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Basin-scale water-balance dataset (BSWB): an update

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Abstract. This paper presents an update of a basin-scale diagnostic dataset of monthly variations in terrestrial water storage for large river basins worldwide (BSWB v2016, doi:10.5905/ethz-1007-58). Terrestrial water storage comprises all forms of water storage on land surfaces, and its seasonal and inter-annual variations are mostly determined by soil moisture, groundwater, snow cover, and surface water. The presented dataset is derived using a combined atmospheric and terrestrial water-balance approach with conventional streamflow measurements and re-analysis data of atmospheric moisture flux convergence. It extends a previous existing version of the dataset (Mueller et al., 2011) temporally and spatially.

1 Introduction

Terrestrial water storage (TWS) plays a key role in the hydrological cycle. It encompasses all water stored on land surfaces, and its seasonal and inter-annual variations are determined by soil moisture, groundwater, snow cover, and surface water. Especially soil moisture is essentially contributing to land–atmosphere coupling (e.g., Koster et al., 2006; Seneviratne et al., 2006, 2010; Hirschi et al., 2011; Miralles et al., 2014; Guillod et al., 2015). In particular, it is important for numerical weather prediction (e.g. Beljaars et al., 1996; Drusch, 2007; Orth et al., 2016) and seasonal forecasting (e.g., Koster et al., 2000; van den Hurk et al., 2010), as well as for climate simulations of present and future climate (e.g. Shukla and Mintz, 1982; Milly and Dunne, 1994; Koster et al., 2009; Seneviratne et al., 2013).

Despite recent activities in assembling in-situ soil moisture observations (Dorigo et al., 2013), global coverage remains limited. This is even more the case for in-situ observations of the other components of TWS. Remote sensing can help to increase the spatial coverage with observations. For soil moisture, the European Space Agency (ESA) Climate Change Initiative (CCI, http://www.esa-soilmoisture-cci.org) provides a long-term global soil moisture product from merging data from active and passive microwave sensors (Liu et al., 2012). However, penetration depth is limited to the top few centimeters of the soil (Owe and Van de Griend, 1998). On the other hand, remote-sensing based measurements of TWS from the Gravity Recovery and Climate Experiment (GRACE; Tapley

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et al., 2004; Ramillien et al., 2008; Humphrey et al., 2016) only go back to 2002. Thus for further retrospective evaluation of TWS, alternative approaches are required.

Here, we rely on a combination of streamflow measurements (relatively broadly available) and an observation assimilating atmospheric re-analysis system to diagnose TWS variations on basin scale (e.g., Seneviratne et al., 2004; Hirschi et al., 2006a). This allows for an evaluation of TWS variations in gauged river basins worldwide and over a longer time period (mostly limited by the availability of streamflow data). The presented basin-scale water-balance dataset of monthly TWS variations (BSWB v2016) extends a previous version of the dataset (Mueller et al., 2011, hereafter referred to as BSWB v2011, data available at www.iac.ethz.ch/url/bswb) temporally and spatially.

2 Methodology

The method used to derive the BSWB v2016 dataset is based on publications describing previous versions of the data (Seneviratne et al., 2004; Hirschi et al., 2006a; Mueller et al., 2011). For a given river basin, the terrestrial water balance can be expressed as

$$\left\{\overline{\frac{\partial S}{\partial t}}\right\} = \left\{\overline{P} - \overline{E}\right\} - \left\{\overline{R}\right\} \quad , \tag{1}$$

where S represents the TWS of the given basin, P the precipitation, E the evapotranspiration, and R the measured streamflow, which is assumed to include both the surface and the groundwater runoff of the area. The overbar denotes a temporal average (i.e. monthly means) and $\{\}$ a space average over the basin.

Neglecting the contribution of the liquid and solid water in clouds (Peixoto and Oort, 1992), the atmospheric water balance for the same area can be expressed as

$$\left\{\overline{\frac{\partial W}{\partial t}}\right\} = -\left\{\overline{\nabla_H \cdot \boldsymbol{Q}}\right\} - \left\{\overline{P} - \overline{E}\right\} \quad , \tag{2}$$

where W represents the column storage of water vapor and $\boldsymbol{Q}$ the vertically integrated two-dimensional water vapor flux. The operator $(\nabla_H \cdot)$ denotes the horizontal divergence. Eliminating the term $\left\{\overline{P} - \overline{E}\right\}$ between (1) and (2) results in the combined atmospheric and terrestrial water balance equation

$$\left\{\overline{\frac{\partial S}{\partial t}}\right\} = -\left\{\overline{\frac{\partial W}{\partial t}}\right\} - \left\{\overline{\nabla_H \cdot \boldsymbol{Q}}\right\} - \left\{\overline{R}\right\} \quad . \tag{3}$$

The monthly variations in TWS of the studied basin can thus be expressed as the sum of three terms only: the change in atmospheric water vapor content, the water vapor flux convergence, and the measured river streamflow. The term $\left\{\overline{\partial W/\partial t}\right\}$ is usually negligible for annual means, but not for monthly means, particularly during the spring and fall seasons (Rasmusson, 1968; Seneviratne et al., 2004).

