DirectWB

The global continental water balance using GRACE spaceborne gravimetry and high-resolution consistent geodetic-hydrometeorological data analysis – Phase I

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GRACE and continental hydrology

GRACE gravity measurements provide a direct measure of water storage changes over continents. As such, it enables—for the first time—to close the continental water balance on large scales, and a direct determination of actual evapotranspiration ET_a—the unknown component of water balance—from terrestrial precipitation P and runoff measurements R on large scales. Atmospheric moisture flux divergence (∇Q) offers another independent way of determining water storage changes, where there is no need for ET_a information. This allows for a mutual intercomparison of data from three independent disciplines and an evaluation of hydrological and atmospheric models. Thus the overall objectives of the DWB project are

- ***the direct analysis of large-scale water balances***, and
- ***the quantification of the related uncertainties for large-scale catchment areas in different climatic zones***.

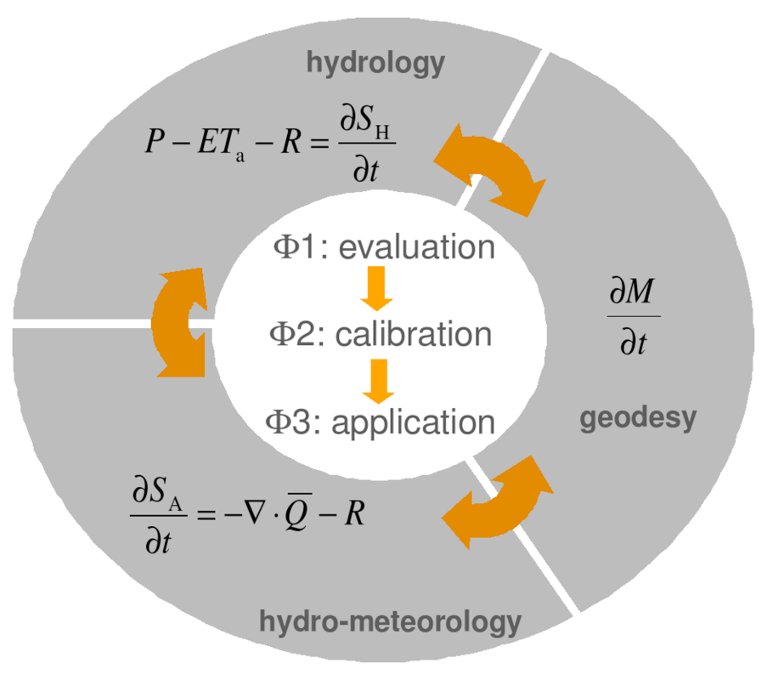


Figure 1: *Project overview*

In order to achieve consistent water balances, the mass change rates from GRACE, hydrology, and hydrometeorology have to be evaluated with respect to natural fluctuations and intrinsic errors. Statistical investigations are needed to characterize the respective contributions. This is the main objective in Phase 1 (2007–2008). An open loop evaluation scheme for selected catchments for the different data sources is shown in figure 2.

