Difficulties inherent in deriving high-frequency signal from series of overlapping GRACE RL04 solutions

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Abstract:

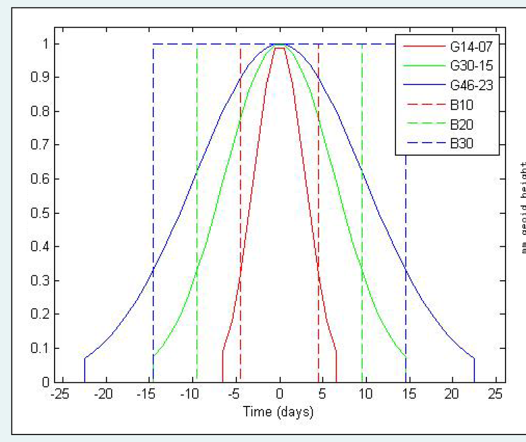
Hydrological and oceanographic analysis with GRACE has repeatedly demonstrated that the satellites' results at the annual and interannual level are excellent. However, few people have looked at GRACE results at frequencies faster than that, largely due to the monthly nature of the released fields. Through the use of an overlapping windowing technique, the frequency resolution of CSR GRACE RL04 has been enhanced, allowing weekly to monthly signals to be analyzed. We compare these results to other high-frequency GRACE series and external data. We determine that while GRACE retrieves appropriate hydrological signal at frequencies below 3 cycles/year, the signal-to-noise ratio makes it difficult in most areas to trust GRACE results at frequencies much above that. GRACE does seem able to retrieve valid signal up to 6-10 cycles/year, but only in regions where the non-seasonal signal is large compared to the expected error. Particular attention should be paid to GRACE signals with monthly or shorter periods, to make certain what GRACE reports has physical relevance.

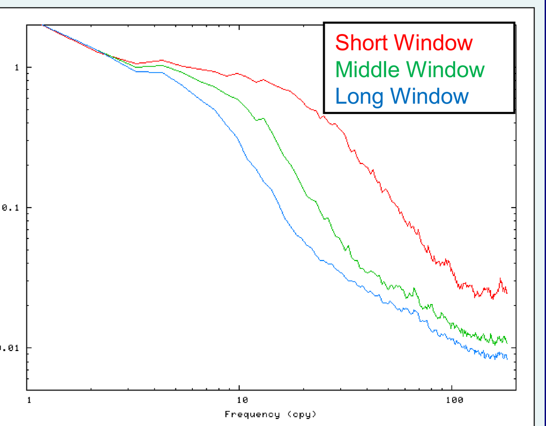
Overlapping Windowed Series:

Three "daily" CSR RL04-type series were made for 2005-2007 using an overlapping sliding-window technique.

Gaussian temporal windows give clean cutoff qualities and keep less "signal" above 30cpy. The degree/order characteristics are largely the same as in rectangular windows.

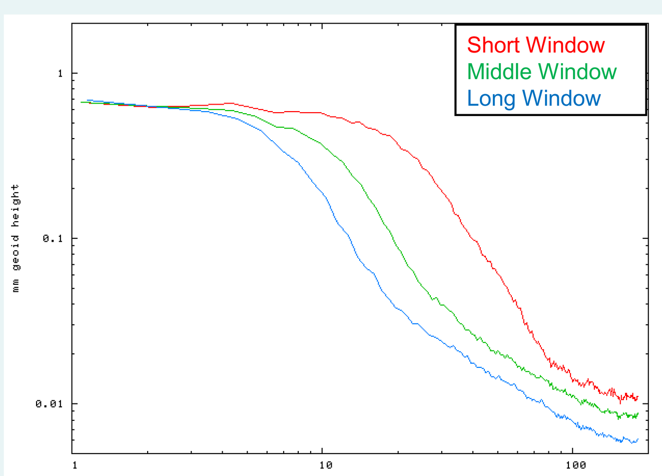
The series here are regularized using a preliminary constraint matrix by H. Save, and C_{20} has been replaced by SLR values.



