ICESat, GRACE, and Time Varying Gravity: SLR Contributions and Applications

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Abstract

Temporal changes in the Earth's gravity field have a rich history of study, prediction, measurement, and with today's technologies, monitoring. Over the past 25 years, the need to improve the modeling of these effects within SLR precision orbit determination investigations and in the context of the geophysical interpretations of the results developed from SLR, has progressed significantly and added challenging complexity to SLR pursuits. Laser altimeter missions, like ICESat and DESDynI provide another component for better understanding and monitoring geodynamical systems having topographical manifestations.
The GRACE mission, launched in 2002, has now operated for approximately 6 years, producing monthly and ten-day snapshots of the variations of the gravity field of the Earth. The available solutions either from spherical harmonics or from mascons provide new monitoring capabilities for integrated surface mass flux. Through extensive validation with independent sources, GRACE derived products have been shown to be highly reliable. A wide range of independent sources of derived time gravity variations, when tested in forward modeling approaches for GRACE, have been shown to significantly reduce the variance levels seen in GRACE highly precise KBRR data analyses. This paper will review some of the comparisons which have been made comparing GRACE-derived science products with these independent sources – including ocean tides, atmospheric pressure variations, surface hydrological mass variations, and ice sheet mass changes from ICESat. We will also show the significant improvement obtainable in SLR orbit recoveries if these same forward models are applied.

Introduction

Satellite Laser Ranging was the first satellite tracking technology with sensitivity to gravity field variations ongoing within the Earth's system like tides. Given that SLR alone was able to deliver high measurement precision in the 1970s and 1980s, the study of global-scale mass motion was coupled with many SLR analysis activities with SLR contributing significantly to improving tide models at their longest wavelengths (e.g. Christodoulidis et al, 1988).

SLR analyses over the last two decade, in addition to improving models of the tides and static gravity model, have also allowed time histories of the longest wavelength components of the gravity field to be estimated. These investigations both confirmed and at times confounded geophysical models which predicted these changes (e.g. Cox and Chao, 1998) where for example, the anticipated secular rate of J_2 was observed to have significant deviations. .

Starting in 1980, a major effort was expended to meet the orbit accuracy requirements needed to support the TOPEX/Poseidon (T/P) mission. These investigations were afforded a lead time of more than a decade before the 1992 launch of T/P. A central component of this effort was to improve the time-averaged gravity model while also assessing the sensitivity of the radial component of this orbit to various sources of mass redistribution. As a result of these analyses and the requirements they defined, accurate tide modeling goals were developed, and long wavelength models improved and tested for orbit applications using SLR. The SLR and DORIS tracking systems were also simultaneously assessed to ensure that their data could support the orbit determination refinements delivered from much more complicated tide models. .

TOPEX/Poseidon was highly successful in delivering radial orbit accuracies which significantly exceeded pre-launch mission goals and ushered in a new era in the remote sensing of the ocean using radar altimetry. Whereas ±14 cm RMS orbits were sought, ±3 cm orbits were delivered. This in turn compelled the orbit determination teams to revisit both the time averaged and time variable gravity models. These investigations resulted in significantly more complex models, especially for ocean and solid earth tides, and improved gravity fields, which when adopted, improved the orbits henceforth. This cycle has been repeated until the present where we are now realizing nearly ±1 cm radial RMS orbits on Jason and reprocessed TOPEX/Poseidon orbits are close to approaching this level of accuracy. The history of these improvements is depicted in Figure 1.

