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Anomalous ocean load tide signal observed in lake-level variations in Tierra del Fuego

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[1] We demonstrate the application of a 100 km long lake as a sensor for studying the tidal effects on Tierra del Fuego main island. The lake-level variations observed in Lago Fagnano reflect both the direct response to the tidal potential and the indirect effect of the ocean tidal loading. Modeling both contributions explains the observed tidal signal in the lake to about 70%. Underestimated model load tide amplitudes are found to be probably responsible for the remaining difference. We interpret this discrepancy as a hint for regional elastic lithosphere properties differing substantially from those represented by currently available global models. **Citation:** Richter, A., J. L. Hormaechea, R. Dietrich, R. Perdomo, M. Fritsche, D. Del Cogliano, G. Liebsch, and L. Mendoza (2009), Anomalous ocean load tide signal observed in lake-level variations in Tierra del Fuego, *Geophys. Res. Lett.*, *36*, L05305, doi:10.1029/2008GL036970.

1. Introduction

[2] The observation of the response of the solid earth to tidal forcing provides unique insights into the elastic properties of the lithosphere [*Melchior*, 1983]. To date, elastic modeling of surface loading effects such as the load tides usually assumes uniform rheological properties over forcing and response fields of global to continental scales [*Ivins and James*, 1999] although earth tide measurements have provided observational evidence for lateral heterogeneities in elastic properties of the lithosphere [*Melchior and De Becker*, 1983]. Nevertheless, the inadequate knowledge of both the orders of magnitude and the horizontal scales of these lateral variations do not allow, at present, to account for regional anomalies in the modeling of surface load effects. In particular, the impact of major tectonic-geological structures on the elasticity of the lithosphere is still poorly understood.

[3] Earth tide and load tide effects have been studied for half a century using a variety of observation techniques [*Melchior*, 1983] such as gravimetry, satellite positioning (applying global navigation satellite systems - GNSS) [*Urschl et al.*, 2005], strain meters, and tilt meters. In order to increase the base length and thus the sensitivity of the latter, water tube tilt meters were developed [*Kääriäinen and Ruotsalainen*, 1989]. In utilizing Lago Fagnano as a sensor by observing its tidal lake-level variations, we extend the base length by a factor of 10^3 and pass from local infinitesimal gradients obtained by conventional tilt meters to regional finite differences.

[4] Lago Fagnano, the largest lake of Tierra del Fuego, southernmost South America, features unique conditions for studying the response of a lake level to the ocean tidal loading. This 100 km long, narrow lake extends in E–W direction over the southern part of the archipelago's main island (Figure 1a), which is surrounded by the Atlantic, Pacific and Southern oceans. The Atlantic shelf off Tierra del Fuego is among a number of places on earth where the semi-diurnal ocean tides reach particularly large amplitudes [*Isla and Bujalesky*, 2000; *Pugh*, 1987] (Figure 1c).

2. Observation of Lake Tides

[5] Between February 2004 and February 2005, pressure tide gauge measurements were carried out simultaneously at three locations in Lago Fagnano (Figure 1b). At location B, additional data were recorded 2003/2004 and 2005/2006. Aanderaa WLR7 water-level recorders were operated on the lake bottom in 5 m water depth with a recording interval of 15 min. Based on the tide gauge readings continuous lake-level time series were derived. Local air pressure, temperature dependent water density and possible datum shifts due to instabilities of the instrument mooring were taken into account in the data processing [*Richter et al.*, 2005]. The accuracy of the lake-level determination is assessed as ±2.5 mm for an individual measurement. Finally, a harmonic tidal analysis of the lake-level records was carried out using the TASK-2000 software package [*Murray*, 1964]. As a result, the harmonic constants of the four main tidal constituents M2, S2, K1 and O1 were obtained for all three locations. The additional lake-level series recorded at site B were analyzed in the same way and were used to assess the accuracy of the obtained tidal harmonic constants (Table 1). For example, the 2003/2004 (recording interval 60 min) and 2005/2006 (10 min) records yielded amplitudes of 1.85 and 2.15 mm and phase angles of 339° and 336°, respectively, for the M2 constituent.

