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CAMELE: Collocation-Analyzed Multi-source Ensembled Land Evapotranspiration Data

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Abstract

Land evapotranspiration (ET) plays a crucial role in Earth's water-carbon cycle, and accurately estimating global land ET is vital for advancing our understanding of land-atmosphere interactions. Despite the development of numerous ET products in recent decades, widely used products still possess inherent uncertainties arising from using different forcing inputs and imperfect model parameterizations. Furthermore, the lack of sufficient global in-situ observations makes direct evaluation of ET products impractical, impeding their utilization and assimilation. Therefore, establishing a reliable global benchmark dataset and exploring evaluation methodologies for ET products is paramount. This study aims to address these challenges by (1) proposing a collocation-based method that considers non-zero error cross-correlation for merging multi-source data and (2) employing this merging method to generate a long-term daily global ET product at resolutions of 0.1° (2000-2020) and 0.25° (1980-2022), incorporating inputs from ERA5L, FluxCom, PMLv2, GLDAS, and GLEAM. The resulting product is the Collocation-Analyzed Multi-source Ensembled Land Evapotranspiration Data (CAMELE). CAMELE exhibits excellent performance across various vegetation coverage types, as validated against in-situ observations. The evaluation process yielded Pearson correlation coefficients (R) of 0.63 and 0.65, root-mean-square-errors (RMSE) of 0.81 and 0.73 mm/d, unbiased root-mean-square-errors (ubRMSE) of 1.20 and 1.04 mm/d, mean absolute errors (MAE) of 0.81 and 0.73 mm/d, and Kling-Gupta efficiency (KGE) of 0.60 and 0.65 on average over resolutions of 0.1° and 0.25°, respectively.

1. Introduction

Land evapotranspiration (ET) plays a critical role in the global water and energy cycles, encompassing various processes such as soil evaporation, vegetation transpiration, canopy interception, and surface water evaporation (Zhang et al., 2019;

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Zhao et al., 2022; Lian et al., 2018). Accurately estimating global land evapotranspiration is vital for understanding the hydrological cycle and land-atmosphere interactions, as it serves as an intermediary variable connecting soil moisture and air temperature (Miralles et al., 2019; Gentine et al., 2019). Therefore, providing a reliable ET dataset as a benchmark for further research is crucial.

In recent decades, numerous studies have focused on estimating global land evapotranspiration, resulting in many datasets. However, discrepancies often arise among these simulations due to algorithm and principle variations (Restrepo-Coupe et al., 2021; Han and Tian, 2020). Additionally, evaluating ET products is challenging due to the limited availability of global-scale observations, which hampers their direct use (Pan et al., 2020; Baker et al., 2021).

The fusion of multi-source data is a suitable option to address these uncertainties. Recent studies have explored several approaches to integrate multiple ET products, including Simple Average (SA) (Ershadi et al., 2014), Bayesian Model Average (BMA) (Hao et al., 2019; Ma et al., 2020; Zhu et al., 2016), Reliability Ensemble Average (REA) (Lu et al., 2021), Empirical Orthogonal Functions (EOF) (Feng et al., 2016) and machine-learning-based methods (Chen et al., 2020; Yin et al., 2021). However, the primary challenge lies in calculating reliable input weights based on a selected "truth" (Koster et al., 2021), which can involve averaging or incorporating other relevant geographical information as a benchmark. Moreover, previous research has predominantly focused on regional-scale ET estimation, necessitating a more straightforward and reliable global simulation method.

Recently, collocation methods have emerged as promising techniques for estimating random error variances and data-truth correlations in collocated inputs (Stoffelen, 1998; Li et al., 2022, 2023b; Park et al., 2023). These methods consider the errors associated with collocated datasets as an accurate representation of uncertainty without assuming the absence of errors in any datasets. It is important to note that while collocation methods, such as TC and EIVD, can estimate the variance (or

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

covariance) of random errors, they cannot evaluate the bias of the products. One primary advantage of collocation analysis is that it does not require a high-quality reference dataset (Su et al., 2014; Wu et al., 2021). However, a crucial prerequisite for applying collocation methods is the availability of many spatially and temporally corresponding datasets. For instance, the classic triple collocation (TC) method requires a trio of independent datasets. Su et al. (2014) used the instrumental regression method and considered lag-1 time series as the third input, proposing the single instrumental variable algorithm (IVS). Dong et al. (2019) introduced the lag-1 time series from both inputs, proposing the double instrumental variable algorithm (IVD) for a more robust solution. Gruber et al. (2016a) extended the original algorithm to incorporate more datasets, partially addressing the independence assumption to calculate a portion of error cross-correlation (ECC). Dong et al.(2020a) further proposed the extended double instrumental (EIVD) method, enabling ECC estimation using three datasets. Collocation methods have found widespread application in the evaluation of geophysical variable estimates, including soil moisture (Deng et al., 2023; Ming et al., 2022), precipitation (Dong et al., 2022; Li et al., 2018), ocean wind speed (Vogelzang et al., 2022; Ribal and Young, 2020), leaf area index (Jiang et al., 2017), total water storage (Yin and Park, 2021) sea ice thickness and surface salinity (Hoareau et al., 2018), and near-surface air temperature (Sun et al., 2021).

Recently, many studies have utilized collocation approaches to evaluate evapotranspiration products, with the TC method to assess uncertainties. For example, Barraza Bernadas et al. (2018) considered the uncertainties of ET from the Breathing Earth System Simulator, BESS (Jiang et al., 2020; Jiang and Ryu, 2016), Moderate Resolution Imaging Spectroradiometer, MOD16 (Mu et al., 2011), and a hybrid model; Khan et al. (2018) utilized extended triple collocation (ETC) (McColl et al., 2014) to investigate the reliability of ET from MOD16, The Global Land Data Assimilation System (GLDAS) (Rodell et al., 2004) and the Global Land Evaporation

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Amsterdam Model (GLEAM) (Martens et al., 2017) over East Asia; Li et al. (2022) employed five collocation methods (e.g., IVS, IVD, TC, EIVD, and EC) to analyze the uncertainties of ET from ERA5-Land (ERA5L) (Muñoz-Sabater et al., 2021), GLEAM, GLDAS, FluxCom (Jung et al., 2019), and the Penman-Monteith-Leuning Evapotranspiration V2 (PMLv2) (Zhang et al., 2019).

