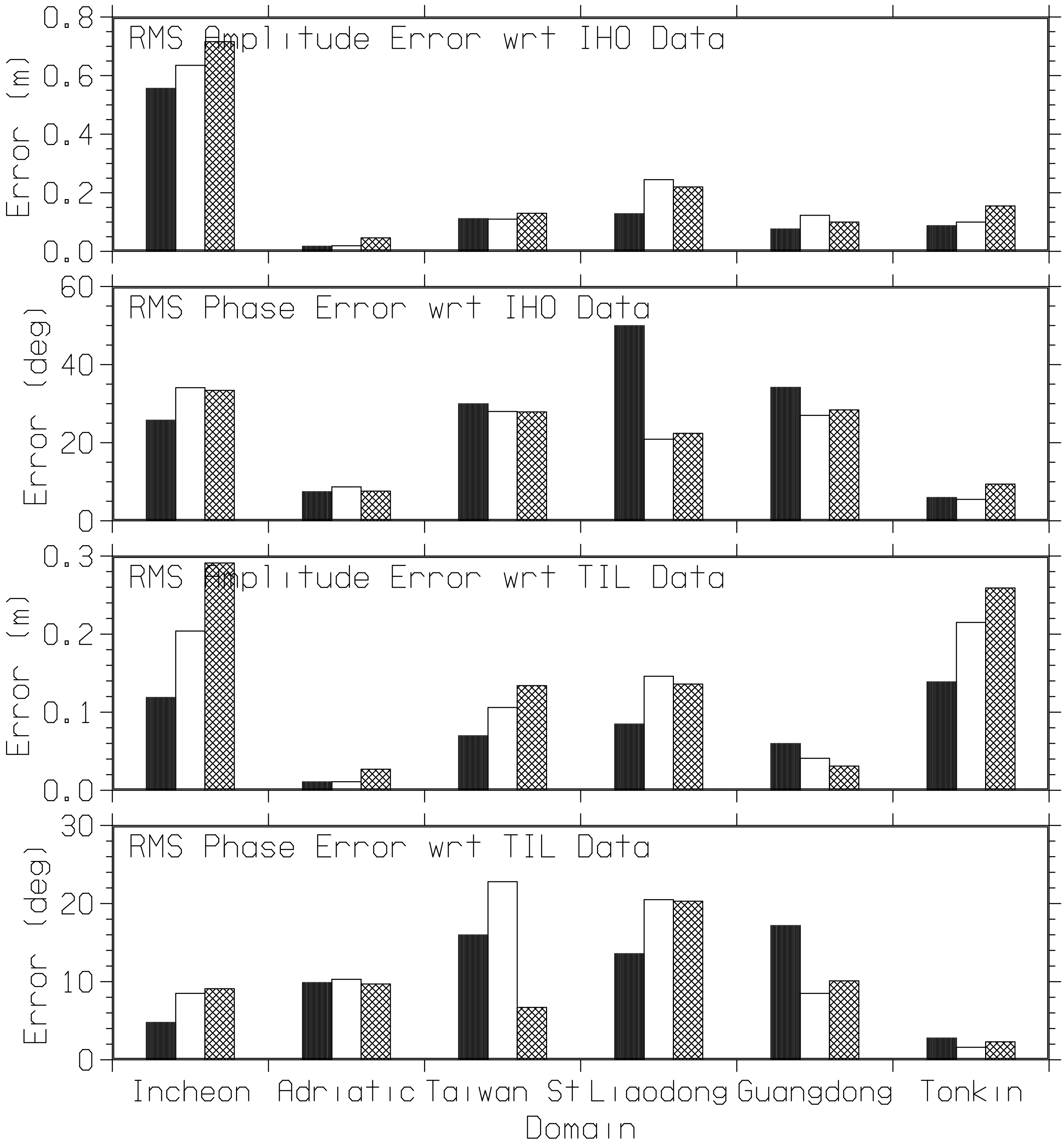

Fig. 16 — Comparison of RMS errors for NCOM with BCs from a local OTIS analysis (black bars), an OSU regional tidal DB (white bars), and the OSU Global tidal DB (cross-hatched bars) for the additional domains (except for Messina St).