[6] In contrast to all other contributions to lake-level variations the tidal lake-level signal is of persistent periodic nature. Over an observation time as long as one year the tidal signal is clearly separated from the non-persistent variations by means of the harmonic analysis. Therefore, non-tidal lake-level phenomena (e.g. atmospherically driven variations, seiches, inflow and steric effects) have no significant effect on the determined tidal parameters and thus are not considered here.

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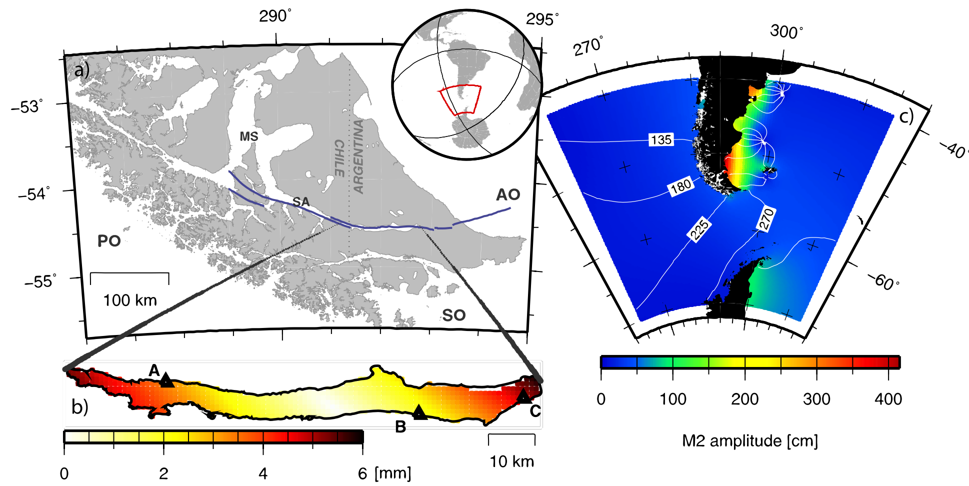

Figure 1. (a) Map of Tierra del Fuego. Blue line shows the Magallanes-Fagnano fault system according to *Lodolo et al.* [2003]; PO, Pacific Ocean; SO, Southern Ocean; AO, Atlantic Ocean; MS, Magellan Strait; and SA, Seno Almirantazgo. Inset indicates the load domain for the load tide modeling (red box). (b) Zoom view of Lago Fagnano depicts the tide gauge locations A, B, and C in the lake (triangles) and the M2 lake tide model amplitudes for each of the finite elements of the lake grid. (c) Load domain for the load tide modeling. Colors indicate the amplitude and isolines the phase lag relative to equilibrium high tide in the 0° meridian for the M2 wave according to the FES2004 ocean tide model.

[7] In the following we restrict ourselves to M2 because this wave provides the largest signal-to-noise ratio among the analyzed constituents and its frequency is clearly separated from those of other natural daily or sun-synchronous forcings. The determined M2 amplitudes and phase angles are given in Table 1. This constituent yields the largest amplitudes observed, reaching 4.7 mm at site C. All the findings presented for M2 are confirmed also by the results for S2 (35% of M2 amplitude) and K1 (45%). However, for the O1 harmonic (17%) the signal-to-noise ratio does not provide significant results.

3. Modeling the Lake Tides

[8] The lake-level changes recorded on the lake bottom of Lago Fagnano reflect the combined effect of variations of the water surface and vertical deformations of the solid earth surface. Two driving mechanisms are responsible for the lake-level signal with persistent tidal periods: first, the external tidal potential provokes a direct response of the solid earth, and second, the tides of the surrounding seas produce an indirect surface load effect comprising a potential and deformation component as well. In both cases, as a consequence of the mass conservation of the water contained in a lake, the relative differences of these contributions over its surface are effective rather than their absolute magnitudes. These lake tides of Lago Fagnano were modelled numerically for the four main constituents considering the surface deformations and gravity potential changes produced by both the direct and indirect effects. For this purpose, the water surface of Lago Fagnano was represented by a grid of 1 km × 1 km finite elements.

