Accuracy assessment of ocean tide models around Antarctica

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Received 24 June 2005; revised 27 September 2005; accepted 29 September 2005; published 8 December 2005.

[1] Accurate ocean tide models for the circum-Antarctic seas are required to remove unwanted signals from floating ice elevation and space-borne, time-variable gravity measurements (e.g., GRACE). We present accuracy assessments for several global (CSR4, FES2004, FES99, GOT00.2, NAO.99b, TPXO6.2) and Antarctic (CADA00.10 and CATS02.01) ocean tide models using coastal and pelagic tide gauges, gravimetric data and GPS records of ice shelf surface elevation. The accuracies of CSR4 and NAO.99b are poor in the ice shelf regions. The optimum model for the entire circum-Antarctic seas is TPXO6.2, with a root-mean-square deviation of ~5–7 cm, ~40% lower than the next best model, FES2004. The main exception is the Filchner-Ronne Ice Shelf where CADA00.10 and CATS02.01 most accurately represent observations from two sites near the Rutford Ice Stream grounding line.
Citation: King, M. A., and L. Padman (2005), Accuracy assessment of ocean tide models around Antarctica, *Geophys. Res. Lett.*, *32*, L23608, doi:10.1029/2005GL023901.

1. Introduction

[2] Ocean tides around Antarctica have come under renewed focus due to a range of new, accurate satellite remote sensing missions (e.g., GRACE [*Tapley et al.*, 2004] and ICESat [*Zwally et al.*, 2002]), and the discovery of tidal modulation of ice stream and ice shelf flow in Global Positioning System (GPS) data [*Bindschadler et al.*, 2003]. Accurately removing the contribution of the tide is an essential step in utilizing such data for studies of seasonal cycles and longer-term ice mass balance trends. For example, to prevent aliasing of mismodeled tides above the GRACE error budget, sub-cm accuracy tidal prediction is required [e.g., *Ray et al.*, 2003]. Numerical ocean tide models are available for the global oceans, the circum-Antarctic oceans only, or individual regions therein. However, present model accuracy around Antarctica is estimated to be of order 10 cm in regions for which no high-quality nearby tide data are available [*Padman et al.*, 2002]. While tide model accuracy in the deep, non-polar oceans improved to 2–3 cm following the assimilation of TOPEX/Poseidon (T/P) radar altimeter data [*Andersen et al.*, 1995], this was not mirrored in the Antarctic oceans due to the ~66°S latitudinal cut-off of T/P (Figure 1). Further limitations to model accuracy in this region include: *i*) paucity of bathymetric data, especially under the ice shelves; *ii*) inaccurate definitions of coastline and ice-shelf grounding line locations; *iii*) scarcity of high-quality tidal data for assimilation into models; and *iv*) the need for theoretical developments with regard to ice-ocean frictional processes. As a result, predictions from the various models are divergent, especially near the large ice shelves [e.g., *Ray et al.*, 2001].

[3] Previous studies assessing the accuracy of various ocean tide models around Antarctica have focused on specific regions. *Shepherd and Peacock* [2003] tested several models with tide gauge records around the Antarctic Peninsula, while *Padman and Fricker* [2005] tested models for the Ross Ice Shelf. A more geographically diverse test of (relative) model accuracy was provided by *King et al.* [2005], who compared onshore GPS measurements of ocean tide loading (OTL) displacements with those based on various models. However, OTL is a response to ocean tides integrated over fairly coarse spatial scales, therefore the results do not assess model accuracy on smaller scales. In addition, onshore GPS data were not available at the southern extents of the large ice shelves, where ocean model accuracy is most uncertain. To address these shortcomings, we describe the use of geographically widespread measurements of ocean tide to quantify the accuracy of several global and regional models for predictions of Antarctic tides.

