Large-scale water balance estimations through regional atmospheric moisture flux modelling and comparison to GRACE signals

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Abstract Terrestrial water storage variations for continental-scale river catchments and basins derived from global and regional atmospheric moisture budgets modelling are evaluated and compared to GRACE satellite measurements. The regions considered in this study are the Amazon basin, the river catchments of Yenisei and Lena, the Sahara and Central Australia. If GRACE is taken as reference, the regional simulations have the potential to add value to the global moisture budgets for periods with small storage variation amplitudes. If the synoptic period is dominated by convective rainfall, the regional atmospheric model tends to overestimate precipitation.

Key words joint land-surface–atmosphere modelling; WRF; GRACE; regional atmospheric modelling; continental water balance modelling; atmospheric moisture flux divergence

INTRODUCTION

The motivation of this study is to determine the capabilities of global and regional hydro-meteorological modelling for continental and basin-scale water budget estimations. For large-scale river basins with measured discharge and regions without discharge, it is possible to compute monthly to seasonal terrestrial water storage changes from atmospheric moisture budgets. In this context, the central research question is whether regional atmospheric models with increased spatial and temporal detail are able to improve the global atmospheric moisture budgets. Several pilot regions were selected for the application of the regional atmospheric model and analysis of atmospheric water budgets. Three of these catchments are characterized by a constrained water balance. Monthly water storage changes, derived from both regional and global atmospheric fields are compared to mass variations observed by GRACE. The vertical integral of moisture flux divergence (D) is compared to the water budgets of the selected basins.

METHODOLOGY

Atmospheric and terrestrial water budgets

The atmospheric water budget over a specific region is driven by lateral moisture fluxes and by exchange to the land surface. This relation is given by:

$$D + \mathrm{d}W / \mathrm{d}t = E_a - P \qquad (1)$$

where W describes the atmospheric water storage, D the vertical integral of moisture flux divergence, E_a the actual evapotranspiration and P the precipitation. For all variables the unit is millimetre per month (mm/month).

D is defined as the vertical integral of moisture flux divergence:

$$D = \nabla \bullet \vec{Q} \equiv \nabla \bullet \int_{p=0}^{p=p_{sfc}} \vec{v}_h q \frac{\mathrm{d}p}{g} \qquad (2)$$

where air pressure p denotes the vertical coordinate. q, $\vec{v}$ and g stand for specific humidity, horizontal wind vector and gravity acceleration. In terms of SI, the unit of D is kg/m^{2}s.

For weekly or monthly temporal scales, the variations in atmospheric water storage, dW/dt can be neglected. The divergence is then directly linked to the terrestrial water storage. Using equation (1) the combined atmospheric–terrestrial water budget follows as:

$$-D - \mathrm{d}S/\mathrm{d}t = R \tag{3}$$

with discharge R and the terrestrial water storage changes dS/dt.

The GRACE satellites capture temporal alterations of variable masses on Earth with a monthly time scale. Introducing mass variations from GRACE dM/dt, equation (3) becomes:

$$-D - \mathrm{d}M/\mathrm{d}t = R_M \tag{4}$$

with R_M denoting the basin discharge derived from GRACE. For gauged basins, R_M can be checked against observed discharge. This approach was applied for the Amazon basin (Syed *et al.*, 2005) and the Pan-Arctic region (Syed *et al.*, 2007).

For basins with known or negligible runoff (R = 0), dM/dt can be directly correlated to the water storage term of the water budget equation:

$$-D - R = \mathrm{d}S/\mathrm{d}t \approx \mathrm{d}M/\mathrm{d}t \tag{5}$$

with dS/dt denoting the terrestrial water storage variations derived from –D and R. This approach was followed for example by Hirschi *et al.* (2005) and Seitz *et al.* (2008), and is also adopted in this study.

Regional water budget modelling

Usually, fields from global circulation models have a relatively coarse spatial resolution. Regional atmospheric modelling by dynamic downscaling provides a way to increase spatial and also temporal resolution. Within the scope of this study, the regional Weather Research and Forecast Model WRF from NCAR is used to refine global atmospheric fields from ECMWF and NCEP re-analyses.

Study areas

Four different regions were chosen for a simulation with the regional atmospheric model and the corresponding water budget analysis (Fig. 1). The Australian domain encompasses the Central Plane. Sahara refers to the arid basin of the Northern African desert excluding the Chad depression. For these two regions it is assumed that no discharge leaves the area surrounding their boundaries (R = 0). Hence, terrestrial water storage variations derived from GRACE should equal the atmospheric moisture budget.

