Time variations in the GRACE gravity field: Applications to global hydrologic mass flux

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Abstract. Monthly Gravity and Climate Experiment (GRACE) geopotential solutions computed by UTCSR and JPL for 18 distinct months in 2002-2004 (22 solutions in all) have been analysed for secular and annual time variations. Many low degree and order terms have significant Signal/Noise (S/N) in the time-dependent parameters including a secular C_{201} trend which implies increasing oblateness during this period counter to the long-term trend from post-glacial rebound. However the majority of time-terms have poor discrimination $S/N \leq 2$ and in the applications it was generally necessary to smooth all terms to get ”realistic” results. In sum, global time-signals associated with seasonal water mass flux between the continents and oceans are clearly evident. On continents these GRACE seasonal signals indicate water storage variations as large as 18 cm (thickness equivalent) over the breadth of the Amazon basin and of smaller magnitudes over other large drainage basin systems in Siberia, Southeast Asia and Central Africa. Similarities between these GRACE results and hydrologic models (drainage runoff, precipitation rate) are shown. In the oceans the GRACE results reveal seasonal changes with amplitudes as large as 3 cm/month (water thickness equivalent) over places such as the western Chukchi Sea. We have also computed the trend and annual terms in the global ocean mass flux from the significant time-varying harmonics. The results are compatible with recent estimates of the eustatic (mass-only) secular rate from tide gauges, hydrography and glacial wasting, and Topex/Poseidon - steric estimates of annual change in sealevel.

1 Geopotential with Time Varying Coefficients

The GRACE Project has supplied us with 22 ”monthly” geopotential solutions to at least 70x70 in spherical harmonics for which the best sub-monthly models of geophysical time variations in the range-rate between the two subsatellites have been removed (e.g., from tides and meteorology; Tapley et al, 2004). We use the standard geopotential model in the C_{nmi} coefficients:

$$U_e = \mu_e/r \sum_n \sum_m \sum_i C_{nmi}(r_e/r)^n Y_{nmi}(\phi,\lambda),$$
$$Y_{nm1} = P_{nm}Cos(m\lambda),\ Y_{nm2} = P_{nm}Sin(m\lambda) \qquad (1)$$

where P_{nm} are fully normalized Associated Legendre Functions of degree n and order m , and r, ϕ, and λ are radius to the c.m. of the Earth, geocentric latitude and longitude respectively. Also μ_e and r_e are the (Gaussian) mass and mean equatorial radius of the Earth.

We first fit (by least squares) the 22 ”monthly” coefficients C_{nmi} (with their formal standard errors) to the time variable model:

$$C_{nmi} = C_{nmi,0} + C_{nmi,t}t$$
$$+C_{nmi,c}Cos(\alpha t) + C_{nmi,s}Sin(\alpha t) \qquad (2)$$

where α is annual rate, and the first two terms on the right are the mean and secular terms. We then convert the time-dependent harmonics to water-layer equivalents (Munk and Macdonald, 1960):

$$H_{nmi,(t,c,or\,s)} =$$
$$r_e(2n+1)[3(\rho_w/\rho_e)(1+k_n^{'})]^{-1}C_{nmi,(t,c,or\,s)} \qquad (3)$$

where ρ_w is the density of water, ρ_e is the mean density of the Earth and $k_n^{'}$ are the load Love numbers (Munk and Macdonald, 1960; Wagner and McAdoo, 1987).

The errors in the water-layer harmonics are taken as the product of the diagonals of the inverse times the standard deviation of the fitted 22 monthly harmonic terms (see figures 1 & 2). (Since the four JPL monthlies during 2003 covered nearly the same GRACE data as those for UTCSR we scaled up the formal errors for both these models by $2^{1/2}$ in fitting their coefficients to the longer time-series.)

