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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

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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 prior* 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 UTCSR 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. 2006) 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

(Bettadpur 2007b) are not restored. As we only focus on the 161-day S_2 alias errors, restoring GAC or not will not affect our analysis.

Ocean pole tide effects are represented with a self-consistent equilibrium (SCEQ) model based on satellite altimeter data (Desai 2002). Details of the RL04 data processing standards are given by Bettadpur (2007a). RL04 is compared with GRACE RL01 solutions covering the period April 2002 to December 2006 (the longest available record of RL01 data). RL01 processing details are given by Bettadpur (2003). A major difference between the RL01 and RL04 is the ocean tide model. RL01 employs the CSR4.0 model (Eanes 2002), with some omissions from the full CSR4.0 model (see the comments in Moore and King (2008, last paragraph of Section 2) for details). Han et al. (2005) showed that S_2 differences between FES2004 and CSR4.0 can largely explain the 161-day period alias they found in the Filchner-Ronne ice shelves in Antarctica.

2.2 Filtering of GRACE gravity solutions

High degree and order GRACE spherical harmonic coefficients (e.g., those over degree and order 20) are dominated by noise, as evidenced by longitudinal stripes in gravity field maps. Swenson and Wahr (2006) found that the stripes are associated with correlations among certain spherical harmonic coefficients. By removing these correlations, the stripes are suppressed significantly. We apply a modified version of the decorrelation filter of Swenson and Wahr (2006) to the GRACE solutions. For a given spherical harmonics order (6 and above), we use least squares to fit and remove a polynomial of order 4 from even and odd coefficient pairs. This processing step is denoted as P4M6. After this, 500 km Gaussian smoothing (Jekeli 1981) is applied, and the mean of all 67 (or 53 for RL01) solutions is removed to obtain time series of gravity variation for both RL01 and RL04. 500 km radius Gaussian smoothing is reasonably effective in removing most residual spatial noise after P4M6 filtering. A larger radius would further reduce the noise, but the signal would also be greatly attenuated (Chen et al. 2007). A global gridded ($1° \times 1°$) surface mass change field is then computed for each month.

Non-tidal atmospheric and barotropic oceanic mass changes are removed in GRACE level-2 processing (Bettadpur 2007a). Therefore, surface mass time-series reflect mainly contributions from other sources: terrestrial water storage changes over land; snow/ice mass changes over polar ice sheets; unmodeled baroclinic oceanic mass changes; errors in GRACE measurements; and errors in background geophysical models used in GRACE data processing, such as ocean tide models (Knudsen 2003; Ray et al. 2003; Han et al. 2005).

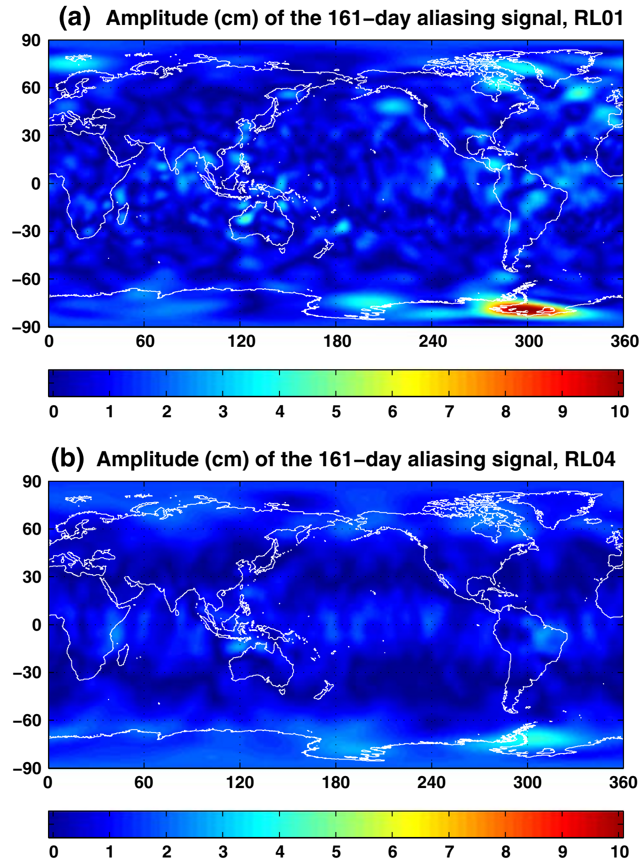

Fig. 1 **a** Least square fit amplitude (cm of equivalent water height) of the 161-day S_2 alias from the 53 monthly GRACE solutions in RL01. **b** As in **a** but for RL04

