Improvements in Arctic Gravity and Geoid from CHAMP and GRACE: An Evaluation

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Summary. The near-polar CHAMP and GRACE satellites are now acquiring vitally important new information on the geoid and gravity field of the polar regions. This investigation demonstrates that CHAMP and GRACE data are dramatically reducing the large gaps in our knowledge of the Arctic region, constraining the long wavelength geopotential (>300 km) and beginning to yield the high accuracy marine geoid which is needed for Arctic oceanographic and sea ice studies. Using a detailed Arctic surface gravity field and an independent altimetric gravity field as benchmarks we have evaluated the intermediate-to-long wavelength (> 300km) component of seven CHAMP and two GRACE satellite-only gravity models such as the GFZ EIGEN, the NASA PGS and UT/CSR. We evaluate, spectrally, the errors in - and differences between - these satellite-only models in the Arctic at wavelengths from 300 to 2500 km. The GRACE models accurately resolve Arctic gravity to *full* wavelengths as short as 500 km while the CHAMP models do so to full wavelengths as short as 1000 km. However the CHAMP models continue to show improved resolution as more and better (e.g. lower elevation) data are incorporated. The best CHAMP models agree well with the detailed Arctic ARC-GP model to an rms (error of commission) of better than 2.06 mGal (gravity)and 31 cm (geoid) for all wavelengths (full) longer than 1100 km. GRACE-only geoids are precise to 40 cm or better (all wavelengths) over large areas of the Arctic. CHAMP and GRACE-based geoids could have the accuracy required to detect (together with altimetry) the poorly known dynamic topography of the Arctic Ocean. As an example, a GRACE/detailed-gravity hybrid geoid is presented.

Key words: Arctic, CHAMP, geoid, GRACE, gravity, sea ice

1 Introduction

An accurate Arctic gravity field - and geoid - is critically needed by Arctic geologists, geophysicists, geodesists and particularly by oceanographers and cryosphere scientists. Studies of Arctic ocean dynamics and sea ice should benefit substantially from new geoids derived using CHAMP (CHAllenging Minisatellite Payload), GRACE plus surface data. GRACE and CHAMP will provide the long wavelength portion of an accurate marine geoid to which recent and forthcoming altimeter data can be referred. Such a geoid is vital, for example, if we are to use ICESat altimeter data for precise estimation of sea ice elevation and thickness (Farrell et al., 2003). Similarly, this geoid will be needed for applying ENVISAT and CryoSat altimetry to estimation of dynamic topography and ice elevation. The near-polar orbit of the GRACE and CHAMP missions enables them to reduce long-wavelength gravity and geoid errors in the Arctic by at least as much as is possible globally.

1b. Detailed Gravity A decade ago gravity fields of the Arctic were filled with large data voids. Since 1993 great progress has been made in detailed gravity mapping of this ice-covered, inaccessible region. A gravity field covering the ocean between 60°N and 81.5°N (Fig. 1a) was derived using ERS-1 altimeter data (Laxon and McAdoo, 1994, 1998). Recently, the international Arctic Gravity Project (ARC-GP; Forsberg, Kenyon et al., 2002) gravity field was derived from airborne, surface and submarine data and was released. This ARC-GP field (Fig. 1b) fills a number of the large gaps in data coverage that existed heretofore. Despite this progress, gaps in gravity data coverage (Childers et al., 2001) remain particularly in the northernmost Arctic Ocean. To fill in these gaps and accurately underpin the detailed gravity fields, the accurate long (>300 km) wavelength geopotential information from the GRACE and CHAMP satellite missions is essential. Only by combining the accurate, long-wavelength information from GRACE and CHAMP with detailed surface gravity will it be possible to compute the required high-accuracy marine geoid. Note the strong similarity between the detailed gravity fields in Fig. 1a (south of 81.5°N, ERS' northern limit) and Fig. 1b even though the input gravity data are largely independent. The gravitational expression of seafloor details such as continental shelf edges, the Nansen-Gakkel ridge and the Chukchi Borderland can be seen clearly in both figures. This similarity or coherence between the ARC-GP and ERS fields validates the ARC-GP. Therefore we will use the more extensive ARC-GP field as our "benchmark" for evaluating GRACE and CHAMP gravity.

