Computers & Geosciences 93 (2016) 12–20

Contents lists available at ScienceDirect

Computers & Geosciences

journal homepage: www.elsevier.com/locate/cageo

Research paper

Modelling of global mass effects in hydrology, atmosphere and oceans on surface gravity

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ARTICLE INFO

Article history:
Received 10 July 2015
Received in revised form
11 March 2016
Accepted 28 April 2016
Available online 3 May 2016

Keywords:
Gravity effect
Continental water storage
Non-tidal ocean loading
Atmosphere

ABSTRACT

We present a Matlab™/Octave-based software tool mGlobe to compute the effect of atmospheric, continental water storage, and non-tidal ocean mass variations on surface gravity. These effects must be considered or reduced prior to any analysis of geophysical phenomena using observations of superconducting gravimeters. Contrary to the alternative providers, mGlobe allows the computation for an arbitrary location worldwide, supports a larger number of input models and offers more flexibility in terms of computation settings. The high number of supported models is important for assessment of model uncertainties. Discrepancies exceeding 75% were found. The continental water storage effect showed low sensitivity to spatial and temporal resolution. The deficient temporal resolution affects the non-tidal loading and atmospheric effects significantly. The same holds true for the influence of the spatial resolution on atmospheric effects. To compensate this effect, we introduce a site-specific correction factor based on differences between the real topography and model's orography.

1. Introduction

Observations of absolute and superconducting gravimeters contain information on the gravity effect of a wide range of phenomena like Earth and ocean tides, Earth rotation, transport of hydrological and atmospheric masses or the Earth's internal geodynamic processes. Geophysical studies of a specific phenomenon therefore need to comprise the consideration of all sources of gravity variations, provided that the magnitude of these variations is in the order of magnitude of the gravity signal of interest. The need for reducing disturbing gravity effects even grows with the ongoing accuracy increase of absolute and superconducting gravimeters. The gravity effect of global-scale water mass transport is a prominent example of a reduction that has emerged in past decades (van Dam and Wahr, 1998; van Dam, 2001) and needs to be considered in order to resolve small gravity changes of up to few tens of nm s^{-2}. More recent studies (e.g. Boy and Hinderer, 2006; Wziontek et al., 2009) discussed the computation of the continental water storage effect considering different global hydrological models at various sites, concluding that the corresponding gravity effect contributes significantly to the seasonal variation of surface gravity. Depending on the location, the global hydrological effect may exceed or at least interfere with the contribution of the local hydrology (Longuevergne et al., 2009), i.e., water storage variations within few kilometres from the actual point of observation. Numerous studies discussed the complex assessment of the local hydrology contribution to gravity variations (e.g. Creutzfeldt et al., 2010; Hasan et al., 2006; Hinderer et al., 2012; Virtanen et al., 2006). The continental water storage effect plays a key role in such studies because using a different global hydrological model or the neglecting the global effect may affect the conclusions in terms of the magnitude and phase of local water storage variations. Similarly, this applies for the purposes of validation or calibration of local hydrological models using gravity residuals (e.g. Creutzfeldt et al., 2012; Naujoks et al., 2010).

To meet the increasing demand for assessing the continental water storage gravity effect, the GGP/Strasbourg Loading Service[1] (Boy et al., 2009) provides the corresponding time series for a selected group of superconducting gravimeters using four global hydrological models. In addition, estimations of the non-tidal ocean loading and atmospheric effect are provided. The non-tidal ocean loading is the effect of the ocean mass transport uncorrelated to the

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[1] http://loading.u-strasbg.fr/GGP

http://dx.doi.org/10.1016/j.cageo.2016.04.014
0098-3004/

tidal processes. The tide related mass transport is reduced within the tidal analysis of observed gravity variations or by means of ocean tide models[2] (e.g. Egbert and Erofeeva, 2002; Lyard et al., 2006; Matsumoto et al., 2000). Similar to the continental water storage effect, previous studies (e.g. Boy and Lyard, 2008; Kroner et al., 2009) showed that the non-tidal ocean loading effect must be considered also at sites hundreds of kilometres away from the coast and that the discrepancies between different ocean models can exceed the amplitude of respective variations.

Besides Earth tides, the atmospheric effects are the most important source of gravity variations. Generally, two different approaches are used for the computation of the atmospheric effect. The empirical approach seeks the relation between the observed air pressure variation and gravity (e.g. Warburton and Goodkind, 1977). Typically, the least square adjustment between the gravity residuals and the air pressure yields an admittance factor of about -3 nm s^{-2}/hPa. The physical approach utilizes atmospheric models for the determination of the mass distribution that is then transformed to gravitational and loading effects (e.g. Merriam, 1992). The latter approach allows us to take into account the gravity effects of remote atmospheric masses, i.e., variations that are not correlated to the local air pressure. Besides the GGP/Strasbourg Loading Service, global atmospheric corrections are also provided by the Atmacs service[3] (Klügel and Wziontek, 2009). Compared to the GGP Loading Service, Atmacs utilizes weather models with higher temporal (3 versus 6 h) and spatial resolution (7 km versus 0.75°), but with worse time coverage (starting 2004 versus 1979). The common denominator for both services is the restricted number of available sites and the fact that the provided atmospheric effect does not take the real topography into consideration.