[9] The lake level's direct response to the tidal potential represents the effect of the equilibrium tide [*Pugh*, 1987] for an elastic earth reflecting the quasi-static adjustment of a water surface to an equipotential surface of the earth's gravity field that is affected by the tidal potential and the elastic deformation of the earth. In contrast to the oceans, Lago Fagnano can be expected to obey the equilibrium tide theory, because its fundamental seiches period of 2 h is far below the tidal periods and the lake is too narrow (mean width 6 km compared to Rossby radius 220 km) for a significant influence of the earth rotation on the tidal waves.

[10] Time series of the tidal potential were produced [*Wenzel*, 1996] and converted into the vertical displacement of the lake level relative to the earth surface [*Torge*, 2001] applying the Love numbers k and h [*Farrell*, 1972] for the Gutenberg-Bullen A earth model of degree $n = 2$ and accounting for the water mass conservation. A harmonic analysis of the obtained time series resulted in the harmonic constants of the direct tidal potential contribution to the four main constituents for each lake grid element.

[11] The load tide modeling, on the one hand, requires a load model which quantifies the mass displacement in space and time and, on the other hand, an earth model describing the elastic response of the solid earth to the surface load. Our load model was derived from the global ocean tide model FES2004 [*Letellier*, 2004]. Time series of the sea-level changes $\Delta H(Q, t)$ were extracted from this model for the sea-covered finite elements Q of a grid extending between 40° and 100°W and 40° and 70°S with a resolution of 0.5° × 0.25° (Figure 1c). The earth model was repre-

Table 1. Amplitudes a and Phase Lags ϕ of the Lake-Level Variations in Lago Fagnano on the M2 Tidal Frequency[a]

	A		B		C		
	obs.	mod.	obs.	mod.	obs.	mod.	σ
a (mm)	3.3	2.3	2.0	1.4	4.7	3.4	0.2
ϕ (deg)	158	168	333	346	340	347	3

[a]Phase lags ϕ are with respect to equilibrium high tide in the 0° meridian. Obs., obtained from harmonic analysis of lake-level records Feb. 2004–Feb. 2005 at the three locations A, B, C in the lake; mod., a numerical model. Standard deviations σ of the tidal parameters estimated from the three annual lake-level records observed at site B are included as accuracy measures.

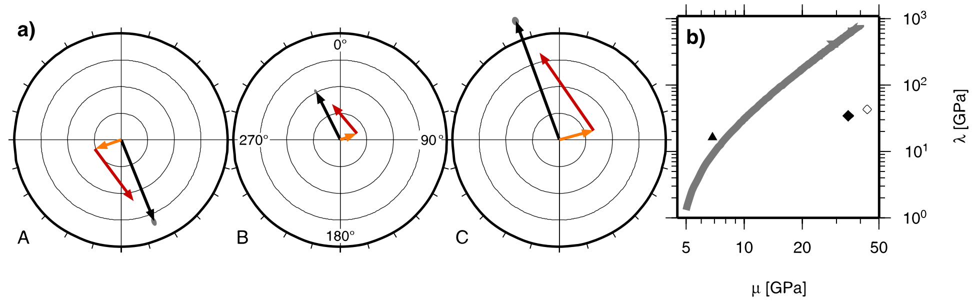

Figure 2. (a) Vector representation of observed and modelled tidal lake-level variations at the tide gauge locations A, B, and C in Lago Fagnano for the M2 harmonic. Vector length reflects the tidal amplitude (concentric isolines in 1 mm intervals), and vector direction depicts phase lag relative to equilibrium high tide in the 0° meridian. Black vectors, observed tidal signal; gray ellipses, observation confidence intervals; orange vectors, modelled direct lake-level response to tidal potential; and red vectors, modelled lake-level response to ocean tidal loading. (b) Lamé parameters μ and λ describing elastic material properties. The curve indicates hypothetic μ, λ pairs representing the effective elastic behavior of the lithosphere in the area under investigation if the observed tidal signal amplification would be explained by a scaling of the Green's functions only. Uppermost two layers (solid diamond, depth 0–19 km; open diamond, depth 19–38 km) of the Gutenberg-Bullen A Earth model [*Alterman et al.*, 1961] and dry, consolidated clay [*Helgerud et al.*, 1999] (triangle) values included for comparison.

