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Propagation and amplification of tide at the northeastern coast of the Antarctic Peninsula: an observational study

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Abstract: The amplification and propagation of the tide at the northeastern coast of the Antarctic Peninsula was studied by analysis of instantaneous sea levels measured at the tidal station of Base Esperanza, at the northern end of the Antarctic Peninsula (63°22.46′S, 56°59.33′W), at the northeastern coast of Marambio Island (Seymour Island, 64°14.11′S, 56°34.51′W) and near Base Matienzo, Larsen nunatak (64°54.23′S, 60°2.60′W) at the edge of the Larsen ice-shelf. By means of harmonic analysis the amplitudes and phases of the most energetic ten tidal constituents were obtained. The tidal regime was typified by means of the factor F and a preponderantly semidiurnal mixed tide was obtained. Significant southward amplification was observed in the amplitudes of semidiurnal constituents, and a less evident amplification was obtained in diurnal ones. Consequently, slightly southward diminution in factor F, from 0.75 (Esperanza) to 0.6 (Matienzo), was found. Both southward amplification in amplitudes and northward propagation of the main tidal constituents obtained from numerical global models show good agreement with the present observations.

key words: tide, measurements, tidal constituents, Antarctic Peninsula

1. Introduction

Tidal observations are not evenly distributed worldwide. Of all coastal regions in the World Ocean, the Antarctic Continent has particularly few sea level measurements, especially in the South Atlantic and South Indian Ocean sectors (Lutjeharms and Stavropoulos, 1985). Robertson *et al.* (1998) presented a description of thirty-one tidal gauge observations at the Weddell Sea, twenty-one observations were in open water and ten records were obtained under, or at the edge of, an ice shelf—tiltmeters and gravimeter were used to obtain tidal elevation under the ice shelves. In shallow water areas around Antarctica observations of sea level are very scarce and generally limited to the summer season because weather conditions are extremely severe during the rest of the year and coastal water often freezes. The study of the tidal dynamics in the Weddell Sea is not possible using only observations of sea level, but a preliminary view of the tidal propagation and amplification can be achieved using cotidal and corange charts obtained from tide global numerical models. Numerical models (Schwidersky, 1979, 1981a, b, c; Cartwright and Ray, 1990) and more recently satellite altimeter data (Kantha, 1995; Le Provost *et al.,* 1998) have been used to provide global features of the circulation and propagation of the main tidal constituents. In addition, the high-resolution semi-inverse global model presented by Egbert *et al.* (1994) gave a very realistic simulation of the tide at many locations around the Antarctic continent. The main differences between observations and global ocean models arise in shallow water regions where the inaccuracies in bottom depths can often have errors as high as 100% (Kantha, 1995). Even though such global tidal models give very good results for the deep ocean, they have not enough resolution to describe the dynamics in shelf areas close to the coast.

The aim of this work is to study the amplification and propagation of the tidal waves along the Northeastern Antarctic Peninsula, Northwestern Weddell Sea, by analysis of sea level data collected at Base Esperanza, Marambio Island and Base Matienzo. In Section 2, field studies and data processing are described. Computed harmonic amplitudes and phases and the atmospheric effect on sea level are presented in Section 3. Finally, a discussion of the main results is presented in Section 4.

2. Field studies and data processing

Sea levels at the north of the Antarctic Peninsula (Base Esperanza, 63°22.46′S, 56°59.33′W, Fig. 1) were measured from Jan/1/1971 to Jul/1/1972. Sea levels were gathered by a basic tide gauge with a float and counterweight inside a vertical tube (Unesco, 1985). The float had an electrical resistor (heater) to avoid that seawater inside of the tube was frozen. This tidal record is the longest one measured at the Northern Antarctic Peninsula (Legal *et al.,* 1995). The tidal analog record was digitized with one hour sampling interval and 13127 data were obtained. Afterward (in 1993), the National Oceanic and Atmospheric Administration, USA (NOAA) and the Navy Hydrographic Service of Argentina installed a Next Generation Water Level Measurement System (NGWLMS) in Esperanza Bay. Nevertheless, the data record gathered by this system presents several gaps (Vetere, personal communication, 2002).

