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Continental Hydrology Loading Observed by VLBI Measurements

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Abstract

Vertical deformation due to hydrological loading is large enough to be seen in VLBI geodetic parameter estimates. Typical peak-to-peak vertical variations are 3-10 mm at VLBI sites. The hydrological signal at VLBI sites generally has a seasonal character, but we also observe interannual variations. These variations are caused by temporal variations of the geographic distribution of surface mass. Here, we have calculated the mass loading derived from GRACE gravity measurement time series from 2003 to 2011. Specifically, we have evaluated the convolution of Farrell's loading Green's function with the global loading mass field, given by a global grid of equal-area GRACE mascons [2]. We compare hydrology site loading series derived from GRACE with those computed using the GLDAS hydrology model derived by the NASA GSFC GLDAS team [1]. We obtained a clear reduction in baseline length and site position scatter when hydrology loading was applied in the VLBI analysis.

1. Hydrology Data

Vertical and horizontal hydrology loading is computed using the GLDAS NOAH model and the NASA GSFC GRACE Mascons. The GLDAS NOAH model is available at various resolutions, starting from a 0.25^o x 0.25^o global angular grid with a 3-hourly time resolution [1]. The GRACE Mascons are provided with 10-day resolution on a 2^o x 2^o equal area grid from the beginning of the GRACE period (2003) [2]. In our analysis we use a monthly average of the GLDAS NOAH model. The GLDAS NOAH model contains three parameters that are of interest to us: soil moisture, snow water equivalent, and canopy water. Since the GLDAS model does not account for ice sheet processes, areas with permanent frost are masked out. Another problem with the GLDAS NOAH model is that it is not designed to model groundwater, which is a significant part of the hydrology system.

GRACE monitors the gravity field of the earth at a very high precision. By measuring temporal variation in the gravity field, GRACE is essentially measuring the total surface mass change. This allows it to detect changes in groundwater stocks, mass changes within the oceans, and the mass balance over ice sheets. The GRACE GSFC mascons were generated employing modeling for atmospheric pressure variation, non-barotropic ocean response, and ocean tides [2].

The variability distribution (soil moisture + snow water + canopy water) of the GLDAS hydrology signal is similar to that for the GRACE Mascons, which can be seen in Figure 1. It can be seen that the variation of the hydrology signal is large in South America, Southern Africa, and South Asia, which means that we can expect a large loading signal in these places.

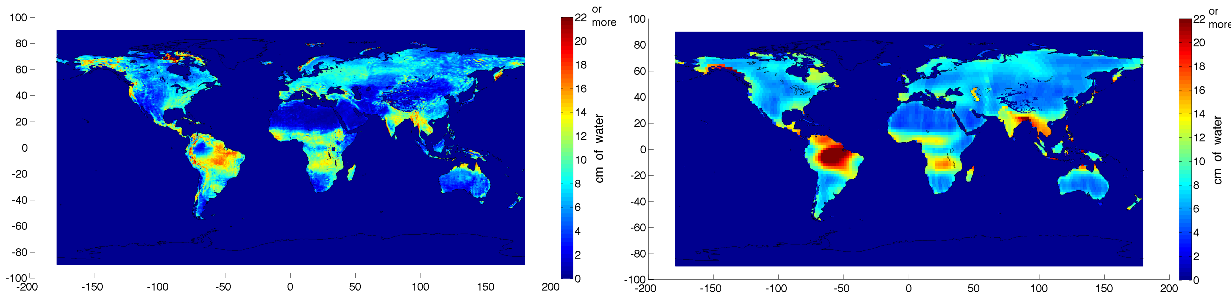

Figure 1. Standard deviation of the hydrology mass parameters in cm of water for (a) the GLDAS NOAH model and (b) the GRACE Mascons for areas without permanent ice. The range is from 0 to 22 cm.

2. The Green's Function Approach

According to Farrell (1972) [3] the local vertical displacement at time t due to mass loading at a point with coordinates (λ,φ) is given by

$$u_V(\lambda,\varphi,t) = \iint \Delta m(\lambda',\varphi',t) G_R(\psi)\cos(\varphi')d\lambda' d\varphi' \tag{1}$$

$$u_{EW}(\lambda,\varphi,t) = -\iint \sin(A)\Delta m(\lambda',\varphi',t) G_H(\psi)\cos(\varphi')d\lambda' d\varphi' \tag{2}$$

$$u_{NS}(\lambda,\varphi,t) = -\iint \cos(A)\Delta m(\lambda',\varphi',t) G_H(\psi)\cos(\varphi')d\lambda' d\varphi'. \tag{3}$$

Here Δm is the mass change, ψ is the angle between radial vectors to (λ',φ') and to (λ,φ), and $G_R(\psi)$ and $G_H(\psi)$ are the vertical and horizontal Green's functions. A is the azimuth angle between the local north vector and a vector pointing along the great circle toward the loading mass.