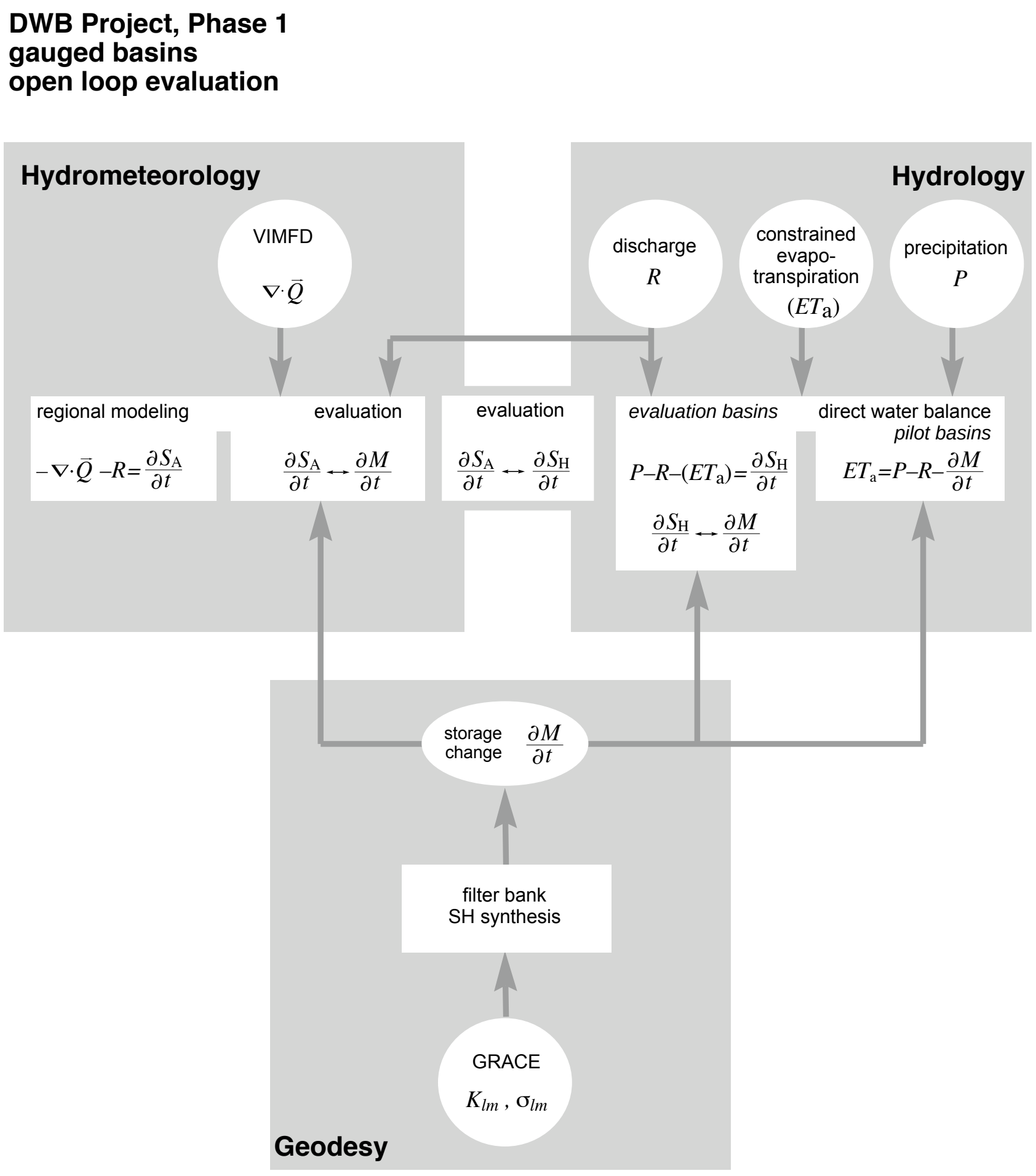


Figure 2: *Project integration in Phase 1 – Open loop evaluation*

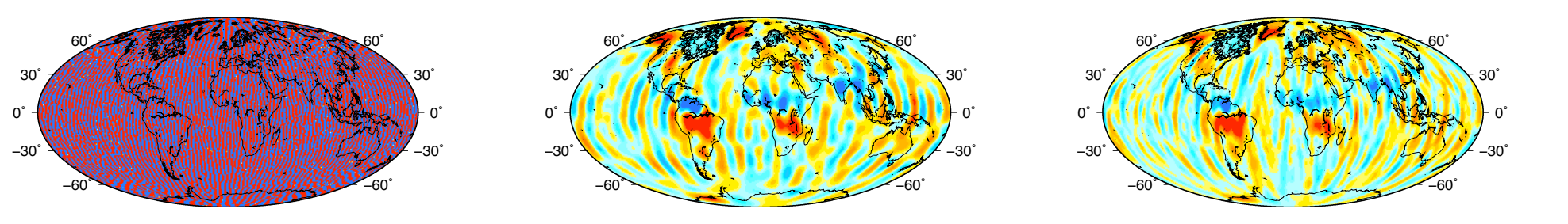
Geodesy

Tasks

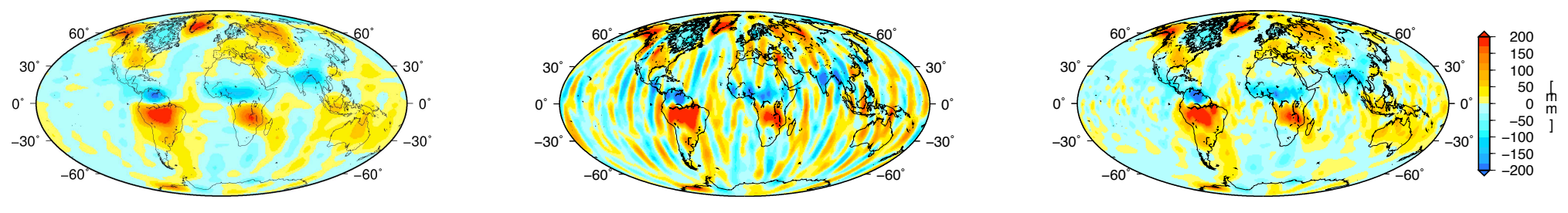
- Design, implementation, and testing of spherical harmonic filters.
- Computation and provision of mass change rates to the hydrology and hydrometeorology groups.
- Development of FFT-based tools for error propagation of full error variance-covariance matrices.
- Creation of an initial framework for constraining GRACE mass change rates using reliable hydrological mass change rates.

Filtering GRACE data

A set of isotropic, anisotropic, and stochastic filters were implemented and designed. Mass change rates after applying a few of the filters are shown in figures 3(a)–3(f). Similarly, time-series of mass change rates of one small (Aravalli, western India) and one large catchment (Ob, Siberia) are shown in figures 4(a) and 4(b), respectively.