Moreover, error information derived from collocation analysis is valuable for merging multi-source ET data. Park et al. (2023) combined three reanalysis-based evaporation (E) and transpiration (T) estimates (i.e., ERA5L, GLDAS, and MERRA2) to improve the accuracy of evapotranspiration (ET) over East Asia. Li et al. (2023b) combined four products, including FluxCom, Global Land Surface Satellite (GLASS) (Liang et al., 2021), GLEAM, and PMLv2, to improve ET accuracy in the Nordic Region.

Although the above studies have demonstrated that collocation analysis can effectively assess the random error variance of ET (evapotranspiration) products and integrate error information from multiple data sources, these studies did not consider the issue of non-zero error covariance (ECC) between different ET products. Li et al. (2022) 's global ET product evaluation research revealed clear non-zero ECC conditions between ERA5L and GLEAM and PMLV2 and FLUXCOM. In TC analysis, non-zero ECC can result in significant biases in TC-based results (Yilmaz and Crow, 2014). Furthermore, when using TC-based error information for fusion, it is crucial to consider the information related to ECC, as this can help improve the fusion accuracy (Dong et al., 2020b; Kim et al., 2021b).

In this study, we proposed a collocation-based data ensemble method, considering non-zero ECC conditions, for merging multiple ET products to create the Collocation-Analyzed Multi-source Ensembled Land Evapotranspiration data, abbreviated as CAMELE. The second section of this paper presents the selected data information for this study. In the third section, we explained the error calculation method for collocation analysis and the weighted calculation method that considered ECC. The fourth section analyzed the global errors of different ET products obtained through

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

these calculations and the distribution patterns of the corresponding weights. We evaluated the accuracy of the fused products and compared them with existing products using reference values from site measurements. In the fifth section, we discussed the inherent errors in the methods, analyzed the ECC between the products, and compared the differences between different fusion schemes. Finally, in the sixth section, we summarized the results obtained from this research.

2. Datasets

We selected five widely used land evapotranspiration (ET) products that spanned the period from 1980 to 2022. Furthermore, we incorporated in-situ observations to compare our merged product comprehensively. Table 1 shows the spatial and temporal resolutions of the input datasets.

TABLE.1 Summary of evapotranspiration products involved.

Name	Schemes	Resolution		Period	Reference
ERA5-Land	H-TESSEL	0.1°	hourly	1950-present	(Muñoz-Sabater et al., 2021)
GLDAS-2	CLSM/Noah /LSM	0.25°	3-hourly daily	2.0: 1948-2014 2.1: 2000-present 2.2: 2003-present	(Li et al., 2019a; Rodell et al., 2004)
GLEAM-3.7	GLEAM model	0.25°	daily	3.7a: 1980-2022 3.7b: 2003-2022	(Martens et al., 2017)
PMLv2-v017	Penman-Monteith-Leuning	0.083°	8-day average	2000-2020	(Zhang et al., 2019)
FluxCom	Machine learning	0.083°	8-day average	2001-2015	(Jung et al., 2019)

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

2.1. ERA5-Land

The European Centre for Medium-Range Weather Forecasts (ECMWF) produces the latest advanced ERA5-Land dataset, referred to as ERA5L, a global hourly reanalysis dataset with a spatial resolution of 0.1°. It covers the period from January 1950 until approximately one week before the present (Muñoz-Sabater et al., 2021). ERA5-Land is derived from the land component of the ECMWF climate reanalysis, incorporating numerous improvements over previously released versions. It is based on the Tiled ECMWF Scheme for Surface Exchanges over Land incorporating land surface hydrology (H-TESSEL), utilizing version CY45R1 of the ECMWF's Integrated Forecasting System (IFS). The dataset benefits from atmospheric forcing data, which acts as an indirect constraint on the model-based estimates (Hersbach et al., 2020). The dataset is available through the Climate Change service of the Copernicus Center at http://cds.climate.copernicus.eu.

Evapotranspiration in ERA5L, defined as "total evaporation," represents the accumulated amount of water that has evaporated from the Earth's surface, including a simplified representation of transpiration from vegetation into the vapor in the air. The soil water and energy balance are computed using standard soil discretization. Readers could consult section 8.6.5 of the IFS documentation (ECMWF, 2014). The original dataset is interpolated from (1801, 3600) to (1800, 3600) using kriging interpolation and then upscaled from an hourly to a daily resolution, changing spatial resolution from 0.1° to 0.25°.

2.2. GLDAS

The Global Land Data Assimilation System (GLDAS) product utilizes advanced data assimilation methodologies, integrating model and observation datasets for land-surface simulations (Rodell et al., 2004). GLDAS employs multiple land-surface models (LSMs), namely Noah, Mosaic, Variable Infiltration Capacity (VIC), and the

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Community Land Model (CLM). Together, these models generate global evapotranspiration estimates at fine and coarse spatial resolutions (0.01° and 0.25°) and temporal resolutions (3-hourly and monthly). The most recent iteration of GLDAS, version 2, consists of three components: GLDAS-2.0, GLDAS-2.1, and GLDAS-2.2. GLDAS-2.0 relies entirely on the Princeton meteorological forcing input data, providing a consistent temporal series from 1948 to 2014 (Sheffield et al., 2006). The GLDAS-2.1 simulation commences on January 1, 2000, utilizing the conditions from the GLDAS-2.0 simulation. On the other hand, GLDAS-2.2 is simulated from February 1, 2003, employing the conditions from GLDAS-2.0 and forcing with meteorological analysis fields from the ECMWF Integrated Forecasting System (IFS). Additionally, the GRACE satellite's total terrestrial water anomaly observation is assimilated into the GLDAS-2.2 product (Li et al., 2019a).

