1. Introduction

Continental water storage (CWS), including ground water, snow and ice, is a key climate variable which impacts many parts of Earth system science and engineering. Changes in CWS will affect Earth’s geocentre, gravity field and shape through surface mass loading. If other effects on these geodetic observables, including tidal and other sources of surface mass loading and perhaps technique-specific errors, can be eliminated, then it should be possible to obtain consistent multi-technique estimates of regional CWS. It is possible to discriminate surface mass loading in the frequency domain because it is the only phenomenon that changes the geodetic observables at decadal to seasonal periods (we are here limited by the time span of our data). CWS is the largest source of surface mass loading (Figure 1); atmospheric pressure can be modelled and removed comparatively easily, and loading due to changes in ocean dynamics is negligible. However, longer-term (seasonal) changes in CWS cannot so readily be discriminated from other geophysical phenomena which deform the Earth, notably plate tectonics and glacio-isostatic adjustment (GIA), which we address here.

2. Surface mass loading theory

A surface mass load \( J \) which depends on position \( \Omega \) may be described as an equivalent layer of sea water with thickness expressed as a spherical harmonic expansion of coefficients \( T_m^n \),

\[
T_m^n(\Omega) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} T_m^n(l_m) Y_l^m(\Omega),
\]

where \( Y_l^m(\Omega) \) are spherical harmonic functions. For a spherical elastic Earth this will lead to a change in gravitational potential \( \Phi(\Omega) \), with coefficients (Farrell, 1972):

\[
\Phi_\Omega = \Phi - \phi = \frac{k_m}{2} \sum_l \sum_{m=-l}^{l} T^n_m Y_l^m(\Omega) + \frac{\rho_g}{\rho_s} \Phi_L(\Omega),
\]

where \( g \) is the gravitational acceleration and \( \rho_g \) and \( \rho_s \) are the mean densities of the Earth and of sea water. Accompanying this there will be vertical displacements \( \delta H(\Omega) \) and lateral displacements \( \delta V(\Omega) \), with

\[
\delta H = \delta h - \rho_g \delta V; \quad \delta V = \frac{\rho_g}{\rho_s} \delta H.
\]

Love-Shell numbers \( h, k \), and \( l \) (Figure 2a) may be taken from a standard Earth model such as PREM (Dziewonski & Anderson, 1981). In practice, the observed variability of surface mass loads (Figure 1) makes it preferable to combine spherical harmonics in a set of modified basis functions that allow continental load variation whilst maintaining a mass-conserving, gravitationally-equilibrated ocean response (Figure 2b; Clarke et al., 2007), an approach analogous to “fingerprinting” (e.g. Tamisiea et al., 2001).

3. Tectonic plates and boundary zones

Earth’s surface is divided into around a dozen major plates separated by boundary zones which vary from near-zero to a few hundred kilometres in width (Figure 3). In plate tectonic theory, the seismically modelled sites within the stable plate interiors are purely lateral, and may be described by rigid-body rotation about the plate’s dipole pole. Provided the plates are large enough and are sufficiently densely populated, this allows ready separation of plate tectonic motion from that due to large-scale loading, because the latter incorporates lateral deformation and vertical motion. However, sites in the plate boundary zones and any others known to be experiencing local motions cannot contribute to the estimation of the plate and surface mass load models: Furthermore, sites in the plate interiors may suffer from glacio-isostatic adjustment (Box 4).

5. Estimation strategies

We will use IGS “repol” and ILRS weekly coordinate and geocentre data, and monthly gravity field data from GRACE and SLR. Two strategies are possible:

1. (1) A priori model: the GIA signal from the coordinate time series using an a priori model (or ensemble of models), then estimate a rigid plate model and use the residuals from this to determine the surface load (e.g. van der Wal et al., 2009). The GIA-detrended gravity can be used either with the coordinate residuals or independently.

2. (2) Simultaneous. Wahl et al. (2000) show a relationship between surface uplift and geoid height change \( \Delta\Phi(\Omega) \) due to GIA, which in our case can be used to eliminate or isolate GIA because we have both observables. "Simultaneous, model-independent" estimation of plate tectonics, GIA and CWS is therefore possible at low spherical harmonic degrees.

References


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