Low Degree Spherical Harmonic Influences on GRACE Water Storage Estimates

J.L. Chen [1], Matt Rodell [2], C.R. Wilson [3], J.S. Famiglietti [4]

[1]Center for Space Research, University of Texas at Austin
[2]Hydrological Science Branch, NASA Goddard Space Flight Center
[3]Department of Geological Sciences, University of Texas at Austin, Austin, TX 78712, USA
[4]Department of Earth System Science, University of California, Irvine

Abstract. We estimate terrestrial water storage variations using time variable gravity changes observed by the Gravity Recovery and Climate Experiment (GRACE) satellites during the first 2 years of the mission. We examine how treatment of low-degree gravitational changes and geocenter variations affect GRACE based estimates of basin-scale water storage changes, using independently derived low-degree harmonics from Earth rotation (EOP) and satellite laser ranging (SLR) observations. GRACE based water storage changes are compared with estimates from NASA's Global Land Data Assimilation System (GLDAS). Results from the 22 GRACE monthly gravity solutions, covering the period April 2002 to July 2004, show remarkably good agreement with GLDAS in the Mississippi, Amazon, Ganges, Ob, Zambezi, and Victoria basins. Combining GRACE observations with EOP and SLR degree-2 spherical harmonic coefficient changes and SLR observed geocenter variations significantly affects and apparently improves the estimates, especially in the Mississippi, Ob, and Victoria basins.

Keywords: GRACE, Low Degree Gravity, Basin, Water Storage, Geocenter

1. Introduction

The Gravity Recovery and Climate Experiment (GRACE) satellite mission is jointly sponsored by the US National Aeronautics and Space Administration (NASA) and German Aerospace Center (DLR). The goal of GRACE is to produce monthly maps of Earth's gravity field with unprecedented accuracy. These are based on precise measurements of the distance between two satellites orbiting in tandem, as well as data from on-board accelerometers and Global Positioning System (GPS) receivers [Tapley et al., 2004a]. These time-variable gravity fields can be used to infer mass redistribution within the Earth system, including variations of atmospheric surface pressure, terrestrial water storage, snow and ice, and ocean bottom pressure [e.g., Wahr et al., 1998]. Recent studies [Wahr et al., 2004; Tapley et al., 2004b; Rodell et al., 2004b] concluded that seasonal water storage variations can, in fact, be derived from GRACE data for certain large basins (e.g., the Amazon, Mississippi, and Bay of Bengal), when appropriate smoothing is applied. These GRACE-inferred terrestrial water storage changes agree reasonably well with estimates from hydrology models and observations.

Due in part to orbital geometry and the short separation between the satellites (~200 km), very low degree spherical harmonic coefficients, especially the degree-2 zonal term ΔC_{20}, are not well determined by GRACE. Therefore, in most published studies the ΔC_{20} coefficient is excluded. Chen et al. [2004] showed that degree-2 variations, ΔC_{21}, ΔS_{21}, and ΔC_{20}, estimated from accurately measured Earth rotational (EOP) data, appear to have better accuracy than those derived from GRACE. The absence of an ocean pole tide correction in current GRACE data processing, (to be applied in upcoming reprocessing) has significant effects on seasonal variability of GRACE ΔC_{21} and ΔS_{21} [Chen et al., 2004]. Satellite laser ranging (SLR), a well-established technique, can accurately measure the degree-2 zonal gravitational change, ΔC_{20}, and hence provides another independent constraint on GRACE ΔC_{20}.

GRACE does not provide degree-1 coefficient changes ΔC_{11}, ΔS_{11}, and ΔC_{10}, which represent variation of Earth's center of mass relative to the crust-fixed terrestrial reference frame (geocenter motion) [e.g. Chen et al., 1999]. Chambers et al. [2004] suggested that when geocenter motion estimated from SLR is included, GRACE-inferred seasonal global non-steric sea level changes agree better with TOPEX/Poseidon (T/P) and Jason-1 satellite altimeter measurements. This indicates that the absence of geocenter terms in GRACE time-variable gravity fields may have non-negligible effects on terrestrial water storage estimates as well.