GRACE C_{20} coefficients are commonly excluded or replaced by satellite laser ranging (SLR) observations in related studies (e.g., Schrama et al. 2007). However, GRACE's low-degree spherical harmonics, especially C_{20} are particularly sensitive to S_2 tide aliasing error (Chen and Wilson 2008). In order to have a complete global picture of S_2 tide aliasing errors, all spherical harmonics up to degree and order 60 (including C_{20}) are included in our computation.

3 Results

3.1 Global amplitude of the 161-day aliasing signal

At each grid point, we estimate a linear trend and amplitudes and phases of annual, semiannual, and 161-day sinusoids using unweighted least squares. Figures 1a and b show maps of amplitudes (cm of equivalent water height) of the 161-day sinusoid from RL01 and RL04 time series. To have a fair comparison, these two maps (Figs. 1a, b) are derived from RL01 and RL04 time series covering exactly the same period April 2002–December 2006 (when RL01 solutions

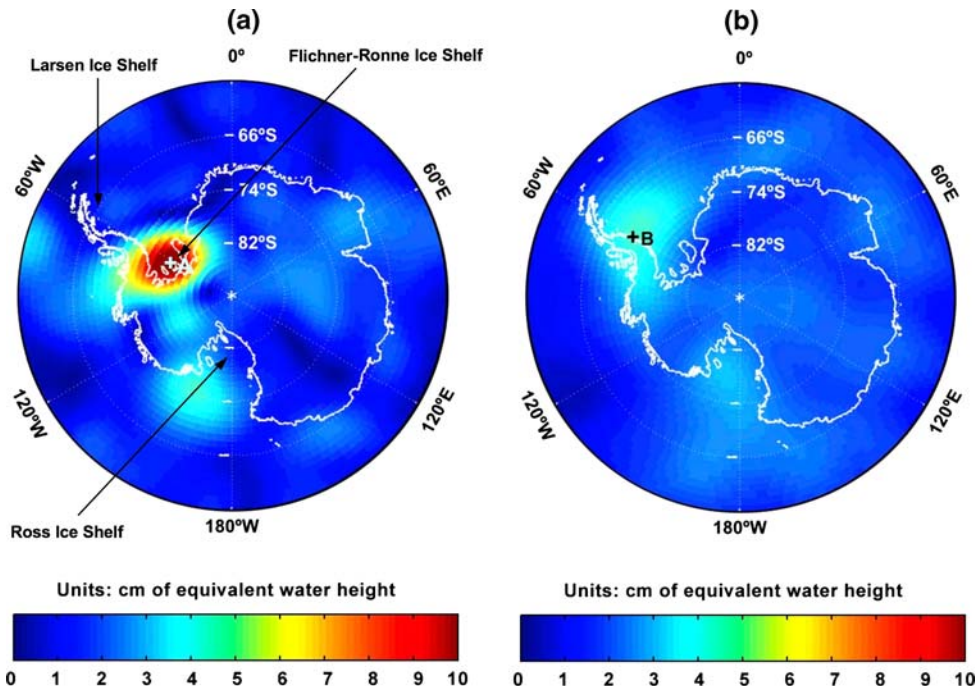

Fig. 2 **a** Detailed view of the Antarctic of the amplitude of the 161-day alias in RL01. **b** As in **a** but for RL04

