1. Introduction

Ocean tide loading (OTL) is the solid Earth’s response to the spatially and temporally varying bottom pressure and gravitational attraction of the ocean, which redistributes tidally, diurnally, and longer periods around the whole Earth. Around NW Europe, the M2 lunar semi-diurnal constituent (Figure 1) is the dominant ocean tide, causing radial OTL, which may be computed by convolution of the local ocean tidal height (ζ) with a Green’s function (G(r,r’)) that depends on the Earth’s rheological properties:

\[ u(r) = \int G(r, r') \zeta(r') \, dr' \]

where \( \zeta \) is the density of sea water and the locations \( r \) and \( r' \) span the ocean domain. We consider radial displacement, using Green’s functions initially derived from the spherically-symmetric Preliminary Reference Earth Model (PREM) (Dziewonski & Anderson, 1981). OTL displacements (OTLD) vary from a few mm to several cm in ampliﬁtude and are detectable using geodetic space geodesy (e.g. Allison et al., 2004; Thomas et al., 2007). Where ocean tides are poorly determined, geodetic measurements of OTLD may be used to validate numerical ocean tide models (e.g. King et al., 2005); conversely, if loads are well known, loading displacements may shed light on Earth rheology (e.g. Ito & Simons, 2011).

2. GPS observations

Here, we estimate OTLD for the 8 major sub-daily tidal constituents, from GPS data at 200 sites spanning at least 3 years (median 1484 days) in the interval 1998-2010, using the Precise Point Positioning mode of the GPSYS/OASIS software (v5.0), with JPL reprocessed orbits and clocks, 7° elevation cut-off, body tides modeled according to the IERS 2003 conventions, and the VMF1 mapping function. We test three strategies:

2. “Residual harmonic” – similar to (1), but a priori OTLD computed using FES2004 and removed at the observation level from major and minor constituents (using hardisp.f), so no nodal corrections required.
3. “Kinematic” – similar to (2), but random-walk positions estimated at 5 min intervals; amplitudes and phases later estimated via a Lomb-Scargle periodogram.

The methods yield OTLD estimates typically within 0.5 mm of each other, so we adopt (2) which is relatively insensitive to the a priori OTL (Figure 2a). Residual OTLD (Figure 2b) reach 3 mm.

3. Ocean tide, crustal, or body tidal causes?

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\[ u(r) = \int G(r, r’) \zeta(r’) \, dr’ \]

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5. New Green’s functions

We explore anomalous ocean tide rheology in two ways. (Figure 5a) Least-squares estimation of a piecewise linear (in log \( \varphi \)) empirical Green’s function tapering to PREM for \( \varphi < 0.05^\circ \) and \( \varphi > 10^\circ \), and comparison with forward models of Green’s functions computed with various reductions in shear modulus \( \mu \) in the PREM asthenosphere (80-220 km). (Figure 5b) Downhill simplex search for best-ﬁtting values of asthenospheric depth, thickness and scaling of \( \mu \). We ﬁnd that (a) a 20% drop in \( \mu \) in the PREM asthenosphere, or (b) a drop of around half this over twice the depth range, both ﬁt the data reasonably well.

4. Upper mantle anelasticity?

Instead, we note the similarity between the OTLD residuals (Figure 2b) and those locations where signiﬁcant OTLD occurs due to oceanic regions with an angular separation \( \varphi \) of 0.5°-2° between the vectors \( r \) and \( r’ \) (Figure 4). This range of \( \varphi \) suggests that poorly modelled rheology within the asthenospheric depth range 25-400 km is responsible for the residual OTLD. Importantly, the oceanic domain is the only well-constrained phenomenon sensitive to asthenospheric rheology at timescales intermediate between those of seismic waves (10^6 s) and post-seismic or glacio-isostatic adjustment (10^10 s); body tides are mostly sensitive to the mid/lower mantle. Regional upper mantle anelasticity may be modelled (Dahlen & Tromp, 1998). We perform a similar analysis using reverse modeling to compare with post-glacial uplift and present-day OTLD.

Acknowledgments

This work was funded in the UK by NERC grants NE/G013619/1 and NE/I001762/1. GPS data were obtained from the IERS-Derived Permanent GPS Network (IPGP), Geodesie National Service (France) and NORSAR GPS project (Norway). We thank NASA JPL for the GPSYS/OASIS software, and Tobias Aste for the crustal loads (used in GIPSY) and Allison (2004) used to compute contour maps of ocean tides.