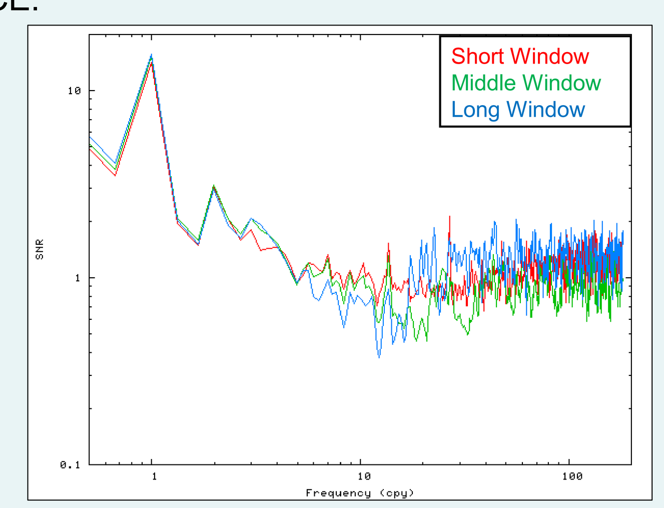


Series created with Gaussian windows:
Short: "10-day" window -- 6cpy cutoff / FWHM = 7days
Middle: "20-day" window -- 12cpy cutoff / FWHM = 15 days
Long: "30-day" window -- 18cpy cutoff / FWHM = 23 days

GRACE High-frequency Error Estimates and Signal-to-Noise Ratio by Frequency:



A simulation GRACE noise-only series was created by Furun Wang for 10 months of 2006-2007. The windowed results look like stripes and have appropriate distribution by degree and order. The frequency spectra (top left) looks very much like the actual (non-annual) spectra of GRACE.

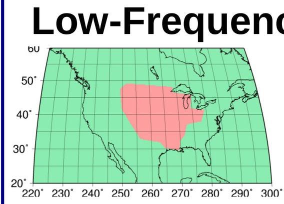


To the right is the global Signal-to-Noise Ratio (SNR) based on the simulation variability, scaled up by 1.8 to better match real GRACE solution variances. GRACE is most trustworthy at frequencies below 3cpy, and may be unreliable at frequencies above 10cpy. 2σ lower-bound error bars were constructed from the RMS of local basin averages, and used in the other plots on this poster.

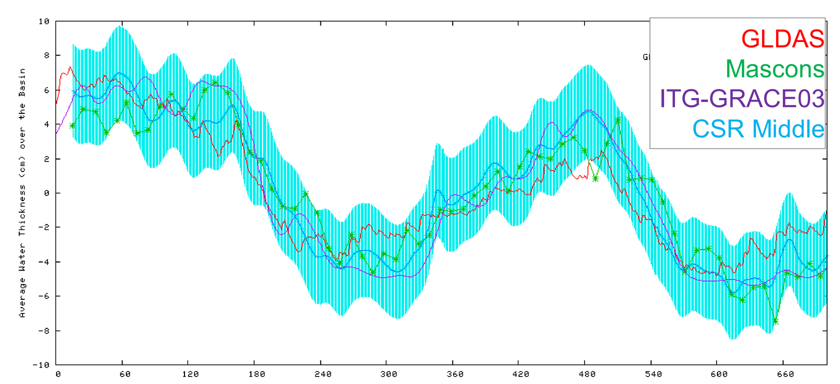
An upper-bound basin-average error estimate was calculated by translating the basin to a quiet region of open ocean and determining the actual high-frequency (f > 3cpy) RMS there. These error levels were always larger than the (un-scaled) simulated ones.

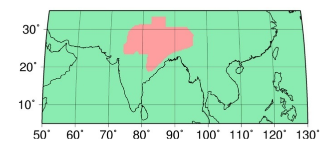
The regularization used here is a preliminary version which still contains significant signal in north-south "stripe" patterns, which makes the SNRs lower than they might be otherwise. Please see Himanshu Save's posted on recent improvements in CSR's regularization technique.