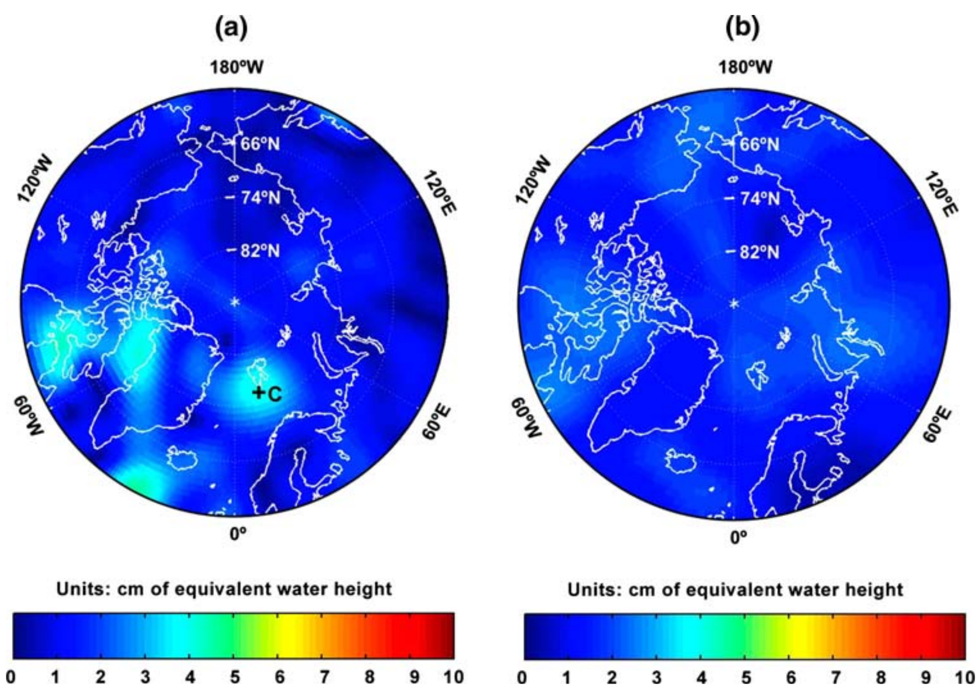

Fig. 3 **a** Detailed view of the Arctic of the 161-day alias for RL01. **b** As in **a** but for RL04

are available). Analysis of RL04 including the period up to February 2008 is discussed in Sect. 3.4. RL01 shows large alias error amplitudes over the Filchner-Ronne ice shelf in Antarctica (over 10 cm). This is consistent with estimates based on GRACE Level 1B range and range rate data by Han et al. (2005), although our magnitudes are somewhat less due to Gaussian smoothing. Relatively large errors are evident elsewhere, at high latitudes, around the Ross Ice Shelf and Greenland, and some tropical and mid-latitude areas.

The RL04 map (Fig. 1b) shows significantly reduced S_2 alias amplitudes, reflecting an improved S_2 tide in FES2004. However, around the Larson C and Filchner-Ronne ice shelve, Fig. 1b indicates an RL04 error somewhat larger than RL01 (Fig. 1a). Figures 2a and b shows this greater detail for the Antarctic, and Figs. 3a and b show details for the Arctic. A few areas around Greenland (south of Svalbard, southeast of Greenland) show amplitudes in the 4–5 cm range (Fig. 3a) in RL01, mostly absent in RL04 (Fig. 3b).