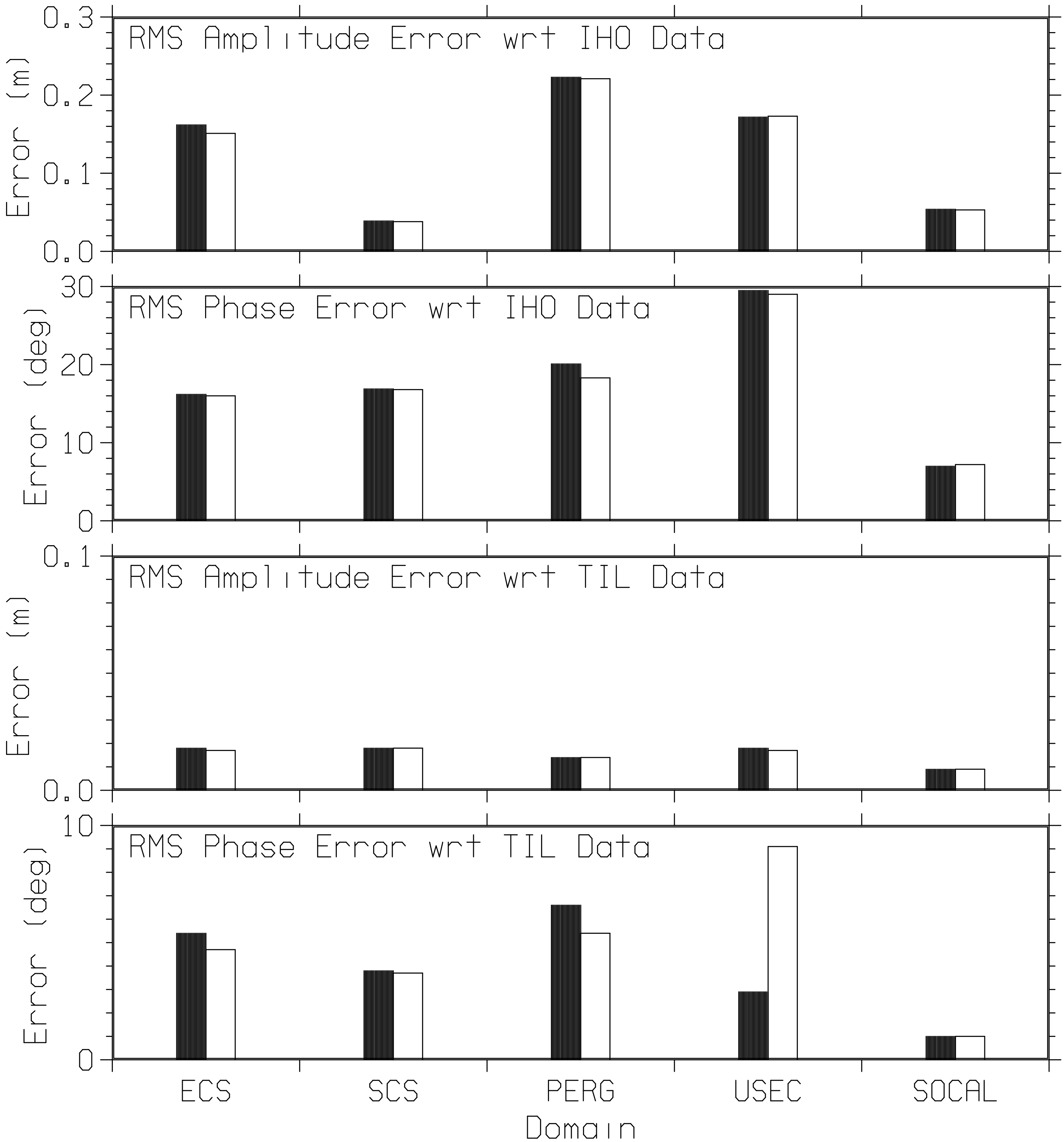

Fig. 17 — Comparison of RMS errors for OTIS with assimilation of the PF altimeter data (black bars) and the NRL altimeter data (white bars) for the five NAVO domains.

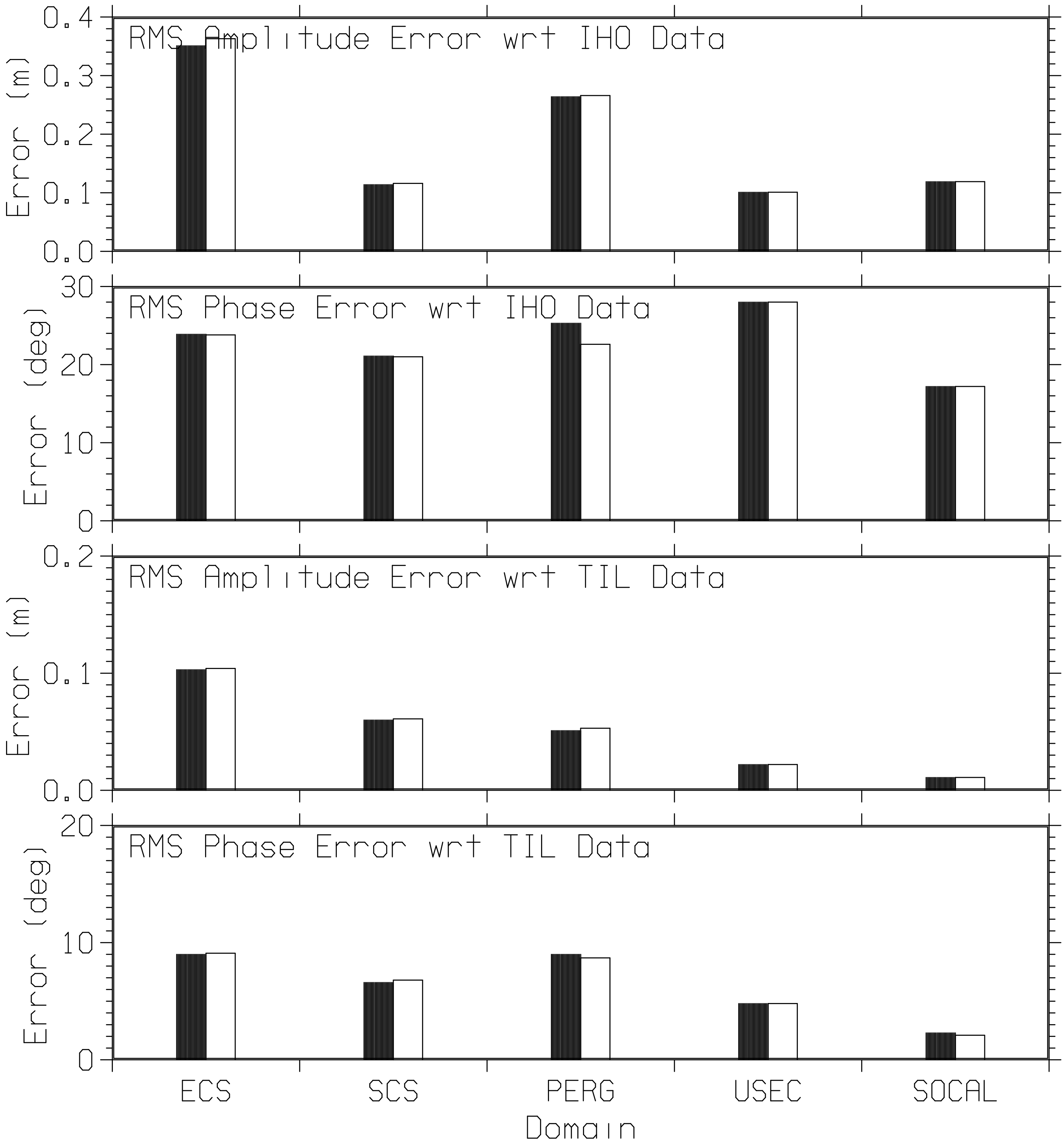

Fig. 18 — Comparison of RMS errors for NCOM with BC from OTIS with assimilation of the PF altimeter data (black bars) and the NRL altimeter data (white bars) for the five NAVO domains.

significant difference is the RMS phase error for OTIS wrt the TIL data for the US East Coast domain (Fig. 17), which is noticeably larger with assimilation of the NRL data. The errors for NCOM using BCs from OTIS are almost identical for the two data sets (Fig. 18). Hence, the tests in the NAVO domains do not show a signficant advantage for using one of these altimeter data sets instead of the other.

5.2 Additional Regional Ocean Domains

Figure 19 shows a comparison of the OTIS RMS errors for six of the smaller domains with assimilation by OTIS of (i) the PF altimeter data and (ii) the NRL altimeter data, and Fig. 20 shows a comparison of the RMS errors for the NCOM tidal simulations conducted in these domains using the two different OTIS tidal solutions for tidal BCs.