Low-Frequency (f < 3cpy) Basin-Average Analysis:

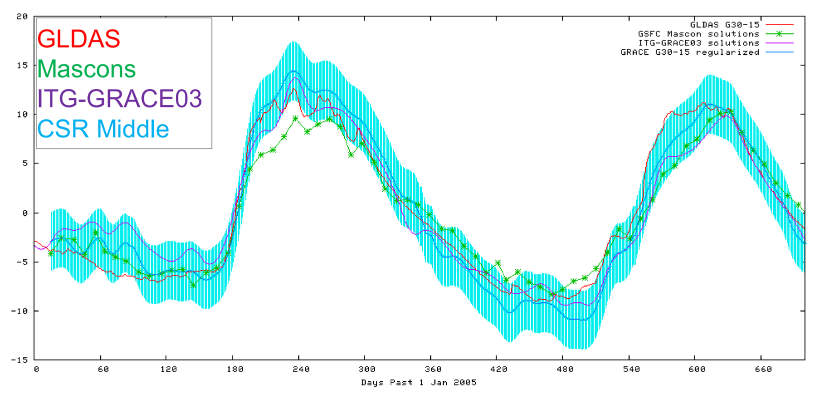


Mississippi Basin
Lowpass GLDAS correlations: 93-95%
Lowpass ITG/mascon correlations: 96-99%





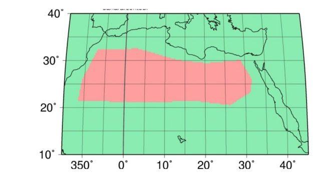
Ganges Basin
Lowpass GLDAS correlations: 98-99%
Lowpass ITG/mascon correlations: 99%



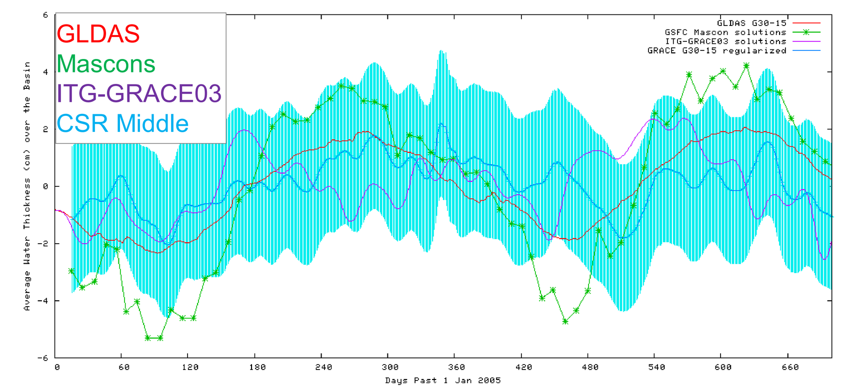
In most basins, low frequency signal can be retrieved equally well by any GRACE series.

In places with small near-annual signal, the four series pick up different signals.

2σ upper-bound error bars are shown, to give an estimate of noise.

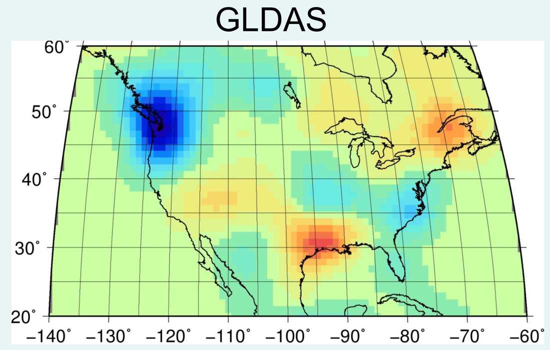


Sahara Basin
Lowpass GLDAS correlations: 98-99%
Lowpass ITG/mascon correlations: 99%