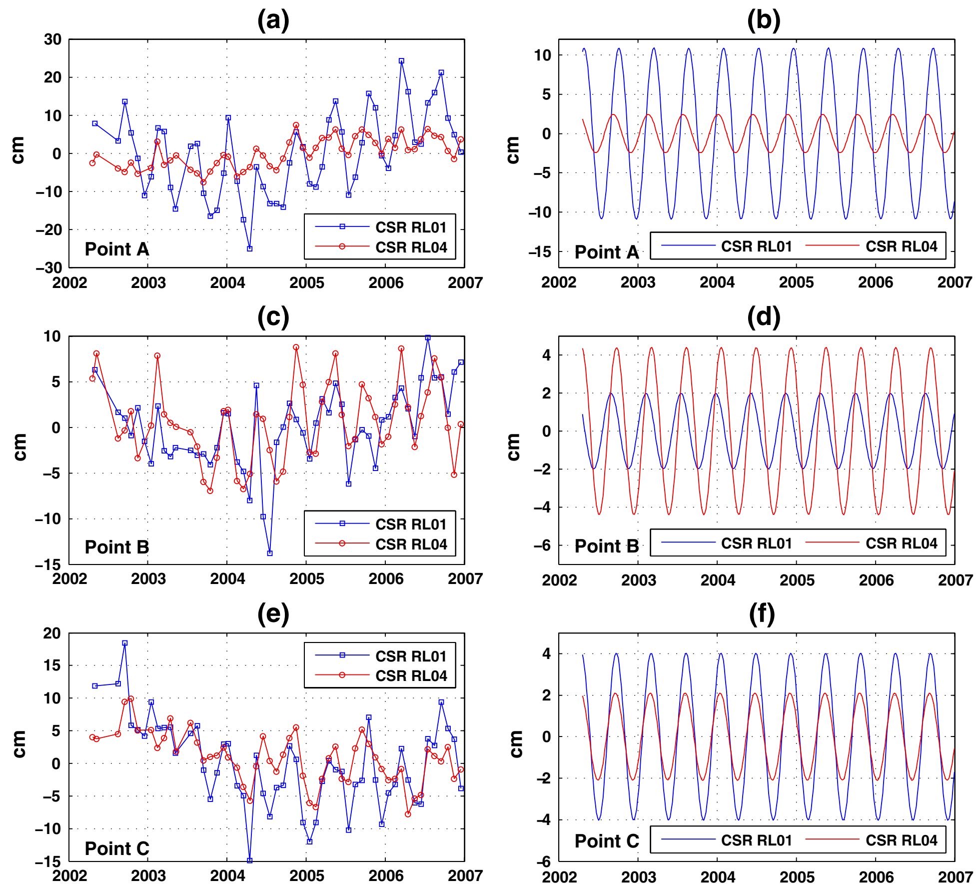

Fig. 4 *Left panels* (**a**, **c**, and **e**) compare apparent mass change time series (RL01 and RL04) at points (*A*, *B*, and *C*) marked by crosses in Figs. 2a, b, and 3a, respectively. *Right panels* (**b**, **d**, and **f**) compare 161-day amplitudes for RL01 and RL04 at points (*A*, *B*, and *C*)

A few tropical ocean and land areas show amplitudes of a few centimeters in Fig. 1b. Some over land, such as in the Amazon Basin, may be due to errors in the S_2 atmospheric tide (Bettadpur 2007a) and/or nonseasonal variations in a strong terrestrial water cycle, which may contribute to the 161 day sinusoid estimate. Others, such as in the tropical Indian Ocean northwest of Australia, may reflect true tide model errors, possibly related to deficiencies in altimetry data sets near coastlines and along the equator where ground track space is maximum (Deng and Featherstone 2006).

A comparison between Fig. 1b and a similar map (top panel of Fig. 8 of Schrama et al. 2007) reveals some interesting differences. The two studies are based on similar CSR RL04 solutions, though with a slightly longer series and other differences noted in the present study. Figure 1b shows the largest S_2 alias error (~ 4 cm) located between the Larson and Ronne ice shelves in the Weddell Sea. On the other hand, Schrama et al. (2007) find (~ 2 cm) in the Weddell sea, but larger amplitudes northwest of Australia and over the Amazon river basin. These differences may be caused by a number of factors, including different filtering techniques, time spans of RL04, and treatment of low-degree spherical harmonics (e.g., C20).

3.2 Time-series at selected locations

The left panels of Fig. 4 compare GRACE mass change time series (RL01 and RL04) at grid points A, B, and C (marked by crosses in Figs. 2a, b and 3a, respectively). The right panels of Fig. 4 compare 161-day sinusoids estimated from the left panels by unweighted least squares as described above. Amplitudes and phases of 161-day sinusoids are listed in Table 1. Each zero-mean time series (with 53 points) has been fit with a 7 parameter model (sinusoids at periods of 1, 1/2 year, and 161 days, plus a linear trend). Using standard linear least squares assumptions (Box and Jenkins 1970, p. 266) the covariance matrix of parameter errors is estimated from the inverse of the 7×7 normal equation matrix, multiplied by post-fit residual time series variance. The covariance matrix is approximately diagonal, and values associated with sinusoidal coefficients are all about 4 percent of post-fit residual variance. A substantially lower post-fit residual variance for all RL04 time series results in reduced standard deviations reported in Table 1.