3. Characteristics of Hydrology Loading Displacements

Figure 2 shows some typical loading series from the GRACE period (2003-2010). The loading series shown are for two representative mid-latitude VLBI sites, Wettzell (Germany) and Hartebeesthoek (South Africa). Both sites are inland sites and are not sensitive to errors in the land-sea mask, which can cause errors for coastal and island sites. It is also clear that the three-dimensional loading displacements are predominantly in the vertical direction. Generally peak-to-peak loading displacements at VLBI sites are 3-10 mm in the vertical and a few millimeters in the horizontal. It can also be seen especially in the vertical that the hydrology loading series for these sites are clearly very seasonal. The peak-to-peak of the loading series is about 8 mm for Hartebeesthoek and 10 mm for Wettzell, which is large enough to be seen in VLBI analysis. The GRACE series has been smoothed since the original series are very noisy. Displacements are dominated by the near-field but the horizontal displacements additionally are more dependent on coherent signals farther away from a station. Horizontal loading series are also more sensitive to errors in the land-sea mask.

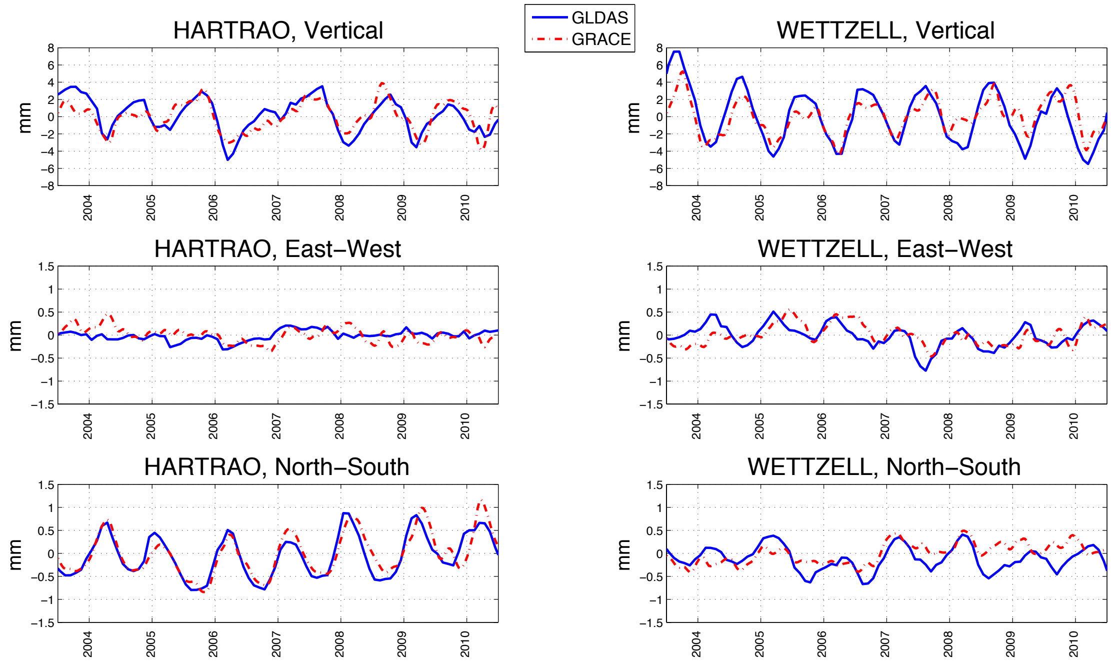

Figure 2. Loading series for Hartebeesthoek, South Africa and Wettzell, Germany.