In this study, to cover the research period from 1980 to 2022 and address potential error homogeneity issues between GLDAS-2.2 and ERA5L (both utilizing ECMWF meteorological driving data), we selected GLDAS-2.0 and GLDAS-2.1 as inputs. The "Evap_tavg" parameter representing evapotranspiration is derived from the original products and aggregated to a daily scale. For more detailed information on the GLDAS-2 models, please refer to NASA's Hydrology Data and Information Services Center at http://disc.sci.gsfc.nasa.gov/hydrology.

2.3. GLEAM

The latest version of the Global Land Evaporation Amsterdam Model 3.7 (GLEAM-3.7) dataset (Martens et al., 2017; Miralles et al., 2011) at 0.25° is used. This version of GLEAM provides daily estimations of actual evaporation, bare soil evaporation, canopy interception, transpiration from vegetation, potential evaporation, and snow sublimation from 1980 to 2022. The third version of GLEAM contains a new DA scheme, an updated water balance module, and evaporative stress functions. Two datasets that differ only in forcing and temporal coverage are provided:

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

GLEAMv3.7a-43-year period (1980 to 2022) based on satellite and reanalysis (ECMWF) data; GLEAMv3.7b-20-year period (2003 to 2022) based on only satellite data. GLEAMv3.7a is used in this study. The data are freely available on the GLEAM website (https://www.gleam.eu).

The cover-dependent potential evaporation rate (E_P) is calculated using the Priestley-Taylor equation (Priestley and TAYLOR, 1972). Then a multiplicative stress factor is used to convert E_P into actual transpiration or bare soil evaporation, which is the function of microwave vegetation optimal depth (VOD) and root-zone soil moisture. For detailed description, please refer to the paper by (Martens et al., 2017). The GLEAM data were validated at 43 FluxNet flux sites and have been proven to provide reliable AET estimations (Majozi et al., 2017).

2.4. PMLv2

The Penman-Monteith-Leuning version 2 global evaporation model (PMLv2) has been developed based on the Penman-Monteith-Leuning model (Zhang et al., 2019; Leuning et al., 2009). Initially proposed by Leuning et al. (2008), the PML model underwent further enhancements by Zhang et al. (2010). The PML version 1 (PMLv1) incorporates a biophysical model that considers canopy physiological processes and soil evaporation to estimate surface conductance accurately (G_s), which is the focus of the PM-based method. This version was subsequently enhanced by incorporating a canopy conductance (G_c) model that couples vegetation transpiration with gross primary productivity, resulting in the development of PML version 2 (PMLv2) as described by Gan et al. (2018). Zhang et al. (2019) applied the PMLv2 model globally. The daily inputs for this model include leaf area index (LAI), white sky shortwave albedo, and emissivity obtained from the Moderate Resolution Imaging Spectroradiometer (MODIS), as well as temperature variables (T_{max} , T_{min}, T_{avg}), instantaneous variables (P_{surf}, P_a, U, q), and accumulated variables (P_{rcp}, R_{ln}, R_s) from GLDAS-2.0. Evaporation is divided into direct evaporation from bare soil (E_s), evaporation from solid water sources (water bodies, snow, and ice) (ET_{water}), and vegetation transpiration (E_c). To ensure its accuracy, the PMLv2-ET model was calibrated against 8-daily eddy covariance data from 95 global flux towers representing ten different land cover types.

In this study, we employ the latest version, v017. The data is freely available through the google earth engine https://developers.google.com/earth-engine/datasets/catalog/CAS_IGSNRR_PML_V2_v017.

2.5. FluxCom

FluxCom is a machine-learning-based approach combining global land-atmosphere energy flux data by combining remote sensing and meteorological data(Jung et al., 2019). To achieve this, FluxCom utilizes various machine-learning regression tools, including tree-based methods, regression splines, neural networks, and kernel methods. The outputs of FluxCom are designed based on two complementary strategies: (1) FluxCom-RS, which exclusively merges remote sensing data to generate high spatial resolution flux data; and (2) FluxCom-RS+METEO, which combines meteorological observations with remote sensing data at a daily temporal resolution. The exclusive use of remote sensing data in the ensemble allows producing gridded flux products at a spatial resolution of 500m, albeit with a relatively low frequency of 8 days. It is important to note that the FluxCom-RS data only covers the period after 2000 due to data availability.

In contrast, the merging of meteorological and remote sensing data extends the coverage back to 1980 at the cost of a coarser spatial resolution of 0.5°. For more detailed information about the FluxCom dataset, please refer to the FluxCom website (http://FluxCom.org/). The data is freely available upon contacting the authors.

In this study, we utilized the FluxCom-RS 8-daily 0.0833° energy flux data and converted the latent heat values to evaporation using ERA5-Land aggregated daily air temperature. Furthermore, the original evaporation data were interpolated to a spatial

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

resolution of 0.1° using the MATLAB Gaussian process regression package.

2.6. Global in-situ observation: FluxNet

The latest FluxNet2015 4.0 eddy-covariance data were used in our study (Pastorello et al., 2020). Following the filtering process by Lin et al. (2018) and Li et al. (2019b), firstly, only the measured and good-quality gap-filled data were used for quality control. Secondly, we excluded days with rainfall and the subsequent day after rainy events to mitigate the impact of canopy interception (Medlyn et al., 2017; Knauer et al., 2018). Additionally, previous studies have indicated an energy imbalance problem in FluxNet2015 data. Therefore, following the method proposed by Twine et al. (2000), the measured ET data were corrected.