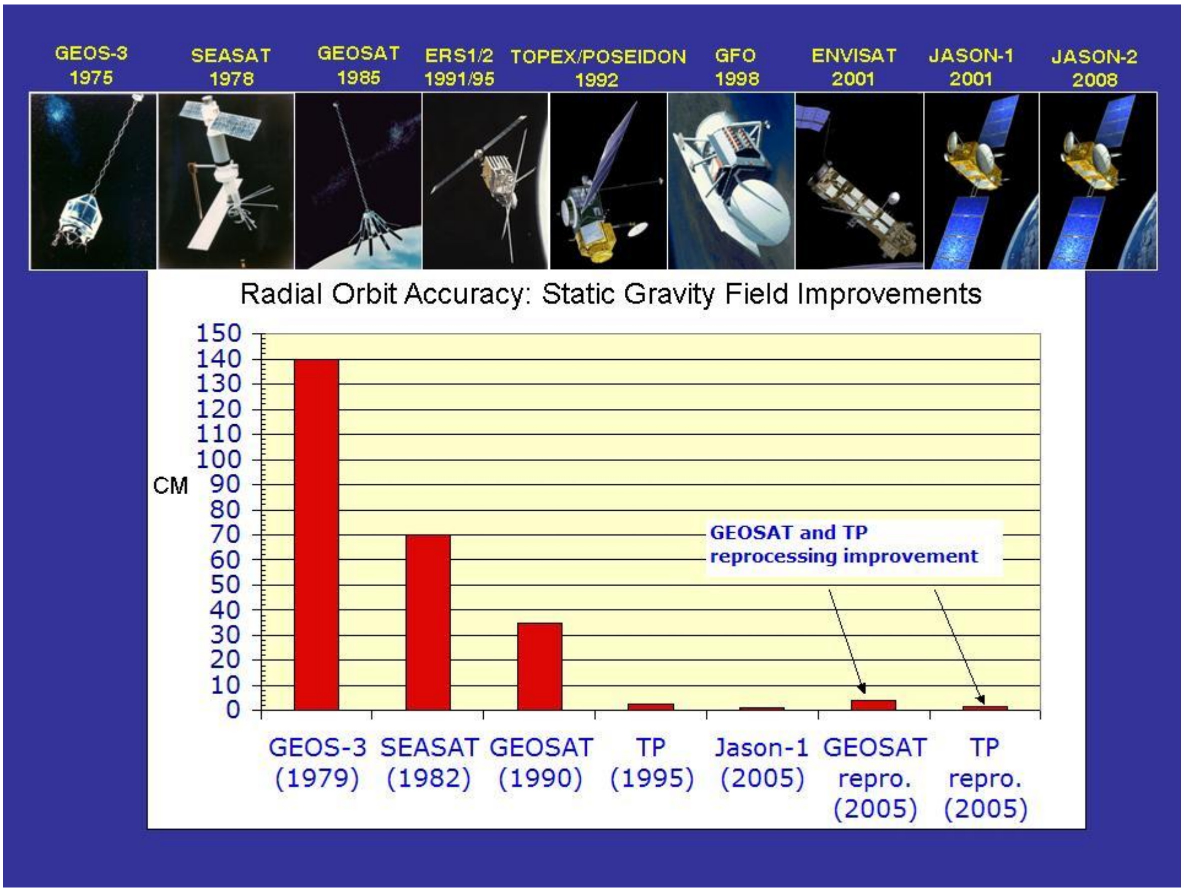

Figure 1. Improved force modeling including large models for tides have yielded a steady improvement in orbit accuracy for altimeter missions.

In parallel, the ability to measure changes in the gravity field with high temporal and spatial resolution has been a major goal for space geodesy missions over the last three decades. Today there are multiple missions that are focused on accurately monitoring mass variations, and using these capabilities to directly measure important manifestations of climate change (GRACE, ICESat, CryoSat, GOCE).

The GRACE Mission stands out given its seven years on orbit continuously acquiring exquisitely accurate intersatellite tracking at the 0.3 micron/sec level, and has driven major advancements in all aspects of monitoring mass motion to isolate signals arising from hydrological and geophysical sources which heretofore could not be measured synoptically. As this paper will show, SLR investigations can benefit from inclusion of a significantly improved time varying gravity time series for precision orbit and reference frame improvements.

GRACE.

The Gravity Recovery and Climate Experiment (GRACE) Mission was designed to monitor local, regional, and global changes in the Earth's gravity field. GRACE is sensitive to changes in the gravity field due to any mass being transported in the Earth's oceans, atmosphere, and on land surfaces within its bandwidth of resolution. Analysis of the data delivered by GRACE yields a direct measure of mass flux with high spatial resolution on the Earth's surface. This is accomplished at one month intervals through the estimation of monthly gravity fields [Tapley et al., 2004]. The spherical harmonic models of the gravity field produced to date from GRACE are at least a two orders of magnitude improvement over any former modeling effort (e.g. Lemoine et al., 1998). This is a result of the special design of the GRACE Mission and its exquisitely accurate measurement of the range-rate between two co-orbiting satellites separated by approximately 250 km using a highly stable K-Band link (KBRR). These data give GRACE unique sensitivity to the accelerations induced on low Earth orbiting satellites from the surface mass along the satellite's ground track

In the analysis of the GRACE data, it has been desirable to forward model time varying gravity signals that are captured in independent and well tested models. The forward models include extensive high degree and order spherical harmonic representations of the solid Earth and ocean tides, global variations in atmospheric surface pressure, and the response of the oceans to atmospheric pressure loading that is non-barothropic. Figure 2 shows a comparison of the atmospheric pressure modeling delivered by two different forecasts. These are large effects clearly sensed by GRACE. To eliminate atmospheric pressure changes through forward modeling, we are now using 3hr global time series in our analyses.