2. mGlobe overview

To enable the computation for an arbitrary location worldwide, we have developed a comprehensive Matlab®/Octave-based toolbox (mGlobe) for the computation of the effect of the continental water storage, non-tidal ocean loading and atmosphere on surface gravity. To tackle the significant discrepancies between different models as introduced above, mGlobe enables the loading of a majority of freely available models by default (see Table 1), and contains a build-in conversion tool for other hydrological or ocean models. This option allows for including models like the WaterGAP Global Hydrology Model (WGHM) (Döll et al., 2003) or similar models that represent total continental water storage variations in different storage compartments. Considering total water storage variations is of particular relevance for comparing global hydrological models to GRACE (e.g. Van Camp et al., 2014; Neumeyer et al., 2008; Weise et al., 2012). The computation of the atmospheric effect utilizes the ERA Interim or MERRA pressure level data and surface level data downloaded in NetCDF file format. A digital elevation model (DEM) can be utilized in the computation of hydrological as well as atmospheric effects. A DEM is particularly important for computation of the atmospheric effect, as the impact of a low spatial resolution of atmospheric models will be minimized by using the DEM instead of gravity observations themselves. Thus, essential gravity variations that are anti-correlated to air pressure but of different origin will not be reduced by mistake. Additional features like the restriction of the computation to a certain basin, dividing the gravity contributions into the loading and the attraction part or the integration of user-provided high-resolution coastlines allow us to obtain more specific results. In these respects, mGlobe provides more flexibility than the existing services. In mGlobe, both the global and the local zone are included in the computation of atmospheric effects whereas the local zone is excluded from the computation of hydrological effects. The latter is due to the high spatial and temporal variability of hydrological processes which is not reflected in global hydrological models. A detailed local hydrological model including high-resolution information on topography and infrastructure (e.g., to capture the shielding effect of the gravimeter building) and in situ hydrological monitoring data are recommended for subtracting the local hydrological effect (Creutzfeldt et al., 2008). In mGlobe, the radius of the local zone around the site of interest can be set between 0.05° and 1.0° (spherical distance). For all effects, the user can set the position, computation period and the time resolution. The more specific settings are described in detail in the corresponding sections below.

The mGlobe graphical user interface of the continental water storage console is shown in Fig. 1. The Matlab version requires Mapping and Statistics toolboxes and can be downloaded from http://github.com/emenems/mGlobe The Octave version can be downloaded from http://github.com/emenems/mGlobe_octave.

3. Study sites

In this study, mGlobe results were evaluated at three sites equipped with a superconducting gravimeter (SG), namely Vienna, Conrad observatory (both in Austria) and Sutherland (South Africa, Table 2). The SG in Vienna was installed in an underground laboratory from August 1995 until the end of October 2007. Afterwards, this gravimeter has been moved to the Conrad observatory in the north-eastern margin of the Eastern Alps. The upgraded dual sphere SG in Sutherland has been in operation since the end of 2009. The SG observations in Vienna and at the Conrad observatory were acquired from their operators while the observations of the SG in Sutherland were downloaded from the ISDC (Information System and Data Center for geoscientific data) data servers.[4] Prior to the mGlobe evaluation, the gravity time series were corrected for steps and spikes using the TSoft software (Van Camp and Vauterin, 2005), decimated to one hour sampling and corrected for tides, polar motion, length of day and instrumental trend. The tidal parameters were derived from tidal analyses using the ETERNA package (Wenzel, 1996), i.e., the tidal parameters include the ocean tides The instrumental trend was estimated using the least square adjustment. Absolute gravity observations could not be used at Vienna due to accuracy limitations caused by high site noise. No absolute gravity observations were available for the Sutherland site.

4. Continental water storage

The aim of the continental water storage module in mGlobe is to compute the non-local hydrological contribution to surface gravity variations. This contribution can be divided into a loading and gravitational part. The loading part is related to the surface deformation caused by mass transport, i.e., water storage changes. The gravitational part is related to the vertical component of Newton's attraction of water masses. The calculation itself is divided into several zones depending on the spherical distance (ψ) between the mass and the measurement point. The closer to the measurement point, the higher is the degree of spatial discretization, i.e., the original model values are linearly interpolated

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[2] http://holt.oso.chalmers.se/loading/

[3] http://atmacs.bkg.bund.de

[4] http://isdc.gfz-potsdam.de