After data filtering and processing, 212 sites are selected. The selected sites are distributed globally, primarily in North America and Europe. The International-Geosphere–Biosphere Program (IGBP) land cover classification system (Loveland et al., 1999) was employed to distinguish the 13 Plant Functional Types (PFTs) across sites, including evergreen needle leaf forests (ENF, 49 sites), evergreen broadleaf forests (EBF, 15 sites), deciduous broadleaf forests (DBF, 26 sites), croplands (CRO, 20 sites), grasslands (GRA, 39 sites), savannas (SAV, nine sites), mixed forests (MF, nine sites), closed shrublands (CSH, three sites), deciduous needle leaf forests (DNF, one site), open shrublands (OSH, 13 sites), snow and ice (SNO, one site), and permanent wetland (WET, 21 sites).

3. Method

In this study, the fusion of products consisted of three steps: (1) the collocation method (IVD and EIVD) was used to calculate the random error variance of the selected input products, determine the regionally optimal products, and set an error threshold; (2) aiming for minimum MSE, the weights of different products on each grid were calculated; (3) the products were fused according to the weights to obtain a long sequence of evapotranspiration products. Since IVD and EIVD were developed by combining instrumental variable regression and the extended collocation system, a description of TC and EC algorithms was also included.

3.1. Triple collocation analysis

Since its development in 1998, the implications and formulations of the triple collocation problem have been investigated in many studies. Two notations are proposed, based either on combinations of covariances or cross-multiplied differences between inputs, denoted as difference and covariance notations (Stoffelen, 1998; Dorigo et al., 2010; Su et al., 2014; McColl et al., 2014). These two notations are mathematically identical under the TC-based rescaled scheme (Gruber, 2016). Here, we used difference notation for demonstration.

The commonly used error structure for triple collocation analysis (TCA) is:

$$i = \alpha_i + \beta_i \Theta + \varepsilon_i \tag{1}$$

where $i \in [X, Y, Z]$ are three spatially and temporally collocated data sets; Θ is the unknown true signal for relative geographical variable; α_i and β_i are additive and multiplicative bias factors against the true signal, respectively; ε_i is the additive zero-mean random error.

The above structure is also a typical instrumental variable (IV) regression. Thus, this provides another perspective to introduce more variables (>3) (Dong and Crow, 2017; Su et al., 2014) and polynomial models (Yilmaz and Crow, 2013; De Lannoy et al., 2007) to the standard TC. We recommend that the readers refer to Su et al. (2014) for a more detailed discussion on using the IV framework.

The basic assumptions adopted in TC are as follows: (i) Linearity between true signal and data sets, (ii) signal and error stationarity, (iii) independency between random error and true signal (error orthogonality), (iv) independence between random errors (zero error cross-correlation, zero ECC). Although many studies have indicated that some of these assumptions are often violated in practice (Li et al., 2018, 2022; Jia et

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

al., 2022), the formulation based on these assumptions is still the most robust implementation (Gruber et al., 2016b). A discussion on these assumptions will be provided in the discussion section.

The data sets first need to be rescaled against an arbitrary reference (e.g., X). The others are scaled through a TC-based rescaling scheme:

$$Y^X = \beta_Y^X\left(Y - \overline{Y}\right) + \overline{X} \qquad Z^X = \beta_Z^X\left(Z - \overline{Z}\right) + \overline{X} \tag{2}$$

The overbar denotes the mean value, and β_Y^X and β_Z^X are the scaling factors as:

$$\begin{cases} \beta_Y^X = \dfrac{\beta_X}{\beta_Y} = \dfrac{<\left(X-\overline{X}\right)\left(Z-\overline{Z}\right)>}{<\left(Y-\overline{Y}\right)\left(Z-\overline{Z}\right)>} = \dfrac{\sigma_{XZ}}{\sigma_{YZ}} \\ \beta_Z^X = \dfrac{\beta_X}{\beta_Z} = \dfrac{<\left(X-\overline{X}\right)\left(Y-\overline{Y}\right)>}{<\left(Z-\overline{Z}\right)\left(Y-\overline{Y}\right)>} = \dfrac{\sigma_{XY}}{\sigma_{ZY}} \end{cases} \tag{3}$$

where <·> is the average operator, σ_{ij} is the covariance of data sets i and j.

Subsequently, the error variances could be estimated by averaging the cross-multiplied data set differences as follows:

$$\begin{cases} \sigma_{\varepsilon_X}^2 =< (X - Y^X)(X - Z^X) > \\ \sigma_{\varepsilon_Y^X}^2 = {\beta_Y^X}^2 \sigma_{\varepsilon_Y}^2 =< (Y^X - X)(Y^X - Z^X) > \\ \sigma_{\varepsilon_Z^X}^2 = {\beta_Z^X}^2 \sigma_{\varepsilon_Z}^2 =< (Z^X - X)(Z^Y - Y^X) > \end{cases} \tag{4}$$

Expanding the bracket and expressing the rescaling factors yields:

$$\begin{cases} \sigma_{\varepsilon_X}^2 = \sigma_X^2 - \dfrac{\sigma_{XY}\sigma_{XZ}}{\sigma_{YZ}} \\ \sigma_{\varepsilon_Y}^2 = \sigma_Y^2 - \dfrac{\sigma_{YX}\sigma_{YZ}}{\sigma_{XZ}} \\ \sigma_{\varepsilon_Z}^2 = \sigma_Z^2 - \dfrac{\sigma_{ZX}\sigma_{ZY}}{\sigma_{XY}} \end{cases} \tag{5}$$