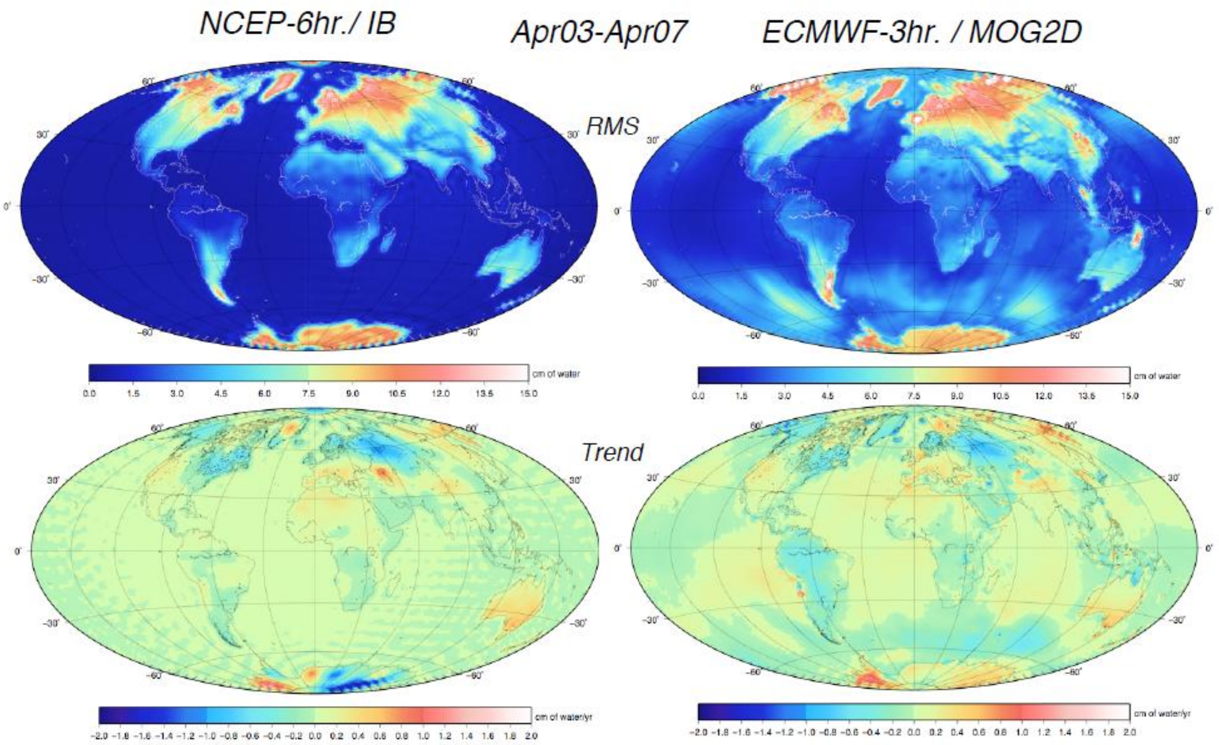

Figure 2. Atmospheric pressure variations are forward modeled in GRACE data reductions. Herein we show the 4 year average variation and secular trend from two independent atmospheric forecasts. Units are surface mass in equivalent cm of water.

With these forward models being applied, the continental hydrological mass flux can be isolated and monitored using GRACE. For example, at GSFC we have made regional solutions for mass flux using a mascon representation (Rowlands, et al, 2005). Shown below (Figure 3) is a ten-day GRACE-recovered time series of the surface mass change over India. Each cell is 4x4 degrees in spatial resolution. Clearly seen is the mass change occurring due to monsoon rains.