2. Data

2.1. Tide Gauge, Gravimetric, and GPS Data

[4] Coastal and pelagic tide gauge (TG) data south of 58°S were obtained from the Global Sea Level Observing System (GLOSS02), and from other, generally shorter records concentrated around the Antarctic Peninsula [*Cartwright*, 1979; *Potter et al.*, 1985; *Speroni et al.*, 2000; *Dragani et al.*, 2004]. Estimates for tidal harmonic coefficients were obtained using standard algorithms [*Foreman*, 1977]. The inverse barometer effect [e.g., *Ponte and Gaspar*, 1999] was not modeled since, for analyses of long TG records, it does not affect the constituent estimates. The TG sites are indicated in Figure 1, distinguishing between long, high-quality records, and shorter records.

[5] The TG sites do not cover the Antarctic coastline where ice shelves are present. Information about tides under ice shelves can, however, be derived from measurements of ice shelf surface elevation determined using gravimetric and GPS data. We assume that, at sufficient distance (a few km) from the grounding line, ice shelves are freely floating [e.g., *Shepherd and Peacock*, 2003] and hence these records are valuable measurements of the ocean tides. Tidal analyses for

0094-8276/05/2005GL023901

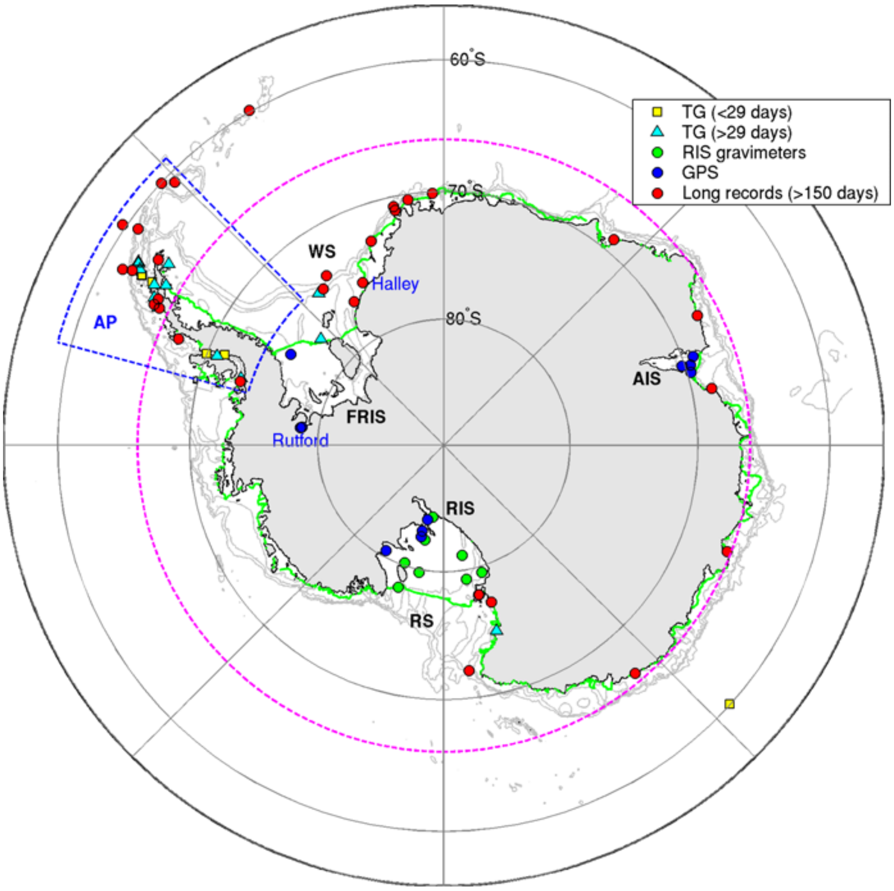

Figure 1. Locations of tide gauge (TG), GPS and gravimeter sites. Key: AIS, FRIS and RIS are the Amery, Filchner-Ronne and Ross ice shelves; RS and WS are the Ross and Weddell Seas; AP is the Antarctic Peninsula. The magenta circle at 66°S is the southern limit of T/P altimetry. The green line shows the approximate location of ice shelf fronts. Locations of GPS sites at Halley Base (on the Brunt Ice Shelf) and near the Rutford grounding line (on the FRIS) are indicated. Bathymetric contours are shown as a guide to the location of the continental shelf break.