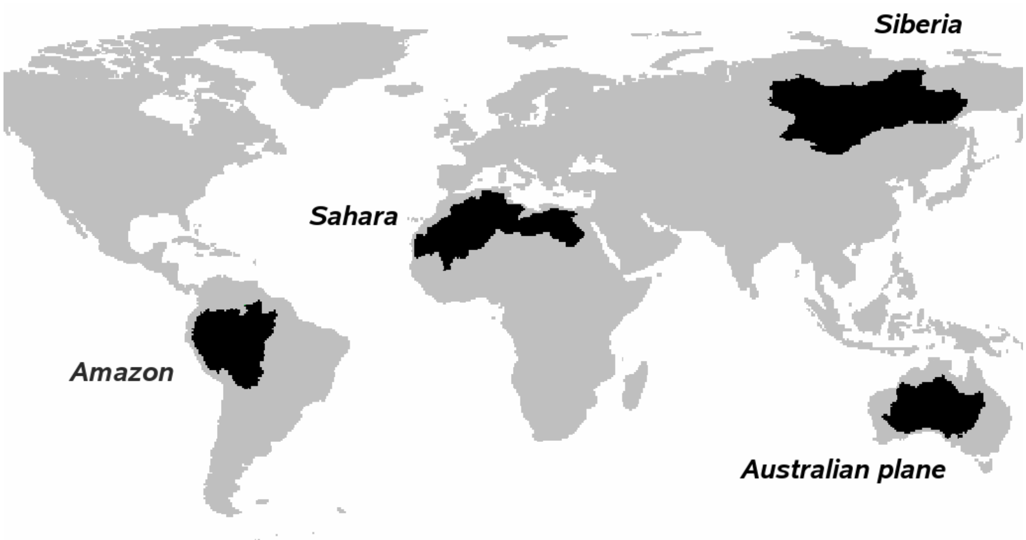

Fig. 1 River catchments and basins without discharge used for this study.

Siberia, comprising the river catchments of Yenisei (Igarka gauge) and Lena (Stolb gauge), and also the Amazon basin (Obidos gauge), represent moist regions but with differing climatic conditions and amplitudes of water storage change.

Data sources

Atmospheric fields Global fields of monthly vertically-integrated moisture flux divergence are gathered from ECMWF Operational Analysis (2001–2007), ERA-INTERIM (2000–2007) and from NCAR NCEP-Reanalysis (2002–2007).

For input to the WRF-ARW model, atmospheric forcing and initial conditions are taken from ECMWF Operational Analysis (OpAnl) ECMWF ERA-INTERIM (EI) and NCEP-Reanalysis I (NNRP). The fields from ECMWF have a resolution of 0.5 × 0.5 and 0.75 × 0.75 degrees and contain 16 and 37 vertical pressure level layers from 1000 to 1 mbar for OpAnl and EI respectively. NNRP is available with 2.5 × 2.5 degree mesh and 17 vertical layers from 1000 to 10 mbar.

Precipitation data Observation-based precipitation data are taken from the Global Precipitation Climatology Center (GPCC). The monthly fields rely on interpolated station data and are available on a 0.5° Gaussian grid.

Discharge data River discharge data are obtained from the Global Data Runoff Centre (GRDC). The data are aggregated to monthly values. Unfortunately, for recent periods, the quantity of available observations is small. Thus, the number of regions that overlap with the GRACE data set is limited.

GRACE data GRACE-derived terrestrial water storage variations from GFZ Potsdam are used. The data are post-processed at the Institute of Geodesy, University of Stuttgart, Germany. Artefacts, such as the strong north-to-south stripe pattern, are removed by application of a 500-km Gaussian low pass filter and the de-striping method developed by Swenson & Wahr (2006).

Data aggregation

For a comparison of terrestrial water storage variations from different models and data sources, harmonization is required. Hence, all the data are spatially aggregated within the borders of a river catchment or a region without discharge. The basis for all comparisons is the amount of terrestrial water storage change, dS/dt, in mm/month.

Regional model set-up

For the regional simulations WRF-ARW, version 3.0.1.1, is used (Skamarock *et al*., 2008). WRF is a hydrometeorological modelling system that simulates atmospheric dynamics but also surface exchange and soil water processes using a SVAT module. For the simulations a spatial resolution of 30 km and 27 vertical layers are chosen. The model is driven by the ECMWF Operational Analysis, ECMWF ERA-INTERIM and NCEP-Reanalysis global data sets. In WRF, for every module, several models can be selected. The physical parameterization used for the different model compartments is given in Table 1.