The RMS errors for OTIS assimilating the PF and NRL altimeter data are mostly similar, though a few of the errors have noticeable differences (Fig. 19), some of which are lower for the assimilation of the PF data and some of which are lower for assimilation of the NRL altimeter data. The RMS errors for NCOM using BCs from OTIS with assimilation of the PF and NRL altimeter data sets are also mostly similar, though 3–4 of the errors have noticeable differences (Fig. 20), but these do not show a clear advantage of one altimeter data set over the other. In summary, the use of the NRL altimetry data does not show an advantange over the use of the PF data for the tests that were conducted.

6. TESTING THE USE OF PCTIDES TO GENERATE TIDAL BCS

We were interested in comparing the use of getting tidal BCs for NCOM from PCTides (PCT) with the other methods of providing tidal BCs for NCOM. The procedure for this is similar to that used to generate tidal BCs with OTIS. PCT is run over the same area as NCOM, a tidal analysis is used to compute the tidal harmonics from the PCT output fields, and this tidal harmonic data is then interpolated to the boundaries of the NCOM domain to provide tidal BCs for NCOM.

6.1 Description of PCTides

PCT is a single-layer, barotropic, tides/surge model that was developed at NRL and is currently being used at NAVO. PCT, like NCOM, is run as a forward model by integrating the model forward in time. PCT solves the two-dimensional, depth-averaged, shallow-water equations (Hubbert et al., 2002). Forcing for PCT can include tides, wind stress, atmospheric pressure, and wave radiation stress; however, we are just using tidal forcing here. PCT also has a wetting and drying capability.

PCT uses a quadratic bottom stress with a Manning's "n", depth-dependent, bottom drag coefficient (Signell and Butman, 1992)

$$c_b = \max\left[\frac{gn^2}{\max\left[H, H_{min}\right]^{\frac{1}{3}}}, c_{b_{min}}\right], \qquad (3)$$

where g is the acceleration of gravity ($g = 9.8m/s^2$), n is Manning's bottom drag coefficient, H is the water depth, H_{min} is a minimum water depth, and $c_{b_{min}}$ is a minimum value of the drag coefficient. In PCT, the constants in Eq. 3 are set to $n = 0.0267$, $H_{min} = 1m$, and $c_{b_{min}} = 0.0001$.

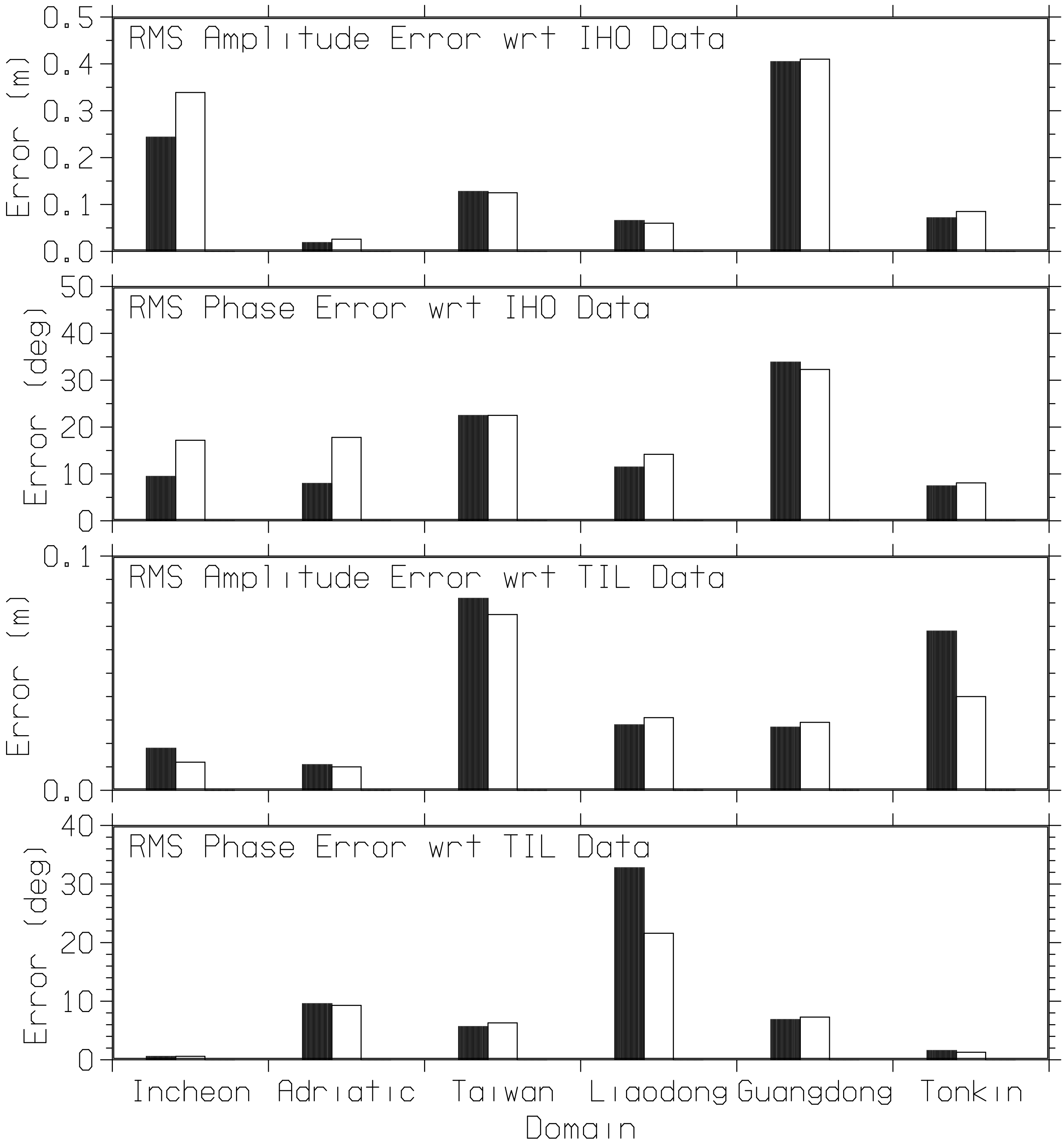

Fig. 19 — Comparison of RMS errors for OTIS with assimilation of the PF altimeter data (black bars) and the NRL altimeter data (white bars) for the Incheon, Adriatic, Taiwan St., Liaodong Bay, Guangdong, and Tonkin Gulf domains.

