Arctic Ocean Tides from GRACE Satellite Accelerations

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Residual Tide Amplitudes, Relative to FES 2004

GRACE measures gravity fluctuations using two satellites in the same low-earth orbit. One satellite is ~220km ahead of the other, and the two satellites are connected by a microwave ranging system that continuously measures their relative separation distance. Because the first satellite is ahead of the second, it's affected by differences in local gravity before the second satellite. This delay can be used to deduce the underlying gravity variations. Many GRACE projects describe these gravity variations using spherical harmonics, but we chose to use mass concentrations (or "mascons") to parameterize variations in local gravity.

7 years of GRACE inter-satellite accelerations were inverted to solve for the following tide amplitude maps. The inversion used point mass mascons separated by 230 km. These accelerations have had FES 2004 and various dealiasing products subtracted, and have been smoothed by a 20 second CRN filter. Tikhonov damping is applied by adding an identity matrix (multiplied by 20) to the covariance matrix before solving for the tide amplitudes. Ampitudes and phases for M2 and K1 were solved simultaneously over the entire region shown in figures 1-2, along with the O1 tide, a constant, linear trend, semi-annual and annual periods (not shown). Each figure is accompanied by a small version of the matching FES tide and its (saturated) color scale which is much larger than the main figure's color scale.

Figure 1

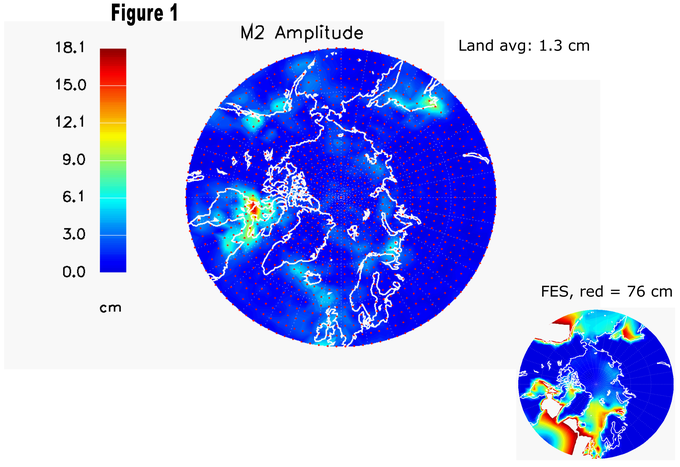


Figure 2

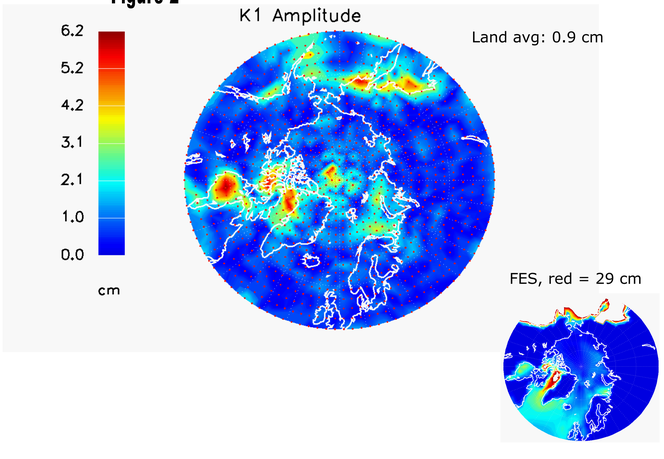


Figure 5

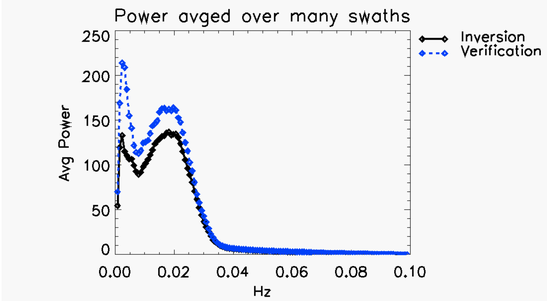


Figure 6

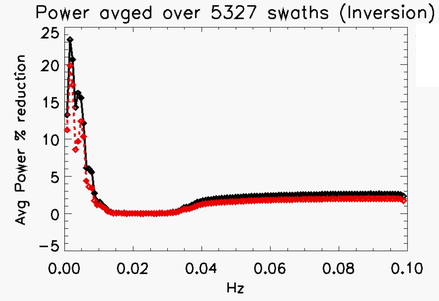
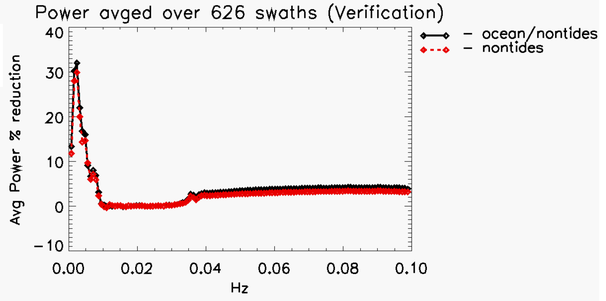


Figure 7



Uncertainty

The full 7 year dataset is split into two independent parts each with 3.5 years of data. Both parts are inverted separately, then the cosine and sine coefficients of the resulting maps are subtracted to obtain the difference maps in figures 3,4. These difference maps likely overestimate the uncertainty in the full 7 year solutions, an effect which is most obvious in K1 at the north pole due to K1's long (~7.5 year) alias period in GRACE data.