Figure 1 shows a generally declining series for C_{201} in 2002-4, an increasing oblateness significantly larger than the

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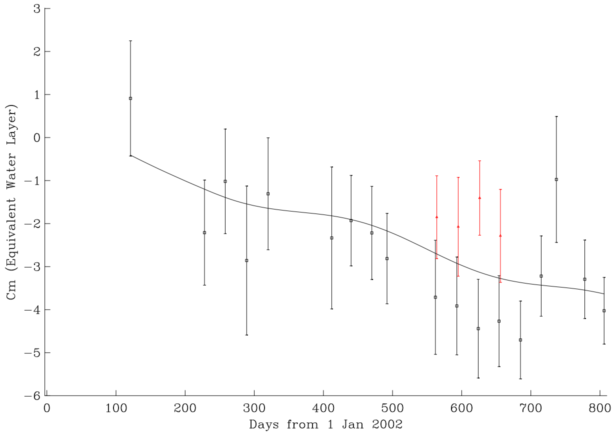

Fig. 1. Change of Geopotential Term C_{201} from Monthly Grace Tracking (2002-4). The data are from "monthly" UTCSR (black) and JPL (red) solutions. The errors are formal SDs adjusted to the overall standard error of the least-squares fitted curve which includes a mean, a trend and two annual terms. The measured trend is $-1.7 \pm 0.5 mm/yr$. The secular rate used for the Grace orbits is (in water equivalent units) 0.10 cm/yr. The long-term trend from satellite tracking is thought to be 0.24 cm/yr but changed to -0.25 cm/yr in the time period 1997-1998 (Cox and Chao, 2002).

"reversal" measured by Cox and Chao (2002) during the last La Nina. This "reversal" is with respect to the long-term trend towards a more spherical Earth which is used in the Grace reference model reflecting two decades of satellite laser ranging (IERS Standards 2000, see Bettadpur, 2003). While the GRACE sensitivity to C_{201} is poor compared to other low degree harmonics, the secular term here has a Signal to Noise ratio $S/N = 3$. However other low degree terms have particularly high S/N in the annual terms such as C_{801} (Figure 2).

Still as figures 3 & 4 show the number of terms to 70x70 with significant annual variations is sharply limited mostly but not entirely to low degree and order.

We note that (i); The higher orders (M) of strong annual terms do not seem to follow the resonant orders of the GRACE orbit but rather the longitude dispositions of the large water transfers on the Earth's surface and (ii); while many monthly fields were also determined to 120x120, their terms above 70 have not proven reliable in the applications even with modest smoothing (see below).

On the other hand, even a perfect 70x70 band-limited geopotential can yield poor estimates from edge effects on small basins (see e.g., Wahr et al, 2004). Thus in the applications we generally limited our results to both smoothed and significantly determined "change terms" only. Our smoothing of spherical harmonics uses the algorithm made popular by L.P. Pellinen (personal communication, 1965) which results in geopotential harmonics representing a surface function continuously averaged over a spherical cap of a given radius.

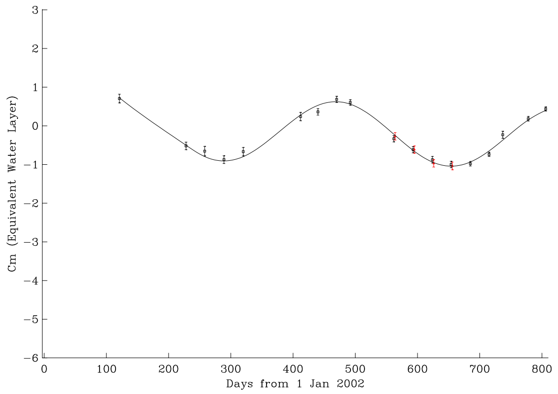

Fig. 2. Change of Geopotential Term C_{801} from Monthly Grace Tracking (2002-4). Data and curve circumstances are the same as in Fig. 1. The signal/noise for the annual terms are $>$ 21 a large improvement over the same result for C_{201}.

