Title: Assessing Hydrologic Cycle Dynamics Using High-Resolution Satellite Imagery

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Abstract: This study presents an investigation of the hydrologic cycle over a two-decade span (2000 – 2020) using high-resolution satellite products, in-situ measurements, and modeled data. The scope of this work encompasses an examination of the accuracy of satellite-based estimates in calculating the water budget, both on a global scale and within the Mississippi River Basin. The global assessment considers land areas spanning latitudes 90°S to 90°N, while the Mississippi River Basin includes the Lower Mississippi, Arkansas-Red, Missouri, Ohio, and North Central sub-basins. We utilize the IMERG version-6 and PERSIANN precipitation datasets to quantify water inflow over these regions. Correspondingly, water outflow estimates incorporate the GLEAM product for evaporation, G-RUN and ERA5 datasets for runoff, and SMOPS and SMAP estimates for changes in soil moisture. The assessment of water budget changes assesses the difference between Inflow (Precipitation) and Outflow (Runoff, Evaporation, *Δ* Soil Moisture) components. Our findings reveal discernible discrepancies in the global water budget over an annual cycle, indicating the presence of water "leaks". These leaks, warranting further investigation, may be attributed to factors such as snow, ice, and groundwater dynamics, which fall outside the scope of this study. On a smaller basin scale, the closure of the water budget is estimated to fall within the combined products' uncertainty. This provides additional validation for the suspected factors contributing to the global scale "leak." Analyzing the annual water cycle components, we find the inherent variability and uncertainty associated with satellite-derived products. The study advances comprehension of hydrologic processes and underscores the imperative for enhanced accuracy in satellite-based measurements. Notably, our findings accentuate the importance of a closed water budget as a defining criterion for the accuracy of these satellite-derived products.

Introduction

Remote sensing has long served as a pivotal tool in the continuous monitoring and enhancement of our understanding of the hydrologic cycle. Over the years, significant advancements have propelled the field forward. Satellite-based hydrological data products encompassing parameters such as precipitation, evaporation, runoff, and soil moisture have emerged as invaluable resources for the comprehensive examination of regional and global water budgets (Sahoo et al. 2011).

A multitude of satellite missions, coupled with sophisticated models and in-situ measurements have amassed a vast repository of data spanning diverse spatial and temporal scales, dating from the early 1980s to the present day. Over this extended timeframe, the integration of advanced algorithms and cutting-edge technology has been instrumental in curating this data, yielding outcomes of notable precision and meaningful insights. Prominent among the state-of-the-art products are precipitation datasets like IMERG (Huffman et al. 2020) and PERSIANN (Nguyen et al. 2019), as well as evaporation and runoff products, exemplified by offerings from GLEAM (Martens et al. 2018) and G-RUN (Ghiggi et al. 2021). Additionally, essential atmospheric and soil moisture information can be derived from sources such as ERA5 (Hersbach et al. 2020), SMOPS (Yin et al. 2020), and SMAP (O'Neil et al. 2010) data*.

In the hydrologic budget analysis, the primary data sources are satellites and in-situ measurements, each possessing its own set of limitations. However, when combined, they offer what is presently regarded as the most comprehensive insight into the Earth's water cycle components. In-situ measurements deliver highly precise but spatially limited point-measurements. Satellite-based products help mitigate this limitation through remote sensing techniques that yield spatially continuous estimates over broad areas. Nevertheless, this expanded coverage comes at the cost of reduced precision and limited temporal sampling, thereby introducing inherent uncertainties. It is these uncertainties that frequently hinder the attainment of a dependable analysis of the hydrological cycle. However, when examined at sufficiently large scales, the merged in-situ and satellite observations can yield highly reliable estimates of water cycle components.

In the endeavor to ascertain the scales and levels at which these measurements can be deemed trustworthy, one can employ the water budget and its closure as a reference. Ideally, in a closed system, such as a large river basin, there should be no "leakage" of water. The presence of any such water "leakage" signals limitations in the chosen satellite products. Consequently, it becomes imperative to address the uncertainties associated with these products before embarking on any meaningful analysis.

In this study, we examine the ability of satellite products to correctly describe the water budget by assessing the difference in water Inflow (Precipitation) and water Outflow (Evaporation, Δ Soil Moisture, and Runoff) in a search for any "leaks". To analyze the water budget and the hydrologic cycle, the focus is typically given to their most pronounced temporal phases – the seasonal, annual, and daily cycles. In the present work, the annual cycle is analyzed when looking at the water movement at a monthly timescale. This allows for a broader perspective that facilitates the identification of long-term trends.

