Abstract
The launch of the Gravity Recovery and Climate Experiment (GRACE) space gravity mission opened new horizons to the scientific community for environmental monitoring. Through the provision of estimates of temporal changes in the Earth’s gravity field, the products generated from the GRACE mission have enabled studies of mass balance changes in polar regions, deformation caused by very large earthquakes, glacial isostatic adjustment and quantification of water exchanges through various hydrological processes. International analysis centres provide estimates of the Earth’s temporally varying gravity field in the form of spherical harmonic coefficients which are then used to quantify the geophysical processes that have caused the changes in the Earth’s gravity field. We have designed an online, publicly available web application that performs the computations to convert the spherical harmonic representations (of the French Groupe de Recherche en Géodesie Spatiale) of the gravity field into estimates of crustal deformation and/or water loads, and provides users with the ability to visualise the estimates. Derived products are also available to download as numerical values for further analysis. This paper describes the scientific basis and technical approaches used by the web portal (grace.anu.edu.au/evasph.php).

Keywords: space gravity, data visualisation, GRACE, hydrology, glacial isostatic adjustment, Earth deformation

1. Introduction
The Gravity Recovery and Climate Experiment (GRACE) mission is a space gravity mission designed to measure changes in the Earth’s gravity field from which mass movement on Earth can then be monitored (e.g., Tapley et al., 2004). Redistributions of mass in the Earth’s atmosphere, oceans and continental water stores (surface water, soil moisture, groundwater) cause changes in the strength of the Earth’s gravity field, both spatially and temporally. Through the detection of such changes, it is possible to quantify the variations in mass and hence constrain models of the geophysical processes that are occurring on and within the Earth. Observations from GRACE have been used to study the mass loss of Greenland and Antarctica (e.g., Velicogna and Wahr, 2006; Luthcke et al., 2006), large-scale continental hydrology (e.g., Rodell et al., 2011), floods (e.g., Leblanc et al., 2009) and even the elastic and visco-elastic deformation of the Earth (e.g., Davis et al., 2004; Tregoning et al., 2009a,b; van der Wal et al., 2008).

The GRACE mission and observations are described in detail elsewhere (e.g. Case et al., 2002; Thomas, 1998; Bettadpur, 2007). In brief, the rate of change of distance between the two
satellites orbiting the Earth is affected by changes in the strength of the Earth’s gravity field. These range changes are measured precisely using a K/Ka-band microwave system, along with the position of the spacecraft using GPS, non-gravitational accelerations (caused by atmospheric drag, solar radiation pressure and thrust events) and the orientation of the spacecraft using star tracking cameras. Converting these observations into estimates of the Earth’s gravity field is an involved process that requires estimating the orbits of the satellites along with the gravity field of the Earth.

Since 2004, several international research groups have made publicly available their estimates of the Earth’s gravity field as derived from GRACE observations, most notably the Center for Space Research at the University of Texas at Austin (CSR), the GeoForschungsZentrum (GFZ) and the Jet Propulsion Laboratory (JPL). Monthly gravity fields are provided in the form of sets of spherical harmonic coefficients, which may be multiplied by Legendre polynomials (trigonometric functions) and various constants (listed in Table 1) to recover the strength of the gravity field at a given location. Spherical harmonic field provided by these centres already have the gravitational changes caused by atmospheric mass, tidal and non-tidal ocean movement taken into account. Because of unmodelled systematic errors in the analysis of the GRACE observations, certain steps need to be undertaken to mitigate correlations between some estimated spherical harmonic coefficients (the so-called ‘de-striping’ filter (e.g., Swenson and Wahr, 2006) to remove north-south striped patterns in the GRACE gravity fields) and to reduce the contribution of noise in higher degree coefficients (through spatial filters (e.g., Wahr et al., 1998)). However, many users are interested in only the end product and how it describes the mass changes on Earth and do not have the expertise to start from the original range rate observations or the available spherical harmonic models.

There are interactive online tools that provide this type of functionality for GRACE solutions that require destriping and/or spatial filtering. For example, the ‘University of Colorado Real-Time GRACE Data Analysis Site’ (http://geoid.colorado.edu/grace) where time series and spatial plots of equivalent water height can be generated (CSR, GFZ or JPL solutions), and ‘The PO.DAAC Ocean ESIP Tool’ (http://gracetellus.jpl.nasa.gov/poet) where equivalent water height spatial maps can be generated. Both of these sites are limited to outputting the computations as mass changes in terms of equivalent water height.