At points A and C, the effect of the new model FES2004 in RL04 is significant, while at point B (between the Larson and Ronne ice shelves), larger RL04 amplitudes suggest that

Table 1 Amplitudes and phases of 161-day S_2 alias errors in surface mass change estimates at three grid points (A, B, C) and in C_{20} and C_{40}, as shown in Figs. 4 and 5

S2 alias errors	RL01		RL04	
	Amplitude (cm)	Phase (deg)	Amplitude (cm)	Phase (deg)
Grid point A	10.86 ± 1.81	231	2.44 ± 0.63	283
Grid point B	1.98 ± 1.07	303	4.39 ± 0.74	252
Grid point C	4.02 ± 1.36	256	2.10 ± 0.64	264
ΔC_{20} ($\times 10^{10}$)	0.62 ± 0.53	286	1.22 ± 0.27	262
ΔC_{40} ($\times 10^{10}$)	0.097 ± 0.060	10	0.067 ± 0.044	12

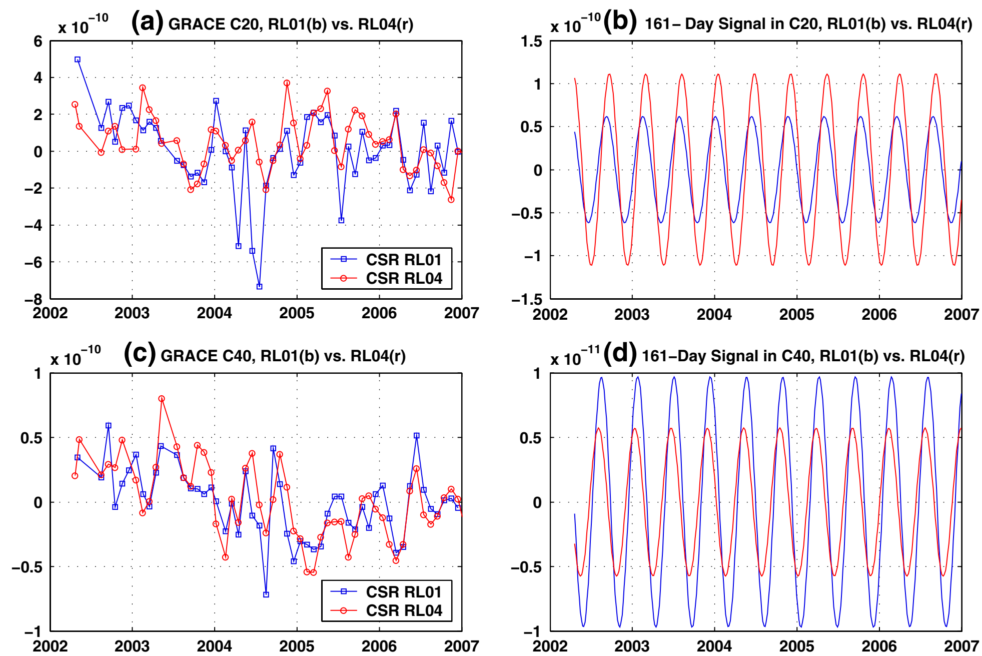

Fig. 5 *Left panels* compare GRACE RL01 and RL04 solutions of **a** C_{20} and **c** C_{40}. *Right panels* (**b**, **d**) compare 161-day amplitudes for RL01 and RL04 solutions of C_{20} and C_{40}. GRACE GAC atmospheric and oceanic averages are not restored

CSR4.0 used in RL01 may be superior. King and Padman (2005) evaluate several ocean tide models (including older versions of FES and CSR models) using independent GPS measurements, and conclude that the FES model appears superior for the Antarctic region. A major limitation of CSR4.0 in the Antarctic is that it omits ice shelves. This accounts for errors in RL01 around the Ronne Ice Shelf.