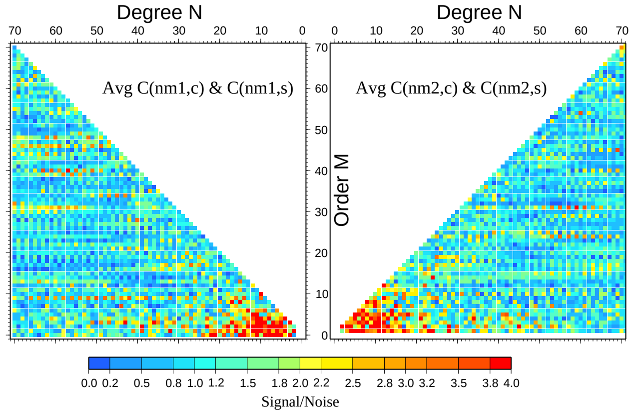

Fig. 3. Signal/Noise for Annual Terms from 22 monthly Grace Geopotentials. Only the 70x70 portion of the determined changes to degree 120 are shown here, the terms above degree 70 are correlated among the monthly fields from a priori constraints and both the potential and time-change parameters for them have proven unreliable in the applications. Only about 30% of the terms have $S/N > 2$, mostly of low degree and order.

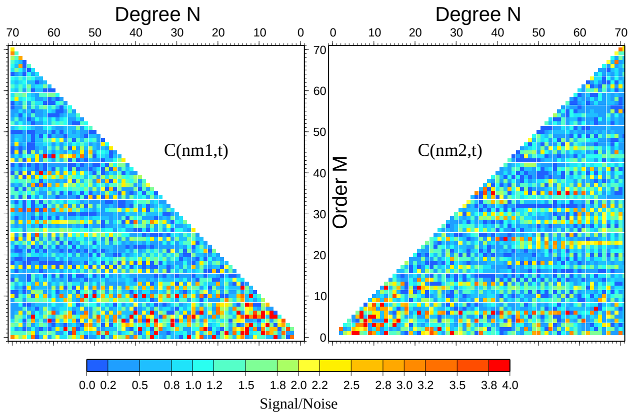

Fig. 4. Signal/Noise for Secular Terms from 22 monthly Grace Geopotentials. See fig. 3 caption.

2 Application: Water Discharge over Large Basins: The Amazon

From the water layer harmonics we have their time-varying components at a location given as:

$$H^{\phi,\lambda}_{t,c,\,or\,s} = \sum_{n} \sum_{m} \sum_{i} H_{nmi,(t,\,c,\,or\,s)} Y_{nmi}(\phi,\lambda), \tag{4}$$

and the amplitude of the annual rate of change of this layer is:

$$H_{an.\,amp.} = \alpha[H_c^2 + H_s^2]^{1/2} \tag{5}$$

Considering the large number of terms (especially those of high degree) with poor S/N discrimination in the time variables, we only examined those with $S/N \geq 2$ and in addition averaged these results over caps of 8.46^o radius (equivalent to $15^o x 15^o$ equatorial squares). Figure 5 shows the annual amplitude rates for the sum of these significant water-layer harmonics.

Amazonian flux dominates the apparent hydrologic signals in Fig. 5 with lower amplitudes evident in Southeast Asia (Mekong drainage) and other continental areas. Less clear is the significance of the variations over the oceans. This is evident on examination of annual precipitation rates from the NOAA CDC re-analysis program (Figure 6) which shows large signals in the tropical and subtropical oceans as well as continental areas. Remarkably though, Figure 7 shows a close correspondence of Grace and CDC precipitation results over the Amazon basin in terms of discharge rate (the opposite of water rate into the basin). The GRACE data interpreted as runoff at the mouth of the Amazon ignores losses due to evaporation and storage, yet overestimates by only about 40% the normal annual flow there with close to traditional timing in early summer.