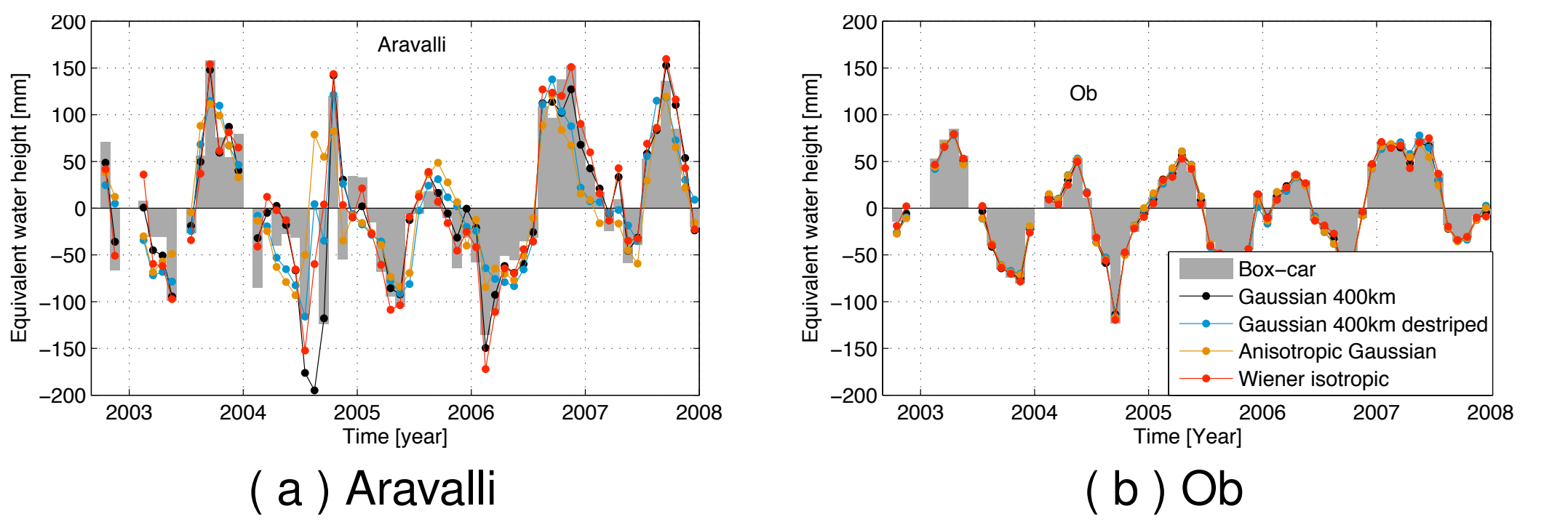


(a) Unfiltered (b) Box-car (c) Gauss 400 km



(d) Anisotropic Gauss (e) Wiener (f) Destriped & Gauss

Figure 3: *Mass change rates before and after filtering (GFZ release 4, February 2003)*

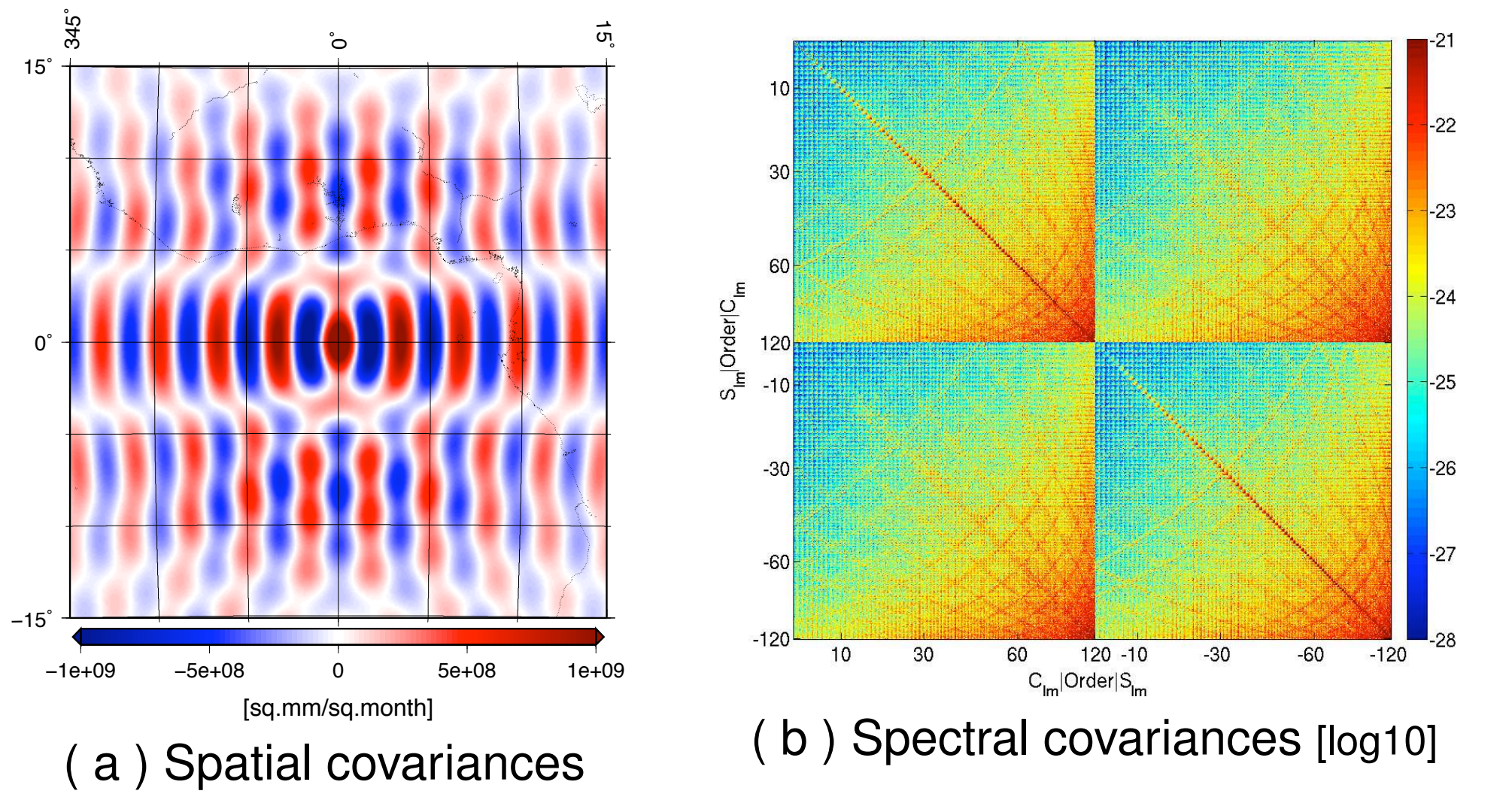


(a) Aravalli (b) Ob

Figure 4: *Time-series of mass change rates of Aravalli and Ob catchments*

Error propagation and covariance matrix handling

FFT-based error propagation tools were developed to propagate the spectral error variance-covariance matrix of GRACE coefficients to the spatial domain, thereby estimating the errors of the mass change rates from GRACE. The covariance structure of GRACE in the spatial domain, and its corresponding spectral error variance-covariance matrix are shown in figures 5(a) and 5(b), respectively.