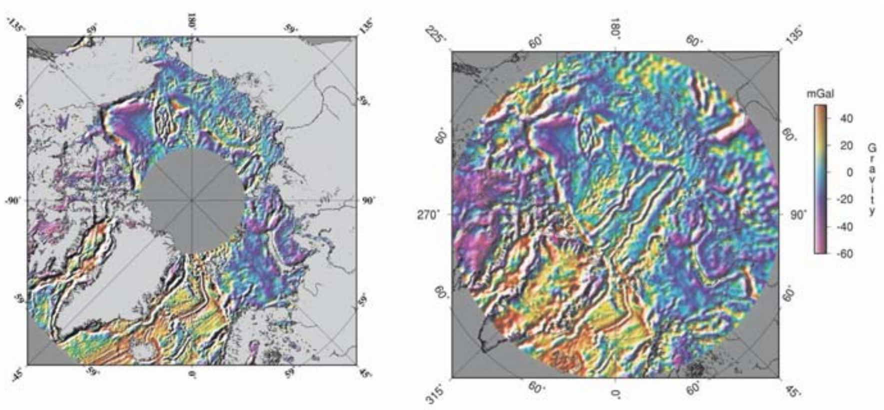

Fig. 1. (a) Arctic Ocean ERS-1 gravity field (left); (b) ARC-GP detailed gravity, Forsberg, Kenyon et al., 2002 (right).

2 GRACE and CHAMP satellite-only Arctic gravity

Fig. 2 displays a plot of the Gravity Recovery And Climate Experiment (GRACE) GGM01S satellite-only gravity model (Tapley et al., 2003) and has been evaluated here in the Arctic for spherical harmonic coefficients complete to degree and order, n, m, =120. This model was based upon a preliminary analysis of 111 days of micro/s level range-rate data between the two GRACE sub-satellites. Although the attenuation of short wavelength gravity signals at GRACE's 480 km current elevation prevents detection of anomalies with wavelengths shorter than 300 km, one can easily see a correspondence between the GRACE gravity and the detailed ARC-GP field in Fig. 1b. Gravity anomalies associated with the continental shelf break, the Nansen-Gakkel ridge and the northernmost Mid-Atlantic (Knipovich) ridge are evident in both Fig. 1b and Fig. 2. Even though the full GRACE GGM01S gravity field displays some artificial north-south, sectorial striping with an approximate wavelength of 350 km at lower latitudes (< 65°N), this GRACE model exhibits little or no such spurious striping in the Arctic. GFZ's GRACE-only EIGEN-GRACE01S model (Reigber et al., 2003a) from 39 days of tracking yields Arctic gravity very similar to that of GGM01S in Fig. 2.

Two recent CHAMP-only gravity models, PGS7772 (Lemoine et al., 2003) and EIGEN2ee (Reigber et al., 2003b) are evaluated over the Arctic and shown in Figs. 3a and 3b, respectively, below. South of 85°N one can see good similarity between the two CHAMP models as well as between each of the two CHAMP models and the GRACE model (Fig. 2). Although one can see some spurious north-south banding in both Fig. 3a and 3b, real geophysical signals with full wavelengths as short as 500 km are clearly evident. Examples include the pro-

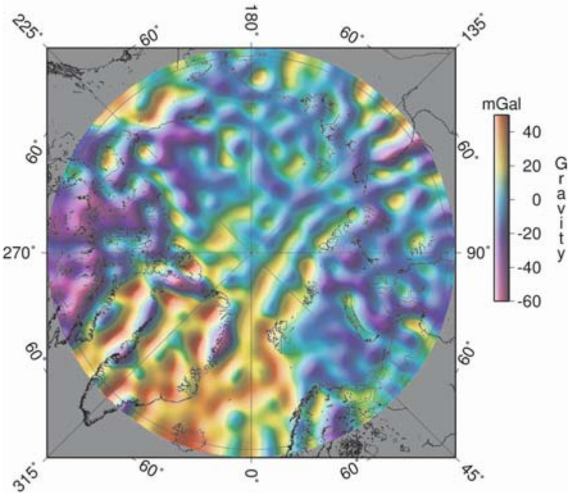

Fig. 2. GRACE GGM01S (120x120) gravity over the Arctic (Tapley et al., 2003).

