S$_2$ tide aliasing in GRACE time-variable gravity solutions

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Abstract Errors in high-frequency ocean tide models alias to low frequencies in time-variable gravity solutions from the Gravity Recovery and Climate Experiment (GRACE). We conduct an observational study of apparent gravity changes at a period of 161 days, the alias period of errors in the S$_2$ semidiurnal solar tide. We examine this S$_2$ alias in the release 4 (RL04) reprocessed GRACE monthly gravity solutions for the period April 2002 to February 2008, and compare with that in release 1 (RL01) GRACE solutions. One of the major differences between RL04 and RL01 is the ocean tide model. In RL01, the alias is evident at high latitudes, near the Filchner-Ronne and Ross ice shelves in Antarctica, and regions surrounding Greenland and Hudson Bay. RL04 shows significantly lower alias amplitudes in many of these locations, reflecting improvements in the ocean tide model. However, RL04 shows continued alias contamination between the Ronne and Larson ice shelves, somewhat larger than in RL01, indicating a need for further tide model improvement in that region. For unknown reasons, the degree-2 zonal spherical harmonics (C$_{20}$) of the RL04 solutions show significantly larger S$_2$ aliasing errors than those from RL01.

Keywords GRACE · Alias error · 161-day · Ocean tide · Gravity · S$_2$

1 Introduction

A primary goal of the Gravity Recovery and Climate Experiment (GRACE) twin satellite mission is to measure Earth gravity change on a global basis at approximately 30-day intervals (Tapley et al. 2004a). Monthly gravity fields are determined from precise measurements of the range and range-rate between the GRACE satellites orbiting in tandem, combined with data from on-board accelerometers and global positioning system (GPS) receivers (Tapley et al. 2004a). Time-variable gravity fields are used to study surface mass variations due to terrestrial water storage (e.g., Tapley et al. 2004b; Wahr et al. 2004), non-steric and non-tidal sea level change (e.g., Chambers et al. 2004; Chen et al. 2005), and ice sheet mass balance (e.g., Velicogna and Wahr 2006a,b; Chen et al. 2006a,b). Specialized techniques also yield estimates of alpine glacier mass changes from GRACE (e.g., Tamisiea et al. 2005; Chen et al. 2006c).

Dominant gravity change signals over land at seasonal and longer time scales are adequately sampled by GRACE’s monthly fields, and higher frequency variations over land due to non-tidal atmospheric mass redistribution are reasonably well removed using European Center for Medium range Weather Forecasting (ECMWF) atmospheric pressure fields (Bettadpur 2007a). But tidal atmospheric mass changes are not well sampled by ECMWF, especially those from S1 and S2 tides (Ray and Ponte 2003). Over the oceans, diurnal and semi-diurnal lunar and solar tides are the dominant
mass variations, and tide models must be used to remove their effects on GRACE measurements. Ocean tide models are imperfect as explained in Ray et al. (2003), and errors are anticipated where constraining radar altimetry and tide gauge observations are limited, including polar and some coastal areas. Tide model errors will appear in monthly gravity solutions at alias periods (Han et al. 2004; Ray and Luthcke 2006). A well-recognized example is the alias of the $S_2$ (semidiurnal) tide, which will appear as a sinusoidal variation at about 161 days in GRACE time series (Knudsen 2003; Ray et al. 2003).

GRACE Level-1 satellite range and range rate data are used by Han et al. (2005) to investigate the 161-day $S_2$ alias in a region near the Filchner-Ronne ice shelves in Antarctica, and indicate that the amplitude of the 161-day aliasing signal could be well over 20 cm of equivalent water height change at some locations in this area, with respect to the a priori reference ocean tide model CSR4.0 (Eanes 2002). Han et al. (2007) estimate long-wavelength components of the ocean tides surrounding Antarctica directly from three years of GRACE satellite-to-satellite ranging measurements. Although GRACE estimates of ($M_2$, $O_1$, and $S_2$ tides) appear in good qualitative agreement with sparse ground measurements at several locations in Antarctica, the comparison indicates regions where the adopted a priori ocean tide model is inadequate (Han et al. 2007). Ray and Luthcke (2006) perform a complete simulation of alias errors in GRACE monthly gravity solutions due to ocean tides errors, and conclude that tide alias errors in GRACE monthly surface mass change estimates are on the order of 1 cm of equivalent water height and may be significantly larger (2–3 cm) in polar regions where ocean tide models are suspect.