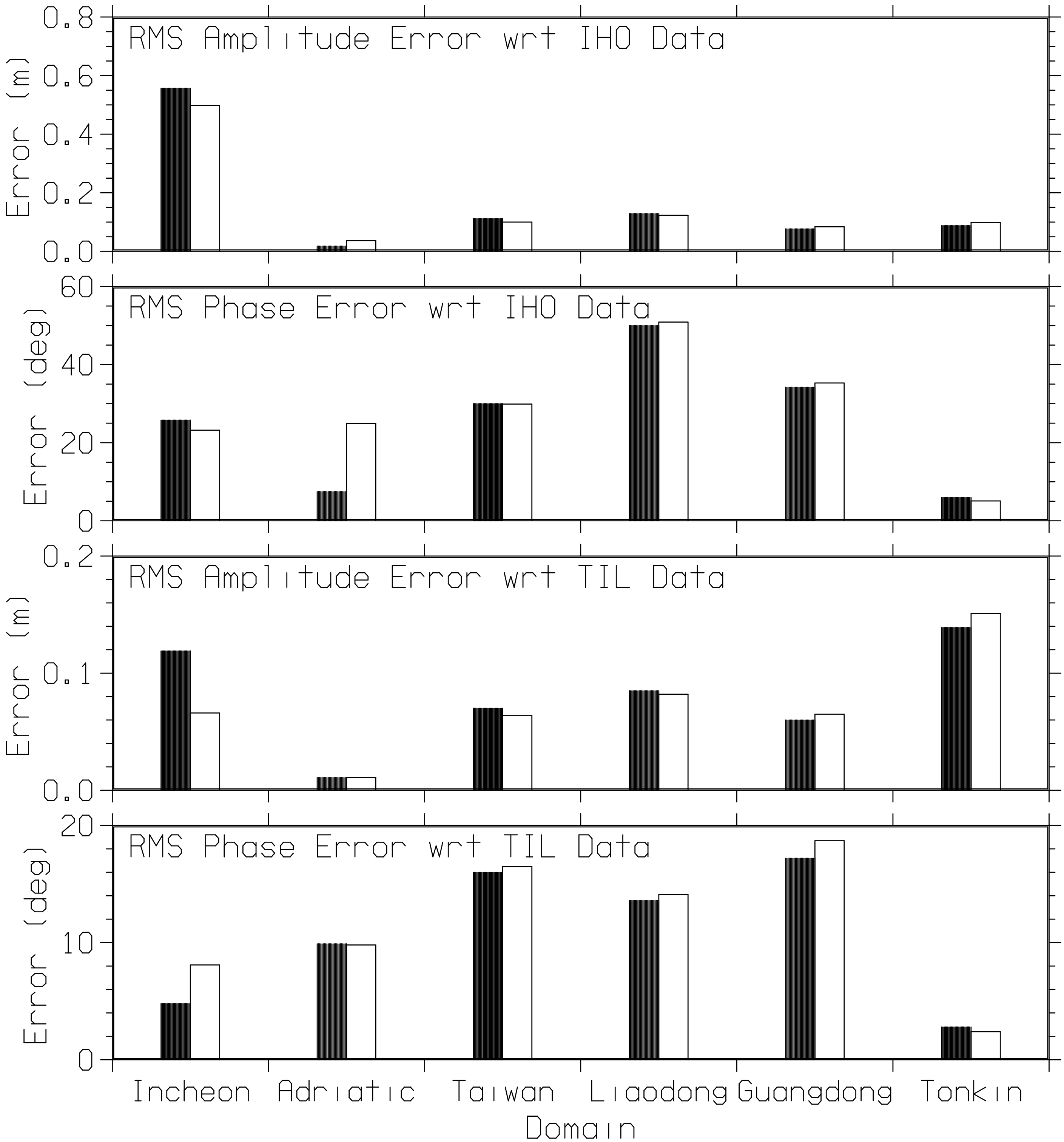

Fig. 20 — Comparison of RMS errors for NCOM with BC from OTIS with assimilation of the PF altimeter data (black bars) and the NRL altimeter data (white bars) for the Incheon, Adriatic, Taiwan St., Liaodong Bay, Guangdong, and Tonkin Gulf domains.

Table 28 — Comparison of Bottom Drag for NCOM and PCTides

depth (m)	1	10	100	1000
NCOM	0.0060	0.0029	0.0017	0.0011
PCTides	0.0070	0.0032	0.0015	0.0007

With these values of the constants in Eq. 3, this drag coefficient has a similar dependence on the water depth as the bottom drag coefficient used in NCOM in Eq. 2 (Table 28).

The DB used to provide the bathymetry here for PCT is NRL's DBDB2 Version 4.0, the same bathymetric DB used here for NCOM and OTIS. And, like for NCOM and OTIS, the bathymetry is corrected for the reference to low tide by adding to the depths at sea points the sum of the amplitudes of the four largest tidal constituents at each grid point.

PCT gets its tidal BCs from the FES2004 global tidal DB. This tidal DB provides only tidal SSH information. However, since tidal SSH is all that PCT needs for its tidal BCs, it is able to use this DB for BCs.

PCT is capable of assimilating both altimeter and IHO tidal SSH data using a simple nudging procedure with a specified time scale and a circular region of influence. The weighting of the relaxation is reduced with increasing distance from the location of the data with a cosine function. Since this assimilation procedure can improve the PCT tidal solution, it was used in the PCT tidal simulations conducted here.

Since PCT is a forward model, a tidal analysis of the PCT output must be performed to compute the tidal harmonics for the tidal solution. Hence, PCT must be run for a sufficiently long time to allow separation of the contributions from the tidal constituents that were used. The length of run required varies from a few days for a single constituent to on the order of 180 days for the main tidal constituents. For the experiments conducted here, PCT was run with the tidal constituents K_1, O_1, P_1, Q_1, K_2, M_2, N_2, and S_2 for a period of 180 days with the output saved at hourly intervals.

6.2 Limitations of PCTides

One limitation of PCT is that the spatial resolution for a longitude- latitude grid must be the same in degrees for both longitude and latitude. Hence, PCT frequently cannot be run on exactly the same grid as NCOM, which is usually set up with the grid spacing in both directions along the grid being about the same in km rather than degrees. However, PCT can be run over the same region as NCOM, and the resolution that is used for PCT can be similar to that used for NCOM.

The data assimilation used by PCT is a simple nudging (i.e., relaxation) procedure, which is less effective than the inverse data assimilation method used by OTIS. Tidal analyses of PCT output often show small circular features in coastal areas that are caused by the nudging of the PCT SSH to the tidal SSH at the IHO stations and which reflect the spatial-scale of the nudging being used. However, the effect of the nudging is not limited to just the area around the location of the data being assimilated and is able to affect the tidal solution over a larger area.