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3 Data sources

3.1 Re-analysis data

The vertically integrated atmospheric moisture flux divergence and water vapor content are taken from the ERA-Interim re-analysis product (Dee et al., 2011) of the European Centre for Medium-Range Weather Forecasts (ECMWF).

ERA-Interim is produced with a 2006 version of the IFS (Integrated Forecasting System, Cy31r2). It has a T255 spherical harmonic representation for the atmospheric dynamic and thermodynamic fields, corresponding to grid-spacings of about 80 km, on 60 vertical levels from the surface up to 0.1 hPa. Here we use the interpolated 0.5x0.5°product. The re-analysis covers the period 1979 to near present and uses a 12-h 4D-Var assimilation technique. The two ERA-Interim fields used in the water-balance computations (i.e. atmospheric moisture flux divergence and water vapor content) contain assimilated humidity and wind observations from radiosondes. Additional documentation on ERA-Interim can be found at http://www.ecmwf.int/en/research/climate-reanalysis/era-interim.

3.2 Streamflow data and catchment boundaries

The monthly streamflow data has been obtained from the Global Runoff Data Center (GRDC). We use the GRDC reference dataset (http://www.bafg.de/GRDC/EN/04_spcldtbss/43_GRfN/refDataset_node.html) which compiles time series of river discharge data of 718 stations of the GRDC database longer than 20 years, each capturing a basin area greater than 10 000 km^2. The GRDC reference dataset time series are updated regularly.

Catchment boundaries are provided by the GRDC as shape polygons. These are used to average the ERA-Interim fields over the basin area (see below).

4 BSWB v2016 dataset

4.1 Processing

The ERA-Interim atmospheric moisture flux divergence and water vapor content are processed to monthly averages first. Then these fields are averaged over the basin area using the fractional coverage of the catchments in each ERA-Interim grid cell as a weighting factor. For the basin averaging, we use the R-package 'raster' (http://cran.r-project.org/web/packages/raster/). Note that basin masks with the fraction of grid cell inside the catchment are provided for different spatial resolutions as part of the BSWB v2016 dataset (see Section 6).

From the GRCD reference dataset, the monthly data is used. The provided flags are applied in the following way:

- flag 99 (usage not recommended by the provider) is set to missing data

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– monthly data based on more than ten missing daily values is set to missing data

When available we use the GRDC modified data, else the original (provided) data is used. Finally, the monthly variations in TWS are calculated using Equation 3.

The critical domain size for water-balance computations using high resolution reanalysis data is assumed to be of the order of 10^5 km^2 (Yeh et al. 1998; Berbery and Rasmusson 1999; Seneviratne et al. 2004). Smaller basins often suffer from an imbalance between moisture convergence and streamflow (see below, and e.g., Hirschi et al., 2006a; Mueller et al., 2011). For consistency with BSWB v2011, we consider basins greater than 35 000 km^2. Moreover, only basins covering more than six overlapping years of streamflow and re-analysis data are presented. Consequently, the BSWB v2016 dataset covers the time period 1979–2015, but is often limited by availability of streamflow data. The resulting global coverage with basins is displayed in Figure 1. Currently, the BSWB v2016 dataset encompasses 341 river basins.

4.2 Imbalance and drift correction

In the long term, the water input to a basin should be balanced by the water output. As the contribution of the changes in column storage of water vapor are negligible for annual to long-term means, column integrated moisture flux convergence should be balanced by streamflow. This assumption is generally correct for multi-year means, although some regions may show persistent trends, e.g., due to groundwater withdrawal (e.g., Zektser et al., 2005; Rodell et al., 2009). Other neglected factors are inter-basin groundwater flow as well as direct groundwater discharge to the ocean. This latter term is not included in the measured streamflow and represents approximatively 6% of the total annual global water gain by the oceans (Zektser and Loaiciga, 1993).