Table 1 Physical parameterization of the regional model.

Domain	Amazon	Siberia	Sahara	Australia
Area (10^3 km^2)	4 673	4 873	5 272	3 880
Longwave radiation	RRTM	RRTM	RRTM	RRTM
Shortwave radiation	Goddard	Goddard	Goddard	Goddard
Microphysics	WSM5	WSM5	WSM5	WSM5
Planetary boundary layer	MM5 similarity	MM5 similarity	MM5 similarity	MM5 similarity
Surface layer	Yonsei	Yonsei	Yonsei	Yonsei
Land surface model	NOAH-LSM	NOAH-LSM	NOAH-LSM	NOAH-LSM
Cumulus parameterization	Kain-Fritsch / Betts-Miller-Janjic	Kain-Fritsch / Betts-Miller-Janjic	Kain-Fritsch	Kain-Fritsch

For all regions, similar physical settings are applied. Additionally, for the moist areas, two different cumulus parameterization schemes are tested. All simulations started in 2001; the period until 2002 is considered for model spin-up. The simulation time step varies from 60 to 180 s. The results are stored with a 6 hourly interval.

RESULTS AND DISCUSSION

Amazon

The comparison of terrestrial water storage variations from the atmospheric water budget shows significant differences between the regional and global fields for the Amazon (Fig. 2). Besides variable driving data from ECMWF ERA-INTERIM (EI) and NCEP-Reanalysis I (RA), three different parameterization types were used with the regional atmospheric model: (1) Constant sea surface temperature (SST) as initialized at model start and Kain-Fritsch (KF) cumulus parameterization; (2) variable SST derived from the global driving data with KF; and (3) variable SST with Betts-Miller-Janjic (BMJ) cumulus scheme. For the regional simulations the BMJ option is closer to the global model than KF. The two different KF runs show that using a variable SST also adds more water to the storage.

With NCEP driving, KF with constant SST leads to dryer conditions than BMJ, but KF+SST still gives the highest amplitude in storage variations.

If the results are compared to GRACE-derived water storage changes it can be seen that the water budgets from the global fields agree very well. With respect to GRACE the regional model is not able to add value for ECMWF driving data. In the case of NCEP with parameterization scheme 1, the regional model is able to improve the global results for spring 2004 and 2005 in terms of GRACE.