In this paper we describe a new website (grace.anu.edu.au/evasph.php) that allows users to generate estimates of geophysical parameters from GRACE spherical harmonic fields, for user-selected locations and/or regions of the Earth. The GRACE fields can be computed to generated estimates of change in geoid height, changes in load in terms of equivalent water height or in terms of elastic or viscoelastic deformation of the surface of the Earth. Time series can be generated at single points or for user-defined regions. We describe briefly the mathematical theory that is used to perform the computations (and associated uncertainties of the estimates) as well as tools that are used to interface between the user, website and background software that actually performs the computations. We provide examples of some of the capabilities of the website and actual computations.

2. The Data Visualisation Tool (DVT)

The Data Visualisation Tool (DVT) is a web based application that provides access to the data products via an easy-to-use web interface. The interface is built using PHP, a server side scripting language designed for producing dynamic web pages. Google Maps API is used to provide a
map interface that allows users to specify a geographical location or region by double-clicking on the map. Interaction between users and the interface as well as communication between interface and the backend server are handled by a client-side script written in JavaScript. jQuery, a general purpose Javascript library, is used throughout to simplify some of the coding tasks. A PHP script running on the server parses the input parameters, feeding them to Fortran programs for computation. Results from the Fortran programs are then passed to either the Generic Mapping Tools (Wessel and Smith, 1998) to produce spatial plots or returned back to the client script to produce time series plots using the JavaScript Visualisation library, dygraphs. Data files generated are also made available through URL links for users to download the computed numerical values.

The web interface is made up of two components: the google map interface on the left for inputting geographical locations/regions, and a configuration panel on the right for other information needed for computation. A screenshot of this interface is shown in Figure 1.

The DVT is able to generate three types of solutions:

1. Spatial plots of the gravity field changes for any user-defined rectangle regions on the Earth. It can also generate movies by computing a requested set of images for a region and then forming an animated gif. The grid size for computation is specified by the user (default is $2^\circ$).
2. Time series of equivalent water height, visco-elastic deformation, geoid height or elastic deformation for any user-selected single location on the Earth.
3. Time series of integrated water change for regions on the Earth.

In all cases, users can input information by clicking on the map. The locations can be changed by either dragging the marker across the map or by typing values into data entry boxes provided (see Figure 1). In the third case, users can either select pre-defined surface drainage basins on the Australian continent, upload a file containing coordinates of vertices of a polygon or can describe a polygon by double-clicking multiple points on the Google map.

In all cases, users must then select the way in which the gravity changes are to be interpreted. Options are:

- as a change in geoid height (approximately equivalent to mean sea level)
- as an amount of water, expressed as an equivalent water height (EWH)
- as a surface deformation caused by a visco-elastic process within the Earth, known as glacial isostatic adjustment (e.g., Farrell and Clark, 1976)
- as a surface deformation caused by the elastic deformation of the Earth as a result of changes in surface loads (such as surface water and/or soil moisture)

3. Mathematical theory

We use the GRACE spherical harmonic fields of the French Groupe de Recherche en Géodesie Spatiale (GRGS) (Bruinsma et al., 2010), which provide 10-day, abutting estimates of the gravity field. The spherical harmonic models are provided to degree and order 50 and, because of the way in which the GRGS solutions are generated, do not require any of the filtering or decorrelation steps (i.e. de-striping and spatial smoothing) to be applied before being used (Bruinsma et al., 2010). A spherical harmonic gravity field up to degree and order $n$ corresponds to a global
spatial resolution of 180/n degree in latitude and longitude; therefore, GRGS models provide a spatial resolution of 3.6 degree or ∼400 km. We first removed from all fields the mean value of each coefficient; therefore, all computations are of anomalies relative to a mean value over the entire time span.