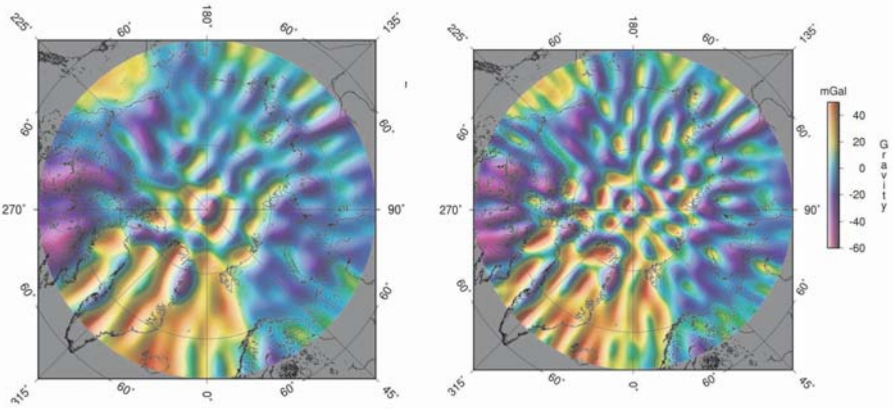

Fig. 3. CHAMP-only Arctic gravity: (a) [LEFT] PGS7772 (100x100) model (Lemoine et al., 2003), (b) [RIGHT] EIGEN-2ee (120x120 plus some terms to 140) model (Reigber et al., 2003b).

nounced gravity low off the northeastern coast of Greenland, the north-south trending, positive, shelf-break anomaly at ~228°E along the western edge of the Canadian Archipelago (e.g. Banks Island). Note that north of 85°N the CHAMP models in Fig. 3 show ring-like anomalies that differ substantially from "reality" (i.e., Fig. 1b or 2). These poor results north of 85°N are likely due to CHAMP having a lower tracking precision than GRACE or to the inclination of CHAMP's orbit which is 87° as opposed to GRACE's more nearly polar, 89°, inclination.

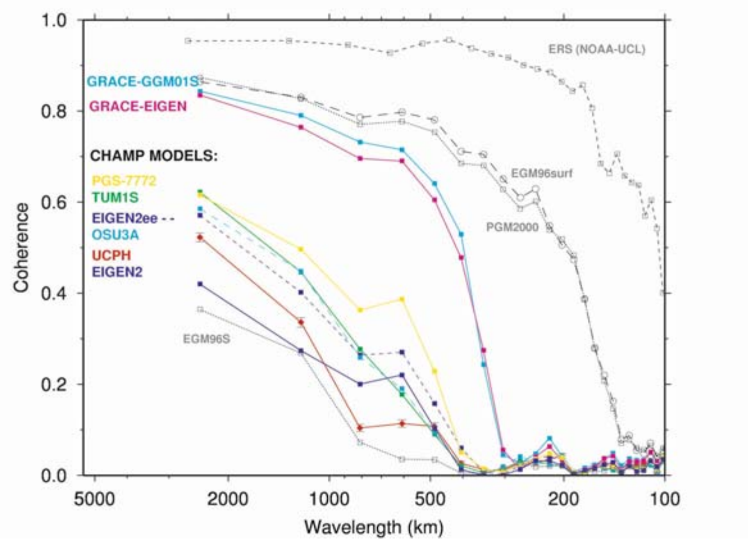

Fig. 4. Squared coherency between the ARC-GP Arctic gravity and various GRACE and CHAMP satellite only-models (in colors) plus coherency (in gray) between ARC-GP and OTHER gravity models (see text).