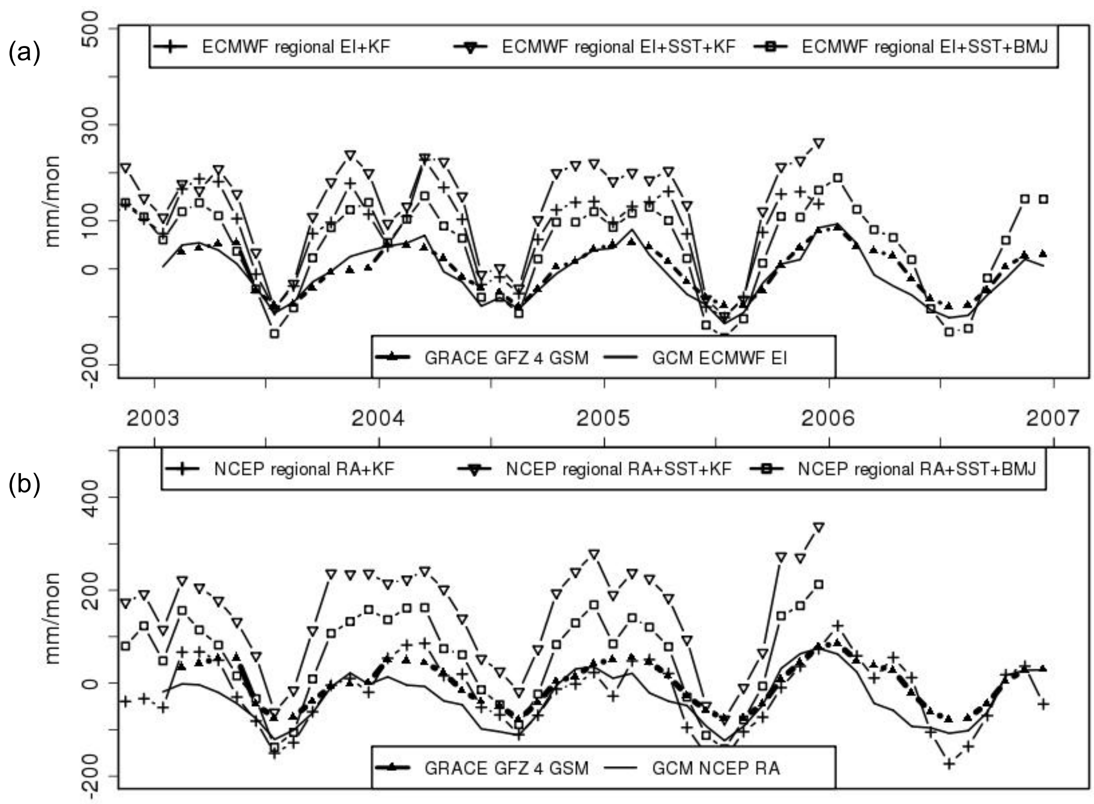

Fig. 2 Amazon Basin water storage variations $dS/dt = -D - R$ for ECMWF and NCEP reanalysis data in mm/month from: (a) regional modelling, and (b) global fields (solid line) and for GRACE dM/dt (solid triangle).

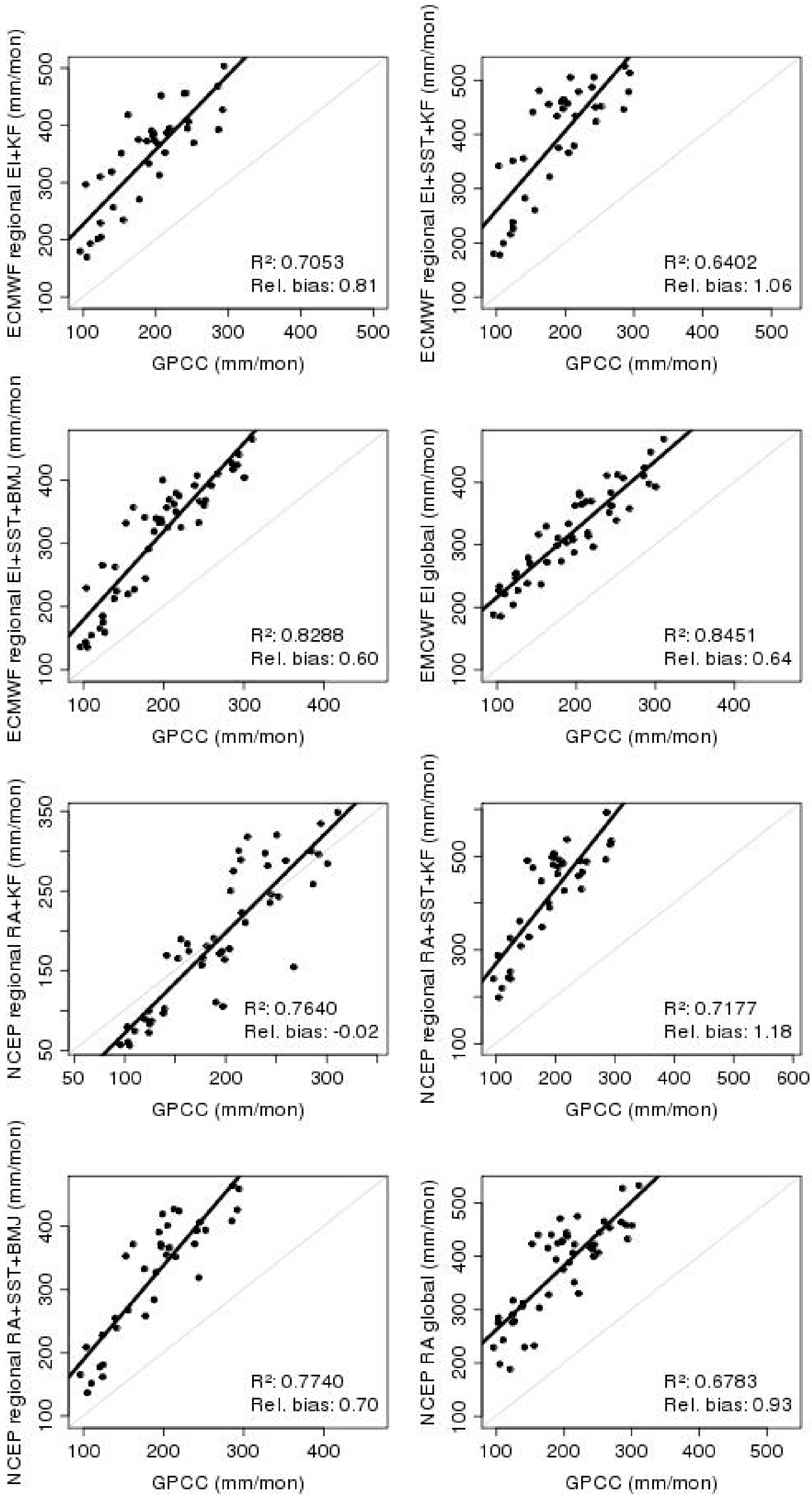

Fig. 3 Amazon: simulations *versus* GPCC precipitation data for ECMWF and NCEP global and regional models.

