

Extreme Southern Ocean Tide Modeling

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Abstract. Predictability of barotropic ocean tides is significantly less accurate in the coastal regions, littoral and shallow seas, and oceans not covered by TOPEX/POSEIDON (T/P) than in deep oceans (>1000 m depth) within $\pm 66^\circ$ latitude. Barotropic ocean tide models (mostly with spatial resolutions at 50 km or longer), benefited primarily from T/P altimetry and hydrodynamic modeling, allow predictions of deep ocean tidal amplitudes with an estimated accuracy of 1-2 cm (1σ). Even with the availability of most recent suite of available global tide models based primarily on T/P data, e.g., GOT00, NAO99, Delft, FES00, extreme Southern Ocean tides below 60S are limited both in accuracy and resolutions, especially in regions near Antarctica where parts of ocean surfaces are seasonally or permanently covered with ice. In our initial study with the objectives to improve tides in Antarctic oceans for accurate prediction of ground-line locations to enhance ice mass balance studies, we provide an assessment of accuracy of tide models in the region. In addition to global models, regional models such as the Padman models (Weddell Sea and Ross Sea) are currently available. Test models below 50S are presented using available T/P and ERS-2 altimeter data over ocean surfaces as well as retracked ERS-2 data over sea surfaces covered with ice.

Keywords. Ocean tide modeling, satellite altimetry, Southern Ocean

1 Introduction

Ocean tides play a significant role in the complex interactions between atmosphere, ocean, sea ice, and floating glacial ice shelves. Tidal currents create turbulent mixing at the bottom of an ice shelf contributing to the creation of rifts for the possible detachment of part of icebergs and can influence heat

transport between the ice shelf and sea water (Robertson et al., 1998). Tides near and under floating ice shelves and sea ice influence grounding line locations and, depending on surface and basal slopes, grounding line migrates with time within a grounding zone (Rignot, 1998b; Metzger et al. 2000).

In particular, tides have been identified as one of the dominant causes for grounding line migration in several studies, including Petermann Gletscher, Greenland (Rignot, 1998a), West Antarctic glacier (Rignot, 1998b), Filchner-Ronne Ice Shelf (Rignot et al., 2000), and Schirmacher Oase, E. Antarctica (Metzger et al., 2000). Improved knowledge of grounding line is inherently necessary to study ice mass balance and its contribution to the global sea level change.

A number of global tide models (over 20) have been developed from 1994-1996, e.g., the FES95.2.1 model (LeProvost et al., 1998) and CSR3.0 (Eanes and Bettadpur, 1996) based primarily on T/P altimeter data. Most of these models are defined between $\pm 66^\circ$, with almost all empirical models based on the "truly" global hydrodynamic tide model developed by C. LeProvost et al. (1998). Accuracy evaluations indicated that the deep (>1000 m) ocean tides are accurate to 2-3cm rms (vector differences of the in-phase and quadrature components), while coastal and littoral tides and polar tides are much less accurate (Shum et al., 1997). By 1996, a number of improved global ocean tide models became available. A non-exhaustive list includes: YATM4d (Tierney et al. University of Colorado, assimilated model), Arthur Smith (Delft Technical University empirical model), TPXO.3 (G. Egbert, Oregon State University deep ocean assimilation model), D&W98 (Desai & Wahr, JPL/CU deep ocean empirical Model), CSR4.0 (R. Eanes, University of Texas empirical model), GOT99.2b (R. Ray, 1999, NASA/GSFC empirical/patched model), NAO99 (K. Matsumoto et al., 2000, National Astronomical Observatory assimilated model), and the FES99 (C.

LeProvost, LEGOS/GRGS assimilated model). A study was performed concentrating on the fidelity of the new tide models' performance in the coastal region.

2 Assessment of Tide Model Error in South Ross Sea

The dynamical tide model CATS02.01, Circum-Antarctic Tidal Simulation, is a 10-constituent model for the Southern Ocean (Padman et al., 2002). The grid is $1/4 \times 1/12$ degree (longitude x latitude) and extends from 86°S to 58°S . The 10 constituents are 4 diurnal (O_1 , K_1 , P_1 , Q_1), 4 semidiurnal (M_2 , S_2 , K_2 , N_2), and 2 long-period tides (M_m , M_f). The TPX05.1 T/P altimetry assimilation model was used for its open ocean boundary conditions. To get preliminary error assessment of tide models in the south Ross Sea, this regional CATS02.01 model and two global models, GOT99.2b and NAO99, were compared with each other for 8 common short-period constituents. RMS model differences at all available grid points below 58°S for the in-phase ($H\cos G$) and quadrature ($H\sin G$) components of these 8 constituents are listed in Table 1. Except for Q_1 constituent, differences between models GOT99.2b and NAO99 are larger than those involving the CATS02.01 model for all constituents. Thus, the CATS02.01 model shows the smallest differences, although marginal, relative to other models. The M_2 , S_2 , K_1 , and O_1 constituents dominate model differences.