To assess the similarity between our benchmark ARC-GP field (Fig. 1b) and the new GRACE-only and CHAMP-only models we have computed the squared coherency (or the coherency spectrum) between each of these satellite models and the ARC-GP. Coherency, C, can be interpreted as the correlation coefficient as a function of wavelength. Signal-to-noise (SNR) equals C/(1 – C) so SNR = 1 when C = 0.5. Among satellite-only models prior to CHAMP, e.g. EGM96S (Lemoine et al., 1998) and GRIM5S1 (Biancale et al., 2000) we have found that EGM96S (70x70) produces the highest coherency (see Fig. 4) and, in turn, all CHAMP models shown produce higher coherency than EGM96S. The CHAMP models shown include PGS7772 (100x100), TUM1S (60x60/140x140, Gerlach et al., 2003), Eigen2ee, OSU3A (70x70, Han et al., 2004), UCPH (90x90, Howe et al., 2003) and EIGEN-2 (Reigber et al., 2003c). The coherency curves indicate that CHAMP models shown all do a significantly better job of resolving Arctic gravity than any pre-existing satellite-only model. Moreover CHAMP models confidently resolve full wavelengths as short as 1000 km and are improving. Of the CHAMP models, PGS7772 yields the highest coherencies by a slight margin over TUM1S, EIGEN2ee and OSU3A. Coherencies for the two GRACE models in Fig. 4, GGM01S (Tapley et al., 2003) and EIGEN-GRACE01S (Reigber et al., 2003a) are very similar and are each substantially higher than those of the CHAMP models. The PGM2000 and EGM96surf models (360x360; Lemoine et al., 1998; Pavlis, pers comm) are based wholly (EGMsurf) or in part (PGM) on detailed surface gravity data some of which were included in ARC-GP. The NOAA-UCL model (Laxon and McAdoo, 1998; Fig. 1a) was derived from re-tracked ERS-1 data.

3 Low-pass filtered gravity

Short-wavelength, surface gravity anomalies are attenuated at satellite elevation (>450 km for CHAMP and GRACE) and hence are difficult (or impossible) to detect with satellites. This difficulty is referred to as “omission error”. In order to minimize the effects of this omission error in our comparisons we have low-pass filtered the data using a gaussian filter with a full width of 550km, which is equivalent to a 2.5° radius. Before filtering the data are projected from geographical to rectangular map coordinates. In Fig. 5 the detailed ARC-GP (cf. Fig. 1b) is shown after filtering on the left (5a) and the identically filtered GGM01S is shown on the right (5b). Note the striking similarity of these two models after filtering. The correlation coefficient between them is 0.987! The EIGEN GRACE01S (Reigber et al., 2003a) yields a nearly identical correlation coefficient of 0.986.

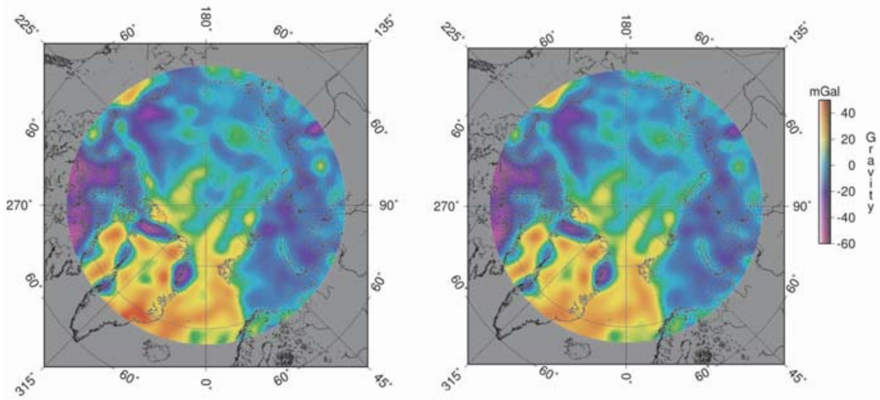

Fig. 5. (a) ARC-GP low-pass filtered with a 2.5° gaussian (left); (b) low-pass filtered GRACE GGM01S (right).