Figure 3 shows the correlations between simulated precipitation and GPCC data. It becomes quite evident that rainfall is largely overestimated by all types of simulations. In terms of precipitation, global and regional models show less deviation than for the atmospheric moisture divergence. Hence, for the Amazon, it can be concluded that: (1) the global atmospheric moisture budgets better resemble GRACE observations than the regional simulations do; and (2) with respect to GPCC, all models tend to overestimate the precipitation amounts, regardless of whether ECMWF or NCEP driving data are used.

Siberia

Different from the Amazon region, the water budget variations of Yenisei and Lena are much smaller in extent due to the dearth of radiation energy. Figure 4 depicts the terrestrial storage variations for global and regional simulations and GRACE. Between the global and regional simulations only small deviations exist for ECMWF. Hence, the ensemble simulations were stopped in 2004 and only the KF parameterization with constant SST was pursued. For the NCEP re-analysis, the results from the regional model outperform the global simulation regarding GRACE.

Compared to GRACE, the atmospheric models yield similar water storage variations. Only in late spring, when the river runoff reaches its maximum amount the satellite observation does not correlate with the simulations. This effect could be caused by errors in the discharge measurements.

Looking at the performance of precipitation simulations (Fig. 5) reveals some differences between ECMWF Operational Analysis (OpAnl) and ERA-INTERIM (EI). Using the same model parameterization the OpAnl has a correlation of 0.55 with GPCC data while with EI driving the value increases to 0.6. Enabling the variable SST, the correlation improves to 0.83, but then a strong bias is experienced.

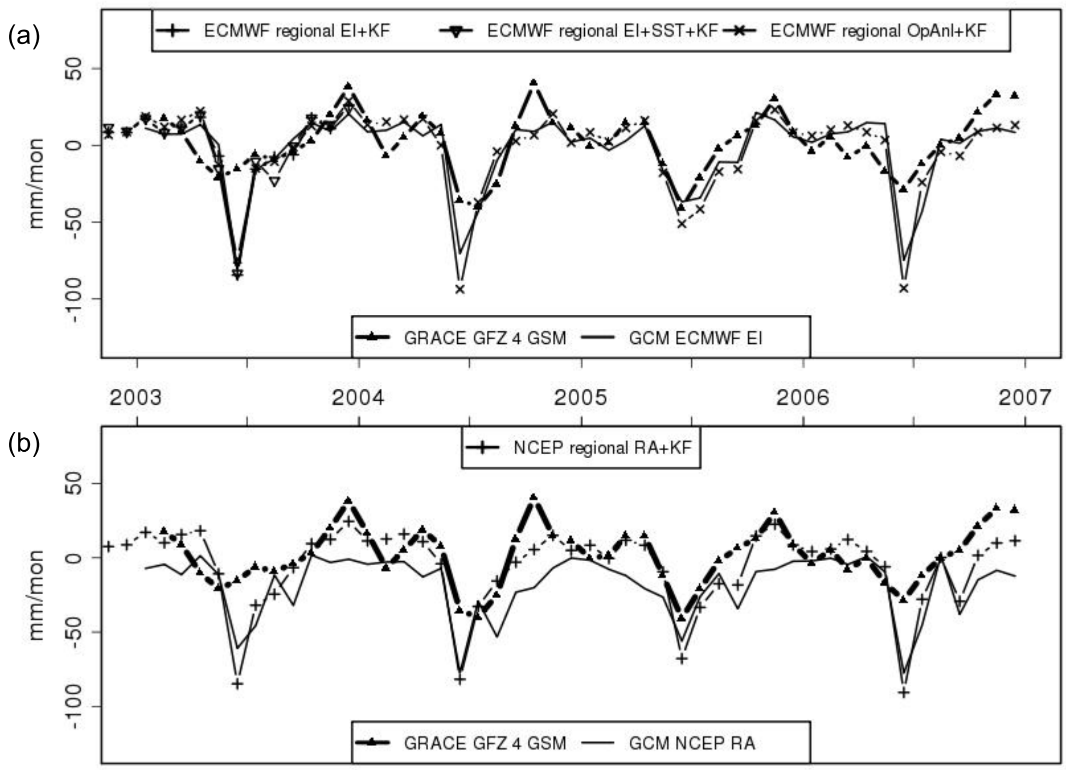

Fig. 4 Siberia (Yenisei and Lena): catchment water storage variations $dS/dt = -D - R$ for ECMWF and NCEP re-analysis data in mm/month from: (a) regional modelling, (b) global fields (solid line) and for GRACE dM/dt (solid triangle).

