Reproducibility of the seasonal cycles of land-surface hydrological variables in Japanese 25-year Reanalysis

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Abstract:
The present article reports the first investigation on the reproducibility of three land-surface hydrological variables (soil moisture, river discharge, and terrestrial water storage) in Japanese 25-year Reanalysis (JRA-25) by a system consisting of the Land Data Analysis (LDA) of JRA-25 and the modified version of a global river flow model, JRA-25 well reproduces the seasonal cycles of observed soil moisture, river discharge, and terrestrial water storage. Detailed examinations revealed that the high reproducibility of the seasonal cycle of soil moisture originates from that of precipitation, that the low amplitude reproducibility of river discharge results from insufficient representation of the land-surface hydrology and insufficient reproducibility of the annual mean precipitation in JRA-25, and that the low amplitude reproducibility of terrestrial water storage predominantly results from insufficient representation of the land-surface hydrological model. An additional comparison in the reproducibility of soil moisture between JRA-25 and operational LDA reveals that the better reproducibility of soil moisture in JRA-25 does not always result from reasonable physical processes. The JRA-25 dataset should be used cautiously for studies in hydrology and meteorology, since the reproducibility varies with basins or areas.

KEYWORDS JRA-25; land-surface model; soil moisture; river discharge; terrestrial water storage

INTRODUCTION

Land-surface hydrological processes play important roles in the Earth’s climate system through atmosphere-land interactions and affect human activities through water resources and disasters. In spite of the significance of the global-scale land-surface hydrological processes, hydrological variables such as soil moisture, river discharge, and terrestrial water storage (TWS), computed with land-surface hydrological models have been widely used as a proxy for observations due to observational difficulty on a global scale. These variables have been obtained from both atmospheric (re)analysis data (e.g., Coe, 2000) and offline simulations with observed atmospheric forcing (e.g., Hirabayashi et al., 2005). The (re)analysis-based variables feature consistency in atmosphere-land surface hydrological data, while those of the offline simulation have higher accuracy in land-surface hydrological data. Previous studies validated land-surface hydrological variables in (re)analyses: soil moisture (Li et al., 2005), river discharge (Coe, 2000), and TWS (Nakaegawa et al., 2007), since these land-surface hydrological variables tightly interact with atmosphere are good indicators for the reproducibility of (re)analysis, and are used for forecast model initial conditions and climate research (e.g., Kanamitsu et al., 2002; Yamamoto et al., 2007).

Japanese 25-year Reanalysis data (JRA-25) was produced with the Japan Meteorological Agency’s (JMA’s) latest numerical assimilation system employing a three-dimensional variational method and specially-collected observational data (Onogi et al., 2007). Onogi et al. (2007) showed that soil moisture in Illinois was reproduced as qualitatively as soil moisture in other reanalyses; however, soil moisture in the Amazon River basin was unrealistically low due to insufficient quality control of the observed atmospheric data. Hence, further examination of the reproducibility of hydrological variables in JRA-25 provides significant information about its performance.

This study presents for the first time the seasonal cycle reproducibility of three land-surface hydrological variables in JRA-25 (soil moisture, river discharge, and TWS), by comparing observed data, since the reproducibility of the hydrological variables has not yet been well investigated compared with that of atmospheric variables in JRA-25. In addition, I compared the reproducibility between JRA-25 and operational Land Data Analysis (OLDA; for details see section below entitled “Comparison between JRA-25 and OLDA”).

ESTIMATION AND EVALUATION

Estimation

Land-surface hydrological processes in this study are represented by a system consisting of the Land Data Analysis (LDA) of JRA-25 (Onogi et al., 2007) and the Global River flow model using the Total River Integrated Pathway (TRIP; Oki and Sud, 1998) (GRiveT; Nobara et al., 2006). LDA uses the JMA-Simple Biosphere (SiB), which is modified for long-term integration. LDA computes the land-surface hydrological variables with atmospheric forcing obtained from JRA-25 and with the variables from the snow-depth analysis. GRiveT forced with surface and subsurface runoff in LDA of JRA-25 computes river-channel water storage and discharge according to a digital river network of TRIP. Nakaegawa and Hosaka (2008) modified GRiveT to enable us to assign distributed river current speeds obtained with calibration for each grid and to implement the groundwater process. Since the runoff in LDA of JRA-25 is the sum of surface and subsurface runoff, I assume that the surface runoff ratio \( \varphi = 0.5 \) and the total runoff is separated into the two variables. This assumption is supported by an additional experiment (see in Supplement Information).