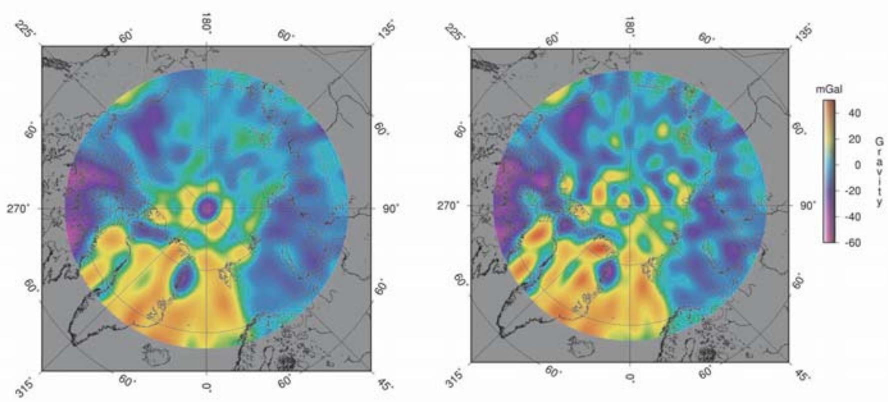

Fig. 6. (a) CHAMP Eigen2ee low-pass filtered with a 2.5° gaussian (left); (b) low-pass filtered CHAMP PGS-7772 (right).

In Fig. 6, a gaussian filter identical to that used on ARC-GP and GRACE models (cf. Fig. 5) was applied to the two CHAMP models Eigen2ee and PGS-7772 (cf. Fig. 3a,b). These two filtered CHAMP models show excellent qualitative agreement with our benchmark ARC-GP model (Fig. 5a) except within about 6° of about the north pole where disagreement is clear as ring-like artifacts discussed above persist. The correlation coefficients between the filtered Eigen2ee and ARC-GP as well as between PGS-7772 and ARC-GP are 0.862 and 0.909 respectively. We have done the same filtering to other CHAMP models and the corresponding correlation coefficients are shown in Table 1. The residuals or differences between filtered ARC-GP and the various CHAMP and GRACE models are also shown in Table 1.

GRAVITY RMS Difference	(mGal)	GEOID RMS Differences (m)	Correlation Coef w.r.t ARC-GP
GRACE (GGM01S)	2.34	0.35	0.987
GRACE (EIGEN-GRA)	2.47	0.36	0.986
CHAMP (PGS-7772)	5.69	0.59	0.909
CHAMP (TUM-1S)	6.29	0.664	0.886
CHAMP (OSU3A)	6.43	0.681	0.881
CHAMP (EIGEN-2ee)	6.86	0.696	0.862
CHAMP (EIGEN-2)	8.02	0.778	0.817
CHAMP (UCPH)	8.31	0.993	0.807
vs other global satellite model:			
Multi-Sat(EGM96S)	8.24	0.995	0.780

Table 1. RMS Differences and correlation coefficients between ARC-GP and satellite models after 2.5° gaussian filtering.

4 Geoids combining GRACE and surface data

In Fig. 7a note the GRACE GGM01S (Tapley et al., 2003) geoid which has been constructed using all s.h. coefficients complete to degree and order 120. Plotted in Fig. 7b is a hybrid geoid which combines GRACE data at long wavelengths and ArcGP at short ones using a remove-restore method as follows. First the GRACE/ggm01s and and the ArcGP geoids were both low- pass filtered (with a 3.5° radius gaussian) . Then the filtered ARC-GP is subtracted from the ArcGP itself to get residuals which then are added the back to the low pass-filtered GRACE.

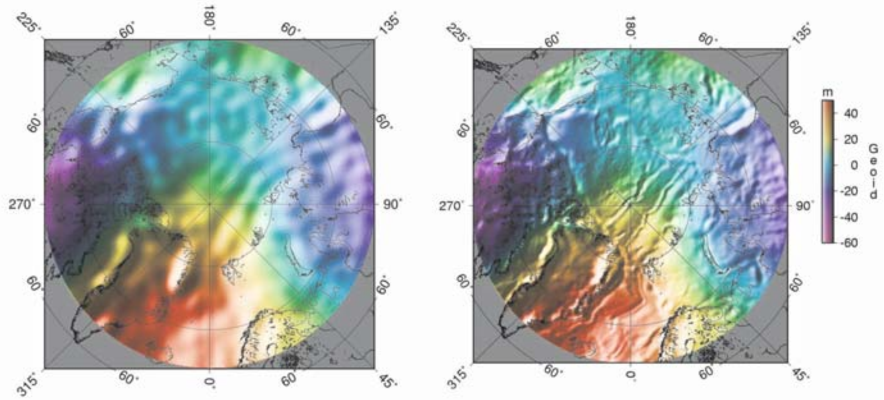

Fig. 7. (a) GRACE GGM01S 120x120 geoid (left), and (b) a hybrid geoid combining GRACE and ARC-GP models (right, see text).