In particular smaller river basins preferentially suffer from an imbalance between long-term means of the vertically integrated water vapor flux and the streamflow of the basin. Figure 2 displays this imbalance as the long-term average of $\left\{\overline{\partial S/\partial t}\right\}$ vs. the domain size of the river basins. As mentioned, the critical domain size for water-balance computations using high resolution reanalysis data is of the order of 10^5 km^2 (Yeh et al., 1998; Berbery and Rasmusson, 1999; Seneviratne et al., 2004). Our results roughly confirm this threshold as the imbalance is diminished above this basin size.

As a consequence of the imbalance, the temporal integration of the diagnosed monthly variations in TWS, i.e

$$S(t) \quad = S_0 + \int_{t_0}^{t} \left\{\overline{\frac{\partial S}{\partial t}}\right\} dt \qquad with\ S_0 = 0\ mm, \tag{4}$$

shows a drift in TWS. The likely reason for this drift are biases in the atmospheric moisture convergence data (Seneviratne et al., 2004). The errors in the runoff measurements are expected to be small, i.e., around 5% (Winter, 1981) for longer-term averages. Thus, these drifts in TWS unlikely correspond to actual variations, though the latter can be important in some regions and could con-

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tribute to part of the signal (see above). As widespread information on such natural sources of drifts in TWS is not available, the most appropriate procedure is to assume that the observed drifts are purely artificial and remove them by a high-pass filter.

The drift correction is achieved by subtracting a running mean with a 3-year window from the original estimates of TWS variations. This forces the long-term average of $\left\{\overline{\partial S/\partial t}\right\}$ to zero (cf. red dots in Figure 2) and allows to remove the artificial drift without losing the short-term variability. Note that a remaining imbalance might persist on Figure 2 due to non-complete years of data.

We provide both the original and the drift-corrected estimates as part of the BSWB v2016 dataset. In this way, the application of alternative filters (e.g., LOESS filter) to the original estimates is still possible for the user. Note that due to the presented reasons, the BSWB data is not applicable for trend analyses.

5 Comparison with previous version

To check the consistency of the updated BSWB v2016 dataset with the previous BSWB v2011, we compare timeseries of both versions for some river basins. Note that due to the availability of ERA-Interim and streamflow data, BSWB v2011 was restricted to the 1989–2008 time period. ERA-Interim has been updated and temporally extended since then (see http://www.ecmwf.int/en/about/media-centre/news/2011/extension-era-interim-reanalysis-1979).

Figures 3 and 4 show time series of the BSWB v2011 and BSWB v2016 datasets for selected basins. The datasets agree very well, both for the absolute TWS variations as well as for its anomalies (i.e., anomalies with respect to the mean seasonal cycle). Correlations amount to 0.99 on the average for absolute TWS variations and are mostly higher than 0.85 for the anomalies (for basins with at least four overlapping years of data, see Table 1). This good agreement is also visible in the scatter plots based on all basins covered by both datasets (Figure 5), which again show high correlations between BSWB v2011 and BSWB v2016 both for absolute values and the anomalies. Despite this close agreement, differences between BSWB v2011 and BSWB v2016 exist and are likely related to changes in ERA-Interim. For instance the previously existing negative outlier in Europe in 2003 was caused by a strong moisture divergence which has been alleviated in the extended ERA-Interim version (see Figure 3).

6 Data availability

The presented basin-scale diagnostic dataset of monthly variations in terrestrial water storage (BSWB v2016) is available for download at the ETH data archive: doi:10.5905/ethz-1007-58. The data is provided in individual ASCII files for each of the river basins and contains time series of the uncorrected monthly variations in terrestrial water storage (in units of mm/d) as well as the drift-corrected data (see Section 4.2). Moreover, gridded masks of the river basins are provided to facilitate comparison

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with other gridded data (e.g. climate model output). The masks are made available in NetCDF format for three spatial resolutions (1x1°, 0.5x0.5°and 0.25x0.25°) and contain the fraction of the grid cell inside the respective catchment. Older versions of the BSWB dataset are available at the following website: www.iac.ethz.ch/url/bswb.

7 Conclusions

We present an update of a basin-scale diagnostic dataset of monthly variations in terrestrial water storage for large river basins worldwide (BSWB v2016). The dataset is derived using a combined atmospheric and terrestrial water-balance approach with conventional streamflow measurements and atmospheric re-analysis data from ECMWF ERA-Interim. It extends the existing version of the dataset (Mueller et al., 2011) temporally and spatially. Overall, the update shows very good agreement with the previous version of the dataset. BSWB data proved to be valuable for climate and land-surface model evaluation (e.g., van den Hurk et al., 2005; Hirschi et al., 2007; Balsamo et al., 2009; Dutra et al., 2010) and the investigation of land surface processes (e.g., Fischer et al., 2007), as well as for the evaluation of other large-scale estimates of TWS (e.g., Hirschi et al., 2006b; Troch et al., 2007).