There are three main questions investigated in this work: 1) Does the water budget close? 2) What are the differences in the water budget between the global and local scale? and 3) How do different products compare when estimating the same quantity? The preceding inquiries are addressed through the computation of the water budget components and analyses of the products they were built on.

Data

Except for evaporation, the present study uses multiple datasets for each environmental variable considered in monitoring and analyses of the hydrologic cycle. The datasets, their domains, documentation, and resolutions are listed in Table 1, with a single month of each product (May 2019) mapped over the Mississippi River Basin.

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* Refer to Table 1 for the full name a description of the products

Table 1 List of datasets used in the study.

Product	Spatial Resolution	Temporal	Time Span	Reference
IMERG (Integrated Multi-satellitE Retrievals for GPM)	0.1°	monthly	2000 - 2021	Huffman et al. 2020
PERSIANN (Precipitation Estimation from Remote Sensed Information Using Artificial Neural Networks)	0.25°	monthly	2003 - 2022	Nguyen et al. 2019
SMOPS (Soil Moisture Operational Product System)	0.25°	daily	2002 - 2021	Yin et al. 2020
SMAP (Soil Moisture Active Passive)	9 km x 9km	monthly	2015 - 2023	O'Neil et al. 2010
GLEAM (Global Land Evaporation Amsterdam Model)	0.25°	monthly	2003 - 2022	Martens et al. 2018
ERA5 (fifth generation ECMWF atmospheric reanalysis of the global climate)	0.1°	monthly	2000 – 2023	Hersbach et al. 2020
G-RUN (Global Runoff Reconstruction)	0.5°	monthly	2000 - 2020	Ghiggi et al. 2021

All datasets are obtained from publicly available repositories.

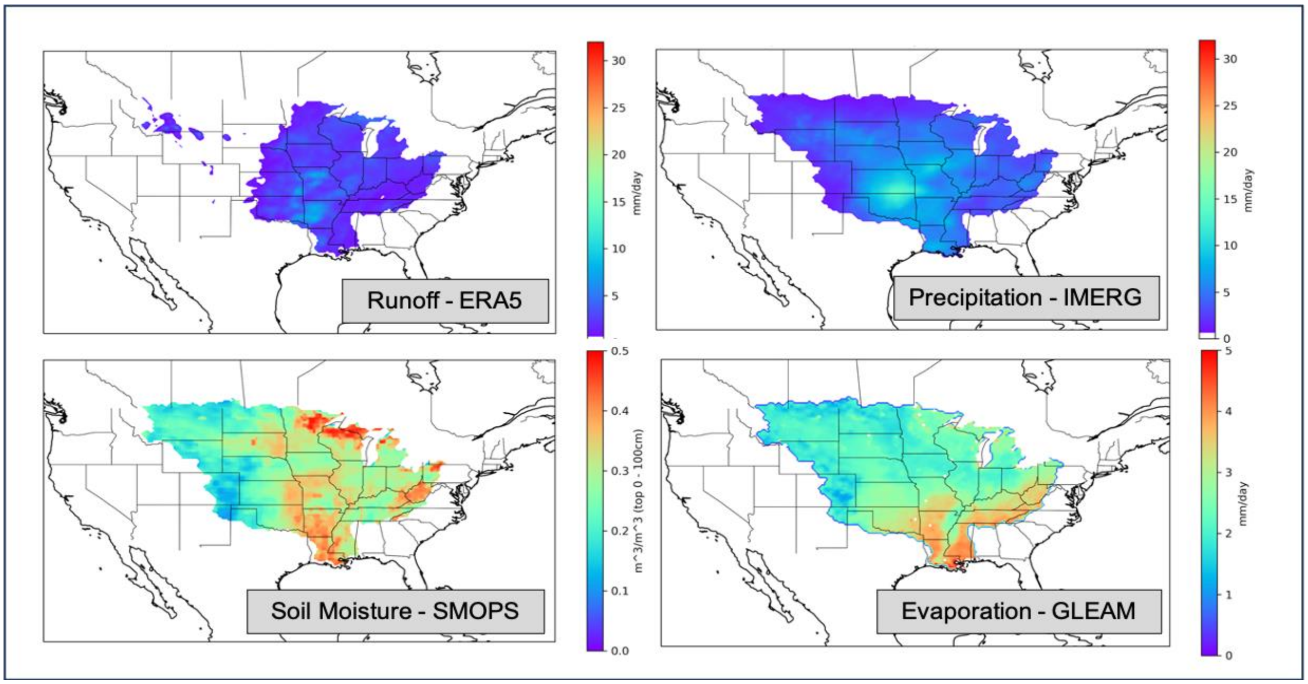

Figure 1 Distribution of hydrologic parameters over the Mississippi River Basin; monthly means for (top right) precipitation, (top left)runoff, (bottom right) evaporation, and (bottom left) soil moisture.