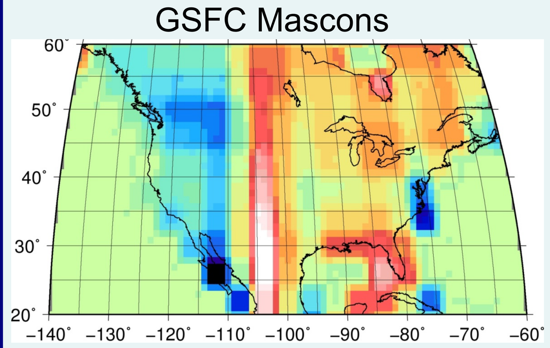


High-Frequency (f > 3cpy) Basin-Average Analysis:

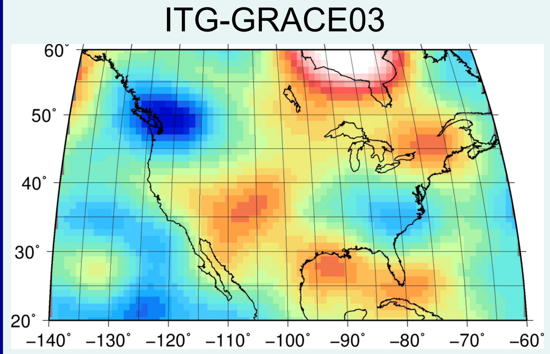
GLDAS



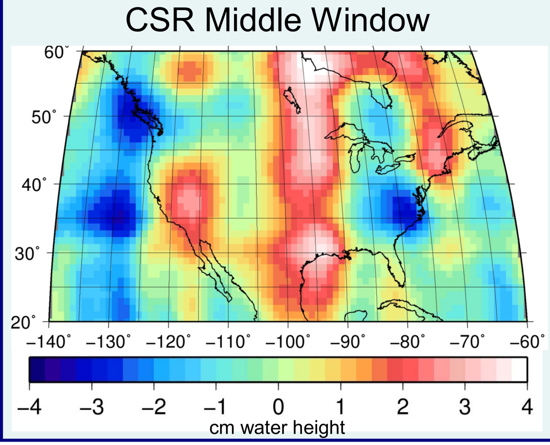
GSFC Mascons



ITG-GRACE03



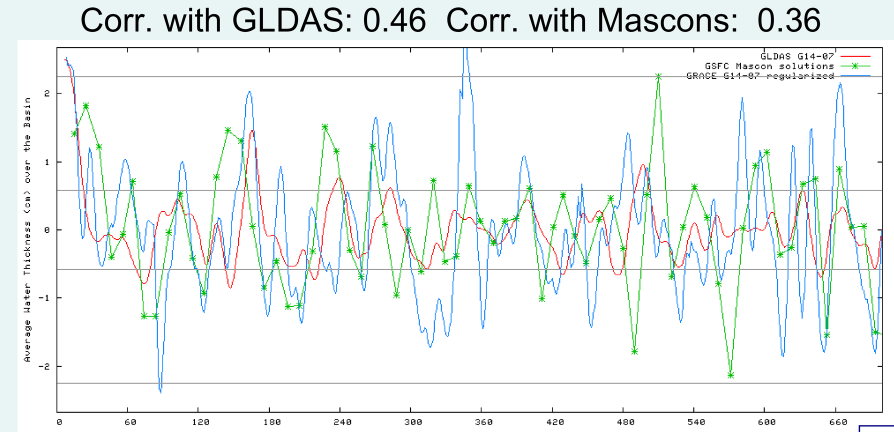