When selecting various scaling references, it is essential to note that the absolute error variances remain consistent. However, this choice can have an impact on the estimation of data sensitivity to the actual signal ($\beta_i^2\sigma_\Theta^2$), which serves as a crucial indicator for comparing spatial error patterns. In order to address the reliance on a specific scaling reference, Draper et al. (2013) introduced the fractional root-mean-squared-error ($fMSE_i$). This measure is obtained by normalizing the unscaled error

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

variance with respect to the true signal variance:

$$fMSE_i = \frac{\sigma_{\varepsilon_i}^2}{\sigma_i^2} = \frac{\sigma_{\varepsilon_i}^2}{\beta_i^2 \sigma_\Theta^2 + \sigma_{\varepsilon_i}^2} = \frac{1}{1 + SNR_i} \tag{6}$$

where $SNR_i = \frac{\beta_i^2 \sigma_\Theta^2}{\sigma_{\varepsilon_i}^2} \in [0,1]$ is the normalized signal-to-noise ratio. $SNR = 0$ indicates a noise-free observation, while $SNR = 1$ corresponds that the variances of estimates equal that of the true signal.

Following similar ideas, Mccoll et al. (2014) extended the framework to estimate the data-truth correlation, known as extended triple collocation (ETC):

$$\begin{gathered} R_i^2 = \frac{\beta_i^2 \sigma_\Theta^2}{\beta_i^2 \sigma_\Theta^2 + \sigma_{\varepsilon_i}^2} = \frac{SNR_i}{1 + SNR_i} = \frac{1}{1 + NSR_i} \\ R_i^2 = 1 - fMSE_i \end{gathered} \tag{7}$$

In comparison to the conventional coefficient of determination R_{ij}, which is influenced by data noise and sensitivity. It is important to note that R_i^2 is merely based on the data set i, whereas R_{ij} is influenced by both data set i and reference j. In other words, R_i^2incorporates the dependency on the chosen reference. Thus, TC-derived $fMSE_i$ and R_i^2 serve as superior indicators for assessing the actual quality of data, as discussed by Kim et al. (2021b) and Gruber et al. (2020).

3.2. Double instrumental variable technique

The assumed error structure in TC is also a typical instrumental variable (IV) regression. In practical usage, finding three completely independent sets of products is usually tricky. Su et al. (2014) effectively improve the applicability of the TC method by using the lag-1 time series (e.g., $X_{t-1} = \alpha_X + \beta_X \Theta_{t-1} + \varepsilon_{X,t-1}$) from one of the two sets of data as the third input for TC. In this way, we only need two independent products for input.

Such process includes another assumption that all data sets contain serially white errors (i.e., $< \varepsilon_{i,t} \varepsilon_{i,t-1} >= 0$, zero auto-correlation). Building upon this, Dong et al. (2019) utilizes the lag-1 time series from both data sets as inputs and propose a more

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

stable double instrumental variable (IVD) method.

For a double input $\left[X, Y \text{ with } \sigma_{\varepsilon_X \varepsilon_Y} = 0\right]$, the linear error model and related lag-1 time series can be expressed as:

$$\begin{cases} X = \alpha_X + \beta_X \Theta + \varepsilon_X & I = \alpha_X + \beta_X \Theta_{t-1} + \varepsilon_{X_{t-1}} \\ Y = \alpha_Y + \beta_Y \Theta + \varepsilon_Y & J = \alpha_Y + \beta_Y \Theta_{t-1} + \varepsilon_{Y_{t-1}} \end{cases} \tag{8}$$

where I and J are the lag-1 time series of X and Y, respectively.

Assuming product errors are mutually independent and orthogonal to the truth, the covariance between the products is expressed as:

$$\begin{cases} \sigma_X^2 = \beta_X^2 \sigma_\Theta^2 + \sigma_{\varepsilon_X}^2 \quad \sigma_Y^2 = \beta_Y^2 \sigma_\Theta^2 + \sigma_{\varepsilon_Y}^2 \\ \sigma_{XY} = \beta_X \beta_Y \sigma_\Theta^2 \\ \sigma_{IX} = \beta_X^2 L_{\Theta\Theta} \quad \sigma_{JY} = \beta_Y^2 L_{\Theta\Theta} \end{cases} \tag{9}$$

where $L_{ii} =< i_t i_{t-1} >$ is the auto-covariance. Therefore, the IVD-estimated dynamic range ratio scaling factors yields:

$$s_{ivd} \equiv \frac{\beta_X}{\beta_Y} = \sqrt{\frac{\sigma_{IX}}{\sigma_{JY}}} \tag{10}$$

Hence, the random error variances of X and Y can be solved as:

$$\begin{cases} \sigma_{\varepsilon_X}^2 = \sigma_X^2 - \sigma_{XY} * s_{ivd} \\ \sigma_{\varepsilon_Y}^2 = \sigma_Y^2 - \dfrac{\sigma_{XY}}{s_{ivd}} \end{cases} \tag{11}$$

3.3. Extended instrumental variable technique

Furthermore, by adopting the designed matrix in extended collocation (EC) (Gruber et al., 2016a), Dong et al. (2020a) present the extended double instrumental variable technique (denoted as EIVD) to estimate the error variance matrix with only two independent data sets.