(a) Spatial covariances (b) Spectral covariances [log10]

Figure 5: *Spatial and spectral covariances of GRACE mass change rates*

Summary

- A set of deterministic (isotropic and anisotropic), and stochastic filters were implemented and designed.
- The mass change rates from deterministic anisotropic filters are better (visually more pleasing) than from the isotropic filters. However, since the deterministic filters are non-physical, they are prone to leakage.
- Stochastic Wiener-type filters are not successful due to the lack of full variance-covariance information.
- The use of different filters provides different mass change rates for the same catchment, particularly if the catchment considered is small compared to the spatial resolution of GRACE, or if the amplitude of the hydrological signal is low.
- FFT-based tools for error propagation have been completed.
- An initial framework for constraining GRACE mass change rates using reliable hydrological mass change rates has also been developed.

Hydrometeorology

Tasks

- Evaluation of global and regional hydrometeorological modelling for continental and basin-scale water budget estimations.
- Investigation of the potential of regional atmospheric models for an improvement of global atmospheric moisture fields with increased spatial and temporal resolution
- Development of tools for hydrometeorological data analysis.
- Adaptation of WRF regional atmospheric model for vertically integrated moisture flux divergence (VIMFD) calculations.
- Evaluation of the mass change rates from atmospheric modelling compared to those from hydrology and GRACE.

Atmospheric modelling

- Global 6-hourly fields of VIMFD obtained from ECMWF ERA-40 reanalysis (1960–2001), ECMWF Operational Analysis (2001-2007), and from NCAR NCEP-Reanalysis (2002-2006).
- Atmospheric forcing and initial conditions were both gathered from NCEP-Reanalysis I (NNRP) and ECMWF Operational Analysis (ECMWF opAnl) for the WRF-ARW model.
- For regional downscaling of global atmospheric fields, the computation of VIMFD was implemented into the WRF-ARW model as a diagnostic function. Several tests were carried out to assure a correct execution on parallel architectures.
- The WRF-model was applied with 30 × 30 km^2 horizontal resolution, 28 vertical layers and a simulation timestep of 120 seconds.

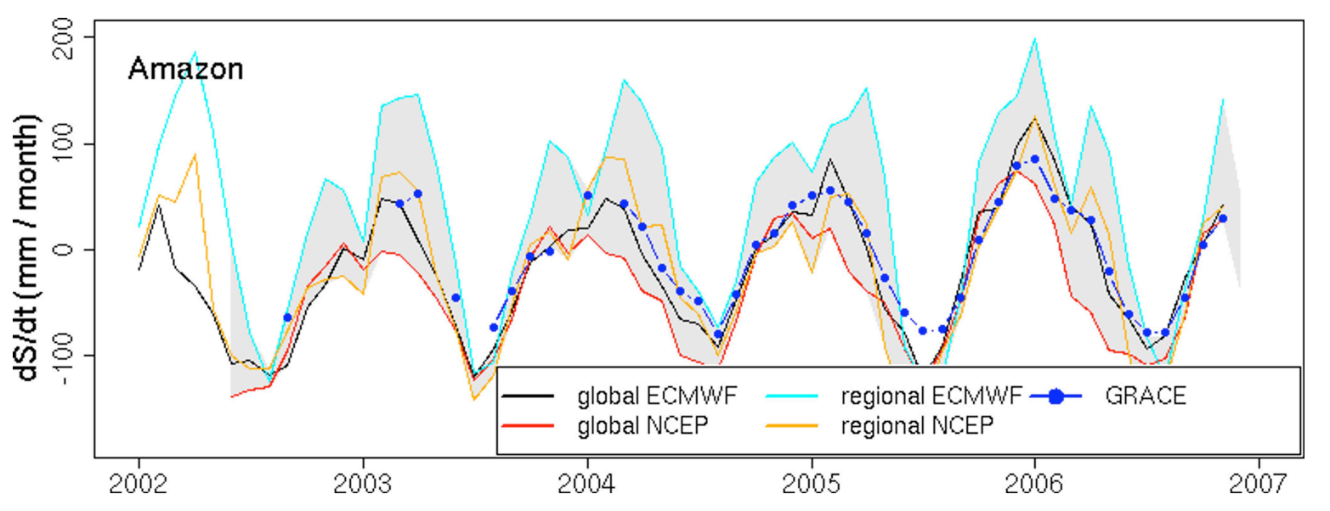


Figure 6: *Comparison of* $\frac{\partial S_\mathrm{A}}{\partial t}$ *from atmospheric models with* $\frac{\partial M}{\partial t}$ *from GRACE.*

Evaluation

Atmospheric modelling is performed for four climatically selected test regions: Amazon, Siberia (Yenisei and Lena), Sahara, and the central plane of Australia. The modelled mass change rates are evaluated with filtered GRACE mass change rates (destriped and smoothed with a Gaussian 500 km filter).