The first objective of this study is to estimate global terrestrial water storage changes by combining GRACE time-variable gravity fields with degree-2 coefficients ΔC_{21}, ΔS_{21}, and ΔC_{20} from EOP and/or SLR, and degree-1 coefficients (geocenter variations) ΔC_{11}, ΔS_{11}, and ΔC_{10} determined from SLR. Second, for six major river basins, the Mississippi, Amazon, Ganges, Ob, Zambezi, and Victoria, we evaluate the influence of these low degree terms on basin-scale water storage change estimates, and how they affect agreement with NASA's Global Land Data Assimilation System (GLDAS) [Rodell et al., 2004a].

2. Data and Models

2.1 Water Storage Changes from GRACE

At present, the GRACE project has released 22 monthly gravity fields, spanning the period April 2002 to July 2004, and representing approximately monthly average values, though temporal sampling and averaging intervals are not completely uniform [Tapley et al., 2004a]. These fields are provided as fully normalized spherical harmonics up to degree and order 120, except that the Sept. 2002 solution is a 90x90 field because of limited data quality and quantity. The mean gravity field is the GRACE GGM01 gravity model, derived from the first 111 days of GRACE data [Tapley et al., 2004a]. Tidal effects, including ocean, solid Earth, and solid Earth pole tides (rotational deformation) have been removed in the level-2 GRACE data processing. Non-tidal atmospheric and oceanic contributions are also removed in the level-2 de-aliasing process (for details see the Level-2 Gravity Field Product User Handbook by S. Bettadpur, 2003). This means that the GRACE data represent changes caused by non-atmospheric and non-oceanic mass changes, mainly continental water storage changes, as well as unmodeled atmospheric and oceanic effects.

The high degree spherical harmonic coefficients in the GRACE solutions are dominated by noise [Tapley et al., 2004b; Wahr et al., 2004]. Therefore, to simplify the computation we truncate the GRACE solutions at degree and order 60. To further minimize the noise in GRACE-inferred terrestrial water storage change estimates, we apply Gaussian smoothing [Jekeli, 1981; Wahr et al., 1998] to the GRACE fields. Chen et al. [2005] demonstrated that choosing an 800km radius in Gaussian smoothing produces the best RMS (root-mean-square) agreement between GRACE and GLDAS water storage estimates. estimates. Therefore, we use 800km as the smoothing radius in this study. The mean of the 22 solutions is removed from all time series in this study.

We carry out four experiments to estimate global terrestrial water storage variability corresponding to different treatments of low degree terms: 1) the ΔC_{20} coefficient is excluded (similar to the published studies); 2) the ΔC_{20} coefficient is included; 3) ΔC_{21} and ΔS_{21} are replaced with estimates from EOP [Chen et al., 2004], and ΔC_{20} is replaced with the seasonal (annual plus semiannual) least squares fit from SLR estimates [Cheng and Tapley, 2002]; and 4) seasonal geocenter variations are also included (on top of experiment 3) based on published seasonal amplitudes and phases from Chen et al. [1999]. Basin-scale water storage changes are computed from GRACE-derived global fields (after truncation and smoothing) using cosine (latitude) weighting. The six basins (see Figure 1) were chosen based on either large seasonal variability (Amazon, Ganges, and Zambezi basins), large size (Mississippi and Ob basins), or geographical representation (Victoria basin). We also estimate water storage changes in Antarctic and Greenland from GRACE, to test sensitivity of estimates in these regions to the low degree terms. GLDAS does not provide results for these two regions [Rodell et al., 2004a]. Atmospheric and oceanic effects on EOP and SLR degree-2 gravitational changes ΔC_{21}, ΔS_{21}, and ΔC_{20} and geocenter variations are first removed using GRACE atmospheric and oceanic de-aliasing fields [Bettadpur, 2003].

2.2 Water storage change from GLDAS

GLDAS was developed jointly by scientists at the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) and the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Prediction (NCEP) [Rodell et al., 2004a]. GLDAS parameterizes, forces, and constrains sophisticated land surface models with ground and satellite products with the goal of estimating land surface states (e.g., soil moisture and temperature) and fluxes (e.g., evapotranspiration). In this particular simulation, GLDAS drove the Noah land surface model [Ek et al., 2003] version 2.7.1, with observed precipitation and solar radiation included as inputs. GLDAS terrestrial water storage variations used in our calculations are the sum of soil moisture (2 m column depth) and snow water equivalent. Greenland and Antarctica are excluded because the Noah model does not include ice sheet physics. Cosine (latitudinal) weighting is applied when computing the GLDAS water storage changes in the selected basins. The 3-hourly GLDAS time series are smoothed by a 30-day sliding window prior to comparisons with GRACE estimates.