4. Amplitude Variation of Vertical Loading on a Global Grid

To get a better picture of where the loading signal is significant we compute the loading for each cell on a 1^o x 1^o global grid. Two parameters of interest are the amplitude and the phase of the signal. Regions where the amplitude is expected to be large correspond to regions where the variance of the hydrology data is large in Figure 1. The variance plots provide no information about the phase of the signal. To estimate the amplitude and the phase, we fit a function for each cell

$$f(t) = a + bt + c\cos(2\pi(t - d/365.25)), \quad (4)$$

where t is the decimal year. By expanding the cosine term we can use linear least squares to estimate $c > 0$ and $d \in [0, 365.25]$ which are the amplitude and the phase, respectively. The estimated amplitudes and phases can be seen in Figure 3. The loading series peaks at t=d days, when the mass load is minimum.

5. Improvements in VLBI Analysis

We applied our loading series in standard Calc/Solve VLBI analysis to determine whether site position estimates were improved. We ran three solutions (without loading and then with each loading correction) to estimate daily site positions for the sites in our weekly operational R1 and R4 networks. We obtained the following results that can also be seen in Figure 4:

- Baseline length series variances are reduced for 80% of the baselines.

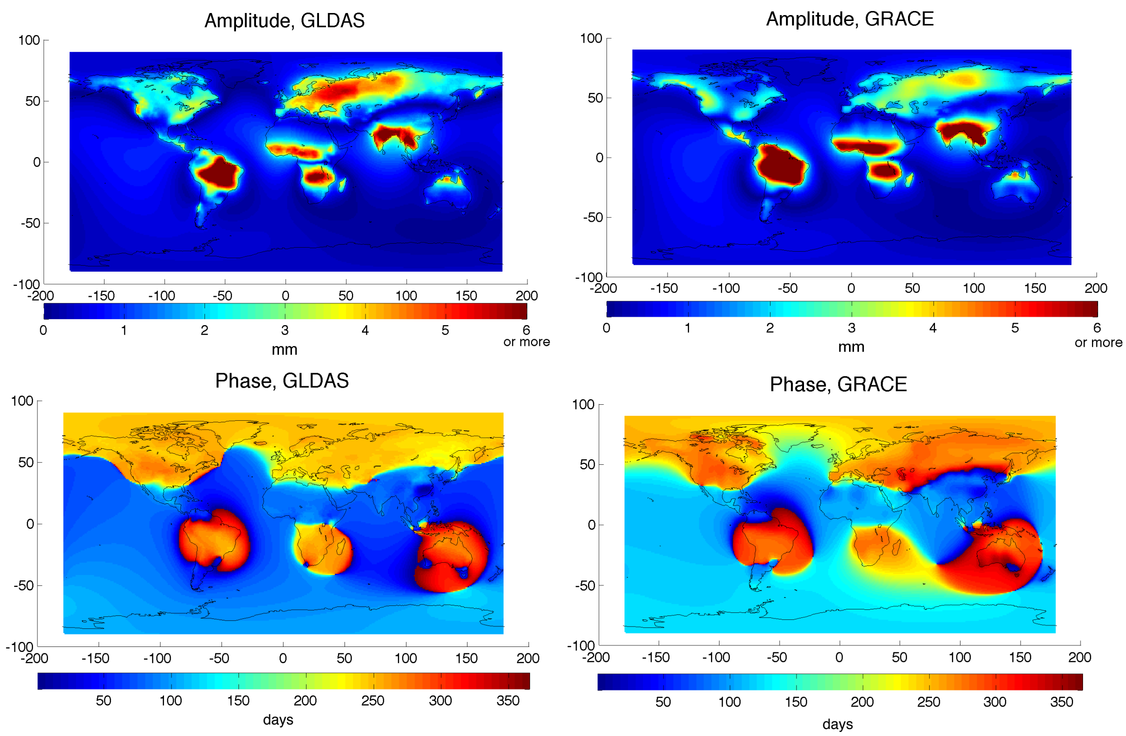

Figure 3. (Upper Left) GLDAS NOAH Hydrology Amplitude (Upper Right) GRACE Hydrology Amplitude (Lower Left) GLDAS NOAH Hydrology Phase (Lower Right) GRACE Hydrology Phase.

- The GLDAS and GRACE hydrology loading series are correlated and have similar amplitudes and phases.
- Applying GLDAS and GRACE hydrology loading series reduces VLBI vertical and horizontal scatter.

6. NASA GSFC Hydrology Loading Service

We have established a loading service http://lacerta.gsfc.nasa.gov/hydlo/ where we provide monthly loading series computed from the GLDAS NOAH model. Our monthly loading series are available for approximately 170 VLBI sites. We also provide loading series on a 1x1 degree global grid that can be accurately interpolated to any point of interest.