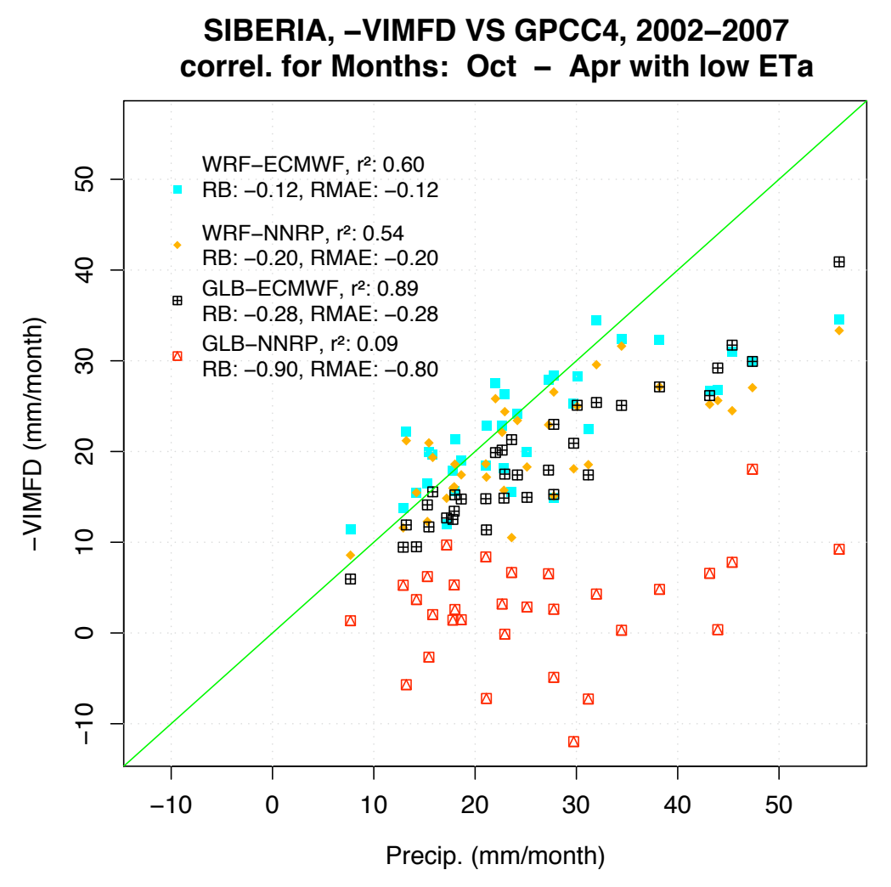


Figure 7: *Correlation and relative bias of regional (WRF) and global (GLB) fields of atmospheric moisture flux divergence with GPCC 4.*

Summary

- For the first time, regionalized atmospheric fields are applied in the scope of GRACE based large-scale water budget analysis.
- Uncertainty bounds for terrestrial water storage changes based on atmospheric moisture budgets are determined.
- Results from regional atmospheric modelling show that dynamical downscaling can improve estimates of VIMFD considerably (compared to GPCC with months where $ET_\mathrm{a}\approx 0$).
- The differences in air mass variations (8) that emerge from regional and global models indicate potential for improving the atmospheric de-aliasing models of GRACE.

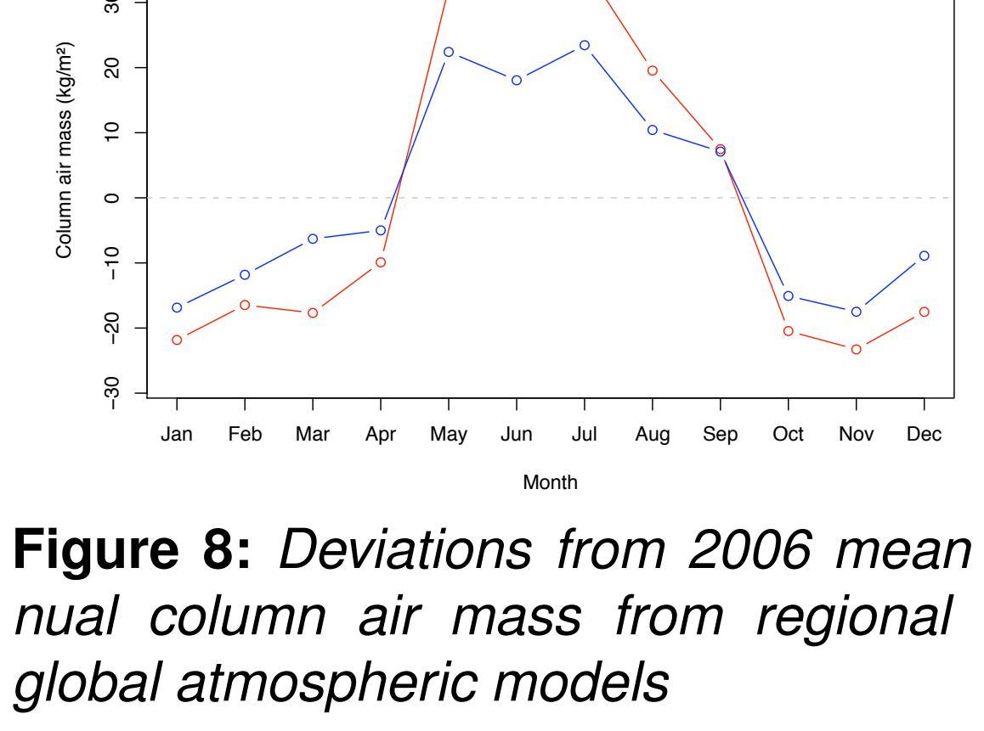


Figure 8: *Deviations from 2006 mean annual column air mass from regional and global atmospheric models*