Table 1. RMS Model Differences (cm) in South Ocean

	CATS-GOT	CATS-NAO	NAO-GOT
K_1	3.31	3.58	4.41
O_1	3.67	3.01	4.01
P_1	1.02	1.28	1.43
Q_1	0.68	0.87	0.82
M_2	3.42	7.97	8.74
N_2	1.62	1.45	1.83
K_2	1.13	1.55	1.66
S_2	3.40	5.01	5.42

To get the picture for the spatial distribution of model difference, the RMS model difference averaged over three combinations and combined in a root-sum-of-squares (RSS) sense for the 8 constituents was computed at every common grid point. Figure 1 shows that three models have the biggest differences reaching up to 30cm around the McMurdo Sound off the Scott Coast in the Ross Sea region.

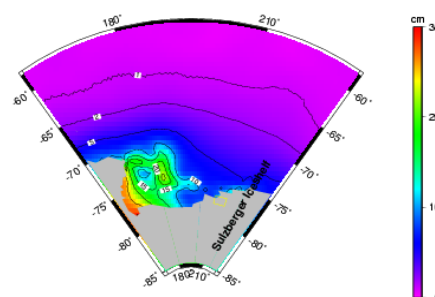


Fig. 1 Combined RMS model differences

Williams and Robinson (1980; 1981) have deployed gravimeters in the south Ross Sea to study tidal dynamics under the ice shelf. The periodic variation in gravity recordings was analyzed to calculate tidal water level fluctuations in the south Ross Sea. Comparisons of these three ocean tide models with ground truth data at the Little America V gravimeter site (1973-1978), located near 78°S and 168°E , are listed in Table 2. Overall, the NAO99 model is closest to the ground truth at this single site and the CATS02.01 model shows the second better comparison. Also diurnal tides show larger model error than semidiurnal ones. In Table 2, RSS is the total difference combined in a root-sum-of-squares sense.

Table 2. Tide Comparison (cm) at Little America V

	GOT99.2b	NAO99	CATS02.01
K_1	26.6	10.4	21.6
O_1	20.4	6.5	16.0
P_1	11.4	3.3	7.3
M_2	2.2	1.7	0.7
N_2	2.9	1.8	3.5
S_2	2.9	0.6	0.5
RSS	35.7	13.0	28.1

Along the tracks of altimeter satellites T/P and ERS-2, height predictions of each of three models were compared with the sea level variations observed by satellite altimeters. Table 3 reveals that, along tracks of the same satellite, all models have similar rms differences from altimeter measurements. It is obviously seen that the rms differences mainly depend on the satellite data that were compared against. Thus the data noise and non-tidal ocean signals in altimeter data seem to dominate the validation results in Table 3 although

the CATS02.01 model shows the slightly best result.

Table 3. Model Validation (cm) with Altimeter Sea Level

	GOT99.2b	NAO99	CATS02.01
T/P	30.71	30.74	30.23
ERS-2	38.37	38.41	38.00

3 Empirical Tide Modeling

We produced a few test tide models using altimeter data of T/P and ERS-2 satellites based on a response method of empirical tidal analysis, in which the admittance function is represented as a Fourier series of 6 parameters in each of diurnal and semidiurnal frequency bands (Ole Andersen, 1994). Andersen (1994) reports that one advantage of this representation of admittance functions is that estimates of the S_2 tidal constituent are derivable from the ERS-2 data at crossover points on 35-day repeat tracks even though the S_2 tidal constituent is aliased to zero frequency by the 35-day sampling. For the T/P satellite, the empirical tidal analysis was done at each individual point separated by 1 second in time from next points along the ground tracks because of the sampling rate (once per 10 days) that is higher than that of the ERS-2 satellite and designed for optimal ocean tidal analyses. The annual signal is solved for along with 12 parameters of this response formulation, which is able to determine harmonic constants of 8 short-period constituents O_1 , K_1 , P_1 , Q_1 , M_2 , S_2 , K_2 , and N_2 . Andersen (1994) applied this response method to a residual tide solution after tidal variations of the 1980 Schwiderski model has been removed from the ERS-1 altimeter data. The test tide analysis in this study, however, is a full tide solution not a residual one.

The model evaluation results discussed in the previous section give us a good confidence on the CATS02.01 model's performance in the south Ross Sea. Thus the test models produced in this study were compared with the CATS02.01 model due to lack of ground truth data for the region.