Figure 4 (left panels) also shows significant differences at interannual time-scales, especially at points A and C. At point C (south of Svalbard), the first few years of RL01 indicate a mass decrease, interpreted by Chen et al. (2006b) as spatial leakage from permanent ice melting on Svalbard. The RL04 time series shows a smaller negative trend for this period. Luthcke et al. (2006b, in Supporting Online Materials) has discussed potential S_2 alias errors in northeast Greenland in the 10-day mascon solutions (Rowlands et al. 2005), which could be related to the leakage from S_2 alias errors over the oceans.

3.3 S_2 alias errors in low-degree spherical harmonics

The RL04 map (Fig. 1b) shows evidence of zonal patterns, with two lows at ∼30° latitude and three highs in polar regions and tropical regions. Similar patterns are not evident in RL01 solutions (Fig. 1a). These can be related to S_2 alias errors in low-degree zonal spherical harmonics, especially C_{20} and C_{40}. To demonstrate this we compare RL01 and RL04 C_{20} and C_{40} time-series during the 5-years time period in Fig. 5a and c, and compare the 161-day sinusoids estimated from the left panels by unweighted least squares in Fig. 5b and d, respectively. The amplitudes and phases of the 161-day sinusoids for RL04 C_{20} and C_{40} are listed in Table 1 (uncertainties are determined in the same way as in Sect. 3.2).

The improvement of C_{20} estimates in RL04 solutions (vs. RL01) is evident, especially during 2004 when GRACE orbit contracted slowly to yield a sparse repeat track and

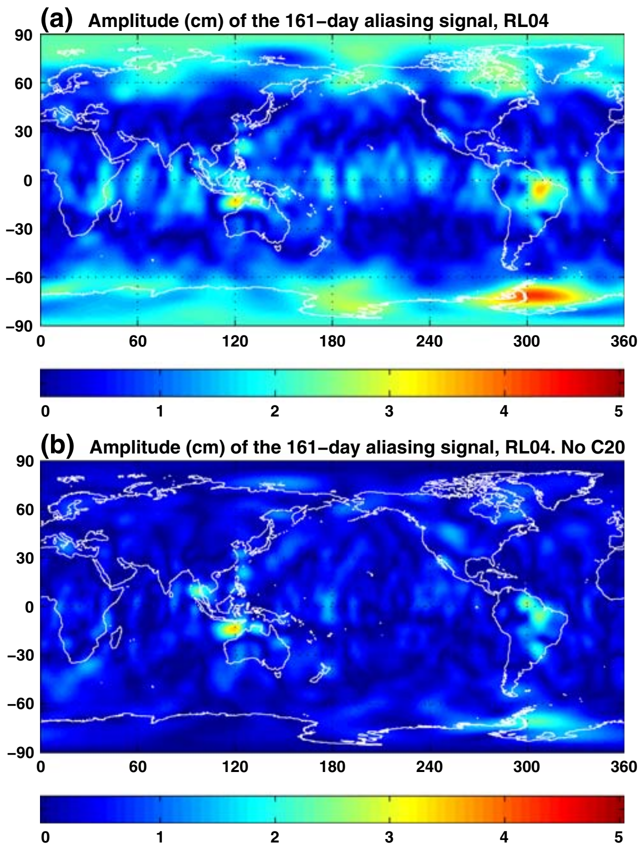

Fig. 6 **a** Amplitudes (cm of equivalent water height) of the 161-day alias signal from 53 CSR RL04 monthly solutions with C_{20} included (same as Fig. 1b, but different color scale). **b** As in **a**, but with C_{20} excluded

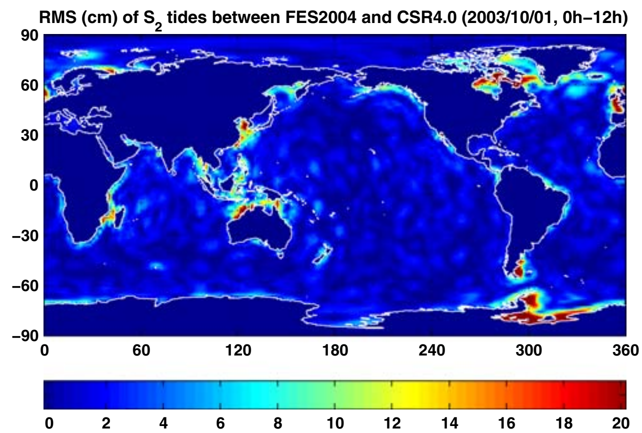

Fig. 7 RMS (units of cm) S_2 ocean tide differences between FES2004 and CSR4.0 during 0–12 h on 1 January 2003