PCT was developed at a time when the available tidal DBs, which are needed to provide tidal

BCs for a local tidal simulation, only included tidal SSH data and did not include tidal currents. For this reason, a tidal BC for PCT was implemented that requires just SSH data.

One such BC, the simple, "clamped" tidal SSH BC, in which the tidal SSH from a tidal DB is specified on the open boundary, works well, but can take a long time to converge. This is because transient motions that occur within the domain as the tides are being spun up cannot radiate out through the boundaries, since the clamped SSH BC reflects these transients back into the interior of the domain. Hence, these transients must be damped within the domain. This damping occurs primarily through bottom friction and, depending on the size and depth of the domain, can take a long time.

Hence, a relaxation zone of specified width in grid-points is used along the open boundary of PCT to relax the interior SSH to the tidal SSH from the DB (Hubbert et al., 2002) and provide some damping of transient motions. The weighting of the external tidal data within this relaxation zone has a value of one at the open boundary and is reduced in strength with distance from the boundary according to a cosine dependence. For velocities, a radiation BC (Miller and Thorpe, 1981) is used for outflow and a zero gradient BC is used for inflow (neither of which requires external velocity data).

Based on our experience with PCT, its open BCs do not work as well as a Flather-type BC (Flather, 1976), which requires the use of external tidal data for both SSH and velocities. We sometimes see noise in the PCT tidal solutions near the open boundaries that can extend fairly far into the interior. And, occasionally, PCT fails to run properly for a particular domain. It is thought that these problems might be caused by the BCs that PCT is using.

Since PCT is run as a forward model, obtaining tidal harmonic information from the PCT solution requires performing a tidal analysis of the PCT output. If several tidal constituents are being used, the tidal solution must extend over a sufficiently long time to allow the tidal analysis to be able to separate the different constituents. Since OTIS is run in frequency space rather than being integrated forward in time, tidal harmonic information from the run is output directly and no tidal analysis is needed.

6.3 Results from Testing PCTides

6.3.1 Incheon, Korea

Table 29 shows errors for the PCT tidal solution and for NCOM when run with tidal BCs from the PCT tidal solution for both the IHO and TIL data for the Incheon, Korea domain (Fig. 9). These errors can be compared with those in Tables 14 and 15 for OTIS and for NCOM when run with BCs from OTIS.

The RMS error for the PCT tidal solution wrt the IHO data is larger than that for OTIS for amplitude (0.492 vs 0.244 m), but slightly smaller for phase (8.1°vs 9.5°). Most of the difference in the RMS amplitude error is due to the larger underprediction (i.e., mean error) of the tidal amplitude at the IHO stations by PCT, i.e., -0.403 for PCT vs -0.018 m for OTIS. The RMS error for PCT wrt the TIL data is also higher than the error for OTIS (0.181 vs 0.018 m for amplitude and 4.3°vs 0.6°for phase).

Table 29 — Tidal Errors for Incheon, Korea Domain for PCT and for NCOM with BC from PCT

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	stations
errors for PCT solution wrt IHO data							
M_2	-0.403	0.408	0.492	-1.2	6.5	8.1	26
errors for PCT solution wrt TIL data							
M_2	-0.166	0.166	0.181	-2.0	2.8	4.3	19
errors for NCOM with PCT BC wrt IHO data							
M_2	-0.654	0.654	0.726	26.4	27.1	33.5	26
errors for NCOM with PCT BC wrt TIL data							
M_2	-0.305	0.305	0.305	4.3	5.6	10.7	19

The RMS error for NCOM with BCs from PCT wrt the IHO data is larger than that for NCOM with BCs from OTIS for both amplitude (0.726 vs 0.557 m) and phase (33.5°vs 25.8°). The large amplitude errors for both BCs are due to the large mean underprediction of the amplitude at the IHO stations (-0.654 and -0.467 m for the PCT and OTIS BCs, respectively). The large phase errors for both BCs are due to the large mean phase lags for NCOM at the IHO stations, i.e., 33.5°and 16.7°for the PCT and OTIS BCs, respectively). The RMS error for NCOM with BCs from PCT wrt the TIL data is larger than that for NCOM with BCs from OTIS for amplitude (0.305 vs 0.119 m), and phase (10.7°vs 4.8°).

6.3.2 Adriatic Sea

In the Adriatic Sea domain (Fig. 10), the PCTides simulation became unstable as the energy within the domain increased to unreasonable values. We expect that this was due to insufficient radiation of energy out of the domain by the open BCs that PCTides uses.

6.3.3 Taiwan Strait

Table 30 shows errors for the PCT tidal solution and for NCOM when run with tidal BCs from the PCT tidal solution for both the IHO and TIL data for the Taiwan Strait domain (Fig. 11). These errors can be compared with those in Tables 19 and 20 for OTIS and for NCOM when run with BCs from OTIS.

Table 30 — Tidal Errors for Taiwan Strait Domain for PCT and for NCOM with BC from PCT

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	stations
errors for PCT solution wrt IHO data							
M_2	0.026	0.132	0.256	-5.2	11.2	16.8	31
errors for PCT solution wrt TIL data							
M_2	-0.035	0.044	0.060	-5.0	6.4	11.3	98
errors for NCOM with PCT BC wrt IHO data							
M_2	0.014	0.062	0.086	-7.0	16.0	28.3	31
errors for NCOM with PCT BC wrt TIL data							
M_2	-0.053	0.064	0.081	-2.8	13.5	19.9	98

The RMS error for the PCT tidal solution wrt the IHO data is larger than that for the OTIS tidal solution for amplitude (0.256 vs 0.128 m), but smaller for phase (16.8°vs 22.5°). The RMS error for PCT wrt the TIL data is smaller than the error for OTIS for amplitude (0.060 vs 0.082 m) but larger for phase (11.3°vs 5.7°).

The RMS error for NCOM with BCs from PCT wrt the IHO data is smaller than that for NCOM with BCs from OTIS for amplitude (0.086 vs 0.112 m) and is slightly smaller for phase (28.3°vs 30.0°). The RMS error for NCOM with BCs from PCT wrt the TIL data is larger than that for NCOM with BCs from OTIS for both amplitude (0.081 vs 0.070 m) and phase (19.9°vs 16.0°).

6.3.4 Liaodong Bay

Table 31 shows errors for the PCT tidal solution and for NCOM when run with tidal BCs from the PCT tidal solution for both the IHO and TIL data for the Liaodong Bay domain (Fig. 12). These errors can be compared with those in Tables 21 and 22 for OTIS and for NCOM when run with BCs from OTIS.