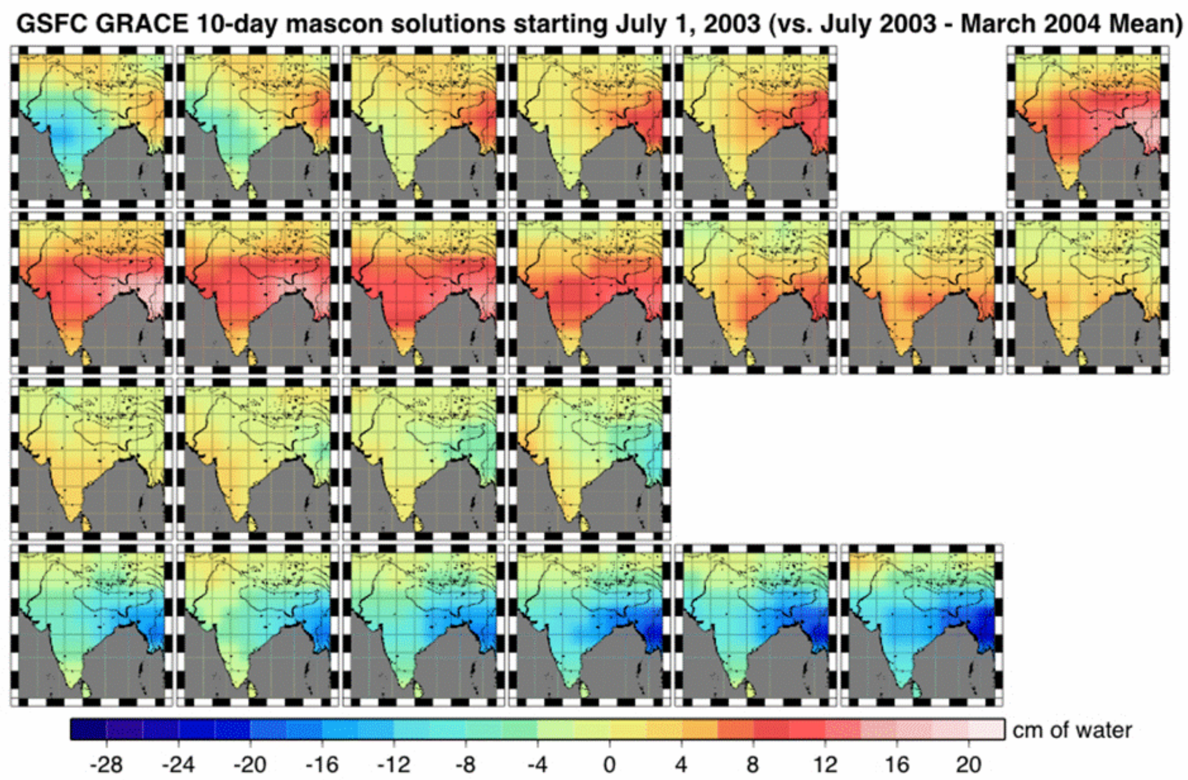

Figure 3. Mascons over the Indian Subcontinent with 400 km spatial resolution and 10-day temporal resolution for 2003-2004. GRACE is capable of observing coherent mass change signal at 400 km spatial and 10-day temporal resolution. Gaps in time series are due to GRACE data outages.

Validation of GRACE Time Series

Before adopting GRACE and the forward models used to support these analyses, it is important to verify GRACE mass flux estimates. The GRACE Science Team has made an extensive effort to verify that the GRACE mass flux estimates are confirmed using independent data sources. Described below are two comparisons performed by our group.

The first study was a comparison of GRACE derived hydrology versus *in situ* data in the Mississippi Basin (Klosko et al, 2009 in press). The Mississippi Basin has accurate surface hydrological modeling available from the Global Land Data Assimilation System (GLDAS, Rodell et al, 2004), which uses advanced land surface modeling and data assimilation techniques. There is also a wealth of groundwater data obtained from a regional well network. This provided an opportunity to quantitatively compare GRACE estimates of the mass flux in the entire hydrological column with those available from independent and reliable sources. The Mississippi Basin is one of the few regions having a large hydrological signal that can support a meaningful GRACE comparison on the spatial scale resolved by GRACE. As noted above, the isolation of the hydrological signal is dependent on the adequacy of the forward mass flux modeling for tides and atmospheric pressure variations. While these models have non-uniform global performance they are excellent over the Mississippi Basin.