Schrama et al. (2007) examines the 161-day $S_2$ alias using the reprocessed GRACE release 04 (RL04) time-variable spherical harmonics gravity solutions for the period January 2003–September 2006, provided by the Center of Space Research (CSR) at the University of Texas at Austin, and show that many regions (especially the tropical ocean northwest of Australia, the Amazon river basin, and the Weddell Sea in Antarctica) still show evidence of the $S_2$ alias, and that magnitude of the alias error northwest of Australia appears the largest. Large tide model errors are normally anticipated in shallow seas and coastal regions or high latitudes lacking satellite altimeter and tide gauge data. Seo et al. (2008) simulate alias errors due to several major tidal constituents using differences between GOT00.2 and TPXO6.2 tide models, and compare the simulated 161-day $S_2$ alias errors with GRACE observations for the period August 2002 to February 2006, including GeoForschungsZentrum (GFZ) RL04 (Flechtner 2007) and the Goddard Space Flight Center (GSFC) (Luthcke et al. 2006a) solutions. They also find a large $S_2$ alias error in the tropical ocean northwest of Australia. In another recent study, Moore and King (2008) estimate the effect of ocean tide alias errors on GRACE estimates of Antarctic ice mass balance. While analysis of the 161-day $S_2$ alias is relatively straightforward, it is more difficult to estimate errors from other constituents, like $K_1$ and $K_2$. Their aliases have much longer periods (around 7.46 and 3.73 years) and may contaminate estimates of trends in Antarctic ice mass balance derived from the studied 6-year period of GRACE observations (Moore and King 2008).

Here we conduct a global re-investigation of the 161-day $S_2$ alias using a longer series (April 2002–February 2008) of GRACE monthly spherical harmonic fields. We examine both the recent RL04 and an earlier release 01 (RL01) solutions provided by CSR. A portion of RL04 (June 2006–September 2007) differs from previous analyses, due to recent reprocessing with corrected atmosphere and ocean dealiasing products (for details, see the January 2008 GRACE newsletters at ftp://podaac.jpl.nasa.gov/pub/grace/doc/newsletters). RL01 and RL04 differ in a number of ways (Bettadpur 2007a), but an important one is the ocean tide model. This will become evident as we examine RL01–RL04 differences over the oceans near the $S_2$ alias period, documenting improvements, and revealing residual problems.

In previous studies (Schrama et al. 2007; Seo et al. 2008), degree-2 zonal harmonics $C_{20}$ in GRACE time-variable gravity solutions are either excluded or replaced by satellite laser ranging (SLR) estimates due to recognized problems with GRACE $C_{20}$ estimates. However, GRACE $C_{20}$ are also subject to significant tide alias errors, especially from the $S_2$ tide (e.g., Chen and Wilson 2008). We will examine how GRACE $C_{20}$ estimates will affect the spatial spectrum of $S_2$ tide alias errors, and if $C_{20}$ alias errors are also related to ocean tide errors. We will also examine $S_2$ tide alias stability as the GRACE orbit decays with time.

2 Data and processing

2.1 GRACE observations

RL04 data used in this study consist of 67 monthly average GRACE gravity fields from April 2002 to February 2008. Each monthly field is a set of fully normalized spherical harmonic coefficients to degree and order 60 (Bettadpur 2007b). Major improvements relative to earlier releases (e.g., RL01) include: a new background gravity model GIF22a, created from the 22-month time-series of UTC/CSR Release-02 products combined with gravity models GGM02C (Tapley et al. 2005) (spherical harmonics degree 121–200) and EGM96 (Lemoine et al. 1998) (spherical harmonics degree 201–360); a new ocean tide model FES2004 (Lyard et al. 2005) for diurnal and semidiurnal periods; and an updated solid Earth pole tide model based on IERS2003 (McCarthy and Petit 2003). GRACE GAC atmospheric and oceanic averages