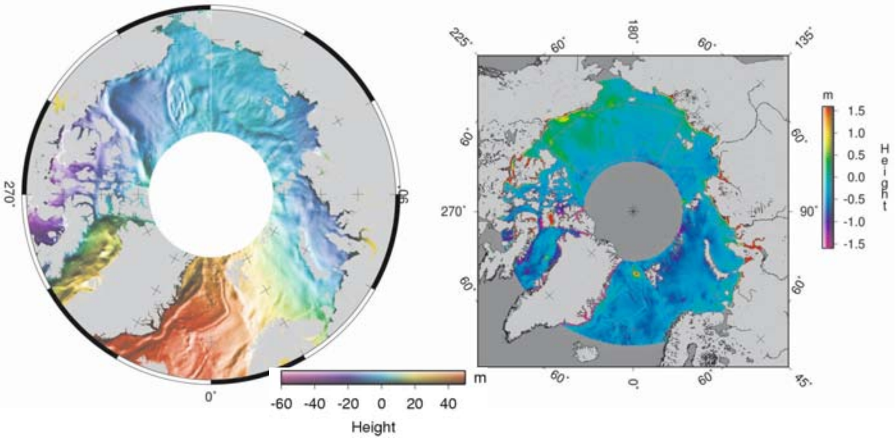

Fig. 8. (a) Left: ERS-1, four-year mean sea surface (MSS), (b) Right: ERS MSS minus hybrid geoid (Fig. 7b); Note the windshield-shaped test region F extending from 150E to 230E (see text).

As a preliminary demonstration of the utility of such a "Hybrid" Arctic geoid we have subtracted it from a mean sea surface (Fig. 8a) constructed from 4 years ('94-'97') of re-tracked ERS-1 data (Peacock and Laxon, 2003) . The difference between this mean sea surface and the hybrid geoid is plotted in Fig. 8b. Does this mean sea surface (MSS) minus geoid represent dynamic topography in the Arctic Ocean? Clearly there are some residual, fine scale geoid artifacts which result however some evidence of dynamic topography, e.g Beaufort Gyre effects may be seen in Fig. 8b. There are few conventional hydrographic observation in the Arctic with which to judge Fig. 8b. In test region F (Fig. 8b) the rms difference signal is less than 19 cm. The corresponding difference between the ERS MSS and the ARC-GP geoid is 27 cm and the difference between the ERS MSS and GRACE geoid is 36 cm. We appear to be on the threshold of detecting dynamic topography of the Arctic Ocean. However the Arctic Ocean's dynamic signal is thought to be more subtle (Maslowski, 2000), more transient and of a smaller spatial scale than that of other ocean basins. So we will need to compute a more precise, detailed, GRACE-based hybrid geoid if we are to confidently detect dynamic ocean topography in the Arctic using satellite altimetry from new and future missions.

5 Conclusions

The new CHAMP and GRACE gravity models are yielding substantial, scientifically important improvements in our understanding of the Arctic geopotential. Our analyses show that CHAMP and GRACE accurately resolve Arctic gravity to *full* wavelengths as short as, or shorter than, 1000 km and 500 km respectively. Moreover CHAMP models continue to show improvement in resolution – a process which should continue as the three-and-half years worth of current CHAMP observations, plus years of future observations, are analyzed. Both CHAMP and GRACE are reducing long-wavelength gravity errors in the Arctic by at least as much as they are globally. The precision of the EIGEN-GRACE and GGM01S GRACE models are nearly identical notwithstanding the larger amount of data in GGM01S.

As an example of how these new satellite missions will benefit Arctic oceanographic and sea ice studies we have presented a preliminary GRACE-ArcGP hybrid geoid. Future GRACE- and CHAMP-based geoids should have the accuracy needed to detect - with altimetry - poorly known dynamic topography of the Arctic Ocean.

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