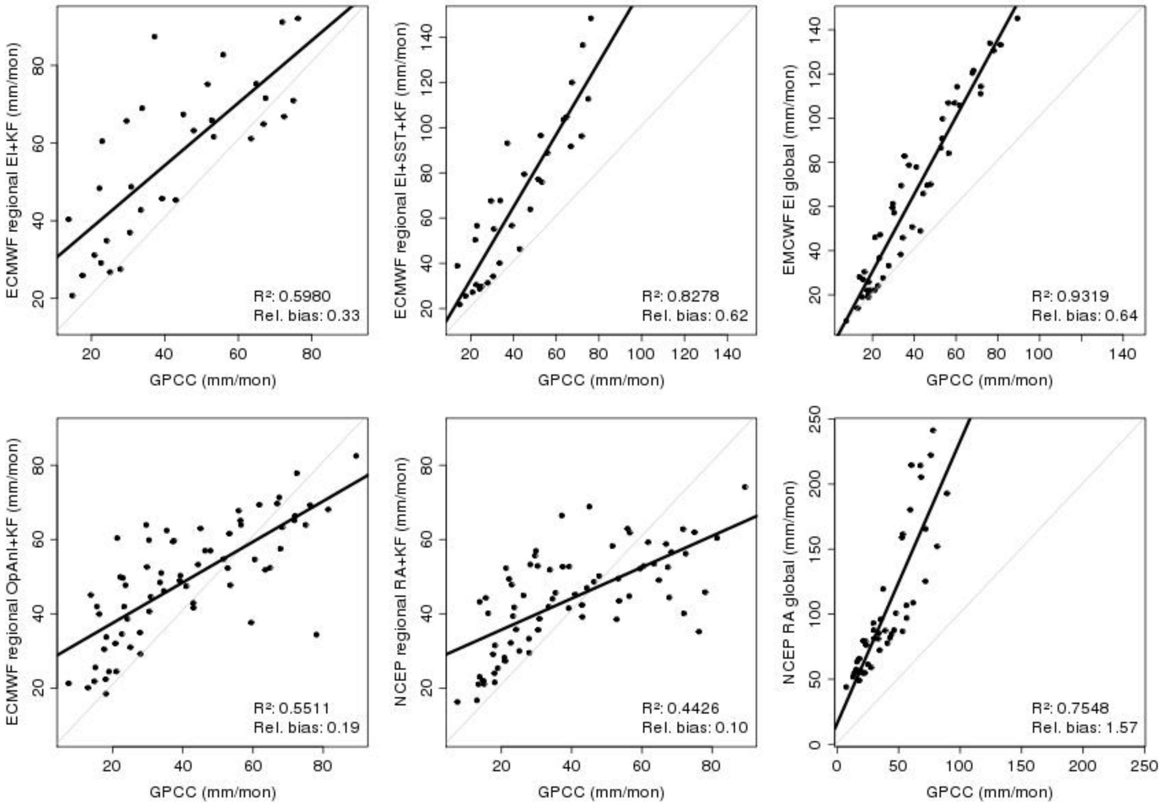

Fig. 5 Siberia: global and regional model simulations *versus* GPCC precipitation data for ECMWF and NCEP global and regional simulations.

The highest correlation, but also the highest bias, is found between the global models and GPCC. The good correlations for the regional simulations with variable SST and GPCC suggest that the ensemble calculations should be continued and also be applied for NCEP driving data.

Sahara

For the arid Saharan domain (Fig. 6) the amplitudes of terrestrial water storage variations are very small compared to the Amazon basin or Siberia. As the region is considered to have no lateral outflow, the runoff term is set to zero. Because the ECMWF ERA-INTERIM re-analysis became available just recently, so far the regional simulations are only available for Operational Analysis driving data.

The comparison of global model data and regional simulations shows a strong correlation for ECMWF in the winter months, but also an overshooting for the summer months. For NCEP, the global and regional realizations are in better agreement.