During the Summer Antarctic Campaign (SAC) 1996–1997 tidal measurements were made at Larsen nunatak (Base Matienzo, 64°54.23′S , 60°2.60′W, Fig. 1) north of the Larsen ice-shelf. This nunatak is approximately 1.5 km long and 0.7 km wide (SHN, 1984). An Aanderaa model WLR-7 water level recorder (with pressure sensor) was installed on December 19, 1996 at 14 m depth, 4 m above the bottom and 40 m from the coast. This instrument was programmed with a sampling interval of 30 min. After 25 days (1202 observations) the coastal water was covered by many little ice floes and, therefore, the instrument had to be recovered. Pressure data from WLR-7 were converted to sea level using standard processing presented in Aanderaa (1990). Sea levels were also measured, from December 20 1996 to January 21, 1997, using visual tide staff and level, recording height from the instantaneous sea level to a fixed point placed

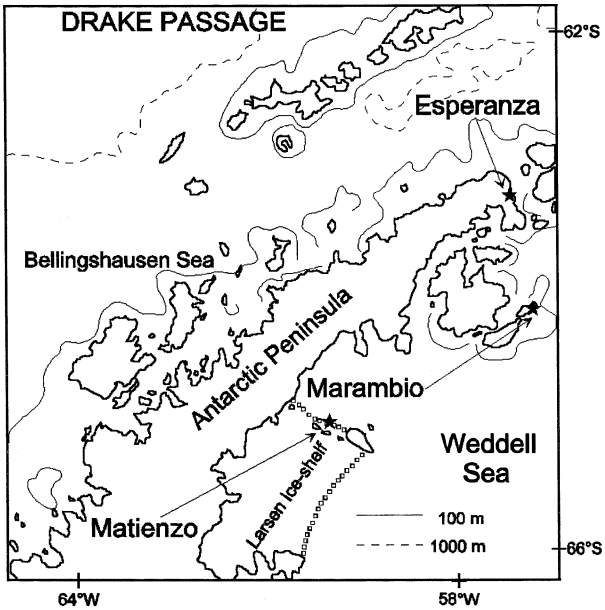

Fig. 1. Region of study. The stars show the locations where the measurements were made. Bottom topography (contours) was obtained from SHN (1997). Contours deeper than 100 m can not be completely drawn because depth data are very scarce on this side of the Weddell Sea.

near the coast. The measurements were 31 days long, with a sampling interval of 30 min (1489 data). Sea levels measured with pressure sensor and visual tide staff and level were successfully correlated and the determination coefficient obtained was 0.96 (Speroni *et al.,* 2000). Tidal measurements were made during the SAC 2000–2001 at Northeastern Marambio Island (Seymour Island, Base Marambio, 64°14.11′S, 56°34.51′W, Fig. 1) approximately 85 km south of Esperanza and 165 km northeast of Matienzo.

An Inter Ocean System model S4A current-meter and pressure sensor was moored 5 m above the bottom (where the depth was 10 m) and 600 m from the coast, on January 27, 2001. In only four days this instrument was twice dragged by ice floes and, therefore, the decision was made to recover the equipment and the data recorded were not analyzed. Simultaneously, from January 27, 2001 to February 28, 2001 sea level was also measured by using a visual tide staff and level. These unpublished measurements were 32 days long, with a sampling interval of 30 min (1536 data).

58-hour data of sea levels measured at Esperanza station are shown in Fig. 2. In this figure it can be observed that the tidal amplitude in Marambio is slightly larger that at Esperanza and that high and low water occur first in Marambio indicating northward propagation of the tidal wave. Sea levels measured in Marambio are shown in Fig. 3. In this figure there are some time intervals with one high and low water per day and others with two high and low waters per day, which shows a mixed tidal regime.