sented by the Green's functions given by *Farrell* [1972] for the Gutenberg-Bullen A model corresponding to load Love numbers developed up to degree n = 10,000. For each lake grid element P and each time step the relative vertical displacement between the earth's crust and the equipotential surface $\Delta r(P, t)$ due to the ocean loading was obtained as an integral over the load model

$$\Delta r(P,t) = \int_Q \Delta H(Q,t) A_Q \rho \left(G_{grav}(\psi_{P,Q}) - G_{vert}(\psi_{P,Q}) \right)$$

with the surface area A_Q of the load model element Q, the density of sea water ρ, and the distance $\psi_{P,Q}$ between the lake element P and load element Q. G_{grav} and G_{vert} (positive in upward direction) are the Green's functions for the change of the equipotential surface and the vertical surface deformation, respectively. Mass conservation and harmonic constants determination for the lake were realized in analogy to the direct effect modeling.

[12] Finally, the theoretical lake tide parameters (Table 1) were obtained as the vector sum of the modelled direct response to the tidal potential and the effects of the ocean tidal loading. The spatial pattern of the modelled amplitudes of the combined M2 signal in Lago Fagnano is shown in Figure 1b. The maximum load tide signal is obtained for the NE end of the lake and amounts to 4.3 mm in amplitude. A comparison with the maximum direct tidal effect of 1.7 mm amplitude demonstrates that the lake tides in Lago Fagnano are clearly dominated by the ocean load tide effects.

4. Comparison and Discussion

[13] In Figure 2a, the M2 harmonic constants of the observed lake tides (black) as well as the modelled effects of the earth tide (orange) and the load tide (red) at the three tide gauge locations are represented as vectors. If the modelled lake tides explained the observed tidal signals completely, a perfect closure would be obtained between the model vector sums and the observed vectors. The diagrams in Figure 2a, though, indicate deviations that are highly significant considering the confidence intervals of the observed tidal constants (Table 1). The modelled vector sequence points exactly to the observed vector, that is, the modelled phase relations are in good agreement with the observed phase angles. This fact confirms the general correctness of our modeling approach involving the direct and indirect response components. Regarding the amplitudes we note, however, that the modelled load tide vectors are too small. They count for only 70% of a vector that would lead to an exact agreement with the observed signal. Thus, the remaining differences between model and observation can be attributed to the load tide contribution, more precisely, to the amplitudes of the modelled load tide signals.

[14] Two sources may be considered as possible causes for the detected inconsistency between the load tide model and the observations: deficiencies in either the applied load model or the earth model (or both). If we regard the load model alone to be responsible for the deficient load tide amplitudes, the underlying ocean tide model must predict the tidal amplitudes too small while reproducing the phases correctly. At regional scales, uncertainties in the predicted amplitudes and phases cannot be dismissed for global ocean tide models like FES2004 [*Shum et al.*, 1997]. Especially the extended Atlantic shelf off Tierra del Fuego and Patagonia, which produces roughly three quarters of the load tide effect in Lago Fagnano due to its proximity and the large tidal amplitudes, is characterized by complicated tidal hydrodynamics apparently not completely reflected by FES2004 [*Savcenko and Bosch*, 2006]. Moreover, the Magellan Strait, which is close to Lago Fagnano, is not included in the tidal predictions of FES2004. Therefore, our load model was complemented by tidal harmonic constants observed in the northern branch of the Magellan Strait [*Salinas et al.*, 2004]. Nevertheless, the southern branch including Seno Almirantazgo, which approaches Lago Fagnano very close (Figure 1a), lacks reliable information on the ocean tides. Predictions applying the ocean tide models GOT00.2 [*Ray*, 1999] and TPXO.7.0 [*Egbert and Erofeeva*,

2002] resulted in similar load tide effects within Lago Fagnano as for FES2004, hence the discrepancies cannot be assigned to just one particular ocean tide model. Considering the orders of magnitude, however, it seems hardly reasonable to attribute the unexplained fraction of the observed lake tides entirely to uncertainties of the ocean tide model: An adjustment of the modelled to the observed M2 signal would require, for example, either an amplification of the tidal amplitudes on the Atlantic shelf in the order of 30%, which would contradict the ranges stated by *Savcenko and Bosch* [2006], or tidal amplitudes in the Magellan Strait exceeding 5 m.