degraded GRACE monthly gravity recovery (Wagner et al. 2006). Despite the use of a newer ocean tide model (FES2004) (Lyard et al. 2006) in RL04 solutions, RL04 C_{20} time-series, however, show a significantly larger 161-day aliasing signal than RL01 time-series, consistent with the appearance of RL01/RL04 maps (Fig. 1a, b). The S_2 alias error is also evident in C_{40}, although relatively smaller than that in RL01. It is not clear yet what really contribute to the particularly large S_2 alias error in RL04 C_{20} solutions (Chen and Wilson 2008). Seo et al. (2008), through simulations, indicate that C_{20} is particularly sensitive to S_2 alias errors (relative to other zonal harmonics, e.g., C_{30}), and suggests that alias errors in the Arctic may have a larger impact on C_{20} due to its geographical shape and location.

In Fig. 6 we compare 161-day sinusoid amplitudes from RL04 time series when C_{20} is included and when it is omitted (Note: Fig. 6a is virtually the same as Fig. 1b, but in different color scales). When C_{20} is excluded, S_2 alias errors at high latitudes are significantly reduced, and show features more consistent with those of Schrama et al. (2007, top panel of Fig. 8). However, Fig. 6 shows somewhat larger errors (~2.5 cm) in the Weddell Sea region (between the Larsen and Ronne ice shelf regions) in Antarctica.

Figure 6 makes it clear that zonal patterns of S_2 alias error are mainly introduced by the errors in C_{20} (and C_{40}). However, how this is related to (both atmosphere and ocean) tide models errors is not clear. To better understand GRACE S_2 alias errors, we show in Fig. 7 global RMS differences between S_2 constituents of FES2004 and CSR4.0 during a particular (but arbitrary) period (0–12 h, 1 January 2003). There are differences of up to 20 cm mostly along the coasts with the largest in the Larsen and Filchner-Ronne ice shelf regions. Good spatial correlation exists between Figs. 1 and 7, which estimates S_2 error from the 161 day alias amplitude. For example, both figures show prominent features northwest of Australia, around Hudson's Bay, and Larsen and Filchner-Ronne ice shelf regions. However, zonal patterns evident in Figs. 1b and 6a are not apparent in Fig. 7, suggesting that the spatial patterns of GRACE S_2 alias errors may not be fully explained by ocean tide models errors in space domain. Further studies involving both atmosphere and ocean tide models are needed to better understand the full spatial spectrum of GRACE S_2 alias errors.

3.4 Stability of S_2 alias errors

Because the GRACE orbit is varying in time, the period or amplitude of the S_2 alias error may also be variable. To examine this question, we compute amplitudes of the 161-day sinusoidal fit to RL04 for 3 different periods: (a) January 2003–September 2006 (the same period investigated by Schrama et al. 2007), (b) April 2002–December 2006, and (c) April 2002–February 2008. Results appear in the three panels of Fig. 8. The general features of zonal patterns and a few areas with large amplitudes appear similar for periods a, b, and c. However, the longer time series tend to show diminished S_2 alias errors in some areas, for example, the Amazon basin and Weddell Sea (between the Larsen and Ronne ice shelves). These changes may be due to improved