ten gravimeter sites on the Ross Ice Shelf (RIS) were reported by *Williams and Robinson* [1980]. Biases exist in their reported constituents, however, since OTL corrections (up to 4–5 cm for K_1 and O_1) were not applied. We corrected for OTL by applying the SPOTL software [*Agnew*, 1997] to the TPXO6.1 ocean tide model, which has previously been identified as one of the better models for the Antarctic [*King et al.*, 2005]. These data were assimilated into two of the models described below (TPXO6.2 and CADA00.10), however both used the constituent values prior to OTL correction and so will be biased by this error.

[6] Fourteen GPS records have been obtained in the last ~5 years from the Amery (AIS), Ross, Filchner-Ronne (FRIS) and Brunt ice shelves. The GPS data have been processed in a consistent manner at each site. For the methodology, see *King and Aoki* [2003]. Locations for all ice shelf records are shown in Figure 1. To obtain tidal estimates compatible with the TG measurements and models (ocean surface relative to the seabed) we corrected for solid earth and pole tides [*McCarthy*, 1996] and OTL displacements as described above. Tidal constituents were then determined as for the TG measurements. Most GPS records were ~4–8 weeks in length, although the record from Halley Station on the Brunt Ice Shelf is ~2 y long. Due to systematic GPS errors related to the satellite orbits, K_1 amplitude may be biased by up to ~0.5 cm in these analyses [*King et al.*, 2005].

2.2. Ocean Tide Models

[7] Six global (TPXO6.2, FES99, FES2004, GOT00.2, CSR4, NAO.99b) and two Antarctic regional (CADA00.10 and CATS02.01) barotropic tide models were assessed. TPXO6.2 [*Egbert and Erofeeva*, 2002] is on a 0.25° × 0.25° grid, assimilates T/P data, and includes an inverse tidal solution for the Ross Sea where the gravimetry data were assimilated (for diurnals K_1 and O_1 only). The finite element model FES99 [*Lefevre et al.*, 2002] is interpolated for distribution on a 0.25° × 0.25° grid and assimilates T/P data and data from eight tide gauges around Antarctica. FES2004 is an update of FES99 on a 0.125 × 0.125° grid. GOT00.2 is an updated version of GOT99.2 [*Ray*, 1999] and assimilates T/P and ERS data (but not over the ice shelves). South of 66°S, GOT00.2 will resemble its prior model, FES94 [*Le Provost et al.*, 1998]. CSR4 is an updated version of CSR3 [*Eanes*, 1994] and assimilates only T/P data, as does NAO.99b [*Matsumoto et al.*, 2000]. GOT00.2, CSR4 and NAO.99b are each on a 0.5° × 0.5° grid. CADA00.10 and CATS02.01 [*Padman et al.*, 2002] are inverse and forward models driven by TPXO5.1 sea surface

Table 1. σ_{Comb} (in cm) for Different Subsets of the Data[a]

Model	High Quality (30)		All (69)		Non Ice Shelf (48)		Ice Shelf (21)		Ice Shelf[b] (11)	
	#	σ_{Comb}	#	σ_{Comb}	#	σ_{Comb}	#	σ_{Comb}	#	σ_{Comb}
CADA00.10	30	15.8	69	17.1	48	19.4	21	10.2	11	11.3
CATS02.01	30	14.8	69	16.9	48	19.0	21	10.3	11	11.2
CSR4	30	13.8	54	22.5	47	16.2	7	32.6	5	30.6
FES2004	30	8.2	69	11.8	48	11.6	21	12.2	11	14.3
FES99	30	11.9	69	17.3	48	19.6	21	10.8	11	11.5
GOT00.2	30	11.1	68	16.0	48	16.4	20	15.2	10	18.4
NAO.99b	30	14.3	57	22.5	48	16.5	9	32.2	7	28.5
TPXO6.2	30	4.9	69	6.5	48	6.7	21	6.1	11	6.4

[a]The number of non-zero points used in each comparison, #, is shown. Two measurements near the grounding line of the Rutford Ice Stream in the southwestern FRIS have been excluded in the computations of these values. Models are ordered alphabetically.
[b]excludes sites assimilated into TPXO6.2.

heights along the northern open boundary at 58°S, with a grid spacing of 0.25° × 0.083° corresponding to ~10 km near 70°S. CADA00.10 assimilates T/P, TG, GPS and gravimeter data from 37 Antarctic sites.