The spherical harmonic coefficients can be evaluated as (Wahr et al., 1998):

\[
\Delta N(\theta, \lambda, t) = \sum_{l=2}^{\text{Max}} \sum_{m=0}^{l} F_n \times P_{lm}(\cos \theta) \left[ \Delta C_{lm}(t) \cos m\lambda + \Delta S_{lm}(t) \sin m\lambda \right]
\]

where \(\theta, \lambda\) are the co-latitude and longitude of the point at which the evaluation is computed at time \(t\), \(l, m\) are the degree and order of the spherical harmonic model, \(F_n\) are normalised associated Legendre functions at colatitude \(\theta\) and \(\Delta C_{lm}(t)\) and \(\Delta S_{lm}(t)\) are the spherical harmonic coefficient anomalies from the GRGS GRACE gravity fields at time \(t\). The value of the function \(F_n\) depends on the type of geophysical process that the user chooses to assume has caused the change in gravity. \(F_n\) has the values as described in Table 1 for the 4 options listed in Section 2.

Vertical deformation is computed for visco-elastic and elastic cases. We also compute horizontal deformation for the elastic case (Table 2) and resolve the deformation vector into a north and east component (Farrell, 1972), while the empirical expression of Purcell et al. (2011) to derive visco-elastic deformation applies only to the vertical component. We are not aware of any comparable expression for deriving horizontal, visco-elastic deformation computations.

Table 1 near here

The GRGS GRACE fields include estimates of the formal uncertainties of the spherical harmonic coefficients. We use these to derive uncertainties of our computed values by propagating the variances:

\[
\sigma_N^2(t) = \left( \frac{\partial N}{\partial \Delta C(t)} \right)^2 \sigma_{\Delta C(t)}^2 + \left( \frac{\partial N}{\partial \Delta S(t)} \right)^2 \sigma_{\Delta S(t)}^2
\]

It is also possible to generate a time series plot of integrated water change for any user-defined region, as well as pre-defined regions for Australia’s 12 major drainage division regions. The mathematical equation to compute the integrated water change is (e.g. Wahr et al., 1998; Ramil-lien et al., 2006):

\[
\Delta EWH(\theta, \lambda, t) = 4\pi R^2 \sum_{l=2}^{\text{Max}} \sum_{m=0}^{l} R \rho_e \frac{2l+1}{3 \rho_w} \left[ A_{lm} \Delta C_{lm}(t) \cos m\lambda + B_{lm} \Delta S_{lm}(t) \sin m\lambda \right]
\]

where \(R\) is the radius of the Earth, \(\rho_e, \rho_w\) are the densities of the Earth and water, respectively, \(k_i\) are elastic load Love numbers of degree \(l\), \(A_{lm}, B_{lm}\) are the spherical harmonic coefficients that represent the geographical region. The uncertainties of the estimates at each epoch are again computed according to Equation 2.

4. Web Application Examples

As described above, the GRACE spherical harmonic fields can be interpreted as a change in geoid height, an equivalent water thickness, visco-elastic or elastic deformation. Each of the output types below can be computed in any of these four change types.
4.1. Spatial Map

Users can generate an anomaly map for any rectangular region by double clicking on the map to specify one corner of the rectangle and then again to specify the opposite corner. A rectangle will then be automatically drawn on the map to indicate the selected region (Figure 2). The selection can then be modified by dragging the two corner markers on the map. The particular epoch for which the anomaly map is required needs to be specified, along with the maximum degree of spherical harmonic coefficients to be computed and the output grid spacing.

Upon clicking the ‘generate visualisation’ button, the requested parameters are parsed to the background Fortran program that then performs the required computations using Equations 1 and 2 (with the appropriate values of $F_n$ from Table 1). The resulting values are then plotted and displayed (Figure 2).

Fig. 2 near here

4.2. Time series plot

A time series plot can be produced for any point on the Earth (Figure 3), configured in a similar way to that for a spatial map. Double clicking on the map specifies a location, which can be changed by dragging the marker to a different location. The requested time span for the time series is specified in the right panel as well as a maximum degree for computation and the type of output required. Figure 3 shows a time series of EWH generated for a location in northern Queensland from 2002 to 2011. The annual cycle of EWH in that area is clearly visible. Grey shadows illustrate the uncertainties computed for each epoch.