In this work, data were processed according to Foreman (1977) to obtain the tidal constants, associated errors were calculated using the computational methodology given

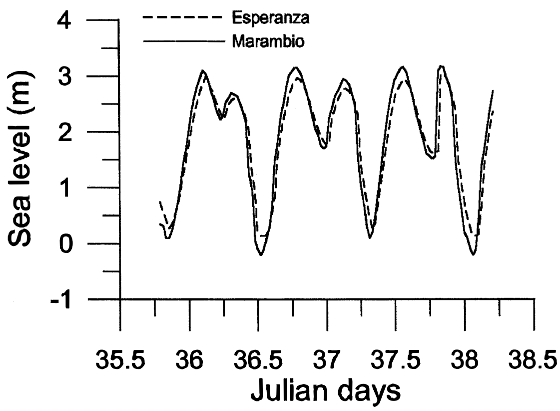

Fig. 2. Sea levels simultaneously measured at Esperanza and Marambio.

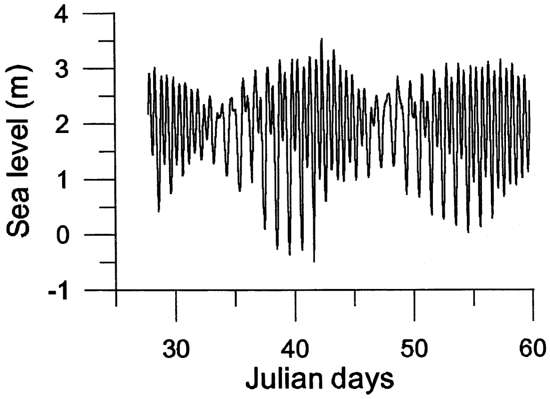

Fig. 3. Sea levels measured at Marambio using visual tide staff and level from January 27 to February 28, 2001.

by Pawlowicz *et al.* (2002). The length of the tidal records obtained in Marambio and Matienzo (about a month) did not allow confident estimation of the long period tidal constituents (Mm, Mf and Msf) which could be strongly affected by meteorological fluctuations. The main harmonic constants obtained from the three data series are shown in Table 1. In this table, amplitudes H and phases G of the principal diurnal (O_1, K_1, P_1 and Q_1), semidiurnal (M_2, S_2, K_2, N_2, and L_2) and quarter diurnal (M_4) constituents are presented, where G is the phase relative to Greenwich (Schureman, 1988).

3. Results

The results presented in Table 1 show that semidiurnal constituents M_2 and S_2 have the greater amplitudes and that the diurnal constituents K_1 and O_1 follow them. In order to typify the tidal regime in a quantitative way the Courtier coefficient (or form factor) F (Defant, 1961), which is defined by:

$$F = (H_{K1} + H_{O1}) / (H_{M2} + H_{S2}), \qquad (1)$$

was used.

Using the values presented in Table 1, F=0.75, 0.70 and 0.60 were obtained for Esperanza, Marambio and Matienzo, respectively, resulting in a predominately semidiurnal mixed tidal regime, which is coincident with the tidal classification given by NIMA (1997). The form factor calculated for Esperanza is greater than the calculated value for Matienzo because of the amplification in the semidiurnal constituents. The estimated errors obtained for amplitudes of the main harmonic constants do not exceed 3% of the amplitude in any case. The main harmonic constants obtained for Esperanza, Marambio and Matienzo are shown in Fig. 4. In this figure, an increase of the amplitudes is observed from Esperanza to Matienzo for the M_2 (0.198 m) and the S_2 (0.157 m) constituents. The K_1 constituent presents a slighter amplification (0.061 m) and the O_1 constituent remains almost constant (only 0.021 m between Marambio and Matienzo). Consequently, the observed decrease in F, from 0.75 in Esperanza to 0.6 in Matienzo, is due to the larger amplification of the semidiurnal constituents with respect to the diurnal ones.