7. Conclusions

It has been verified that hydrology loading can be seen in VLBI analysis. Errors due to the loading calculation algorithm are relatively small, whereas errors in the hydrology data are the source of the largest errors in the loading series. The hydrology loading series were computed from both the GLDAS NOAH model and the GRACE Mascons. The series are highly correlated, and both improve the position estimates by accounting for significant variations. We also found that

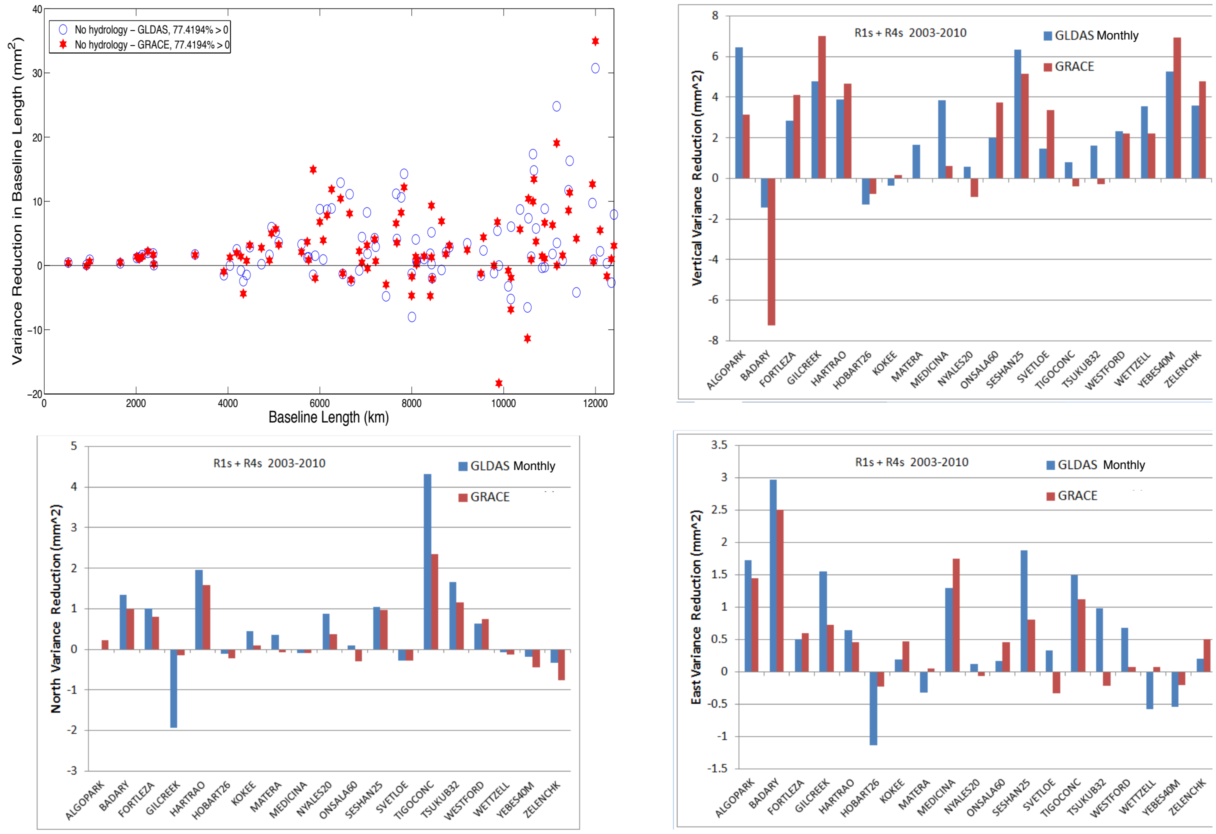

Figure 4. Improvement in baseline length (upper left) and position estimate improvement for the (upper right) vertical, (lower left) north-south (lower right) east-west component. For each site, the left bar is GLDAS and the right bar is GRACE.

almost 80% of the baseline length repeatabilities are improved when hydrology loading is applied in VLBI analysis. We have seen that hydrology loading is usually very seasonal and very significant for some areas such as the Amazon River Basin in South America, Southern Africa, and South Asia. Generally, in comparison with coastal sites, the seasonal signal is usually large for inland sites where the station position estimates are usually improved the most.

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