By looking at the global atmospheric water budgets, it can be seen that NCEP simulates higher amplitudes of storage variations than ECMWF. Operational Analysis and ERA-INTERIM (grey line) also show some deviations, especially in 2003. EI agrees better with GRACE in general. For NCEP, only in the winter periods can a considerable correlation can be stated.

Most of the atmospheric simulations are in close agreement with GRACE for the winter periods, although the amplitude of the signal is very small and the GRACE errors increase from the poles to the Equator.

The systematic disagreement between GRACE and the atmospheric simulations in the summer periods could be caused by ITCZ convective precipitation events that are overestimated by the models, similar to the Amazonian domain. A detailed pattern analysis will verify this assumption.

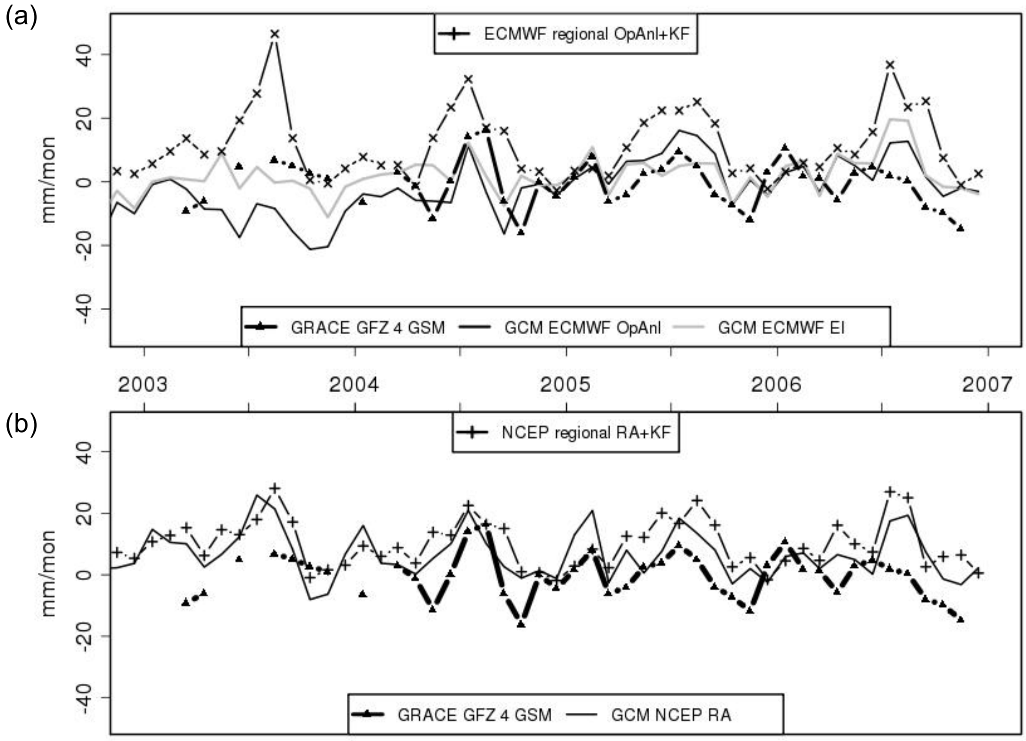

Fig. 6 Sahara: regional water storage variations dS/dt = –D – R for ECMWF and NCEP reanalysis data in mm/month from: (a) regional modelling, (b) global fields (solid line) and for GRACE dM/dt (solid triangle).