CSR Middle Window



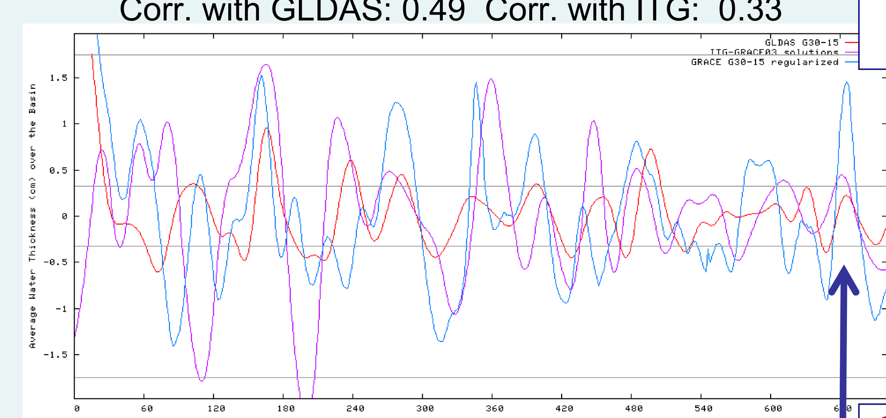
Mississippi Basin:

Correlations between series are low

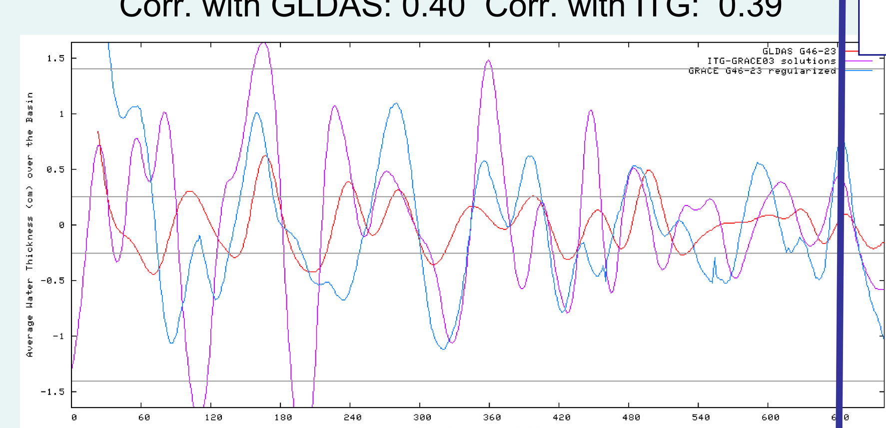
Short Window
Corr. with GLDAS: 0.46 Corr. with Mascons: 0.36