Fig. 3 near here

Figure 4 shows a time series of EWH generated for a location in Greenland from 2002 to 2011. It again clearly shows the annual cycle of EWH as well as a downward trend of EWH, indicating a loss of mass at this location. Note that no correction has been made for the present day glacial isostatic adjustment that is occurring in the region - we do not correct the GRGS spherical harmonic fields for GIA and users must apply a correction a posteriori. There is still considerable debate in the scientific community about the accuracy of GIA models (e.g. Chambers et al., 2010). We will make GIA-corrected spherical harmonic solutions available in the future when the GIA models become more accurate.

Fig. 4 near here

4.3. Basin-scale integrated water change

Figure 5 shows a list of precomputed drainage regions for Australia and the time series of integrated water change for the Murray-Darling Basin. The geographical outline of the region is shown on the map in Figure 5.

Users can also upload the coordinates of the vertices of a polygon or define polygon vertices by double-clicking multiple times on the Google map. In the latter case, the coordinates of the points selected are displayed and can be edited manually. Once the coordinates are entered, clicking the “compute” button invokes the following procedures:

1. the surface area of the polygon is computed (in km$^2$)
2. a spherical harmonic model is generated to represent the polygon region (i.e. coefficients $A, B$ in Equation 3) using the SHTOOLS software (shtools.ipgp.fr).
3. a time series of integrated total water change is generated using Equation 3
4. a plot of the time series is displayed on the web site in terms of water volume and an equivalent water height over the region of the polygon

URL links are provided to permit users to download the time series image, the numerical values and the spherical harmonic coefficients that represent the polygon region. Subsequent computations can be made by either uploading new polygon vertices coordinates or by refreshing the Google map and then clicking a new polygon shape.

Fig. 5 near here

5. Conclusion

The Data Visualisation Tool provides a means of converting temporal gravity field anomalies into geophysical signals of water anomalies and crustal deformation signals. The web site (grace.anu.edu.au/evasph.php) interacts with a suite of data files and Fortran programs to generate numerical results and plotted figures for users. The interactive nature of the portal permits computations on user-specified locations and/or regions, enabling flexibility to generate results from GRACE temporal gravity fields for any particular study region. The website provides a user friendly medium to study hydrology in drainage basins, seasonal and annual changes in mean sea level and deformation of the Earth’s surface around the world.

acknowledgement

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References

Table 1: Values of $F_n$ used when evaluating Equation 1 for different geophysical interpretations of the causes of gravity changes. $R$ is the mean radius of the Earth (6371 km), $\rho_e$ is the average density of the Earth (5515 kg/m$^3$), $\rho_w$ is the density of water (1000 kg/m$^3$), $h_l, k_l$ are elastic Love load numbers (Pagiatakis, 1990).

<table>
<thead>
<tr>
<th>Geophysical Process</th>
<th>$F_n$</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geoid height</td>
<td>$R$</td>
<td>Wahr et al. (1998)</td>
</tr>
<tr>
<td>Equivalent water height</td>
<td>$\frac{R\rho_e}{3\rho_w} \frac{2l + 1}{1 + k_l}$</td>
<td>Wahr et al. (1998)</td>
</tr>
<tr>
<td>Visco-elastic vertical deformation</td>
<td>$1.1677l - 0.5233$</td>
<td>Purcell et al. (2011)</td>
</tr>
<tr>
<td>Elastic vertical deformation</td>
<td>$R \frac{h_l}{1 + k_l}$</td>
<td>Davis et al. (2004)</td>
</tr>
<tr>
<td>Elastic horizontal deformation</td>
<td>$R \frac{l_f}{1 + k_l}$</td>
<td>Farrell (1972)</td>
</tr>
</tbody>
</table>
GRACE data visualisation tool

This is a visualisation tool for GRACE data. Visualisation of the French GRGS spherical harmonic representations are generated dynamically for the region/location and time period specified in the configuration.

Usage

Select the type of visualisation you wish to generate ('Map', 'Point', 'Movie' or 'Basin') then specify an area or a location from the map. Configure the time period/range and the other options and click 'Generate visualisation'.

![Map plot configuration]

Mouse position: (-0.8521, 127.9203)
Reset map

Figure 1: Map plot configuration
Figure 2: Map plot result
Figure 3: Time series of EWH for northern Queensland
Figure 4: Time series of EWH for Greenland
Figure 5: Integrated water change for Murray-Darling basin