Table 31 — Tidal Errors for Liaodong Bay Domain for PCT and for NCOM with BC from PCT

	tidal amplitude error (m)			tidal phase error (°)			number of
const	mean	mean abs	rms	mean	mean abs	rms	stations
errors for PCT solution wrt IHO data							
M_2	-0.029	0.122	0.191	-13.2	32.7	51.0	19
errors for PCT solution wrt TIL data							
M_2	0.044	0.081	0.096	-4.6	22.7	24.9	57
errors for NCOM with PCT BC wrt IHO data							
M_2	0.014	0.068	0.083	11.9	24.9	47.5	17
errors for NCOM with PCT BC wrt TIL data							
M_2	0.054	0.076	0.085	3.8	11.0	15.2	57

The RMS error for the PCT tidal solution wrt the IHO data is larger than that for the OTIS tidal solution for both amplitude (0.191 vs 0.066 m), and phase (57.0°vs 11.5°). The RMS error for PCT wrt the TIL data is larger than the error for OTIS for amplitude (0.096 vs 0.028 m) but smaller for phase (24.9°vs 32.8°).

The RMS error for NCOM with BCs from PCT wrt the IHO data is smaller than that for NCOM with BCs from OTIS for amplitude (0.083 vs 0.129 m) and is slightly smaller for phase (47.5°vs 50.0°). The RMS error for NCOM with BCs from PCT wrt the TIL data is the same as that for NCOM with BCs from OTIS for amplitude (0.085 vs 0.085 m) and is higher for phase (15.2°vs 13.6°).

6.3.5 Guangdong, China

Table 32 shows errors for the PCT tidal solution and for NCOM when run with tidal BCs from the PCT tidal solution for both the IHO and TIL data for the Guangdong, China domain (Fig. 13). These errors can be compared with those in Tables 23 and 24 for OTIS and for NCOM when run with BCs from OTIS.

Table 32 — Tidal Errors for Guangdong, China Domain for PCT and for NCOM with BC from PCT

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of stations
errors for PCT solution wrt IHO data							
M_2	-0.091	0.101	0.157	0.6	10.7	17.1	34
errors for PCT solution wrt TIL data							
M_2	0.010	0.024	0.033	-0.6	5.3	7.6	332
errors for NCOM with PCT BC wrt IHO data							
M_2	0.085	0.103	0.118	2.8	16.8	28.6	32
errors for NCOM with PCT BC wrt TIL data							
M_2	0.076	0.078	0.086	3.7	9.4	11.5	332

The RMS error for the PCT tidal solution wrt the IHO data is significantly smaller than that for the OTIS tidal solution for both amplitude (0.157 vs 0.405 m), and phase (17.1°vs 33.9°). The RMS error for PCT wrt the TIL data is larger than the error for OTIS for both amplitude (0.033 vs 0.027 m) and phase (7.6°vs 6.9°).

The RMS error for NCOM with BCs from PCT wrt the IHO data is larger than that for NCOM with BCs from OTIS for amplitude (0.118 vs 0.077 m) but smaller for phase (28.6°vs 34.2°). Similarly, the RMS error for NCOM with BCs from PCT wrt the TIL data is larger than that for NCOM with BCs from OTIS for amplitude (0.086 vs 0.060 m) but is smaller for phase (11.5°vs 17.2°).

6.3.6 Gulf of Tonkin

Table 33 shows errors for the PCT tidal solution and for NCOM when run with tidal BCs from the PCT tidal solution for both the IHO and TIL data for the Gulf of Tonkin domain (Fig. 14). These errors can be compared with those in Tables 25 and 26 for OTIS and for NCOM when run with BCs from OTIS.

Table 33 — Tidal Errors for Gulf of Tonkin Domain for PCT and for NCOM with BC from PCT

const	tidal amplitude error (m) mean	mean abs	rms	tidal phase error (°) mean	mean abs	rms	number of stations
errors for PCT solution wrt IHO data							
O_1	-0.125	0.150	0.170	6.0	6.0	7.1	8
errors for PCT solution wrt TIL data							
O_1	-0.088	0.088	0.091	7.1	7.1	7.2	15
errors for NCOM with PCT BC wrt IHO data							
O_1	0.023	0.052	0.061	12.2	12.2	13.3	7
errors for NCOM with PCT BC wrt TIL data							
O_1	-0.047	0.047	0.052	10.5	10.5	10.5	15

The RMS error for the PCT tidal solution wrt the IHO data is larger than that for the OTIS tidal solution for amplitude (0.170 vs 0.072 m), and is similar for phase (7.1°vs 7.5°). The RMS error for PCT wrt the TIL data is larger than the error for OTIS for both amplitude (0.091 vs 0.068 m) and phase (7.2°vs 1.6°).

The RMS error for NCOM with BCs from PCT wrt the IHO data is smaller than that for NCOM with BCs from OTIS for amplitude (0.061 vs 0.088 m) but larger for phase (13.3°vs 6.0°). Similarly, the RMS error for NCOM with BCs from PCT wrt the TIL data is smaller than that for NCOM with BCs from OTIS for amplitude (0.052 vs 0.139 m) but is larger for phase (10.5°vs 2.8°).

6.3.7 Summary of results from testing PCTides

Figure 21 shows a comparison of the RMS errors for NCOM run with (i) tidal BC from a local OTIS analysis and (ii) tidal BC from a PCT tidal simulation. NCOM run with tidal BCs from PCT more frequently has smaller errors wrt the IHO data, but more frequently has larger errors wrt the TIL data than NCOM run with tidal BCs from OTIS for the five cases that were compared. On balance, the overall errors for NCOM run with tidal BCs from PCT and from OTIS are fairly comparable. OTIS has some advantages wrt PCT in that it uses a more sophisticated assimilation scheme and tends to give smoother tidal solutions.

7. SUMMARY

This report presents tests of the use of OTIS to provide tidal BCs for a regional ocean model. OTIS is a set of programs developed at OSU to generate optimal tidal solutions within an ocean domain by assimilation of tidal data from various sources including satellite altimeters and coastal tide gauges.

The procedure used to generate tidal BCs for a regional ocean model with OTIS is that OTIS is run on the grid used by the ocean model to generate an optimal tidal solution for the ocean model domain, and tidal BCs for the ocean model are then interpolated from the OTIS tidal solution. The ocean model used for the tests conducted here is NCOM, which is currently used for regional ocean simulations at NRL and for global and regional operational ocean prediction at NAVO.