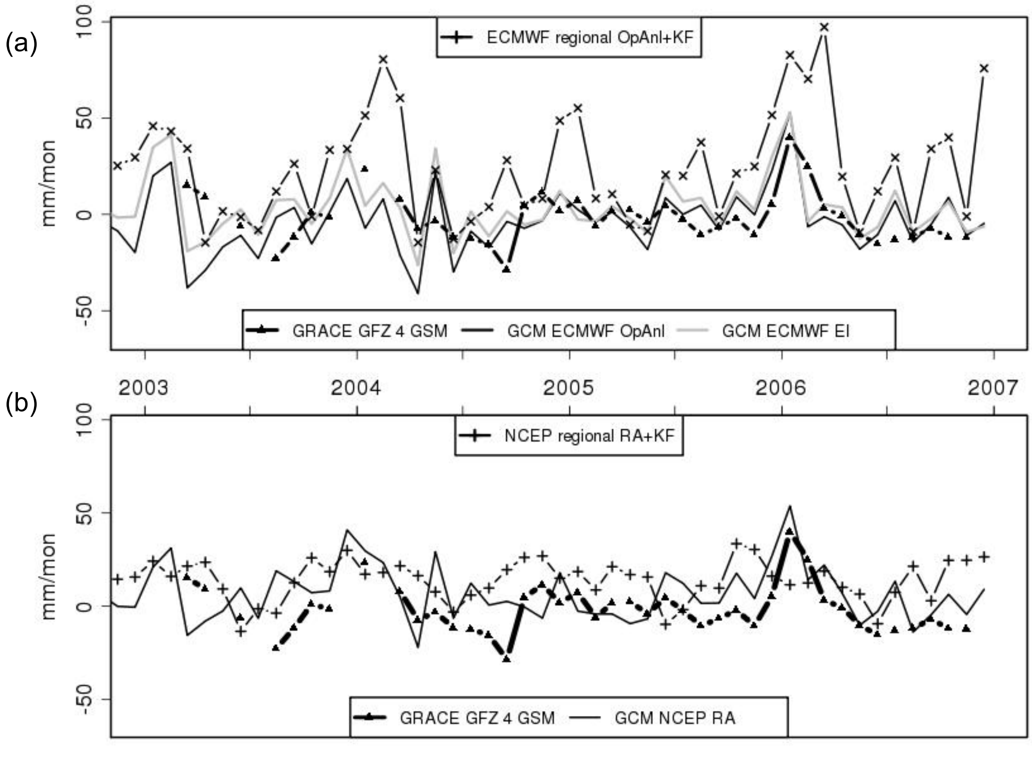

Fig. 7 Australia: regional water storage variations dS/dt = –D – R for ECMWF and NCEP reanalysis data in mm/month from: (a) regional modelling, (b) global fields (solid line) and for GRACE dM/dt (solid triangle).

Australia

The Australian domain (Fig. 7) shows similar characteristics to the Saharan domain. Although the amplitude of water storage variations is more intense than in the Sahara, the relative deviations between global and regionalized atmospheric fields are prominent.

Compared to GRACE, the two global fields from ECMWF (OpAnl and EI) are more consistent than obtained from NCEP.

CONCLUSIONS

For regions with strong amplitudes in water storage variations, atmospheric moisture budgets are a viable substitute for $P - ET$ if GRACE is taken as a reference. However, the atmospheric models tend to overestimate precipitation. For the global models this problem is not directly connected with the moisture divergence because of the non-conservative formulations of the model equations. The WRF model uses a mass conserving formulation here. Hence, the elevated precipitation values react upon atmospheric moisture budgets.

For periods where convective events are non-essential, global and regional models perform in a similar way. If GRACE is taken as a reference, regional modelling does not clearly outperform the global simulations, but for several periods an improvement towards the satellite measurements can be found. Admittedly, for small amounts of mass variations, it must be considered that the GRACE estimates include relatively large errors that emerge from signal de-aliasing and filtering.

In order to identify the structural causes for strong and weak correlations between models and GRACE, the spatial patterns of water storage variations will be analysed in a next step.

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REFERENCES

Hirschi, M., Viterbo, P. & Seneviratne, S. I. (2005) Basin-scale water-balance estimates of terrestrial water storage variations from ECMWF operational forecast analysis. *Geophys. Res. Lett*. **32**, doi:10.1029/2005GL027659.

Seitz, F., Schmidt, M. & Shum, C. K. (2008) Signals of extreme weather conditions in Central Europe in GRACE 4-D hydrological mass variations. *Earth Planet Sci. Lett.* **268**, 165–170.

Skamarock, W. C., Klemp, J. B., Dudhia, J., Gill, D. O., Barker, D. M., Wang, W. & Powers, J. G. (2008) A description of the advance research WRF Version 3 (NCAR/TN-468+STR). Technical report, National Center for Atmospheric Research, Boulder, Colorado, USA.

Swenson, S. & Wahr, J. (2006) Post-processing removal of correlated errors in GRACE data. *Geophys. Res. Lett.* **33**, doi:10.1029/2005GL025285.

Syed, T. H., Famiglietti, J. S., Chen, J., Rodell, M., Seneviratne, S. I., Viterbo, P. & Wilson, C. R. (2005) Total basin discharge for the Amazon and Mississippi River basins from GRACE and a land-atmosphere water balance. *Geophys. Res. Lett.* **32**, doi:10.1029/2005GL024851.

Syed, T. H., Famiglietti, J. S., Zlotnicki, V. & Rodell, M. (2007) Contemporary estimates of Pan-Arctic freshwater discharge from GRACE and reanalysis. *Geophys. Res. Lett.* **34,** doi:10.1029/2007GL031254.