The variables in GRiveT and LDA have the same 6-hour temporal resolution as JRA-25 but have a spatial resolution of 1° after interpolation, unlike the spectral resolution of T106 (equivalent to a horizontal grid size of resolution of T106 (equivalent to a horizontal grid size
of about 1.125°) of LDA, which are referred to as JRA-25 for simplicity. The 9-year integration period is from April 1996 to May 2005.

Evaluation

I evaluated the reproducibility of the three hydrological variables (soil moisture, river discharge, and TWS). I compared soil moisture in the upper 1 m between JRA-25 and observations obtained at the Global Soil Moisture Data Bank (Robock et al., 2000). Observation stations were selected based on data availability for soil moisture in the uppermost 1 m of the profile: 124 meteorological stations (grassland and 8-year observations at longest) and 15 agricultural fields (winter wheat and 35- or 56-year observations) in Russia; a hydrological station, Boissy-le-Châtelet (grassland and 6-year observations) in France; 37 stations (19-year observations at longest) in China; 6 points in Iowa (grassland and 23-year observations) and 19 points in Illinois (grassland and 23-year observation) in the U.S.

The simulated river discharge and TWS are compared with the observed ones, respectively. The observed river discharges were obtained from the Global Runoff Data Center. TWS is computed by the atmosphere-terrestrial combined water-balance method (Masuda et al., 2001). In addition, a dataset of the Global Precipitation Climatology Project (Huffman et al., 1997) was used for evaluating precipitation of JRA-25. The periods of these datasets differ from one another, and as such I have only compared the climatological seasonal cycles of the three variables.

RESULTS

Soil moisture

Figure 1 depicts the correlation coefficients of the soil moisture seasonal cycles between JRA-25 and the observation. The seasonal cycles are generally reproduced well. Since JRA-25 well reproduces the seasonal cycles of precipitation (see Figure S1), it primarily accounts for the high soil moisture reproducibility; in contrast, negative correlations are distributed in the southern part of central Asia (55°E to 80°E, 35°N to 45°N) in the eastern part of Lake Baikal, in eastern China along 120°E, and at the base of Kola Peninsula. Two groups of observation stations in the U.S. show a lack of consistency; the correlation is high in Illinois, as presented by Onogi et al. (2007), while it is negligible in Iowa.

River discharge

Figure 2 displays the seasonal cycle reproducibility for river discharge: (a) the standard deviation (SD) of the JRA-25 amplitude normalized by the observed amplitude, (b) correlation coefficient, and (c) time lag defined with lag correlation (Nakaegawa and Tokuhiro, 2005).

The correlations (the phase differences) are high (zero) in most of the 70 rivers presented in Figure 2b (2c) due to the river current speed calibration to maximize the correlation coefficients with no time lag (refer to a geographical map of the river basins in Figure 1 of Nakaegawa (2006)). The calibration significantly contributes to reducing the phase difference since 35 rivers have a non-zero phase difference without this calibration. However, the calibration does not work well for the Murray, Kolyma, and Brazos Rivers. The calibrated speeds used for the three rivers are all less than 0.07 m s⁻¹ and are much smaller than the measured speeds reported by Nakaegawa and Hosaka (2008). This insufficient calibration of the river current speeds probably stems from weak seasonal cycles of the observed river discharges (Li et al., 2005; Nakaegawa et al., 2007) and insufficient representation in the present version of JRA-25.