Middle Window
Corr. with GLDAS: 0.49 Corr. with ITG: 0.33



Long Window
Corr. with GLDAS: 0.40 Corr. with ITG: 0.39



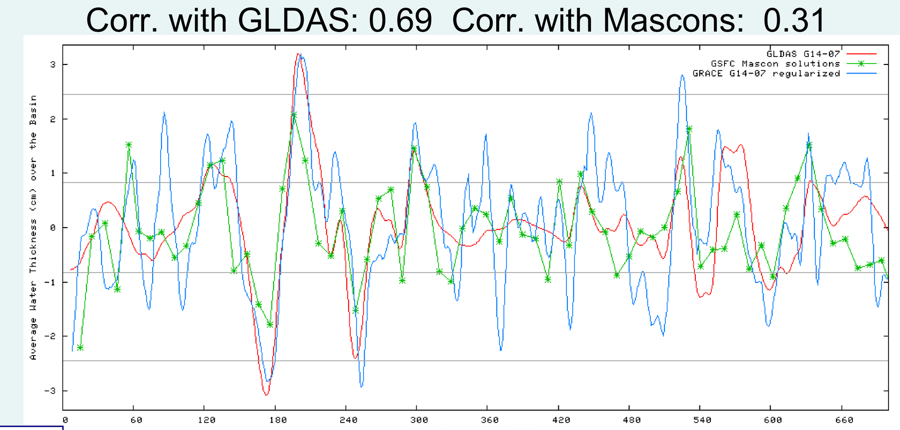
GLDAS
Mascons
ITG
CSR

A stripe-induced false signal in the CSR and mascon solutions, shown to left

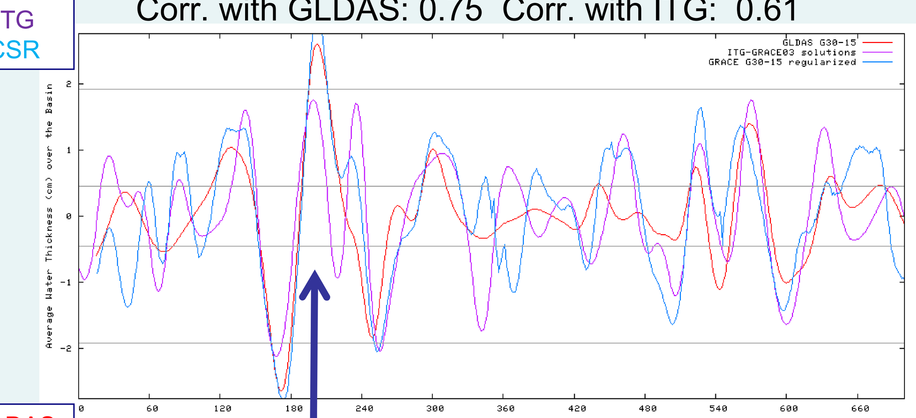
Ganges Basin:

Series show similar, coherent signal between 3-10cpy

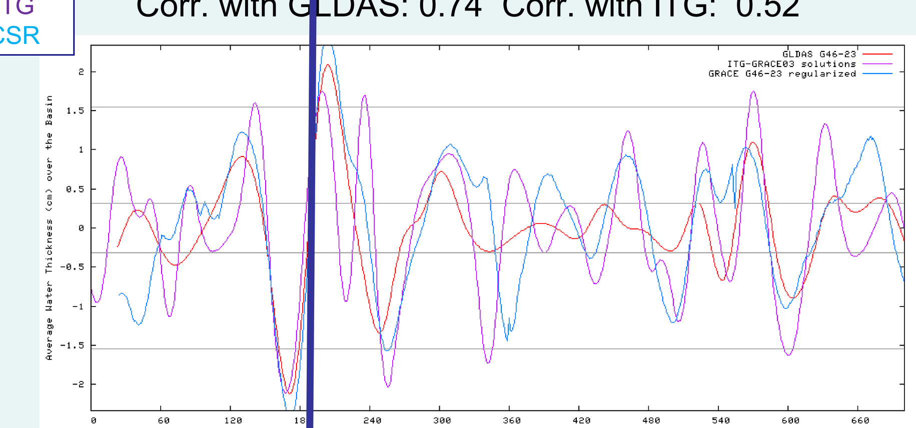
Short Window
Corr. with GLDAS: 0.69 Corr. with Mascons: 0.31



Middle Window
Corr. with GLDAS: 0.75 Corr. with ITG: 0.61



Long Window
Corr. with GLDAS: 0.74 Corr. with ITG: 0.52

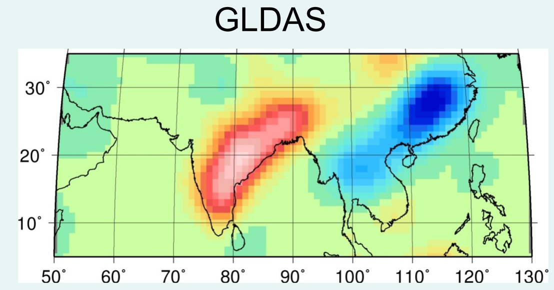


A realistic signal shown by all series (extra stripe in mascons), shown to right

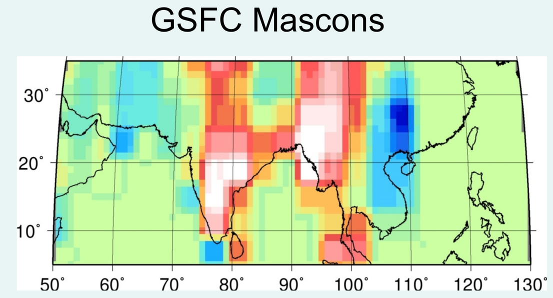
The 2σ upper-bound and lower-bound error bars for the windowed CSR series are shown.