The tides generated by NCOM with tidal BCs from OTIS were compared with the tides generated by NCOM with tidal BCs from regional and global tidal DBs obtained from OSU. Mean, mean absolute, and RMS errors for tidal amplitude and phase were computed by comparison of the tidal solutions with tidal data from coastal tide-gauge stations and from the TOPEX Interleave altimeter data. Tidal errors were also computed for the OTIS tidal solutions themselves and for the OSU tidal DBs; however, the main focus of the testing in this report is the NCOM tidal errors.

Tidal errors were computed for five regional ocean domains being run operationally at NAVO: the East China Sea, the South China Sea, the Persian Gulf, the US East Coast, and the US southern California coast. Tidal errors were also computed for some additional domains: the Korean coast in the Yellow Sea near Incheon, the Adriatic Sea, Taiwan Strait between Taiwan and China, Liaodong Bay in the northeast Yellow Sea, the Chinese coast near Guangdong, China, the Gulf of Tonkin, and Messina Strait between Sicily and Italy.

For the five NAVO domains, the errors for NCOM using tidal BCs from a local OTIS tidal analysis and from the OSU tidal DBs were generally similar. This was not unexpected, since for these large domains, most of the open boundaries of the domains lies in deep water away from the coast where the tides in the tidal DBs are fairly good.

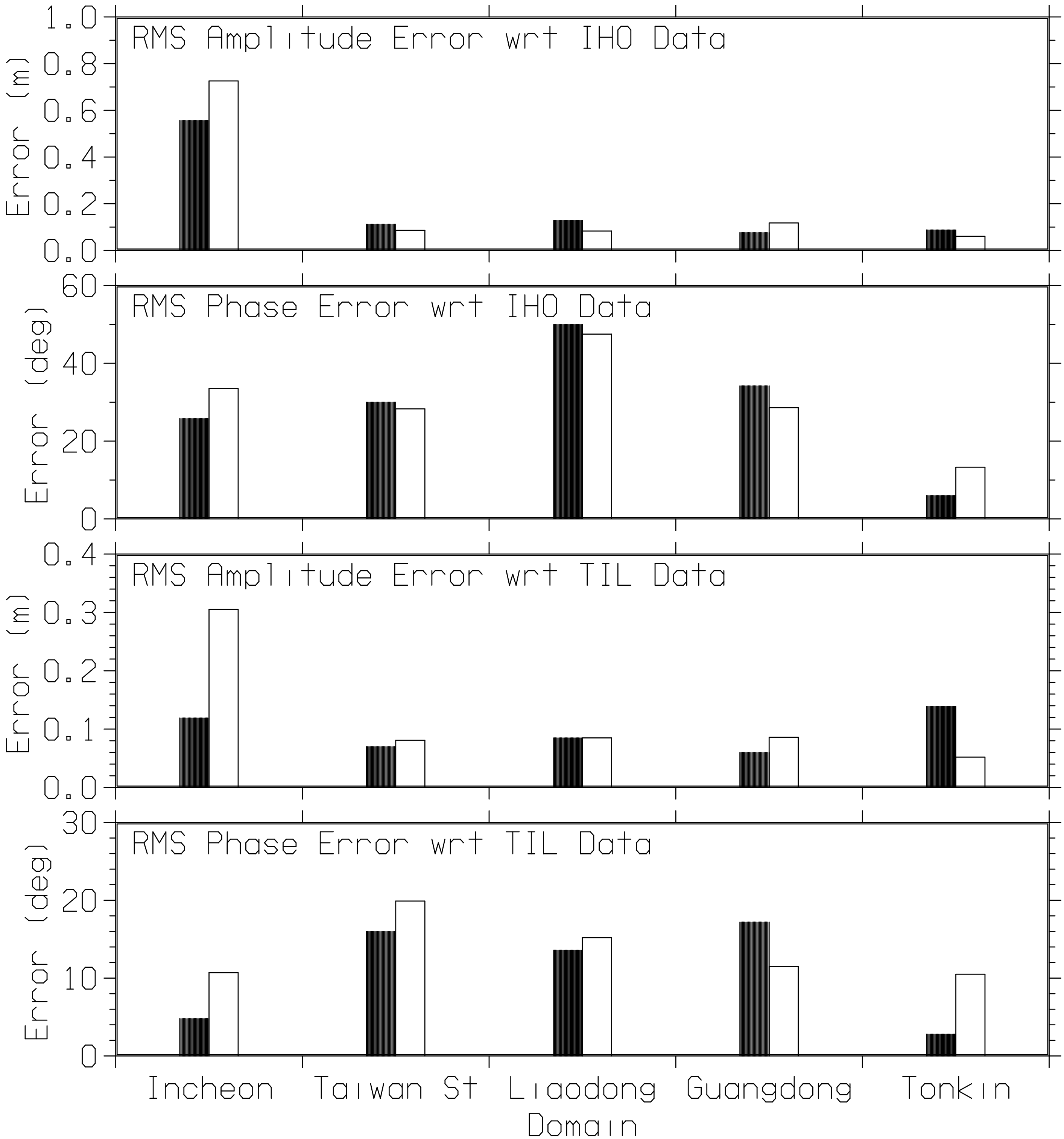

Fig. 21 — Comparison of RMS errors for NCOM with BCs from a local OTIS analysis (black bars) and from a tidal simulations with PCTides (white bars).

For the additional domains that were tested, the errors for NCOM using tidal BCs from a local OTIS analysis and from the OSU tidal DBs were similar for about 40cases, the errors were lower more often with BCs from the local OTIS analysis than with BCs from the OSU tidal DBs. Hence, the BCs from the local OTIS tidal solution were considered to give a slight improvement, overall.

Regardless of the tidal BCs used, for some domains, the bottom drag used by the ocean model needs to be adjusted to optimize the tidal solution. For the Incheon, Korea domain tested here, there was a large amplitude and phase bias in the NCOM tidal solutions that could only be reduced by reducing the bottom drag used by NCOM. The need to reduce the bottom drag may reflect the fine bottom sediments that occur in this area.

The altimeter data assimilated by OTIS for most of the tests conducted in this report is referred to as the Pathfinder data set, and was part of the OTIS software package provided by OSU. A different altimeter data set for assimilation in OTIS has been developed by NRL. The NRL altimeter data set contains a longer time series of altimeter data than the PF data set and, hence, could potentially provide more accurate tidal data. Errors were computed for OTIS and for NCOM using BCs from OTIS for assimilation by OTIS of the NRL altimetry data and the errors for these tidal solutions were compared with the errors obtained with the Pathfinder data. The errors computed using the two altimeter data sets were fairl similar for both the OTIS tidal analyses and for the NCOM tidal simulations using the OTIS tidal solutions for BCs.