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Table 1. Correlations between BSWB v2011 and BSWB v2016 timeseries (drift-corrected data) of absolute TWS variations as well as of the anomalies in the river basins covered by both datasets and with at least four overlapping years of data.

River	Absolute	Anomalies
LENA at STOLB	1.00	0.96
SELENGA at MOSTOVOY	1.00	0.91
YENISEY at IGARKA	1.00	0.98
IRTYSH at OMSK	0.99	0.89
OB at SALEKHARD	0.99	0.91
YUKON RIVER at PILOT STATION, AK	0.98	0.85
COLUMBIA RIVER at THE DALLES, OR	0.99	0.95
MACKENZIE RIVER at ARCTIC RED RIVER	0.99	0.96
RHONE at BEAUCAIRE	1.00	0.96
RHINE RIVER at REES	0.94	0.87
WESER at INTSCHEDE	1.00	0.98
ELBE RIVER at NEU-DARCHAU	0.97	0.93
VOLGA at VOLGOGRAD POWER PLANT	1.00	0.96
Mean	0.99	0.93

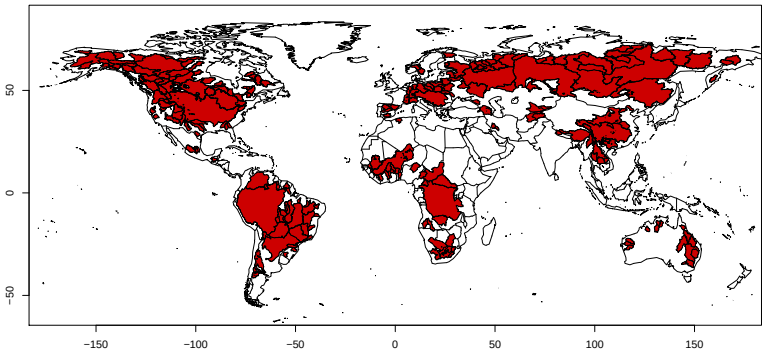

Figure 1. Global coverage of basins.

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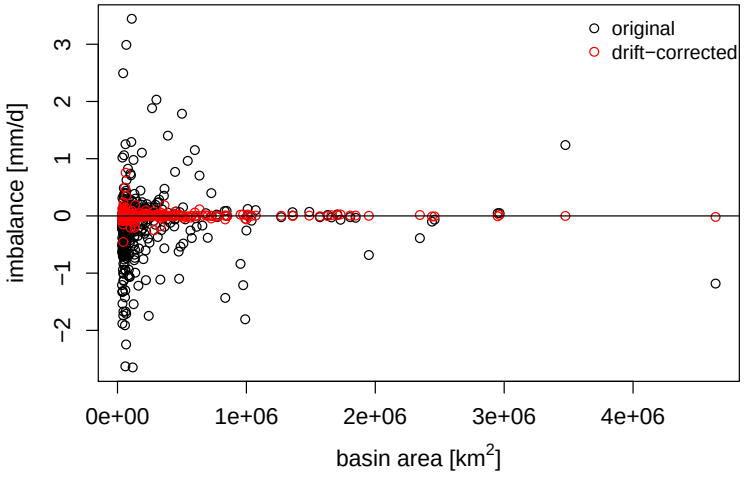

Figure 2. Long-term averages of $\left\{\overline{\partial S/\partial t}\right\}$ as indication for the imbalance vs. domain size of the basins.