As shown in Figure 4, we found that the mass anomalies, as represented by surface layer of water within regional cells have accuracy estimates of ±2-3 cm on par with the best hydrological estimates and consistent with our accuracy estimates for GRACE mass anomaly estimates. This validation confirmed that GRACE could provide critical environmental data records for a wide range of applications including monitoring ground water mass changes.

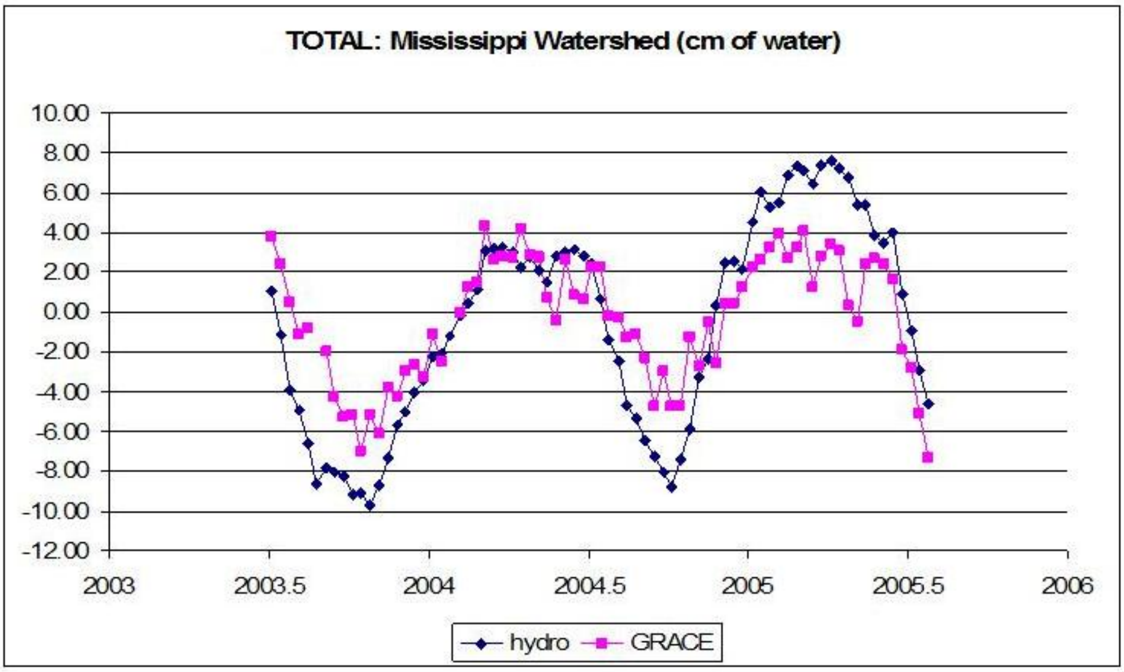

Figure 4. GRACE masons in cm of equivalent water (purple) compared to hydrology (blue) spatially averaged across entire Mississippi watershed. Cross correlation is shown between time series. The RMS agreement between the two time series is 2.9 cm representing the combined error for each independent source.

A second example of our verification activities compares the mass flux occurring over Greenland from two independent sources (Luthcke, private communications) – GRACE, which directly supports estimation of mass changes, and ICESat, which measures changes in the ice surface topography. While the ICESat time series provides distinct measures only twice per year, the GRACE time series is continuous. In order to make this comparison, the density of Greenland's ice was modeled at 0.77 g/cm^3. As shown in Figure 5, there is a remarkable level of agreement of the mass loss occurring over Greenland from these independent systems.