[8] We analyzed only the four major tidal constituents (M_2, S_2, O_1 and K_1) since these are a reliable indicator of total tide model accuracy [*Andersen et al.*, 1995]. Modeled values for these constituents were interpolated to the TG/GPS locations for our comparisons. Where a TG/GPS site was located on land for a specific model grid, we took the modeled values from the nearest ocean grid node, up to ~50 km away. This procedure allows for minor differences in coastline definition. If no nearby ocean point could be found, the amplitude was set to zero.

3. Comparison

[9] To compare each of the models with the tide gauge and GPS data we computed the root-mean-square (RMS) error σ_x for a given constituent x, and the RMS error for the combination of all four constituents (σ_{Comb}) as follows:

$$\sigma_x = \sqrt{\frac{1}{2N}\sum_{j=1}^{N}\left[Z_j^m - Z_j^o\right]^2}, \qquad (1)$$

and

$$\sigma_{Comb} = \sqrt{\frac{1}{2N}\sum_{k=1}^{4}\sum_{j=1}^{N}\left[Z_j^m - Z_j^o\right]^2}, \qquad (2)$$

where N is the total number of locations, and $Z = H[\cos(G) + i\sin(G)]$ is the complex expression of the interpolated modeled (m) and observed (o) tide amplitudes (H) and Greenwich phases (G) respectively for site 'j'. The value of σ_{Comb} for a more complete eight-constituent tidal solution (including Q_1, P_1, K_2 and N_2) is about 1.15 times greater than the four-constituent solution in (2) [*Padman and Fricker*, 2005].

[10] For 30 long (>0.5 yr) tidal records, values of σ_{Comb} (Table 1) and σ_x (Table S1[1]) demonstrate that TPXO6.2 is the most accurate model, with σ_{Comb} = 4.9 cm and σ_x in the range 1.9–3.0 cm. These values are 2–3 times greater than those found for the global deep oceans where T/P data are available [*Andersen et al.*, 1995], indicating the importance of nearby high-quality data as constraints for assimilation models. The next most accurate model is FES2004, with σ_{Comb} = 8.2 cm. Other models have σ_{Comb} > 11 cm.

[11] The high-quality sites are not, however, geographically evenly distributed (see Figure 1); hence, values of σ_{Comb} in Table 1 may not be reliable indicators of model accuracy for the entire circum-Antarctic seas. To address this bias we combined the long tidal records with the shorter ones, giving a total of 69 (48 non ice shelf and 21 ice shelf) sites. The RMS errors are presented in Table 1. For all 69 sites, TPXO6.2 is again the most accurate model with σ_{Comb} = 6.5 cm and σ_x in the range 3.0–3.8 cm (Table S2). FES2004 is the next most accurate model. σ_{Comb} is increased dramatically (~40–70%) for CSR4, FES99, GOT00.2 and NAO.99b. For the non ice shelf sites only, TPXO6.2 is the most accurate model with σ_{Comb} = 6.7 cm, and σ_x in the range 3.1–3.8 cm (Table S3). Again, FES2004 is the next best model, with σ_{Comb} being ~70% greater than for TPXO6.2.

[12] The ice shelf sites are concentrated on the RIS (14 sites) and the AIS (4 sites). TPXO6.2 is also the most accurate model for this category, with a slightly smaller σ_{Comb} than for the non-ice shelf sites (see also Table S4). The order of accuracy for the various models remains the same even when analyses are restricted to ice shelf sites that were not assimilated into TPXO6.2 (Table 1, final column; Table S5). Interestingly, CADA00.10 and CATS02.01 have much smaller RMS values in ice shelf regions than in other regions. For CADA00.10, this result reflects the geographic distribution of the 37 TG, GPS and gravimeter sites incorporated by assimilation. For CATS02.01, the improvement arises due to the use of the same data in selecting a parameterization of benthic friction to optimize model performance. It is evident that the large σ_{Comb} for NAO.99b and CSR4 for all sites is due to low accuracy in the ice shelf regions, especially the diurnal constituents.