3. Results and Comparison

The six panels of Figure 2 (a through e) show water storage changes inferred from GRACE (in the four experiments introduced in 2.1) and estimated from (unsmoothed) GLDAS in the 6 selected basins. All time series are detrended using least squares fit. The Amazon basin shows the greatest seasonal variability (20-30 cm), followed by the Zambezi and Ganges basins. In all six basins, GRACE water storage changes agree remarkably well with GLDAS estimates. To include GRACE ΔC_{20} (red circles) or not (blue crosses) has notable (and sometimes significant) effects on the retrievals. For example, GRACE's ΔC_{20} was not well determined from March to July 2004 (due to degraded ground track coverage), and the effects are evident in the Amazon and Ob basins.

Replacement of GRACE ΔC_{21}, ΔS_{21}, and ΔC_{20} with estimates from EOP and SLR (green squares) also has notable effects, although the improvement relative to excluding ΔC_{20} is not obvious in most basins. However, when EOP and SLR derived ΔC_{21}, ΔS_{21}, and ΔC_{20} are used for the Mississippi basin, the seasonal amplitude from GRACE increases significantly and agrees better with GLDAS. Geocenter (GEOC) variations have an even greater impact on basin-scale water storage changes than the degree 2 terms. Including the geocenter terms (cyan triangles) significantly increases the seasonal variability and improves agreement with GLDAS in certain basins including the Mississippi , Ob, and Victoria.

Table 1 summarizes the amplitude and phase of least-square-fit annual and semiannual variations estimated from each time series shown in Figure 2. The agreement between GRACE and GLDAS is generally very good. For example, in the Ob basin GRACE results from Experiment 4 (EOP/SLR/GEOC) show nearly identical annual amplitude and phase to GLDAS model estimates (5.73 vs. 5.49 cm of water thickness change, and 22° vs. 8°). In the Victoria basin, including EOP and SLR degree-2 terms and SLR geocenter clearly improves the agreement. The annual amplitude is reduced from 7.17 cm (in Experiment 1 when ΔC_{20} is excluded) to 4.64 cm in Experiment 4 (EOP/SLR/GEOC), much closer to the GLDAS estimate (4.94 cm).

In most cases, the phase of the GRACE water storage cycle consistently lags the GLDAS cycle by a few days to weeks. This seems unlikely to be due to errors in the data. A likely explanation is that groundwater storage changes are contributing to the signal seen by GRACE. Groundwater changes should lag near-surface components of terrestrial water storage (soil moisture and snow), and is not incorporated in the GLDAS estimates. Furthermore, one might expect that the addition of groundwater would increase the amplitude of the signal relative to the GLDAS prediction. (e.g., Rodell and Famiglietti, 2001). This suggests that by combining GRACE and GLDAS or other estimates of soil moisture and snow changes, an estimate of groundwater storage change might be obtained.

Table 2 shows the averaged RMS of the residuals between GLDAS and GRACE estimates in the six basins. The RMS estimates also demonstrate the important effects of low degree harmonics on GRACE estimated water storage changes. For example, the RMS in the Mississippi and Ob basins are significantly reduced when EOP/SLR derived degree-2 harmonics change and geocenter motion are applied (Experiment 4, EOP/SLR/GEOC).

4. Conclusion and Discussion

We estimate basin-scale water storage changes using GRACE time-variable gravity observations with different treatments of degree-2 and geocenter terms. Substituting EOP and

SLR estimates of ΔC_{21}, ΔS_{21}, and ΔC_{20} strongly affects the estimates. Geocenter terms also significantly impact basin-scale water storage estimates. Sensitivity to these different treatments depends on location, size, and water storage variability of the region of interest.

In the six selected basins, GRACE water storage changes agree remarkably well with GLDAS soil plus snow water storage changes. Combining EOP and SLR ΔC_{21}, ΔS_{21}, and ΔC_{20} and/or SLR geocenter variations with GRACE data generally improves agreement with GLDAS estimates, particularly in the Mississippi, Ob, and Victoria basins. The apparent phase lag of GRACE relative to GLDAS may be linked to effects of groundwater. Additional experiments (not presented here) indicate that polar regions (i.e., Antarctica and Greenland) are even more sensitive to the various treatments of low degree gravitational terms examined here.