Hydrology

Tasks

- Development of selection schemes for space / time patterns of known water balance.
- GIS based selection of areas of constrainable water balance.
- Quantification of hydrological mass constraints and related uncertainties.
- Evaluation of mass change rates from GRACE and hydrometeorology versus groundbased measurements from hydrology

Selection of suitable basins

Continental water storage changes can be determined if actual evapotranspiration ET_a can be constrained within adequate limits, and if the uncertainty of the measured components (P and R) is quantified. Areas with constrained ET_a belong to climatic zones, where ET_a is limited either by water or energy availability i. e. deserts and high altitude/latitude areas. For hot deserts (high ET_a) mass change rates are assumed to be short-term and random due to lower temporal resolution. For boreal regions ET_a is energy limited during the winter season. During these selected periods GRACE and hydrometeorological data are directly comparable to hydrological data $P-R$ (cf. figure 10).

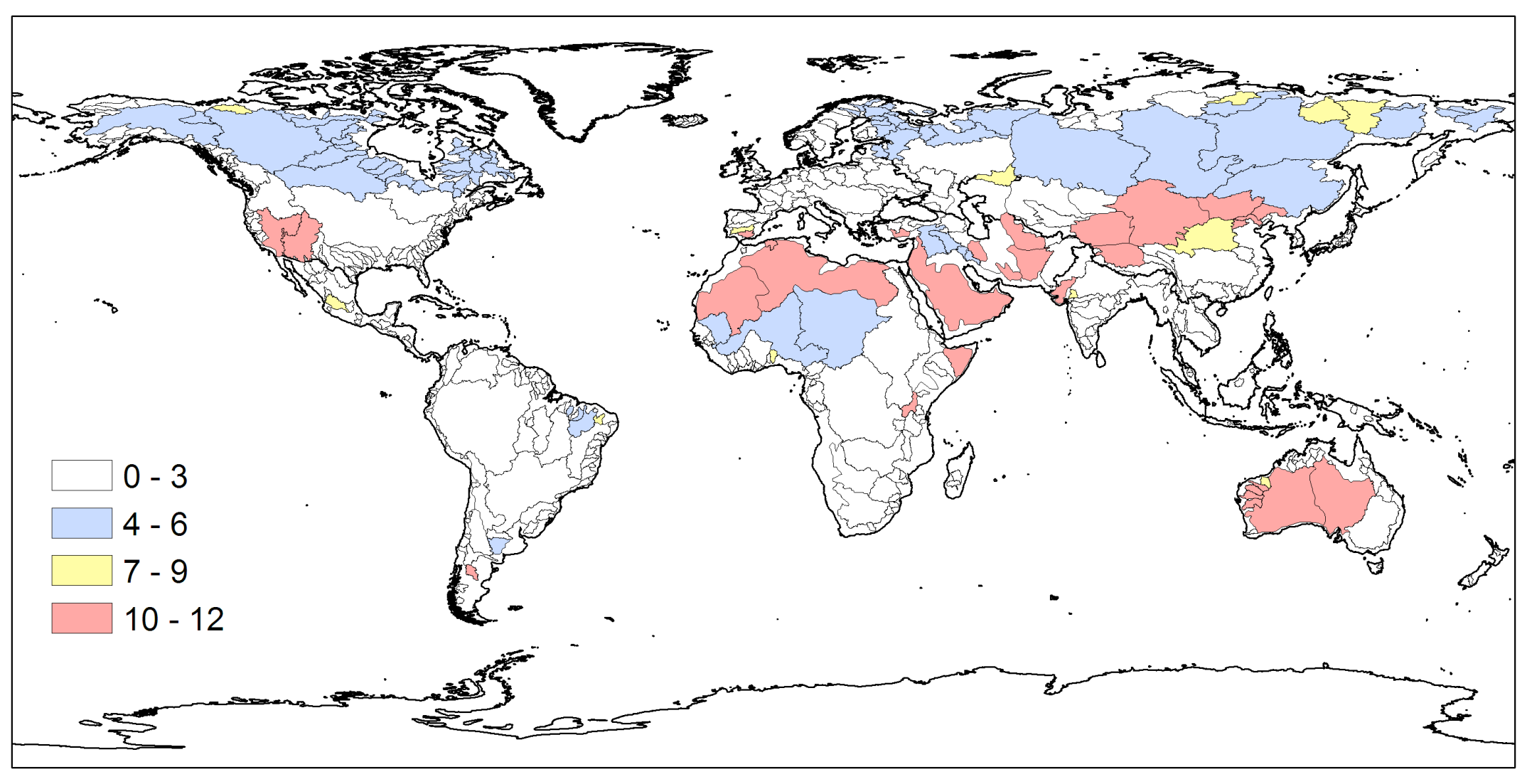


Figure 9: *Number of months with limited* ET_a

GRACE vs. hydrometeorology vs. hydrology

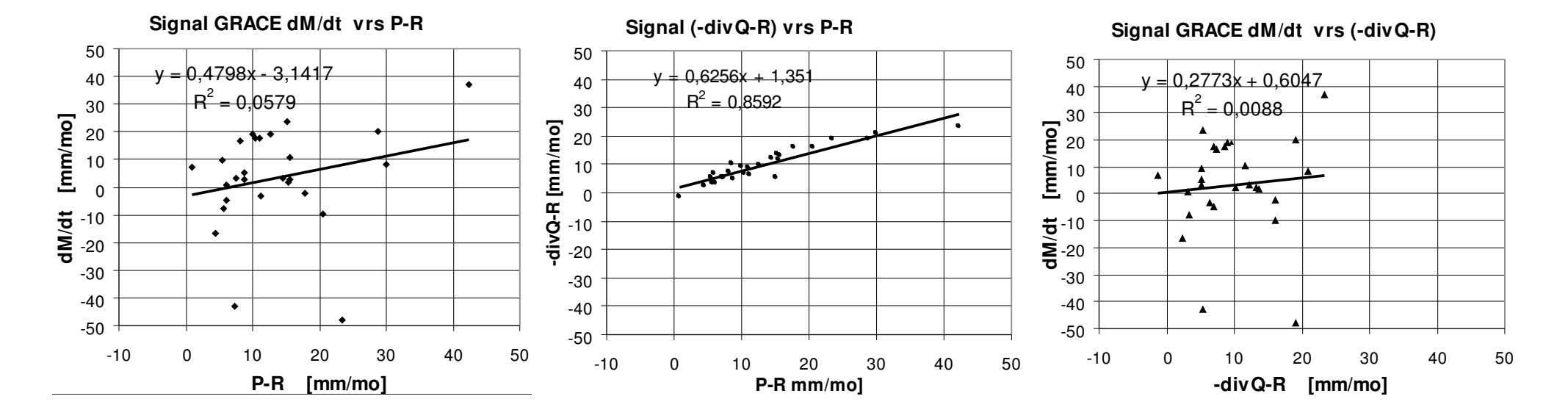


Figure 10: *Scatterplots between monthly storage changes from GRACE, hydrology and hydrometeorology (2003–07) for the Lena Basin* ($ET_\mathrm{a}\approx 0$)*.*

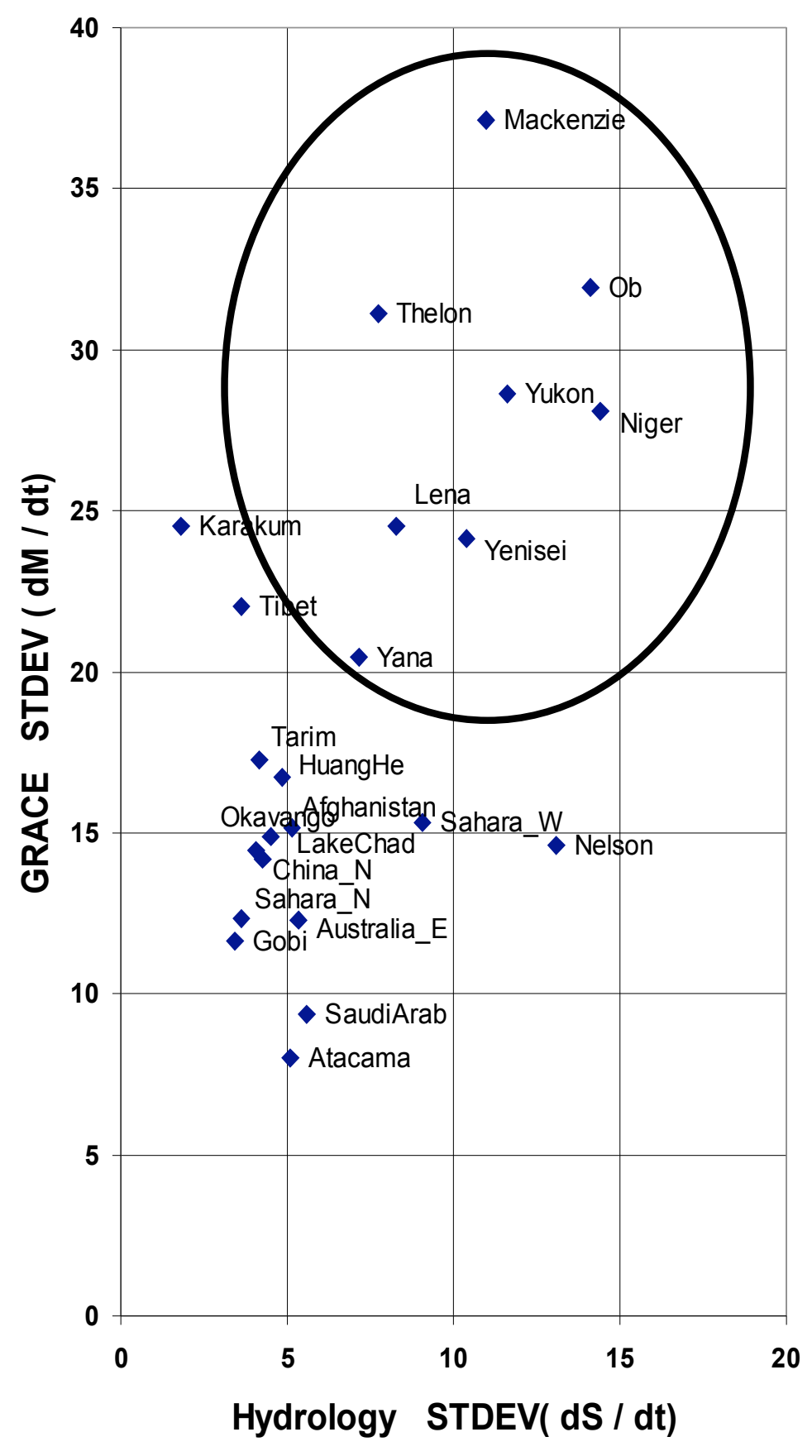
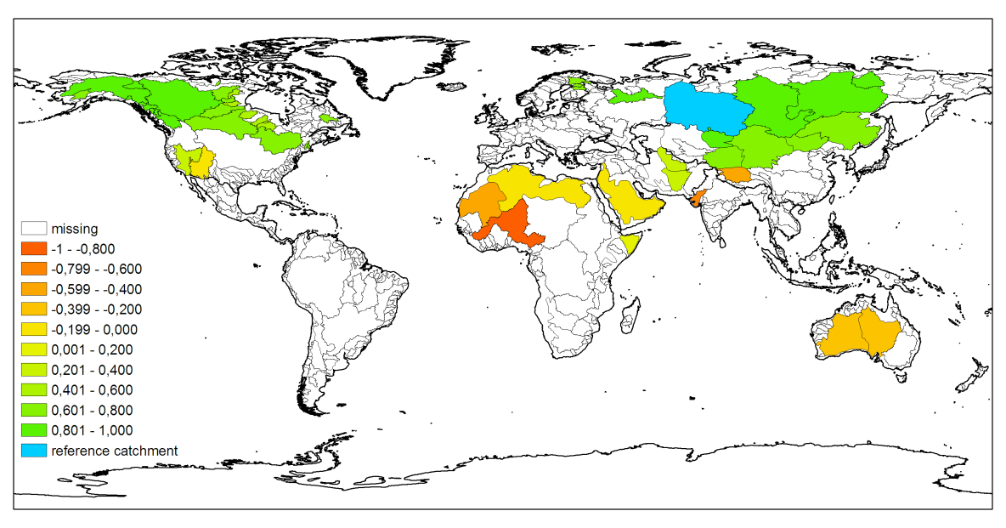
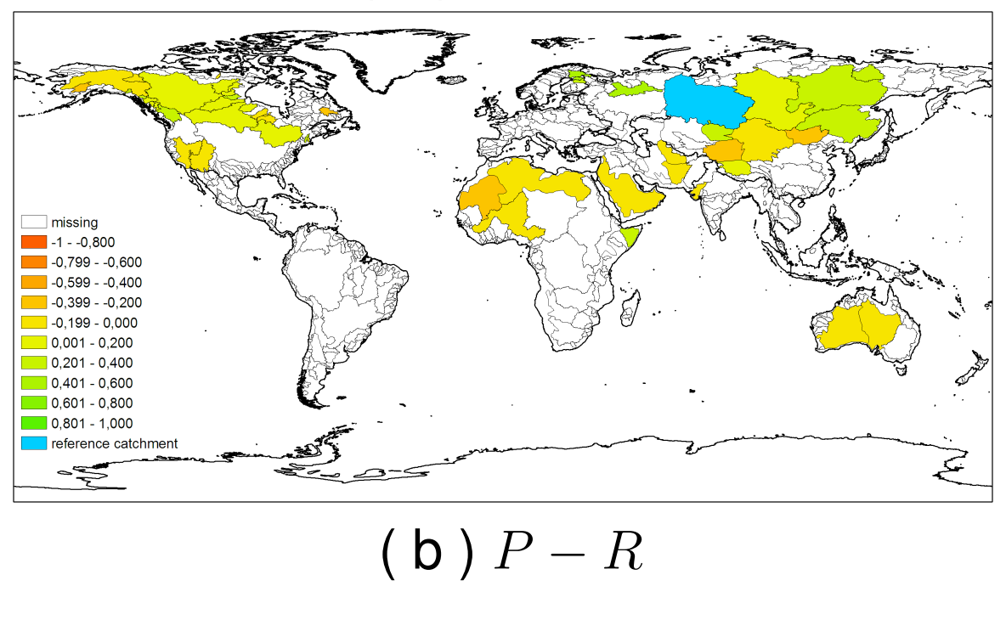