[13] Omitted from the statistics in Table 1, however, are two sites near the grounding line of the Rutford Ice Stream in the southwestern corner of the FRIS (for location, see Figure 1). This is a region of extremely large tides, with $H^m(M_2)$ > 150 cm and a spring tidal range of ~7 m. When these sites are included in the category of ice shelf sites (Table S6), the σ_{Comb} values for CATS02.01 and CADA00.10 change only slightly, while σ_{Comb} increases to >40 cm for the other models. We stress that the data from these two sites are

[1]Auxiliary material is available at ftp://ftp.agu.org/apend/gl/2005GL023901.

reliable estimates of ocean tide, and hence these results suggest that a number of models poorly represent the estuary on the ocean side of the Rutford Ice Stream grounding line. However, we know of no other data elsewhere in this region to permit mapping of the spatial extent of model errors for the FRIS. Because of the distribution of ice shelf sites, values in Table 1 primarily reflect model accuracy for the RIS and AIS, and may significantly underestimate the true model error for much of the tidally energetic FRIS.

[14] Assessments of model accuracy for various regions are presented in Tables S7–S11. TPXO6.2 is the most accurate model for the Antarctic Peninsula, Ross Sea/RIS and AIS regions. CADA00.10 best represents the Weddell Sea/FRIS region based on all sites, while FES99 is the best model when the two sites near the Rutford GL are excluded.

4. Conclusions

[15] Based on comparisons with TG, GPS and gravimeter data, the most accurate ocean tide model for the circum-Antarctic seas is currently TPXO6.2, with a combined RMS error of ~6–7 cm and per-constituent errors of ~2–4 cm. Both CSR4 and NAO.99b are very inaccurate around the large ice shelves ($\sigma_{Comb} > 30$ cm) and should not be used for correcting altimeter or GRACE data, or for computations of OTL displacements in this region.

[16] While TPXO6.2 represents a significant improvement in model accuracy around Antarctica, it is still much less accurate than the ~2–3 cm combined error (~1 cm per-constituent) value reported for global comparisons with deep ocean pressure gauges under the T/P orbit [*Andersen et al.*, 1995]. The good accuracy of TPXO6.2 in Antarctic seas, relative to other models, is achieved by assimilating some of the data used in the validation, hence the quoted accuracy may be overly optimistic for regions well away from assimilated data. Importantly though, the ranking of models in the present study is in general agreement with the OTL-based study by *King et al.* [2005]. Further support for the present study's conclusions comes from comparisons of various models with ICESat crossover elevation difference data from the RIS [*Padman and Fricker*, 2005].

[17] The accuracy of Antarctic tide prediction is unlikely to approach that for the deep ocean until significantly more long-duration, high-quality tidal records are available for assimilation into inverse models. Because of limits in current and near-future altimetric missions, these records will be best made using *in situ* measurements. The need for such records is particularly great for the large ice shelves, where long-duration (order 1 y) GPS measurements offer the most promise. For the FRIS, almost no tide-resolving data records exist, while for the RIS, longer records with greater accuracy than the *Williams and Robinson* [1980] gravimeter data set are required.

[18] **Acknowledgments.** We thank the authors of the respective tide models for making them freely available, and those who have diligently collected and archived Antarctic tide gauge data. The raw GPS data were kindly made available by R. Coleman, K. Nicholls, H. Gudmundsson, H. Corr, R. Bindschadler and R. Onstott (via UNAVCO). W. Dragani and D. Goring provided additional coastal TG data. We thank A. Shepherd and an anonymous reviewer for their constructive comments on this manuscript. LP was funded by the NSF Office of Polar Programs, grants OPP-0125602 and OPP-0125252. This is ESR contribution number 32.

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