For a triplet input $\left[i, j, k \text{ with } \sigma_{\varepsilon_i \varepsilon_j} \neq 0\right]$. The dynamic range ratio scaling factors can be estimated as follows:

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

$$s_{ij} \equiv \frac{\beta_i}{\beta_j} = \sqrt{\frac{L_{ii}}{L_{jj}}} \tag{12}$$

where $L_{ii} =< i_t i_{t-1} >$ is the auto-covariance of inputs. Subsequently, the sensitivity and absolute error variance of the data set follow:

$$\beta_j^2 \sigma_\Theta^2 = \sigma_{ij}\sqrt{\frac{L_{ii}}{L_{jj}}} \qquad \sigma_{\varepsilon_j}^2 = \sigma_{ij}\sqrt{\frac{L_{ii}}{L_{jj}}} - \sigma_i^2 \tag{13}$$

The cross-multiplied factors can be estimated by:

$$\beta_i \beta_j \sigma_\Theta^2 = \sigma_{ik}\sqrt{\frac{L_{jj}}{L_{kk}}} = \sigma_{jk}\sqrt{\frac{L_{ii}}{L_{kk}}} \quad \sigma_{\varepsilon_i \varepsilon_j} = \sigma_{ij} - \beta_i \beta_j \sigma_\Theta^2 \tag{14}$$

Hence, for a triplet with the input of $[X, Y, Z$ with $\sigma_{\varepsilon_X \varepsilon_Y} \neq 0]$: the matrix notation of the above system with $\mathbf{y} = \mathbf{Ax}$ is given as:

$$\mathbf{y} = \begin{pmatrix} \sigma_X^2 \\ \sigma_Y^2 \\ \sigma_Z^2 \\ \sigma_{XY} \\ \sigma_{XZ}\sqrt{\frac{L_{XX}}{L_{ZZ}}} \\ \sigma_{YZ}\sqrt{\frac{L_{YY}}{L_{ZZ}}} \\ \sigma_{ZX}\sqrt{\frac{L_{ZZ}}{L_{XX}}} \\ \sigma_{ZY}\sqrt{\frac{L_{ZZ}}{L_{YY}}} \\ \sigma_{XZ}\sqrt{\frac{L_{YY}}{L_{ZZ}}} \\ \sigma_{YZ}\sqrt{\frac{L_{XX}}{L_{ZZ}}} \end{pmatrix}_{\mathbf{10x1}} \quad \mathbf{A} = \begin{pmatrix} \mathbf{I_{4x4}} & \mathbf{I_{4x4}} \\ \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 \end{pmatrix}_{\mathbf{6x4}} & \mathbf{0_{6x4}} \end{pmatrix}_{\mathbf{10x8}} \quad \mathbf{x} = \begin{pmatrix} \beta_X^2 \sigma_\Theta^2 \\ \beta_Y^2 \sigma_\Theta^2 \\ \beta_Z^2 \sigma_\Theta^2 \\ \beta_X \beta_Y \sigma_\Theta^2 \\ \sigma_{\varepsilon_X}^2 \\ \sigma_{\varepsilon_Y}^2 \\ \sigma_{\varepsilon_Z}^2 \\ \sigma_{\varepsilon_X \varepsilon_Y} \end{pmatrix}_{\mathbf{8x1}} \tag{15}$$

Likewise, the least-squared solution for unknown $\mathbf{x}$ is then solved by:

$$\mathbf{x} = (\mathbf{A}^\mathbf{T}\mathbf{A})^{-\mathbf{1}}\mathbf{A}^\mathbf{T}\mathbf{y} \tag{16}$$

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

3.4. Weight Estimation

Our objective is to predict an uncertain variable, such as evapotranspiration (ET) over time at a specific location, by utilizing parent products that may contain random errors. The underlying concept of weighted averaging is to extract independent information from multiple data sources to enhance prediction accuracy by mitigating the effects of random errors. The effectiveness of this approach relies on the independence of the individual data sources under consideration. Weighted averaging has found applications in various fields following the influential work of Bates and Granger (1969), who proposed the optimal combination of forecasts based on a mean square error (MSE) criterion. In this context, the term "optimal" refers to minimizing the variance of residual random errors in the least squares sense. Mathematically, this weighted average can be expressed as follows:

$$\overline{x} = \vec{\mathbf{W}}^{\mathrm{T}}\vec{\mathbf{X}} = \sum_{i=1}^{N} \omega_i x_i \tag{17}$$

where $\overline{x}$ is the merged estimate; $\vec{\mathbf{X}} = [x_1, \ldots, x_n]^{\mathrm{T}}$ contains the temporally collocated estimates from N different parent products, which are merged with relative zero-mean random error $\vec{\boldsymbol{e}} = [\varepsilon_1, \ldots, \varepsilon_n]^{\mathrm{T}}$; and $\vec{\mathbf{W}} = [\omega_1, \ldots, \omega_n]^{\mathrm{T}}$ contains the weights assigned to these estimates, where $\omega_i \in [0,1]$ and $\sum \omega_i = 1$ ensuring an unbiased prediction. The averaging weights can be expressed as the solution to the problem:

$$\min f\left(\vec{\mathbf{W}}\right) = \mathbb{E}\left(\vec{\boldsymbol{e}}^{\mathrm{T}}\vec{\mathbf{W}}\right)^2 \tag{18}$$

where $\mathbb{E}()$ is the operator for mathematical expectation, the solution of this problem is determined by the individual random error characteristics of the input data sets and can be derived from their covariance matrix (Bates and Granger, 1969; Gruber et al., 2017; Kim et al., 2021b):

$$\begin{gathered} \vec{\mathbf{W}} = \left(\vec{\mathbf{I}}^{\mathrm{T}}\mathbb{E}(\vec{\boldsymbol{e}}\vec{\boldsymbol{e}}^{\mathrm{T}})^{-1}\vec{\mathbf{I}}\right)^{-1}\mathbb{E}(\vec{\boldsymbol{e}}\vec{\boldsymbol{e}}^{\mathrm{T}})^{-1}\vec{\mathbf{I}} \\ \sigma_{\varepsilon_{\overline{x}}}^2 = \left(\vec{\mathbf{I}}^{\mathrm{T}}\mathbb{E}(\vec{\boldsymbol{e}}\vec{\boldsymbol{e}}^{\mathrm{T}})^{-1}\vec{\mathbf{I}}\right)^{-1} \end{gathered} \tag{19}$$

where $\mathbb{E}(\vec{\boldsymbol{e}}\vec{\boldsymbol{e}}^{\mathrm{T}})$ is the $N \times N$ error covariance matrix that holds the random error

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Open Access Earth System Science Data Discussions

variance $\sigma_{\varepsilon_i}^2$ of the parent products in the diagonals and relative error covariances $\sigma_{\varepsilon_i\varepsilon_j}$ in the off-diagonals; $\vec{\mathbf{I}} = [1, \dots, 1]^{\mathrm{T}}$ is an ones-vector of length N; and $\sigma_{\varepsilon_{\overline{x}}}^2$ is the resulting random error variances of the merged estimate.