Methods

Using standardized fields for precipitation, evaporation, runoff, and soil moisture at common resolutions, we conducted a comprehensive assessment of the water budget over both the Mississippi River Basin and globally. This assessment involved qualitative analyses of the annual water cycle.

Time series plots, both annual and monthly, were constructed for the Mississippi River Basin and the global context. To ensure a meaningful usage and comparison between the different products, it was imperative to harmonize the resolution and units of the data. In this study, we adopted a 0.25-degree resolution for the purpose of comparing the products expressed in units of mm/day, ensuring consistency and compatibility for our analyses.

To process the analysis at the scale of the Mississippi River Basin, a shapefile delineating the region of interest, specifically the Mississippi River Basin, is employed. This shapefile serves as the basis for sub-setting the re-gridded arrays based on longitude and latitude coordinates defining the boundary of the Mississippi River Basin. To verify the accuracy of the data orientation post-sub-setting, the products were visualized by overlaying on a map of the CONUS (Continental United States) region.

Given the spherical shape of the Earth, grid boxes closer to the Equator cover a larger area compared to those close to the Poles. To account for these varying areas, it is essential to weight the gridded products data by the corresponding grid box area. This area weighting is determined by a function of the cosine of the latitude at a specific point and the corresponding Earth radius. In the weighting process the sum of the weights was kept equal to 1, accounting only the regions (i.e., grid boxes) with valid data. This consideration is particularly significant for products that encompass data solely over land areas.

The weighted product formula is described as follows:

$$R = radius(latitude)$$

$$Y = radians(latitude) * R$$

$$X = longitude\ \cdot R\ \cdot \cos(latitude)$$

$$Area = X * Y$$

These equations determine the approximate surface area of a rectangular region on Earth’s surface, utilizing the Earth’s radius at a specific latitude (R), as well as the latitude (Y) and longitude (X) adjustments. The computed area is subsequently employed to compute a weighted average of a dataset across a 2D grid. In this process, each data point weight is determined by the geographic area it encompasses, thereby giving greater significance to grid cells with larger areas in the final weighted mean.

To visualize the weighted data, using the units of mm/day, a uniform unit conversion process is necessary. For datasets already in mm/day, no adjustments are required. However, for datasets initially expressed in mm/month, the number of days in each respective month should be employed to convert the units from mm/month to mm/day. The soil moisture data, originally presented as m^3/m^3, entails a more intricate unit transformation procedure. First, monthly averages are obtained. Subsequently, the data are converted to millimeters of water (by multiplying by 1000). Finally, a one-month time lag difference is incorporated to calculate the change in soil moisture.

To deliver final analyses, the data are plotted either as a monthly time series or as an annual cycle. The change in the water budget is presented in the annual cycle through the equation:

Inflow (Precipitation) – Outflow (Δ Soil Moisture, Runoff, Evaporation) = Δ Water Storage.

The utilization of multiple datasets for each metric enables the assessment of uncertainty between the products. These uncertainties should be taken into account when calculating the water budget and making comparisons across datasets. It is important to note that this study does not delve into the analysis of the uncertainty associated with the resulting water budget.