Table 1. Harmonic constants (H: amplitude in m and G: Greenwich epoch in degree) and associated error calculated from measurements obtained at Esperanza, Marambio and Matienzo.

Harmonic	Esperanza				Marambio				Matienzo			
constants	H (m)	e_H (m)	G (°)	e_G (°)	H (m)	e_H (m)	G (°)	e_G (°)	H (m)	e_H (m)	G (°)	e_G (°)
O_1	0.403	0.003	34.9	0.5	0.422	0.008	25.9	1.0	0.401	0.005	8.4	0.7
K_1	0.364	0.004	53.1	0.6	0.405	0.008	46.1	1.0	0.425	0.005	32.4	0.6
P_1	0.118	0.004	49.8	1.7	0.131	0.010	42.8	2.1	0.137	0.004	29.1	1.6
Q_1	0.093	0.003	23.8	2.0	0.093	0.009	9.2	3.0	0.093	0.005	359.4	2.8
M_2	0.627	0.004	274.5	0.4	0.710	0.011	266.2	1.0	0.825	0.010	260.8	0.8
S_2	0.397	0.004	311.7	0.5	0.465	0.012	300.8	1.1	0.554	0.012	298.8	1.0
K_2	0.115	0.003	308.3	1.6	0.135	0.017	297.5	4.0	0.160	0.015	295.5	3.8
N_2	0.085	0.004	256.8	1.7	0.101	0.014	252.1	4.1	0.126	0.012	249.8	3.3
L_2	0.035	0.005	296.8	3.5	0.054	0.012	291.1	7.3	0.046	0.009	283.4	6.4
M_4	0.006	0.002	97.5	18.0	0.012	0.012	25.9	42.1	0.007	0.007	303.0	44.2

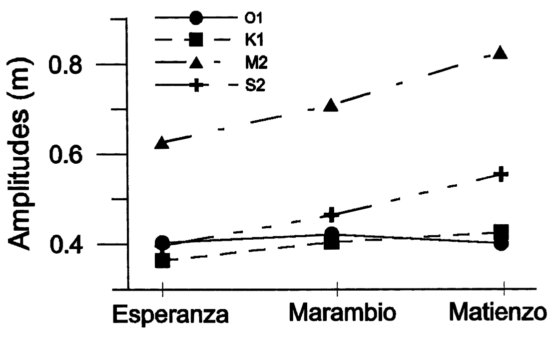

Fig. 4. Amplitudes of the tidal constituents obtained at Esperanza, Marambio and Matienzo.

The differences (residuals) between sea levels observed at Marambio and the predicted ones from the harmonic constants are shown in Fig. 5a. Residuals fluctuate around a mean value of -0.002 m and the differences (positive or negative) can reach up to 0.40 m.

Sea level observation and residual spectra estimated by using of the Fast Fourier Transform are presented in Fig. 5b. The energy corresponding to the residuals is almost two orders of magnitude less than the energy associated with the sea level observations in the diurnal frequency band and almost three orders of magnitude less than the energy in the semidiurnal frequency band. In the quarter diurnal frequency band the spectral energy corresponding to the sea levels is two orders of magnitude higher than the one associated with the residuals. Results show that the harmonic analysis has worked with very high performance. It can be concluded that the residuals are almost completely associated with non-tidal effects, containing approximately 1% of the astronomical tide. The residual spectrum corresponding to Matienzo showed similar spectral features as the spectrum of residuals corresponding to Marambio as discussed by Speroni *et al.* (2000).