Earth Syst. Sci. Data Discuss., doi:10.5194/essd-2016-33, 2016
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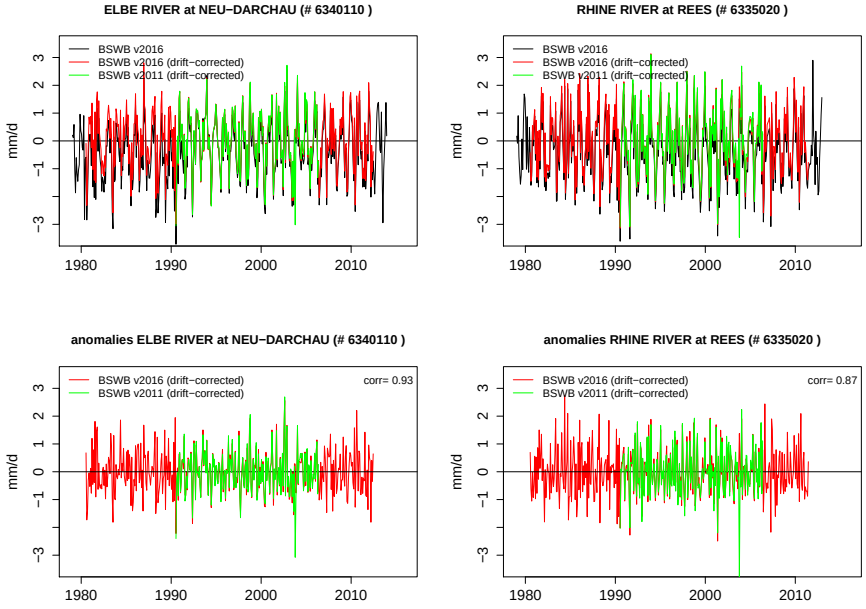

Figure 3. Comparison of BSWB v2011 and BSWB v2016 data of the Elbe (at Neu-Darchau) and the Rhine (at Rees) river basins (with numbers in brackets denoting the GRDC station number). For BSWB v2016, both the original and the drift-corrected data is displayed. Top panels show the absolute time series, bottom panels the anomalies with respect to the mean seasonal cycle (with the correlation between the anomaly time series noted as well).

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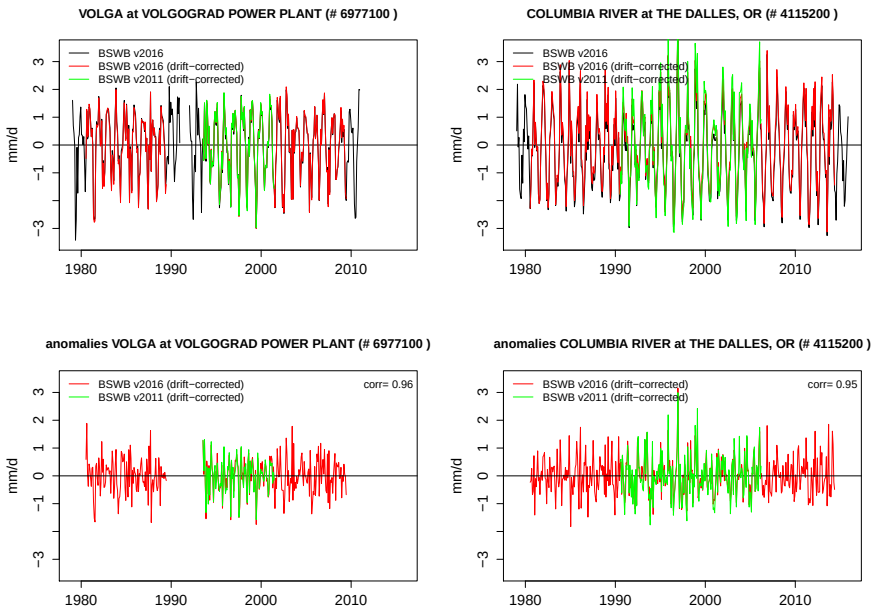

Figure 4. As Figure 3, but for the Volga (at Volgograd power plant) and the Columbia (at The Dalles) river basins.

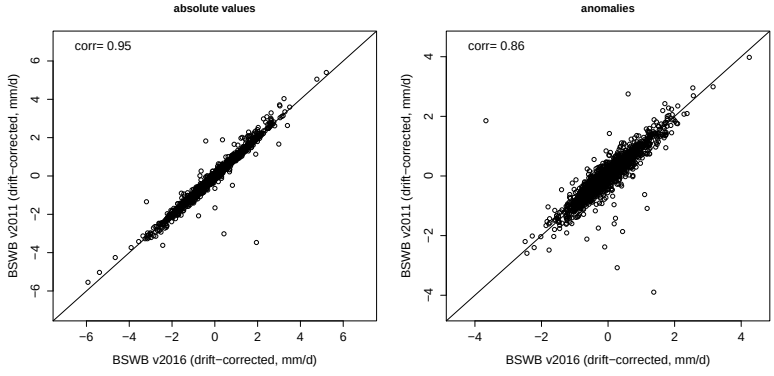

Figure 5. Scatter plots of BSWB v2011 vs. BSWB v2016, all basins covered by both datasets. (left) absolute values of monthly TWS variations, (right) its anomalies with respect to the mean seasonal cycle.