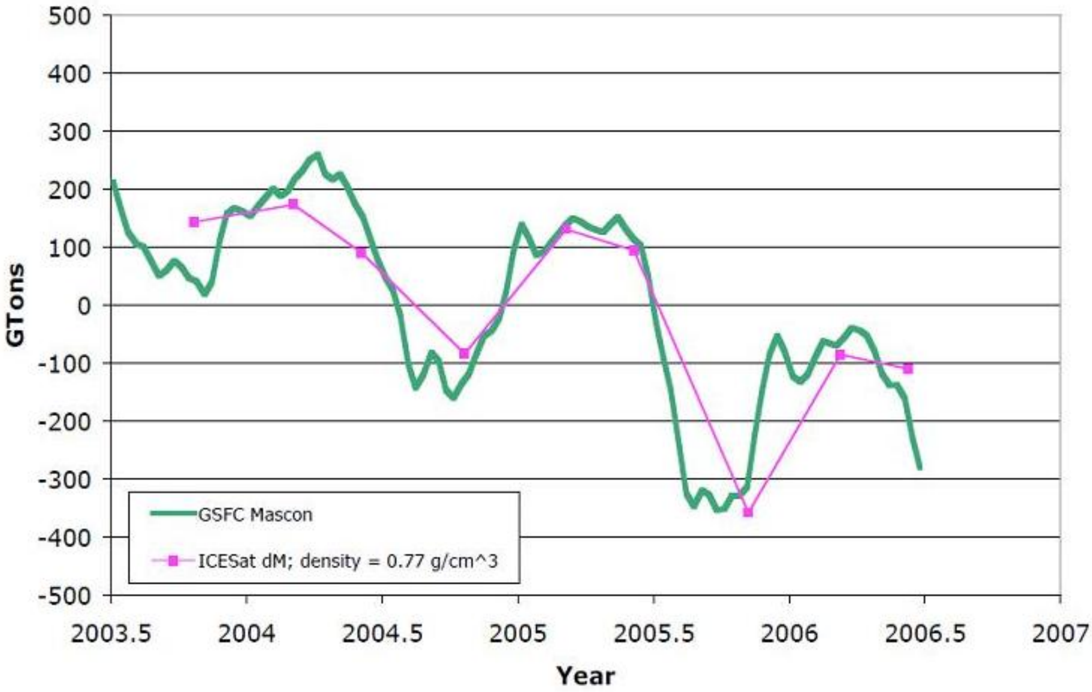

Figure 5. The mass flux over Greenland is estimate using two independent remote sensing systems. GRACE measures the dm/dt whereas ICESat provides a measure of di/dt where m is mass, and i is ice surface height changes. Both systems recover a compatible time series.

SLR Orbit Improvements

Clearly, from the above discussion, one can see that there is a wealth of high fidelity information about the mass flux occurring across the Earth's systems. Furthermore, based on the post solution fit to the GRACE data, we are confident that these series are quite accurate and should not be ignored by other studies requiring precision orbit determination.

As discussed above, one of the most demanding orbit determination applications is found in supporting ocean radar altimeter missions. All orbit errors translate into a corruption of the sea surface heights obtained by these orbiting radars. In Figure 6 we review the mass flux signals and their effect on the orbit of Jason. Clearly, with 1 cm orbits being sought, these are important effects and their neglect results in systematic long wavelength errors in surface height measurements across key ocean basins.