Despite of the remarkably good agreements between GRACE and GLDAS estimated water storage changes in selected basins, many error sources could still affect these estimates. Better determined low degree spherical harmonics change from GRACE itself (from upcoming data reprocessing) and improved geocenter time series should improve GRACE estimates. How to successfully restore real water storage change after the necessary smoothing applied in GRACE data is also a challenging issue for future studies [e.g., Chen et al., 2005]. Ground water change is not considered in this study, limited by data resources. Different land surface models still show significant differences in modeling large-scale water storage changes, although GLDAS appears showing major improvements than other models.

Acknowledgments. We would like to thank the two anonymous reviewers for their insightful comments, which led to improved presentation of the results. This research was supported by NASA's Solid Earth and Natural Hazards and GRACE Science Program (NNG04GF10G, NNG04G060G, NNG04GF22G, NNG04GE99G).

References:

Bettadpur, S., Level-2 Gravity Field Product User Handbook, The GRACE Project, 2003.

Chambers, D.P., J. Wahr, and R. S. Nerem (2004), Preliminary observations of global ocean mass variations with GRACE, Geophys. Res. Lett., 31, L13310, doi:10.1029/2004GL020461.

Chen, J.L., C.R. Wilson, J. S. Famiglietti, and M. Rodell, Spatial Sensitivity of GRACE Time-Variable Gravity Observations, J. Geophys. Res., 2005 (in press).

Chen, J.L., C.R. Wilson, B.D. Tapley, J. Ries, Low Degree Gravitational Changes from GRACE: Validation and Interpretation, Geophys. Res. Lett., Vol. 31, No. 22, L22607 10.1029/2004GL021670, 2004.

Chen, J.L., C.R. Wilson, R.J. Eanes, and R.S. Nerem, Geophysical Interpretation of Observed Geocenter Variations, J. Geophy. Res.,Vol. 104, No. B2, 2683 - 2690, 1999.

Cheng, M.K. and B.D. Tapley, Temporal Variations in the Earth's Gravity Field from SLR and CHAMP GPS data, in Gravity and Geoid 2002, edited by I.N. Tziavos, 424-431, Greece, 2002.

Ek, M. B., K. E. Mitchell, Y. Lin, E. Rogers, P. Grunmann, V. Koren, G. Gayno, and J. D. Tarpley (2003), Implementation of the upgraded Noah land-surface model in the NCEP operational mesoscale Eta model, J. Geophys. Res., 108, 8851, doi:10.1029/2002JD003296.

Jekeli, C., Alternative Methods to Smooth the Earth's Gravity Field, Department of Geodetic Science and Surveying, Ohio State University, Columbus, OH, 1981.

Rodell, M., and J. S. Famiglietti, An analysis of terrestrial water storage variations in Illinois with implications for the Gravity Recovery and Climate Experiment (GRACE), Wat. Resour. Res., 37, 1327-1340, 2001.

Rodell, M., P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D. Toll, The Global Land Data Assimilation System, Bull. Amer. Meteor. Soc., 85 (3), 381–394, 2004a.

Rodell, M., J.S. Famiglietti, J.L. Chen, S. Seneviratne, P. Viterbo, and S. Holl, River basin water budget estimates of evapotranspiration using GRACE derived terrestrial water storage with observation based precipitation and runoff, Geophys. Res. Lett., Vol. 31, No. 20, L20807, 10.1029/2004GL021104, 2004b.

Tapley, B.D., S. Bettadpur, M.M. Watkins, C. Reigber, The Gravity Recovery and Climate Experiment; Mission Overview and Early Results, G eophy. R es. L e tt., Vol. 31, No. 9, L09607, 10.1029/2004GL019920, 2004a.

Tapley, B.D., S. Bettadpur, J. Ries, P.F. Thompson, and M.M. Watkins, GRACE Measurements of Mass Variability in the Earth System, Science, Vol. 305, 503-505, 2004b.

Wahr, J.M., The effects of the atmosphere and oceans on the Earth's wobble and the seasonal variations in the length of day, I: Theory, Geoph. J. R. astr. Soc., Vol.70, 349-372, 1982.