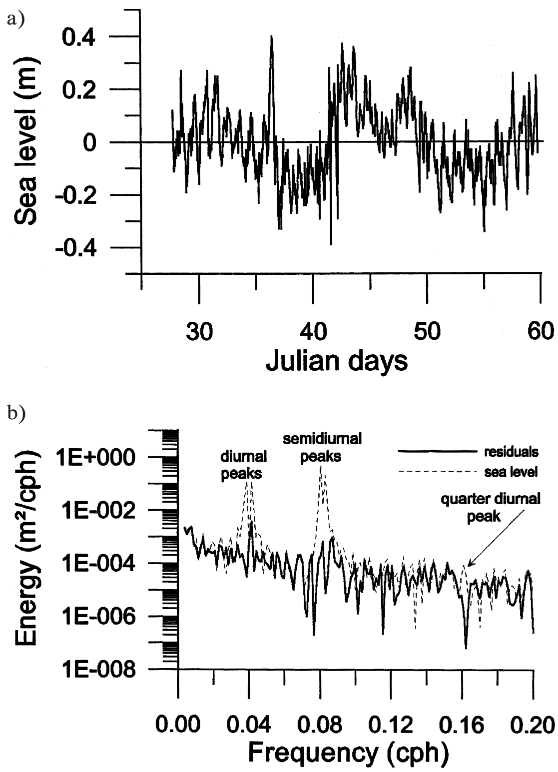

Fig. 5. *(a) Differences (residuals) between observed sea levels and predicted ones using harmonic constants obtained at Marambio and (b) the spectrum of residuals (solid line) presented in Fig. 5a and the spectrum of sea levels (dashed line) presented in Fig. 3.*

4. Discussion

Only a few papers concerning sea level observations at the northeastern coast of the Antarctic Peninsula have been published in the scientific literature. Consequently, the comparison between the results presented in this work and other results is rather difficult. Harmonic constants presented in this work can be used to check results given from tidal global models. Observing the isoamplitude and cotidal charts presented by Egbert *et al.* (1994), Kantha (1995), Le Provost *et al.* (1998) and Robertson *et al.* (1998), it can be noted that, in general, the tidal waves corresponding to the main constituents have amplitudes and phases consistent with those presented in this work.

The main differences between sea level observations and global ocean models arise in shallow water regions where the inaccuracies in bottom depths can often have errors as high as 100% (Kantha, 1995). Even though such global tidal models give very good results for the deep ocean, they have not enough resolution to describe in detail the dynamics in shelf areas close to the coast. Andersen *et al.* (1995) showed that some major differences between global models (Egbert *et al.,* 1994; Sanchez and Pavlis, 1995) occur in areas close to Antarctica, where no altimetry from the Topex/Poseidon satellite exists. In the Weddell Sea differences larger than 0.30 m were seen for the semidiurnal constituents. Robertson (1998) found that the largest discrepancies between the model results and measurements occur over the continental slope and under the ice shelves. The principal error sources are believed to be inaccurate bathymetry in his model, tidal analysis limitations associated with short data record lengths and omission of baroclinic tides. The tidal constants presented in this work, obtained from sea level measurements, improve knowledge of the propagation and amplification of tides along the northeastern coast of the Antarctic Peninsula. Even though numerical models are very powerful tools, additional field measurements along the southern ice-shelf of the Weddell Sea are necessary in order to achieve a more realistic description of the tidal dynamics in this coastal Antarctic region.

References

Aanderaa (1990): Operating Manual for Water Level Recorder model 7. Bergen, Technical Description **175**, 49 p.

Andersen, O.B., Woodworth, P.L. and R. Flather, A. (1995): Intercomparison of recent ocean tide models. J. Geophys. Res., **100**, 25261–25282.

Cartwright, D.E. and Ray, R.D. (1990): Oceanic tides from Geosat Altimetry. J. Geophys. Res., **96**, 16897–16912.

Defant, A. (1961): Physical Oceanography, Vol. II. Oxford, Pergamon Press, 598 p.

Egbert, G.D., Bennett, A.F. and Foreman, M.G.G. (1994): TOPEX/POSEIDON tides estimated using a global inverse model. J. Geophys. Res., **99**, 24821–24852.