Results and Discussion

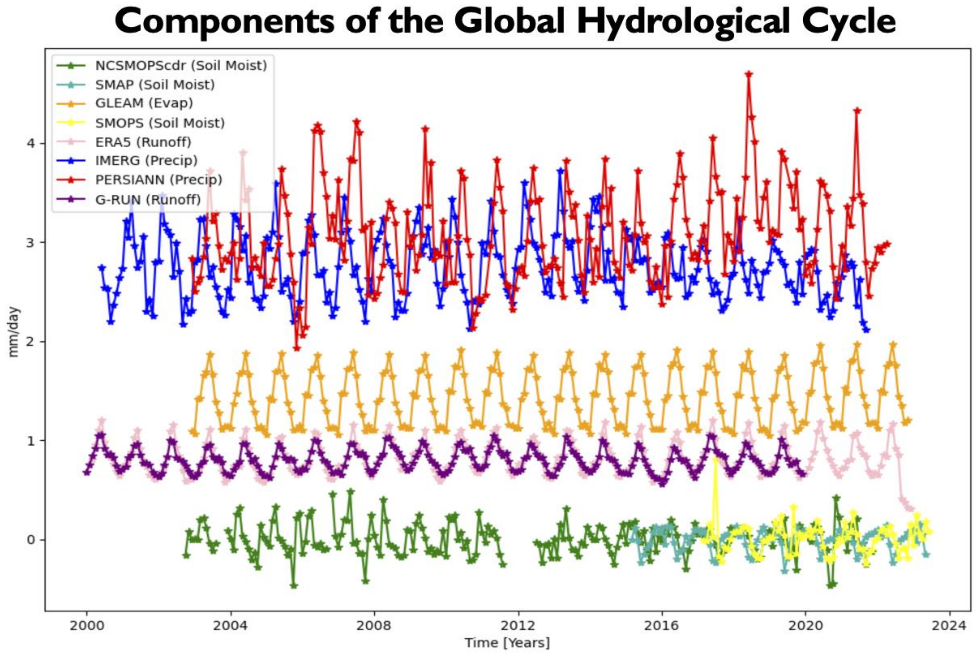

Figure 2 Global cycle components as provided with products considered in this study. Monthly global means at 0.25-degree resolution, weighted by area, correspond to the 2000-2020 time period. (NCS-SMOPScdr: courtesy of Dr. Jin)

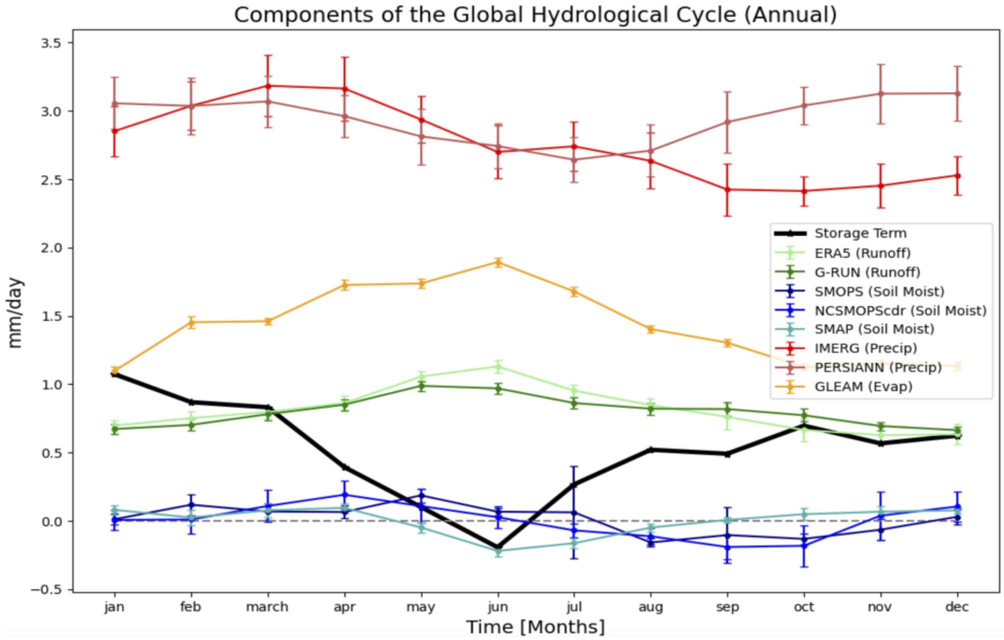

Figure 3 Global annual cycle of hydrological cycle components (colored lines) and the resulting water budget (black line). The water budget as Inflow (Precipitation) – Outflow (Runoff, Δ Soil Moisture, Evaporation).