300km Gaussian smoothing applied to all maps, except the mascons, which are at a 4°x 4° grid. GLDAS maps use a max/min scale of only 3cm.

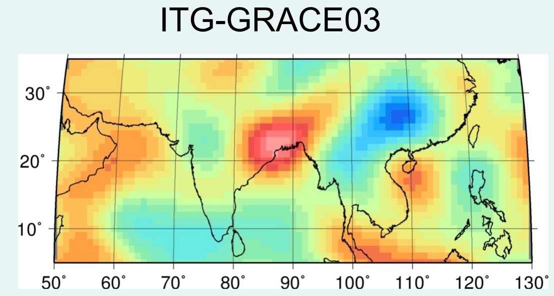
GLDAS



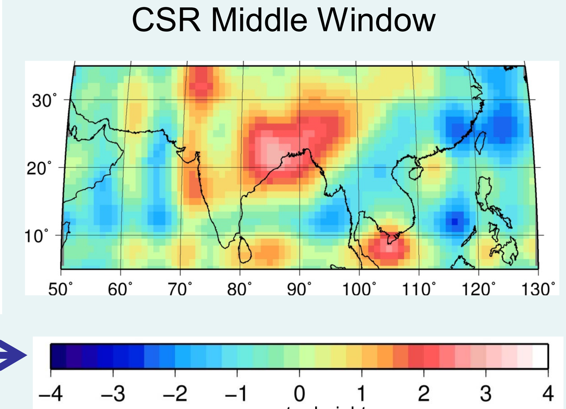
GSFC Mascons



ITG-GRACE03

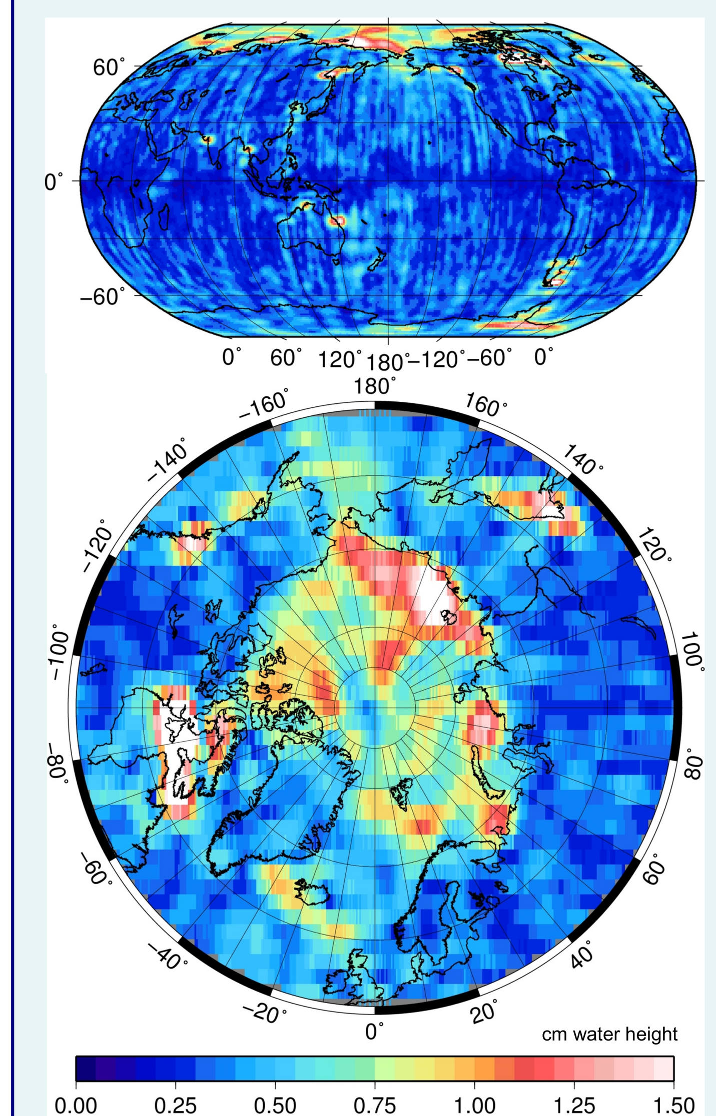


CSR Middle Window



High-Frequency (26.7cpy) M_f Tidal Errors

The RMS in ½°x ½° bins for CSR Short-Windowed Series is shown for frequencies 26-28cpy. The highest variability occurs in regions where the ocean tides are thought to be poorly-modeled. The arctic is a known weak point of the self-consistent equilibrium M_f tide which CSR uses as a model.



These signals cannot be seen by the Middle or Long CSR series, or by ITG-GRACE. The transfer functions of these longer windows prohibit it.

Searching for a specific local signal at a known frequency may allow higher frequencies to be confidently determined than using a generalized basin average.

Other High-Frequency GRACE Series:

Universität Bonn's ITG-GRACE03:
- Spline-based spherical harmonic results to degree 40
- Localized, constrained series
- 15-day nodal values allow creation of a "daily" solution series
- Comparable to the Middle or Long windowed CSR series

GSFC's 10-day Mascons:
- 4°x 4° "mascon" grids over partial continents only
- Localized, constrained series
- Data at non-overlapping 10-day intervals
- Comparable to the Short windowed CSR series

GLDAS-NOAH hydrological model:
- Daily-averaged values available
- Windowed to match the Short, Middle, and Long CSR series

Conclusions and Future Research:

Producing a high-frequency GRACE series which can pick up the seasonal signal is not difficult, but making one that has small enough errors to see non-seasonal signal is. The spectra of the GRACE noises is too similar to the signal for global windowing to help. Some constraint seems needed, if signals smaller than the seasonal are not to be confused with noise.