When only two groups of products are used as input ($N = 2$), it is generally assumed that the errors between them are independent. In this case, the weights are as follows:

$$\begin{gathered}\mathbb{E}(\vec{\boldsymbol{e}}\vec{\boldsymbol{e}}^{\mathrm{T}}) = \begin{bmatrix} \sigma_{\varepsilon_1}^2 & 0 \\ 0 & \sigma_{\varepsilon_2}^2 \end{bmatrix} \\ \omega_1 = \frac{\sigma_{\varepsilon_2}^2}{\sigma_{\varepsilon_1}^2 + \sigma_{\varepsilon_2}^2} \qquad \omega_1 = \frac{\sigma_{\varepsilon_1}^2}{\sigma_{\varepsilon_1}^2 + \sigma_{\varepsilon_2}^2}\end{gathered} \tag{20}$$

In most cases, we can identify three sets of products as inputs ($N = 3$). In this scenario, we consider the possibility of error homogeneity, assuming a non-zero ECC exists between inputs 1 and 2. In this case, the error matrix can be represented as:

$$\mathbb{E}(\vec{\boldsymbol{e}}\vec{\boldsymbol{e}}^{\mathrm{T}}) = \begin{bmatrix} \sigma_{\varepsilon_1}^2 & \sigma_{\varepsilon_1\varepsilon_2} & 0 \\ \sigma_{\varepsilon_1\varepsilon_2} & \sigma_{\varepsilon_2}^2 & 0 \\ 0 & 0 & \sigma_{\varepsilon_3}^2 \end{bmatrix} \tag{21}$$

The weights can then be written as:

$$\begin{gathered}\vec{\mathbf{W}} = \begin{cases} \dfrac{\sigma_{\varepsilon_2}^2 - \sigma_{\varepsilon_1\varepsilon_2}}{\left(\sigma_{\varepsilon_1}^2\sigma_{\varepsilon_2}^2 - \sigma_{\varepsilon_1\varepsilon_2}^2\right) * \mathbb{Z}} \\ \dfrac{\sigma_{\varepsilon_1}^2 - \sigma_{\varepsilon_1\varepsilon_2}}{\left(\sigma_{\varepsilon_1}^2\sigma_{\varepsilon_2}^2 - \sigma_{\varepsilon_1\varepsilon_2}^2\right) * \mathbb{Z}} \\ \dfrac{1}{\sigma_{\varepsilon_3}^2 * \mathbb{Z}} \end{cases} \\ \mathbb{Z} = \frac{\sigma_{\varepsilon_1}^2 + \sigma_{\varepsilon_2}^2 - 2\sigma_{\varepsilon_1\varepsilon_2}}{\sigma_{\varepsilon_1}^2\sigma_{\varepsilon_2}^2 - \sigma_{\varepsilon_1\varepsilon_2}^2} + \frac{1}{\sigma_{\varepsilon_3}^2}\end{gathered} \tag{22}$$

It is essential to acknowledge that before applying these weights for merging the data sets, it is necessary to address any existing systematic differences. Typically, this is achieved by rescaling the data sets to a standardized data space. Consequently, the weights can be derived from the rescaled data sets using Eq (2)-(3) and converge accordingly. This procedure ensures the accuracy and reliability of the merged data sets for further analysis.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

If ECC is not considered (i.e., setting $\sigma_{\varepsilon_1\varepsilon_2} = 0$), Eq (22) represents the weight calculation method commonly used in most TC fusion studies. This method was initially applied by Yilmaz et al.(2012) in the fusion of multi-source soil moisture products and later improved by Gruber et al. (2017) and further applied in the production of the ESA CCI global soil moisture product (Gruber et al., 2019). Dong et al. (2020b) also adopted this approach to fusing multi-source precipitation products. In the study of evapotranspiration, Li et al. (2023b) and Park et al.(2023) utilized a weight calculation method that does not consider non-zero ECC and fused multiple ET products in the Nordic and East Asia, respectively, achieving satisfactory fusion results.

In contrast to the fusion studies mentioned above for evapotranspiration products, for the first time, the consideration of non-zero ECC is incorporated into the fusion process and integrated into the weight calculation. Yilmaz and Crow (2014) have demonstrated that TC underestimates error variances when the zero ECC assumption is violated. Li et al. (2022), in their evaluation study of global ET products using the collocation method, also indicated the existence of error homogeneity issues between commonly used ET products (such as ERA5L and GLEAM), necessitating the consideration of the influence of non-zero ECC. The merging technique employed in this study provides a more explicit characterization of product errors and facilitates the derivation of more reliable weight coefficients, thereby achieving superior fusion outcomes.

The differences in results are evaluated at the site scale by contrasting the scenarios without considering non-zero ECC and directly using simple averages to compare and validate the advantages of the weight calculation method used in our study.

3.5. Merging combination

In this study, we employ five commonly used global land surface evapotranspiration (ET) products as described in the datasets section. PMLv2 and FluxCom have an original resolution of 0.083° and an 8-day average. In this research, they are interpolated to 0.1° resolution, and the values for each data period of 8 days are kept consistent. For example, the values for March 5 to March 12, 2000, are the same. This operation is performed to ensure adequate data for the collocation analysis (Kim et al., 2021a), and any potential errors resulting from it will be discussed in the discussion section.