Wahr, J., S. Swenson, V. Zlotnicki, and I. Velicogna, Time-Variable Gravity from GRACE: First Results, Geophy. Res. Lett., 31, L11501, doi:10.1029/2004GL019779, 2004.

Figures:

Figure 1. Geographical locations of six major river basins examined in this study: the Mississippi, Amazon, Ganges, Ob, Zambezi, and Victoria basins.

Figure 2. Terrestrial water storage anomalies in the a) Mississippi, b) Amazon, c) Ganges, d) Ob, e) Zambezi, and d) Victoria basins estimated from un-smoothed GLDAS (gray curves), GRACE without ΔC_{20} (blue crosses), GRACE with ΔC_{20} (red circles), GRACE with $\Delta C_{21}/\Delta S_{21}$ from EOP and ΔC_{20} from SLR (green squares), and GRACE with $\Delta C_{21}/\Delta S_{21}$ from EOP and ΔC_{20} from SLR plus geocenter change from SLR (cyan triangles). The water height changes represent averaged equivalent water thickness changes in the given basin.

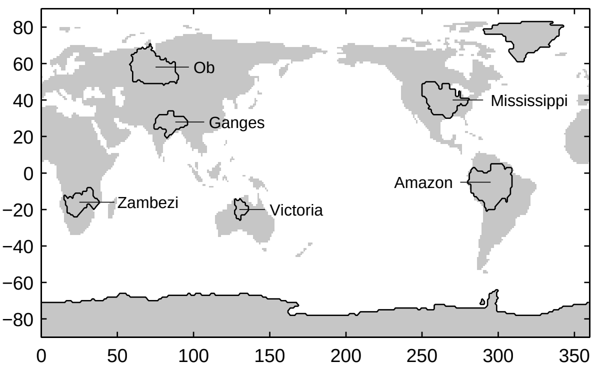
Table

Table 1. Amplitude (Amp.) and phase of annual and semiannual variations of basin-scale water storage changes estimated from GRACE (GRC) and GLDAS. The phase is defined as ϕ in $\sin(2\pi(t-t_0)+\phi)$, where t_0 refers to h^0 on January 1.