Foreman, M.G.G. (1977): Manual for tidal heights analysis and prediction. Pac. Mar. Sci. Rep., **77–10**, 97 p.

Kantha, L.H. (1995): Barotropic tides in the global oceans from a nonlinear tidal model assimilating altimetric tides. 1. Model description and results. J. Geophys. Res., **100**, 25283–25308.

Legal, N., D'Onofrio, E.E. and Mazio, C.A. (1995): Dinámica de marea y corriente en el sector oeste de la Península Antártica. Servicio de Hidrografía Naval, Dpto. Oceanografía, Tech. Rep. **92/95**, 58 p.

Le Provost, C., Lyard, F., Molines, J.M., Genco, M.L. and Rabilloud, F. (1998): A hydrodynamic ocean tide model improved by assimilating a satellite altimeter-derived data set. J. Geophys. Res., **103**, 5513–5529.

Lutjeharms, J.R.E. and Stavropoulos, C.C. (1985): Tidal measurements along the Antarctic Coastline. Oceanology of the Antarctic Continental Shelf, Washington, D.C., Am. Geophys. Union, 273–289 (Antarct. Res. Ser., **43**).

NIMA (1997): Sailing Directions (Planning Guide and Enroute), Antarctica. National Imagery and Mapping Agency, 3rd. ed., Bethedsa, Maryland, 177 p.

Pawlowicz, R., Beardsley, B. and Lentz, S. (2002): Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE. Comp. Geosci., **28**, 929–937.

Robertson, R.A., Padman, A.L. and Egbert, G.D. (1998): Tides in the Weddell Sea. Ocean, Ice and Atmosphere: Interactions at the Antarctic Continental Margin, ed. by S.S. Jacobs and R.F. Weiss. Washington, D.C., Am. Geophys. Union, 341–369 (Antarct. Res. Ser., **75**).

Sanchez, B. and Pavlis, N.K. (1995): Estimation of the main tidal constituents from Topex/Poseidon altimetry using a Proudman function expansion. J. Geophys. Res., **100**, 25229–25248.

Schureman, P. (1988): Manual of harmonic analysis and prediction of tides. Washington, U.S. Government Printing Office, Special Publ. No. 98, 317 p.

Schwiderski, E.W. (1979): Global ocean tides, Part II: the semidiurnal principal lunar tide (M_2), atlas of tidal charts and maps. Dahlgen, Naval Surface Weapons Center, NSWC TR 79–414.

Schwiderski, E.W. (1981a): Global ocean tides, Part III: the semidiurnal principal solar tide (S_2), atlas of tidal charts and maps. Dahlgen, Naval Surface Weapons Center, NSWC TR 81–122.

Schwiderski, E.W. (1981b): Global ocean tides, Part IV: the diurnal luni-solar declination tide (K_1), atlas of tidal charts and maps. Dahlgen, Naval Surface Weapons Center, NSWC TR 81–142.

Schwiderski, E.W. (1981c): Global ocean tides, Part V: the diurnal principal lunar tide (O_1), atlas of tidal charts and maps. Dahlgen, Naval Surface Weapons Center, NSWC TR 79–144.

SHN (1984): Derrotero Argentino, Parte V, Antártida y Archipiélagos subantárticos Argentinos, 5th ed., Pub. H-205, Servicio de Hidrografía Naval, Armada Argentina, Buenos Aires, 479 p.

SHN (1997): Península Antártica, Nautical Chart, 2nd ed., Pub. H-7, Servicio de Hidrografía Naval, Armada Argentina, Buenos Aires.

Speroni, J.O., Dragani, W.C., D'Onofrio, E.E., Drabble, M.R. and Mazio, C.A. (2000): Estudio de la marea en el borde de la barrera Larsen, Mar de Weddell noroccidental. Geoacta, **25**, 1–11.

Unesco (1985): Manual on sea level measurement and interpretation. Intergovernmental Oceanographic Comision, 83 p.