Figure 2a displays the normalized standard deviation (SD) ratio of river discharge amplitude. The amplitudes are underestimated in rivers such as the Amazon River, the Nile Rivers, and rivers flowing in the mid and high latitudinal zone of the Northern hemisphere. Possible causes are mainly two: small annual discharges that usually reduce the amplitude and slower calibrated speed that smoothes the cycles. Figure 3 shows that out of 26 rivers with a SD ratio of less than 0.5, the annual discharge ratio of the simulation to the observation is less than 0.70 for 18 rivers. The speed is less than the general observed value of 0.15 m s⁻¹ for the remaining 8 rivers. Therefore, increases in annual runoff in JRA-25 and implementation of anthropogenic operations would
reduce underestimation for these rivers. The amplitude was overestimated in rivers of Europe, Africa, and the mid latitude of North America. Out of 21 rivers with a SD ratio exceeding 2.0, the annual discharge ratio of the simulation to the observation is greater than 1.5 for 13 rivers. These annual mean overestimations are primarily responsible for the amplitude overestimation, which suggests that decreasing the annual runoff in JRA-25 would improve in the amplitude reproducibility for the rivers. Further comparison shows that the annual mean river discharge ratios are substantially worse than the annual mean precipitation ratios and are positively correlated to them at the 0.02 significance level (0.29 for Pearson’s $r$ and 0.28 for Mann-Kendall’s $r$) (see Figure S2). Therefore, insufficient representation of the land-surface hydrology degrades river discharge reproducibility in JRA-25.

**TWS**

The TWS seasonal cycles are well reproduced in most of the river basins as presented in Figure 4b. However, the correlations are low in the Congo and Nile River basins and rivers of the mid- and high latitudinal Northern Hemisphere. Three river basins have negative correlation coefficients less than −0.4: the Yana, Rio Grande, and Fitzroy River basins. Since the three rivers have no phase difference and high correlations for river discharge as in Figure 2, the other variables can account for the negative correlations. Only 15 river basins have no TWS phase difference, in contrast to river discharge phase difference, because the simulated TWS phases are not tuned to the observed ones (Figure 4c). About half of the 70 river basins (36) have less than or equal to a ±1 month phase difference. If I calibrate the groundwater retarding time for each basin so as to tune the computed TWS phase to the observed one, the phase difference will be improved significantly.

The amplitudes are satisfactorily reproduced and the ratios lie between 0.5 and 2 (Figure 4a). The basins with a ratio less (greater) than 0.5 (2.0) are found to have 11% relative errors in annual precipitations on average as presented in Figure 5; therefore, the JRA-25 land-surface hydrological model is likely responsible for these low reproducibilities. The amplitude is underestimated in rivers in Siberia, the northern part of North America, and the tropical western part of Africa; in contrast, the amplitude is overestimated in the southeastern and eastern part of Asian Monsoon region. These under- or overestimations for both the river discharge and TWS are found in the same regions except for tropical western Africa. The TWS amplitudes are generally better reproduced than the river discharge amplitudes, indicating that the soil moisture, the dominant variable of TWS and a variable with good reproducibility as in Figure 1, contributes to the better TWS reproducibility.
Compared between JRA-25 and OLDA

I compared the three variables between JRA-25 and OLDA to demonstrate the difference in hydrological variables between the two very similar analyses and to identify causes for the difference. OLDA is an operational LDA for seasonal forecasts forced with the JMA's global analysis for operational atmospheric prediction and monitoring. The same version of SiB and the snow depth analysis are used as the land-surface hydrological model in both analyses. The JRA-25 differs from OLDA by three. JRA-25 is used as the atmospheric forcing produced with the three-dimensional data assimilation technique, while OLDA implemented with state-of-the-art methods such as four-dimensional assimilation technique. The digitized Chinese snow depth data are assimilated in only JRA-25. The JRA-25 includes the atmosphere-land interaction since it is a component of the JRA-25 assimilation system, while OLDA does not include them because it is integrated in offline mode.

JRA-25 reproduces the seasonal cycle of soil moisture better than OLDA. The mean correlation coefficient for JRA-25 (OLDA) is 0.45 (0.33), and 92 (52) stations have coefficients exceeding 0.75 for JRA-25 (OLDA). Low reproducibility is distributed among the same stations for both analyses, but 6 stations in the Yangtze River region (106.10°E to 119.47°E, 30.68°N to 34.27°N, the same region as the eastern part of China in Nakaegawa et al. (2007)) and 17 stations in the southern part of west Siberia, including the midstream region of the Ob River basin and the upstream region of the Yenisey River basins (70°E to 105°E, 50°N to 60°N) have better soil moisture correlations in JRA-25 than in OLDA. Only Iowa stations and one station at the base of Kola Peninsula have worse reproducibility for JRA-25 than for OLDA.