Figure 11: *Signal* RMS *of GRACE* $\frac{\partial M}{\partial t}$ *vs. hydrology* ($P-R$) *for* $ET_\mathrm{a}\approx 0$.



(a) GRACE



(b) $P-R$

Figure 12: *Spatial distribution of temporal correlations between Ob and other catchments obtained from the residuals of GRACE* $\frac{\partial M}{\partial t}$ *and of hydrology* ($P-R$) *for* $ET_\mathrm{a}\approx 0$.

Summary

- Direct water balance calculations for pilot basins with large signals deliver reasonable results for mean monthly data.
- Monthly variations of GRACE signals are observed to be in the 20–30 % range of signal amplitudes except for tropical basins. This does not allow for an straight foreward evaluation of different hydrological model approaches without quantification of contributions from climatic variations and intrinsic errors.
- Comparisons between GRACE and hydrological/hydrometeorological data show a reasonable agreement for large signal amplitudes, however, an uncorrelated behaviour for small signals or residuals (high latitudes or deserts ($ET_\mathrm{a}\approx 0$)).
- Inter-comparisons of GRACE, hydrometeorological, and hydrological data provide insights into variability contributions from climatic variations and intrinsic errors. Hydrometeorological and hydrological data fit much better even for small signals (figure 10), thus identifying GRACE signal variations on the selected areas as error. These results also indicate the suitability of the constrained water balance approach—comparing GRACE with both the hydrological and hydrometeorological data.
- Signal RMS for GRACE on selections ($ET_\mathrm{a}\approx 0$) is considerable higher than for hydrology especially for high latitudes (figure 11).
- Investigations on the spatial structure of temporal correlations between different basins show a much higher (artificial) correlation between monthly residuals (deviations from monthly means) for GRACE-GRACE than for hydrology-hydrology (figures 12(a) and 12(b)). This calls for a stochastic correction scheme for improving GRACE signals based on the stochastic information and mass constraints from hydrology .

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