The PCTides model is used for tidal prediction at NAVO, and can assimilate both altimeter data and data from IHO tide stations. Some comparisons were made of tidal solutions computed by OTIS and PCTides, and for NCOM using tidal BCs from OTIS and from PCTides. For the five domains that were compared, errors for the NCOM-predicted tide using tidal BCs from PCTides were generally comparable to the errors using tidal BCs from OTIS.

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Appendix A

CALCULATION SEQUENCE FOR OTIS

The sequence of programs that were run to compute the OTIS solutions that are described in this report are listed in Table A1. All the programs are part of the OTIS package from OSU except the otis_clean script, and the otis_setup and otis_comp_iho2 programs, which were written at NRL.

Table A1 — OTIS Program Calculation Sequence

program	description
otis_clean,u	delete old files
otis_setup.x	set up grid, tidal BCs, and IHO data for assimilation
make optpg.all	compile programs for local OTIS calculation
fwd_fac -u1	run forward model with friction velocity = 1 m/s
mkSpeed	set up file of spatially-varying friction velocity
fwd_fac	run forward model with spatially variable friction velocity
varest	make model covariance file
lat_lon	set up altimeter representer and data lists
repx	compute representers
makedat	make altimetry data set
makeB	make reduced altimetry data set for assimilation
makeB -a -D../prm/iho_data.dat -t	add IHO data for assimilation
rpx_to_p	make representer matrices
rpx_to_p -r	make representer matrices
reduce_b	compute representer coefficients
rlc	run assimilative model
otis_comp.x	set up OTIS tidal solution file for NCOM to use

The function of the otis_clean unix script is just to delete old files from the local OTIS application directory before computing new ones. It is necessary to remove some of these old files so that they do not interfere with the new OTIS calculation.

The program otis_setup replaces some similar OTIS programs and performs the following functions:

(1) The domain, grid, and bathymetry are defined and this information is written to file ../prm/grid. This program can set up a grid based on inputs from the user, but can also obtain an existing grid that was previously set up for NCOM, which was how the otis_setup program was used for this report.

(2) The tidal constituents to be solved for are defined and written to file ../prm/constituents,

which is an ascii file with one tidal constituent written on each line in lower case. For this report, the four main tidal constituents (M_2, S_2, K_1, and O_1) were solved for all of the domains that were run.

(3) The tidal BCs are defined for each of the open boundary points on the grid and are written to file ../prm/obc. These values are interpolated from the OSU tidal DBs that we have at NRL (see Table 1). The procedure used was to interpolate from the highest resolution OSU tidal DB available for that location.

(4) The IHO tide gauge data that are to be assimilated are written to file ../prm/iho_data.dat, which is an ascii file. As previously mentioned, there are a couple of restrictions on the IHO data that can be assimilated. One restriction is that the IHO station must lie within the sea grid cells of the grid being used to compute the OTIS tidal solution. This is done to reduce the chance of assimilating IHO stations that are located in bays or estuaries where the tide is not representative of the tide in the adjacent coastal ocean. The other restriction is that the IHO station must have data for all of the tidal constituents being solved for. This is one of the reasons that only the four main tidal constituents were solved for, i.e., most IHO stations contain data for these four tidal constituents.

The program otis_comp_iho2 is used to:

(1) Look at (visually inspect) the tidal solutions generated by OTIS.

(2) Compute errors for the tidal solutions generated by OTIS wrt tidal data from IHO stations and from the TOPEX Interleave (TIL) altimeter data set. This is the program that was used to compute the errors in this report.

(3) Create the output file ../out/tide_out.tmp containing all of the information needed for NCOM to compute tidal BCs from the OTIS tidal solutions. This includes information about the OTIS grid (which is usually the same as the NCOM grid, but does not have to be), the names of the tidal constituents for which OTIS computed tidal solutions, and the tidal SSH and transport for the OTIS tidal solutions for each constituent.

Note that all of the OTIS programs in Table A1 must be recompiled for a particular domain, except for programs lat_lon and makedat. The OTIS programs must be recompiled because some of the arrays within these programs have dimensions that are hard-wired. The NRL programs otis_setup and otis_comp_iho2.lx do not need to be recompiled when the domain is changed.

Note that in Table A1, the OTIS program fwd_fac, which computes the OTIS forward tidal solution, is run twice, the first time with a spatially constant friction velocity of 1 m/s (specified by the -u1 option in Table A1), and the 2nd time with a spatially variable friction velocity computed from the first run of fwd_fac by program mkSpeed.

Appendix B

INPUT PARAMETER FILE FOR OTIS

The input parameter values that were used in the OTIS input parameter file run_param for the OTIS runs that were conducted in this report are listed in Table B1.

Table B1 — OTIS Parameter Values

parameter	description
1	set quiet mode on =1 or off =0
16000	set max RAM (Mb) available, set=0 if unlimited
../out/h0.ds.out	filename for prior elevations
../out/u0.ds.out	filename for prior transports
../../../DB/h_tpxo	filename for correction model file
1	type of BCs: 1=Elev, 2=Normal flow, 3=Radiation
0	value of constant friction velocity (m/s)
../prm/uv.vel.unf	filename for spatially variable friction velocity
0	Do not (=0) or do (=1) use program diffuse
../dat/tpxbin.dat	filename for data file
../prm/covsc	filename for covariance scales
1.	Open boundary variance scale
1.	Rigid boundary variance scale
1.	Interior variance scale
../prm/covsc	filename for covariance scales
1.	Open boundary variance scale
1.	Rigid boundary variance scale
1.	Interior variance scale
1.	value of damping parameter sig-e
	value of truncation parameter (≤nrep)
8	number of blocks (2*nc*ndat)
1	1/0 - do/not delete old G.dat (WW.dat)
0	1/0 - do/not replace G.dat with WW.dat
1	1/2 - rlc makes final solution

These parameter values are used in the OTIS programs unless superseded by a command line option when running a particular program. For example, the value of "0" specified in Table B1 for the value of the constant friction velocity denotes that a spatially-variable friction velocity will be used to compute the tides in program fwd_fac, which computes the forward tidal solution, and in program rlc, which computes the OTIS data-assimilative tidal solution. Hence, in Table A1, the first time that program fwd_fac is run, the option -u1 is provided to specify that a constant friction velocity of 1 m/s is to be used, since a spatially variable friction velocity has not yet been computed. The second time that program fwd_fac is run, no command line options are provided, and so the spatially-variable friction velocity specified in the input parameter file takes precedence. The value of the truncation parameter is not specified, this is computed automatically based on the amount of computer memory (RAM) available.