Another uncertainty estimate is derived from the tide amplitude on land (which should be zero, and thus estimates noise). Those land estimates (listed on figures 1,2) can be compared to the average ocean value in figures 3,4. K1's average ocean value falls to ~1.2 cm when the anomaly at the north pole is removed.

Figure 3

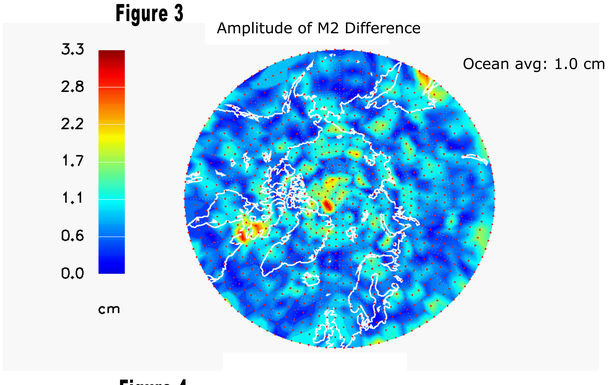
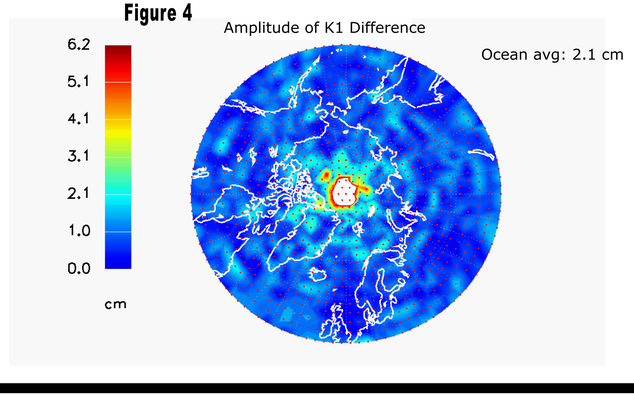


Figure 4



Verification of Residuals

The mascon fields have much larger tide amplitudes in the ocean than on land, and generally have higher amplitudes where FES 2004 is also highest. Land tides are assumed to be due to instrumentation noise, aliasing and leakage from the oceans. These mascon fields should reduce the variance of residual GRACE accelerations. 5 years of residual accelerations recorded every 5 seconds when the satellites are north of 50N are used here because they're processed with a CRN filter cutoff of 50s, whereas the 7 year dataset has more noise due to its 20s cutoff. The first 80% of these accelerations are used to solve for the tides in figures 1,2 and O1, as well as a nontidal part (not shown) consisting of a constant, linear trend, semi-annual and annual amplitudes. The last 20% of the data are reserved to verify that the inverted mascons reduce the variance of acceleration values not used in the solution. The power spectra of inversion and verification accelerations are shown in figure 5.

The accelerations due to the nontidal part of the solution are subtracted from the original accelerations, then the additional reduction in variance due to the tides is calculated. The reduction due to tides is calculated separately for ocean tides (defined as tides at mascons with at least some ocean) and land tides (tides at mascons with no ocean.) Each of these reductions are calculated separately for those accelerations used in the inversion (figure 6) and those reserved for verifications (figure 7). Notice that the black curve is above the red curve in figures 6-7, which shows that the ocean tides provide an additional variance reduction on top of the nontidal parameters even for verification accelerations.

In addition to examining the power spectra, the overall variance reduction at all frequencies can be calculated for ocean tides and land tides, as applied to inversion and verification accelerations respectively:

- Ocean tide variance reduction for inverted accelerations : **1.64%**
- Ocean tide variance reduction for verification accelerations: **1.42%**
- Land tide variance reduction for inverted accelerations : **0.32%**
- Land tide variance reduction for verification accelerations : **0.20%**

Notice that the ocean tides reduce the variance of the verification accelerations by **86%** as much as they reduce the variance of inverted accelerations. The land tides reduce the variance of the verification accelerations by **62%** as much as they reduce the variance of inverted accelerations. Ideally, these percentages (which are for M2,K1,O1 combined) would be 100% for ocean tides and 0% (or negative) for land tides. When M2 is examined alone, its percentages are **98%** for ocean tides and **82%** for land tides. For K1 alone, the percentages are **68%** and **31%**; for O1 alone, they're **72%** and **29%**. Thus M2 appears to be anomalous compared to K1 and O1, in the sense that M2 tides (land and ocean) are unusually effective at reducing the variance of verification accelerations.

Conclusions

- The mascon fields have much larger tide amplitudes in the ocean than on land, and are mostly larger where FES 2004 is also larger. This reinforces the assumption that the ocean solutions do reflect the true tidal signal.
- Ocean tides reduce the variance of accelerations not used by the inversion nearly as well as they reduce the variance of accelerations used in the inversion. Land tides don't, so they're used as noise estimates. M2 land tides reduce the variance of verification accelerations more than expected and more than K1 or O1 for reasons that are currently being investigated.
- Two independent solutions (each using 3.5 years of data) are subtracted to provide another estimate of the uncertainty in the inversions which agrees with the land tide estimate.

References

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