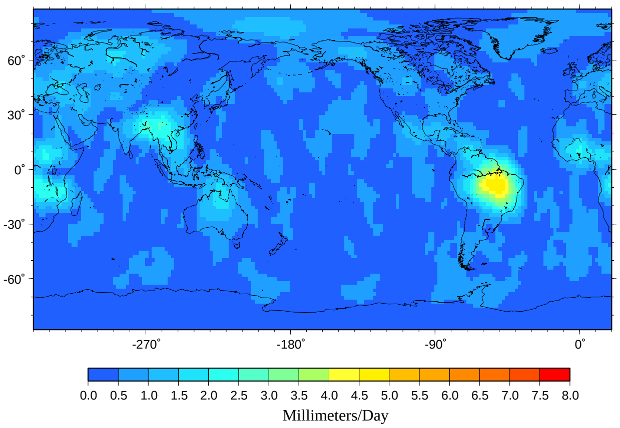

Fig. 5. Amplitude of Annual water level Changes from Grace Monthly Fields, $S/N < 2$ cutoff, 8.5^o cap smoothed. The scale has been set to emphasize the dominance of Amazonia but a closer examination shows: (i), significant amplitudes in S.E. Asia, Central and South Africa, Northern Australia, and Siberia related to known seasonal hydrologic activity and (ii), generally smaller amplitudes over ocean areas which tend to dissipate short-term inputs from river discharges and rainfall.

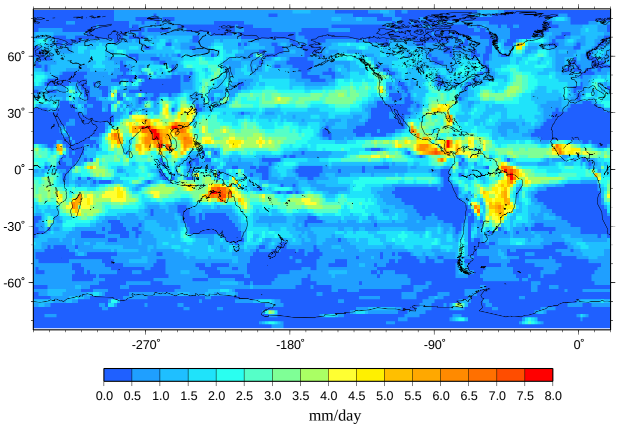

Fig. 6. Amplitude of the Annual Precipitation Rate: 2002-4 from monthly NOAA/NCEP/NCAR Reanalysis grids. Annual changes are large in many ocean areas as well as over land areas seen in fig 5. But over the ocean Grace suggests the changes largely dissipate.

3 Application: Global Mass Flux over the Oceans (eustatic change in sealevel)

Using the same significant and smoothed time-variable terms discussed previously for "Amazonia" we expanded the "basin" to include all the oceans and found a trend and fluctu-

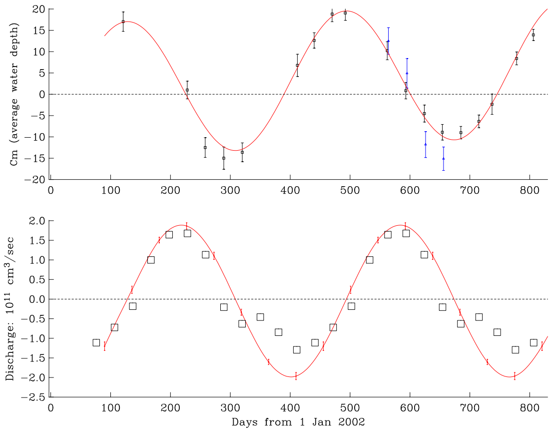

Fig. 7. Changes in Water Depth and Discharge for the Amazon Basin at its mouth from Grace (2002-4). Upper panel; data, equivalent water depth by month from UTCSR (black), JPL (red) geopotential's; red curve, best fit trend and annual terms to this data. Basin area $= 6.17x10^6 km^2$. Lower panel; data (black), from NCAR/NCEP monthly Reanalysis grids averaged over the same basin; red curve, from the derivative of the Grace water-depth curve in the upper panel. The correlation of the Grace discharge with the NCAR/NCEP data is good despite ignoring evaporation losses after precipitation and storage delays before runoff.