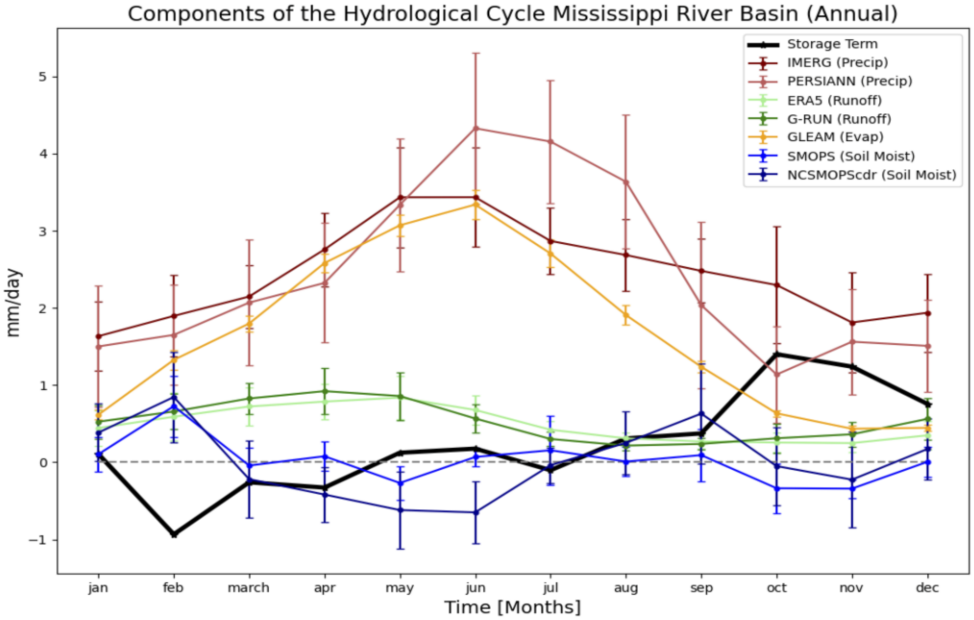

Figure 4 Annual cycle of hydrological cycle components (colored lines) and the resulting water budget (black line) over the Mississippi River Basin. The water budget calculated as Inflow (Precipitation) – Outflow (Runoff, Δ Soil Moisture, Evaporation).

Figures 2-4 provide a graphical representation of the close correspondence between the combined values of evaporation, runoff, and soil moisture and the observed precipitation data. Predominantly, evaporation data emerges as the primary factor influencing water outflow. The precipitation and evaporation datasets consistently adhere to a discernible pattern: a notable increase in precipitation corresponds to an elevated rate of evaporation, reflecting the direct relationship between increased precipitation and the availability of more water for the evaporation process (Fig. 2-4). The observed negative change in soil moisture values signifies a drying trend in the soil, reflecting a loss of moisture relative to the prior month. This pattern remains consistent, wherein months exhibiting a higher rate of evaporation in relation to the volume of precipitation received are associated with negative soil moisture values and a subsequent decrease in runoff (Fig. 2-4).

Upon examining the satellite-based products used to characterize the Earth's water cycle at a granular level, a noticeable disparity in variability and uncertainty emerges when comparing the global analysis (Fig. 3) with that of the Mississippi River Basin (Fig. 4). The mean annual water budget findings across the global domain and the Mississippi River Basin point to an apparent observational gap. This gap can be attributed in part to factors like snow, ice, and groundwater, all of which lie beyond the scope of this study.

Furthermore, the greater magnitude of variability in the global water budget compared to that within the Mississippi River Basin is likely a consequence of insufficient measurements in remote and less accessible regions across the globe. In contrast, the hydrology of the Mississippi River Basin is well-understood and extensively monitored through dense and highly-accurate measurement networks. This comprehensive understanding results in lower variability and reduced uncertainty in the datasets used to describe its water cycle, and the basin closely approximates a closed (zero leakage) water budget.

When analyzing the water cycle components, the variability across products is noticeable (e.g., IMERG and PERSIANN or ERA5 and G-RUN). This leads to the conclusion that although the datasets are derived using a combination of ground-, satellite-, and model-based techniques, there is still room for improvement that can be made to reduce the uncertainty within the individual products.

Conclusions

Although not perfect, the water budget closure is seen as one of the best criteria for estimating the accuracy of various satellite products (Luo et al. 2021, Sheffield et al. 2021, Sahoo et al. 2011). These findings are demonstrated in the study through the strong correlation observed among precipitation, evaporation, runoff, and soil moisture data. As previously discussed, a positive correlation emerges with the rise in precipitation and evaporation, owing to the increased water availability for evaporation. Additionally, a significant correlation is evident between heightened evaporation levels relative to the precipitation data, resulting in a decrease in soil moisture and reduced runoff. This correlation aligns with the expected zero "leakage", indicating that when one variable displays an above-average value, it is offset by corresponding adjustments in other variables. Though these discerned patterns harmonize with the anticipated dataset values, there remains a prospect for further refinement aimed at reducing the inherent divergences among products dedicated to the measurement of analogous parameters. Recognizing these data limitation and uncertainties is vital for accurate scientific reporting.

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