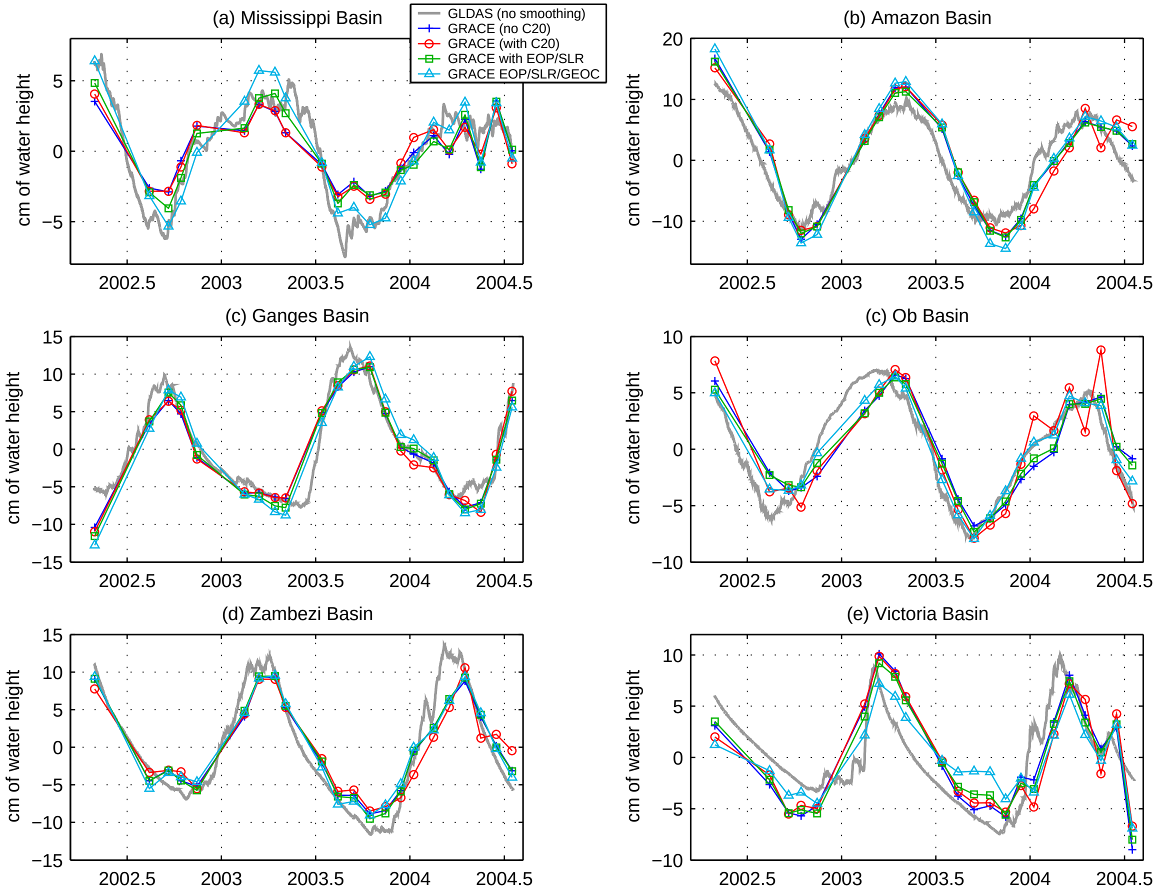
Basins & Cases	Annual Amp. (cm)	Annual Phase (deg)	Semiannual Amp. (cm)	Semiannual Phase (deg)
Mississippi				
GLDAS	4.10	6	1.51	150
GRC (no C20)	2.47	354	0.70	161
GRC (with C20)	2.66	0	0.83	154
GRC (EOP/SLR)	3.13	350	0.93	175
GRC(EOP/SLR/GEOC)	4.72	354	0.46	171
Amazon				
GLDAS	9.27	343	0.44	122
GRC (no C20)	12.38	327	0.37	13
GRC (with C20)	12.46	321	0.67	339
GRC (EOP/SLR)	12.10	325	0.63	11
GRC (EOP/SLR/GEOC)	13.68	327	0.73	13
Ganges				
GLDAS	7.45	188	2.66	329
GRC (no C20)	8.81	187	2.60	359
GRC (with C20)	9.10	190	2.71	357
GRC (EOP/SLR)	9.36	185	2.85	2
GRC (EOP/SLR/GEOC)	10.00	178	2.57	1
Ob				
GLDAS	5.73	22	0.88	183
GRC (no C20)	5.43	348	0.82	205
GRC (with C20)	6.27	2	1.07	182
GRC (EOP/SLR)	5.21	353	0.85	197
GRC (EOP/SLR/GEOC)	5.49	8	0.96	197
Zambezi				
GLDAS	9.44	0	2.49	313
GRC (no C20)	8.47	353	2.53	279
GRC (with C20)	8.03	345	2.81	283
GRC (EOP/SLR)	8.77	352	2.52	281
GRC (EOP/SLR/GEOC)	8.65	356	2.45	266
Victoria				
GLDAS	4.94	358	1.64	334
GRC (no C20)	7.17	6	2.48	283
GRC (with C20)	6.59	0	2.72	286
GRC (EOP/SLR)	6.53	2	2.63	284
GRC (EOP/SLR/GEOC)	4.64	1	2.64	283

Table 2. The average RMS of the residuals between GLDAS and GRACE estimates in the six basins (in units of cm of water height). RMS1, 2, 3, and 4 represent the RMS of GLDAS – GRACE for the four GRCACE experiments (no C20, With C20, EOP/SLR, and EOP/SLR/GEOC), respectively.

Basins	RMS1	RMS2	RMS3	RMS4
Mississippi	1.71	1.54	1.34	1.13
Amazon	3.10	4.02	3.11	3.77
Ganges	1.55	1.73	1.70	2.28
Ob	2.03	2.29	1.76	1.03
Zambezi	2.36	3.01	2.21	2.39
Victoria	2.97	3.20	2.88	2.97



Ob
Ganges
Mississippi
Amazon
Zambezi
Victoria
80
60
40
20
0
−20
−40
−60
−80
0
50
100
150
200
250
300
350



(a) Mississippi Basin
GLDAS (no smoothing)
GRACE (no C20)
GRACE (with C20)
GRACE with EOP/SLR
GRACE EOP/SLR/GEOC
(b) Amazon Basin
(c) Ganges Basin
(c) Ob Basin
(d) Zambezi Basin
(e) Victoria Basin
cm of water height
2002.5
2003
2003.5
2004
2004.5