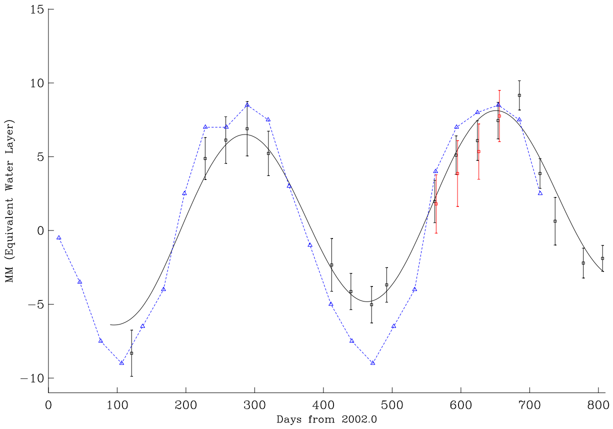

Fig. 8. Variation of Mean Global Ocean Mass: Grace vs T/P Altimetry: 2002-4. Data: with error bars, from Grace monthly geopotential solutions from UTCSR (black), from JPL (red); without error bars (blue-dash) from T/P altimetry - Steric estimates (Chambers, Wahr and Nerem, 2004). The Grace trend of $+1.6 \pm 0.6\, mm/yr$ is compatible with current estimates of eustatic sealevel change from tide gauges, hydrography and glacial ablation.

ation compatible with estimates from altimetry and hydrography (see Figure 8). Our Grace measured annual change (amplitude 6mm) is reduced by about 30% from unsmoothed harmonic values but also does not include contributions from first degree harmonics (Earth Center of Mass changes) which were not resolved in the monthly Grace solutions. As Chambers, Wahr and Nerem (CWN,2004) show, likely annual ECM changes would increase the Grace amplitude by about 10%. On the other hand the Topex/Poseidon altimetry-steric (volumetric change) estimate (CWN, 2004) covers only the T/P ocean which is roughly 95% of the global ocean. A previous study of 10 years of T/P altimetry - steric sealevel (Chen et al, 1998) also agrees well (on average) with our Grace result in timing, but again with somewhat greater amplitude.

In addition to this rough agreement with the annual mass changes we note that a recent estimate from long-term tide-gauges, hydrography and ice-mass wastage of 1-1.5 mm/yr is also compatible with our Grace-measured trend in global ocean mass change (Miller & Douglas, 2004).

In the Grace result shown in Figure 8, as in the Amazonia application, we limited ourselves to smoothed change-terms with significant Signal/Noise (only $\sim 30\%$ of all the terms to 70x70). However to strengthen our finding we relaxed these limitations and first averaged over all terms without smoothing or regard to Signal/Noise. The sealevel trend determined was 1.5 mm/yr with a much larger error estimate of 3.6 mm/yr. Smoothing reduces the error to 0.8 mm/yr with an increased trend of 1.8 mm/yr reflecting the greater influence of C_{201} compared to higher degree terms.

How important is the large Grace-measured C_{201} rate to global sealevel? With smoothing but using all other change terms except C_{201} the sealevel rate reduces to 0.6 mm/yr showing C_{201} is certainly influential but not essential to a positive change. Averaging over the oceans reduces the influence of the secular rate of C_{201} by more than 1/10. Indeed this averaging turns the sign of the C_{201} rate around since the ocean areas are mostly in lower latitudes where greater oblateness results in a positive change.

4 Conclusions

GRACE shows good promise in constraining global hydrologic models in terms of overall mass-transfer though its currently poor sensitivity to higher degree terms limits its usefulness for this purpose. Nevertheless, averaging its implied mass changes over the largest basins yields results for Amazonia (annual) and for global sealevel (both trend and annual) which appear quite realistic.

Acknowledgements. We thank Jaroslav Klokocnik and Katrin Weisse for help with the manuscript. We acknowledge and thank the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, for data (see Fig 8) from their Web site at http://www.cdc.noaa.gov/. The contents are solely the opinions of the authors and do not constitute a statement of policy,

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