[15] A larger damping of the modelled load tide signal with respect to the observed amplitudes might also result from deviations of the applied earth model from the actual elastic features of the lithosphere in the region under investigation. A modification of the Green's functions would produce essentially a scaling of the effects, thus changing their amplitudes but not their phases. The underlying earth model is based on an adjustment of global data sets. Green's functions representing different yet global earth models yield effects differing by not more than 3% [*Francis*, 1992], which is confirmed by test computations applying the Green's functions tabulated by *Farrell* [1972] for continental and oceanic crusts, respectively. The lake tides in Lago Fagnano, however, reveal differences one order of magnitude larger over short distances. The presence of the tectonically active Magallanes-Fagnano fault system (Figure 1a), which represents the transform South America-Scotia tectonic plate boundary in Tierra del Fuego [*Lodolo et al.*, 2003], motivates us to consider substantial deviations of the regional lithospheric properties from those of global models. Recently, it has been demonstrated that it is crucial to account for the near-surface geological situation when modeling load effects [*Ivins et al.*, 2007]. There it is shown that applying an elastic lithosphere rigidity value appropriate for consolidated dry clay [*Helgerud et al.*, 1999] would amplify modelled Holocene load responses in coastal southern Louisiana by 25%. In fact, large parts of Tierra del Fuego are covered by sediments as a consequence of the repeated glaciations during the Late Pliocene and Pleistocene [*Rabassa et al.*, 2000]. Seismic profiling off the Atlantic coast of Tierra del Fuego [*Lodolo et al.*, 2003] has revealed sediment thicknesses of several kilometers. If we assume that the observed tidal signal amplification is caused entirely by regional rheological peculiarities, we may deduce tentative constraints for the effective material properties of the lithosphere in the area under investigation from the scaling of the elastic earth model parameters (Green's functions) necessary to yield load tide effects consistent with our observations. In our case of very short distances (100–200 km) between the load sources (essentially the Atlantic coastal waters off Tierra del Fuego) and the response domain (Lago Fagnano), the Green's functions are dominated by the high degree load Love numbers. *Farrell* [1972] gives numerical values as limits for the asymptotic development of the load Love numbers at the earth surface for increasing degree n resulting from a Boussinesq approximation (elastic, homogeneous, non-gravitating half-space) for an infinite wave number. In *Farrell's* [1972] equation 36 these load Love numbers are expressed as functions of Lamé's elastic material parameters λ ("Lamé's first parameter") and μ (shear modulus or elastic rigidity). Scaling Farrell's asymptotic load Love number limit h'_∞ by an amplification factor of 1.3 yields the curve in the μ-λ-space shown in Figure 2b. It depicts μ-λ pairs describing the elastic behavior of the regional lithosphere that would satisfy our observations under the assumption made above. It points towards material properties similar to those of clay yet somewhat closer to the Gutenberg-Bullen lithosphere.

5. Conclusions

[16] Lake tide signals derived from precise tide gauge observations in Lago Fagnano reveal a significant amplification of ocean tidal loading effects in Tierra del Fuego with respect to predictions based on conventional models. An amplification factor of about 130% as presented here has not been reported so far.

[17] At present, the most likely explanation for the discovered inconsistency appears to be peculiarities of the regional elastic lithospheric properties, at least in combination with regional deficiencies in the ocean tide model used as the load model. This would implicate far-reaching consequences for the elastic modeling of surface load effects also beyond the specific region of our investigation.

[18] Additional observations e.g. of the ocean tides in the surrounding seas or the separation of gravitational and deformation effects by combined gravimetric and GNSS observations could provide a means for a more detailed identification and localization of the origin of the detected deviations of the load tide model.

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