In order to verify the procedure of test tide modeling, the TOPEX data for cycles 4-339 were used as the first set of altimeter data. T/P cycles 4-339 correspond to a 9-year period from October of 1992 to December of 2001. The 8 tidal constituents were determined for each individual point that is separated by 1 second in time from next points along the T/P ground tracks in an area below 50S and within the longitude range between

160E and 215E. The differences between the point-wise-and- TOPEX-derived test model and the CATS02.01 model that are combined in an RSS sense for 8 constituents have an rms difference of 2.3cm for 13,382 points in an area bounded by 66S/58S and 160E/215E. This model difference agrees well with the accuracy of recent tide models like CATS02.01 in deep oceans, which is on a 2-3cm level. Of the 8 constituents, K_1 tide has the largest rms difference of 1.2cm and S_2 tide has the second largest 1.0cm. The load tide of NAO99 model was used to reduce the TOPEX-derived test model from the geocentric (elastic) ocean tide to pure ocean tide to compare it with the CATS02.0 model.

Next, the ERS-2 altimeter data over ocean surfaces were analyzed for the 8 tidal constituents at crossover points in an area below 60S and within the longitude range between 160E and 215E. The ERS-2 cycles 1-59 were used corresponding to a 7-year period from May of 1995 to December of 2001. The rms difference between ERS-2 derived test model and the CATS02.01 model is 8.3cm for 415 crossover points in an area bounded by 66S/60S and 160E/215E. Of the 8 constituents, S_2 tide that has the zero aliased frequency has the largest rms difference of 6.4cm and K_1 tide with the annual aliased frequency has the second largest 3.4cm. The CATS02.01 model has the accuracy on a 2cm level in this test area above 66S. Thus a full tide solution using 35-day-repeat altimeter data alone is not good even over ocean surfaces and in deep ocean areas.

To see the effect of adding ERS-2 data to the tidal analysis of TOPEX data, 31 test locations were selected between 65.8S and 60.2S near the Ross Sea. The TOPEX-alone solutions at these test points have the rms difference of 2.64cm from the CATS02.01 model while those for both of TOPEX and ERS-2 data have 2.63cm. In each tide solution, separate bias parameters at the zero frequency were estimated for different data sets although a common weight was used for both data sets. The ERS-2 only solutions have 10.8cm rms difference from the CATS02.01 model. Thus the improvement of a full ocean tide solution using TOPEX data by adding ERS-2 data is negligible.

Finally, the retracked Ice Data Record (IDR) data for the ERS-2 altimeter produced by the NASA/GSFC were used in the test modeling of ocean tide over sea surfaces covered with ice. Fricker and Padman (2002) reported their use of retracked ERS-2 altimeter data at crossover locations to perform harmonic tidal analysis on the Filchner-Ronne Ice Shelf. Time period of IDR data

used is the same as that of the ERS-2 data described above. For this study, the longitude range of the IDR data was restricted to the one from 165E to 180E due to the large volume of original 20-Hz IDR data. For 1,409 crossover points of the ice tracking-mode in this area below 73.5S, the rms difference between IDR derived test model and the CATS02.01 model is 38.1cm. K_1 tide has the largest rms difference 24.7cm and O_1 has the second largest 19.0cm, both being the constituents with the annual aliased frequency. S_2 tide with the zero aliased frequency has the third largest 12.3cm difference. Thus a full tide solution over sea surfaces covered with ice using 35-day-repeat altimeter data is even worse than the one over ocean surfaces.

4 Conclusions

In the Ross Sea area, two global ocean tide models, GOT99.2b and NAO99, and a regional CATS02.01 model were compared with each other for 8 common short-period constituents. The M_2 , S_2 , K_1 , and O_1 tides are the least accurate constituents of these models in this area. Large model errors that go above 20cm are mostly located in the southwest part of Ross Sea, south of 70S and west of 190E. The CATS02.01 model shows the smallest differences from other models for most of constituents. At a single location, the Little America V gravimeter site, the NAO99 model has the closest agreement 13cm with the gravimeter ground truth for 6 tidal constituents. K_1 and O_1 constituents of the three models show the largest differences from the ground truth data.

The test tide models produced in this study were compared with the CATS02.01 model due to lack of ground truth data for the region. Our test tidal solutions for 8 short-period constituents that were individually determined at crossover points of the ERS-2 altimeter data on 35-day repeat tracks are not good even over ocean surfaces and in deep ocean areas. Each test solution is a full tidal analysis without removing from data the tidal signals implied by any reference tide model. S_2 and K_1 tides were the least accurately determined. By adding ERS-2 data to a full ocean tide solution using TOPEX data alone, we got negligible improvement. Residual solutions with optimal data weights seem to be needed for further investigations.

Use of retracked ERS-2 data over sea surfaces covered with ice in the test tidal analysis gave even poorer results. K_1 and O_1 constituents are the poorest ones for the test tidal solutions over sea

surfaces covered with ice agreeing with the validation results of the CATS02.01 model at a gravimeter site. On the 35-day repeat tracks of the ERS-1 satellite, these diurnal constituents have an aliased frequency of the annual cycle. To overcome this severe tidal aliasing problem, making use of the “closing up” of ERS ground tracks over the south Ross Sea and the overlapping of InSAR swaths needs to be attempted.

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