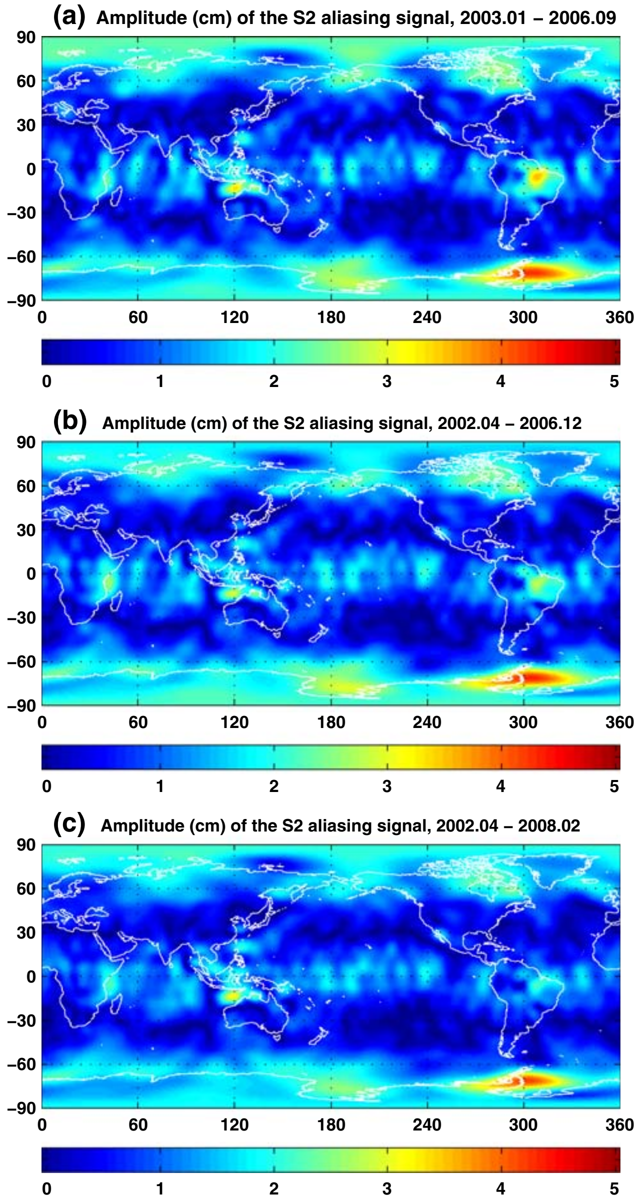

Fig. 8 Least square fit amplitude (cm of equivalent water height) of the 161-day alias from CSR RL04 monthly solutions for 3 different periods **a** January 2003–September 2006, **b** April 2002–December 2006, and c) April 2002 – February 2008

separation of semiannual and 161-day estimates using longer time series.

4 Summary and conclusions

We examine S_2 tide alias errors in GRACE CSR RL01 and RL04 time-variable gravity solutions for the period April 2002 to February 2008 (April 2002 to December 2006 for RL01). Differences reveal global characteristics of the S_2 alias which appears at 161-days. The alias is evident at high latitudes, where observations by satellite altimetry and tide gauges are relatively sparse, but also appears at other latitudes. The S_2 alias in RL01 near the Filchner-Ronne ice shelf is consistent with an earlier study (Han et al. 2005) based on GRACE Level-1b range and range-rate data. Other prominent S_2 alias errors are observed near the Ross Ice Shelf and regions surrounding Greenland and Hudson Bay. S_2 alias errors are significantly reduced in RL04, evidently from the improved tide model (FES2004), but evidence of aliasing remains, indicating the need for further tide model improvements. GRACE S_2 alias errors may reflect S_2 tide errors in both the atmosphere and ocean. The global nature of the GRACE measurement and maps like Fig. 1 should be useful in identifying regions where further tide model effort should be directed.

When a longer record (April 2002–February 2008) of GRACE RL04 solutions is used, the S_2 alias errors over the Amazon basin are significantly reduced, possibly due to improved separation of semiannual terrestrial hydrologic effects from the 161-day S_2 alias. The longer time series also reduces estimated S_2 alias errors in the Weddell Sea area (between the Larsen and Filchner-Ronne ice shelves) in Antarctica, perhaps for similar reasons.

Spatial patterns and magnitudes of remaining S_2 alias errors in RL04 differ somewhat from previous studies (Schrama et al. 2007; Seo et al. 2008), mainly due to inclusion of the GRACE C_{20} coefficient, and different spatial filtering techniques., C_{20} in RL04 appears to show significantly larger S_2 alias errors than RL01. Further study and understanding of C_{20} (and other low-degree spherical harmonics) alias errors are needed to improve GRACE gravity solutions and develop future generations of ocean tide models.

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