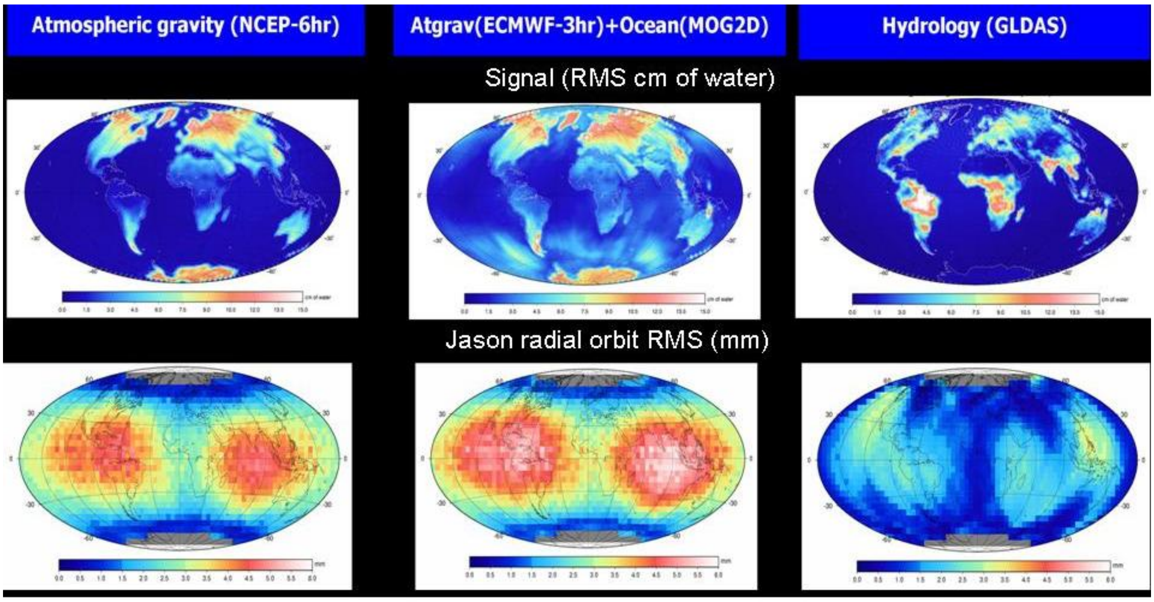

Figure 6. High fidelity mass flux modeling for the well resolved atmospheric pressure, non-barotrophic ocean response to atmospheric loading, and within the continental hydrosphere significantly improves orbit accuracies for altimeter missions. The scale for the top row of figures is mass flux of from 0 to 15 cm of equivalent water; the bottom row is 0 to 6 mm RMS of radial orbit effect (with blue being no change).

In the following tables we provide a direct comparison of these mass flux models on the orbits of Jason and LAGEOS 1 and 2. We provide the RMS of fit to the laser and DORIS tracking data to show that SLR is sensitive to these mass flux sources, and the variance of fit to the data is reduced as these models are employed in orbital solutions.
Table 1 presents the results for Jason.

Table 1. Shown are the RMS of fit to the Jason DORIS, SLR and Altimeter Crossover measurement types tested over 23 cycles when using different time varying gravity models.

Jason Solution	DORIS RMS (mm/s)	SLR RMS (cm)	Alt xover RMS (cm)
No non-tidal time varying gravity (GDR release)	0.4034	1.484	5.579
Atmospheric Gravity using NCEP-6 hr	0.4033	1.444	5.564
ECMWF-3hr + Barotropic Ocean (MOG2d)	0.4033	1.441	5.562
ECMWF- 3hr + Barotropic Ocean (MOG2d) + Hydrology (GLDAS)	0.4033	1.427	5.560

Table 2 presents the results for the LAGEOS 1 and 2 satellites.

Table 2a and 2b. Shown are the RMS of fit to the LAGEOS 1 and 2, SLR measurements tested for all monthly arcs for years 2003 through 2007. Table 2a shows the reduced variance from improved when using different time varying gravity models. Note, annual models complete to degree and order 20 for the mass variations derived from GRACE are inadequate to explain the full hydrological signal.

2(a)

Solution	Description	LAGEOS 1 RMS (cm)	LAGEOS 2 RMS (cm)
Slrtest N (Nominal)	ITRF2005 stations/oloads; GGM02C 10 day empirical corrections	1.6379	1.4782
N_ecmwf6	N + Atmosphere (ECMWF 50x50_6hr)	1.5808	1.4350
N_ecmwf3	N_ecmwf6 + ATGRAV_apr02_jul07_ecmwf_mog2d_boy3hrn9	1.5745	1.4225
N_eigen	N_ecmwf3 + EIGEN GL04S1	1.5804	1.4197
N_eop	N_EIGEN + improved ocean loading	1.4748	1.3395
N_hydro	N_eop + grvtim_sph_v02_annual20x20_apr03_apr07.osts	1.4372	1.3074
N_opr5day	Slrtest +_hydro + 5 day empirical corrections	1.1452	1.1465

2(b)

Solution	Lageos 1 RMS (cm)	Lageos 2 RMS (cm)
Slrtest N (Nominal)	-	-
N_ecmwf6	0.43	0.35
N_ecmwf3	0.45	0.40
N_eigen	0.43	0.41
N_eop	0.71	0.63
N_hydro	0.79	0.69
N_opr5day	1.17	0.93

From both set of tests it is clear that significantly improved orbits and fits to SLR data are obtained with more complete force modeling. It is therefore recommended that the standards adopted for orbit analyses when producing solutions for the ITRF or for altimeter mission support be augmented to include the complete suite of now available time varying gravity models.

Summary

This paper has shown comparisons which have been made comparing GRACE-derived science products with these independent sources – including ocean tides, atmospheric pressure variations, surface hydrological mass variations, and ice sheet mass changes from ICESat. We then show that there is significant improvement obtainable in SLR orbit recoveries if these same models are applied.

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