Globally, the regularized CSR series have low SNRs at frequencies above 3cpy and SNRs of 1.0 above 10cpy. Basin averaging gives seemingly similar results in most areas. GLDAS, ITG-GRACE03, and GSFC's 10-day mascons sometimes give correlated basin averages between 3-10cpy, but have no significant correlation above that. Correlated signals have peak-to-trough heights of 2-4cm, but non-correlated signals of the same size exist. At different times, all three series diverge from the others.

The windowed CSR solutions cannot reliably determine true non-seasonal hydrological signal from stripe-related errors. Nor can the GSFC mascons. ITG-GRACE03's results appear stripe-free, but still have multi-centimeter divergences from GLDAS and the other GRACE series. One might tentatively assume from the lack of stripes that ITG-GRACE03 is better-constrained than the CSR or GSFC series.

Absolutely determining which GRACE series (if any) is correct during times of divergence is difficult due to the paucity of large-scale, high-frequency ground data. Comparisons with GLDAS are suggestive but insufficient, since GLDAS has weaknesses of its own. Searching for locations where high-frequency data exists over a region large enough to be useful for GRACE is an area of ongoing study.

The M_f tidal error test demonstrates that when the signal is large enough, GRACE can determine it. Using an appropriate window is important, since the window's transfer function determines which frequencies have enough gain to be seen. But since little guaranteed hydrology signal can be seen 10cpy, using a shorter window means GRACE will pick up little higher-frequency hydrologic signal, at the cost of more noise at the lower frequencies.

While most previous studies have focused on the annual and semiannual frequencies, the full "seasonal" cycle extends beyond that. Ignoring the other parts of the GRACE results means ignoring most of the GRACE errors. But it also means not seeing the correlated portion of the high-frequency signal shown above. The RL04 noises are still too high to make non-seasonal signal extraction a sure thing. But RL05 GRACE should contain fewer errors, allowing smaller signals to be seen clearly.