The regional mean of the correlation coefficients in the Yangtze River region is improved from 0.32 for OLDA to 0.43 for JRA-25, although the regional mean of the correlation coefficients for precipitation is very high, about 0.95 for both, but that of the root-mean-square error (RMSE) is slightly degraded from 0.32 for OLDA to 0.36 for JRA-25. For example, correlation coefficients are improved from negative values to positive large values in Xuzhou and Lushi due to improved soil moisture reproducibility during summer (June to August; see Figure S3). Improved precipitation during summer in Lushi is responsible for the improvement of the soil moisture reproducibility; in contrast, the overestimated precipitation in Xuzhou causes higher soil moisture for JRA-25 than that for OLDA, leading to the improvement of the soil moisture reproducibility. Therefore, better reproducibility of soil moisture in JRA-25 as compared to OLDA is not always associated with the better reproducibility of seasonal precipitation in JRA-25. The Chinese snow depth data assimilated only in JRA-25 does not affect soil moisture in the stations since the difference in soil moisture during snow-melting season between JRA-25 and OLDA is negligible.

The regional mean of the correlation coefficients in the southern part of western Siberia is improved from 0.09 for OLDA to 0.57 for JRA-25. The precipitation reproducibility has the same features as for the Yangtze River region: a high correlation coefficient of about 0.8 and of RMSE of 0.25 for both analyses. Different stations in this region as well as in the Yangtze River region have their own causes for the improvement: reasonably improved precipitation, underestimated precipitation, and underestimated precipitation.

In Iowa, the correlation for JRA-25 is lower than that for OLDA. The precipitation correlation improved from 0.86 for OLDA to 0.94 for JRA-25, but JRA-25 overestimated annual precipitation by 1.18, more than that for OLDA by 1.09. This overestimation primarily results from too much precipitation in April to June, which degraded the reproducibility of the soil moisture seasonal cycle (see Figure S4). This indicates that good precipitation reproducibility does not always reproduce good seasonal cycles of soil moisture.

Moreover, a holistic comparison in river discharge and TWS reveals that JRA-25 generally reproduces them better than OLDA except for the river discharge amplitude (see Document S1). JRA-25 uses the modified version of GRiveT with the calibrated river current speed and groundwater layer, while OLDA uses the original one without them. The lower reproducibility of river discharge amplitude in JRA-25 is due to the modification of GRiveT, since slower river current speed and retarding in the groundwater layer smoothes the seasonal cycle, though they dramatically improve the phase reproducibility.

Concluding Summary

The present study demonstrated the reproducibility of land-surface hydrological variables in JRA-25. JRA-25 reproduces well the seasonal cycles of soil moisture, river discharge, and TWS. In addition, the study compared the reproducibility of the three variables between JRA-25 and OLDA. The comparison reveals that JRA-25 generally reproduces the seasonal cycles of the observed variables better than OLDA except for river discharge amplitude and that the better reproducibility of soil moisture in JRA-25 does not always result from reasonable amount and seasonal cycle of precipitation in JRA-25.

The reproducibilities of river discharge and TWS are reasonable, but not very good. The reproducibility of land-surface hydrology is found to be insufficient in some river basins, despite the high precipitation reproducibility. These results suggest that better reproducibility of JRA-25 requires a more sophisticated representation of the land-surface hydrological processes: for example, lakes and anthropogenic operations, in addition to appropriate large-scale hydrological parameters: for example, distributed groundwater retard time and unsaturated conductivity. Insufficient precipitation reproducibility also tends to reduce land-surface hydrological reproducibility; therefore, improving precipitation reproducibility is a key to further improving land-surface hydrological variables of JRA-25. The JRA-25 dataset can be carefully applied to studies relevant to hydrology, water resources, and meteorology as long as attention is paid to the reproducibility for each basin or region.

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SUPPLEMENT

S1. A supplementary document containing Figures S1 to S4, Table SI, and Document S1 concerning a result about holistic comparison in river discharge and TWS between JRA-25 and OLDA, are presented in Supplement 1.

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