As mentioned in the methodology section, it is vital to consider the issue of random error homogeneity among different products before applying the collocation method. Although EC or EIVD methods can be used to calculate the ECC between specific pairs of products, it is necessary to determine which pairs of products have non-zero ECC conditions. In previous research, Li et al.(2022) employed five collocation methods (IVS/IVD/TC/EIVD/EC) to analyze the performance of five sets of ET products (ERA5L/GLEAMv3/PMLv2/FluxCom/PMLv2) at the global scale, and applied EC and EIVD methods to calculate the ECC between different products. The results indicated a relatively significant error homogeneity between PMLv2 and FluxCom at a resolution of 0.1° (with a global average ECC of approximately 0.3). The error homogeneity could be attributed to both products utilizing GLDAS meteorological data as input, despite their different methods for ET estimation. At a resolution of 0.25°, ERA5L and GLEAM exhibited a more apparent error correlation (with a global average ECC of approximately 0.4). Considering the long temporal data of GLEAMv3 version a, ECMWF meteorological data was chosen as the driving force, making the error correlation between the two products predictable.

Therefore, this study assumes that non-zero ECC situations occur between PMLv2-FluxCom and ERA5L-GLEAM. We also calculated the possible ECC situations among other products, presented in the discussion section and the appendix. Based on the analysis, our assumed non-zero ECC situations align reasonably well with the actual circumstances.

In addition, previous research suggests that the IVD method outperforms the IVS method in scenarios involving two sets of inputs, while the EIVD method is considered more reliable than the TC method in situations with three sets of inputs (Li et al., 2022; Kim et al., 2021a). Therefore, in this study, the IVD and EIVD methods are selected for computation based on different combinations of inputs. Table 2 presents the data and methods used during corresponding periods. When only two sets of products are available, we employ the IVD method for fusion and calculate weights using Eq. (20). When three sets of products are available, we utilize the EIVD method for fusion and calculate weights using Eq. (22).

TABLE.2 Combination of inputs and accessible methods

Scenario 1 (0.1°)		
Period	**Selected Inputs**	**Method**
(2000.02.26-2000.12.31)	ERA5L/ PMLv2	IVD
(2001.01.01-2015.12.27)	ERA5L/ FluxCom/ PMLv2	EIVD
(2015.12.28-2020.12.26)	ERA5L/ PMLv2	IVD
Scenario 2 (0.25°)		
Period	**Selected Inputs**	**Method**
(1980.01.01-1999.12.31)	ERA5L/ GLDAS20/ GLEAMv3.7a	EIVD
(2000.01.01-2022.12.31)	ERA5L/ GLDAS21/ GLEAMv3.7a	

It should be noted that the same product can have different versions. In this study, appropriate versions are selected based on the following principles: (1) Selection based on the corresponding data coverage duration; (2) Choosing the latest version while considering the assumption of non-zero ECC conditions; (3) Making efforts to select the exact product versions for different periods, to avoid uncertainties caused by version changes. We selected a subset of sites to compare the fusion results using different versions, and the corresponding details will be presented in the discussion section.

3.6. Evaluation indices

Five statistical indicators, namely Root-mean-squared-error ($RMSE$), Pearson's

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

correlation coefficient (R), Mean-absolute-error (MAE), unbiased $RMSE$ ($ubRMSE$) and Kling-Gupta Efficiency (KGE), are selected for comparison with existing products. The relative equations are shown as follows:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(sim_i - obs_i)^2}{n}} \tag{23}$$

$$R = \frac{\sum_{i=1}^{n}\left(sim_i - \overline{sim}\right)\left(obs_i - \overline{obs}\right)}{\sqrt{\sum_{i=1}^{n}\left(sim_i - \overline{sim}\right)^2 \sum_{i=1}^{n}\left(obs_i - \overline{obs}\right)^2}} \tag{24}$$

$$-1 \le R \le 1$$

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|sim_i - obs_i| \tag{25}$$

$$ubRMSE = \sqrt{\frac{\sum_{i=1}^{n}\left[\left(sim_i - \overline{sim}\right) - \left(obs_i - \overline{obs}\right)\right]^2}{n}} \tag{26}$$

Where sim is the simulations, obs is the observation as reference.

The KGE (Gupta et al., 2009) addressed several shortcomings in Nash-Sutcliffe Efficiency (NSE) and are increasingly used for calibration and evaluation (Knoben et al., 2019), given by:

$$KGE = 1 - \sqrt{(r-1)^2 + \left(\frac{\sigma_{sim}}{\sigma_{obs}} - 1\right)^2 + \left(\frac{\mu_{sim}}{\mu_{obs}} - 1\right)^2} \tag{27}$$

Where σ_{obs} and σ_{sim} are the standard deviations of observations and simulations; μ_{obs} and μ_{sim} are the mean of observations and simulations. Similar to NSE, KGE = 1 indicates perfect agreement of simulations, while $KGE < 0$ reveals that the average of observations is better than simulations (Towner et al., 2019).

4. Results

In this study, we aimed to compare and evaluate the performance of fused products at both site and global scales. Specifically, Lu et al. (2021) 's global 0.25° daily-scale ET product derived using Reliability Ensemble Averaging (denoted as REA) was also selected for comparative analysis. At the site scale, the performance of the fused

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

products was evaluated against 212 FluxNet observations and compared with other products, including the simple average. At the global scale, the mean and temporal variations of the land surface ET calculated by the fused products were compared with those of other products.

4.1. Analysis of error variances

This section analyzed the random error variances of the 0.1° and 0.25° inputs obtained using the EIVD method.

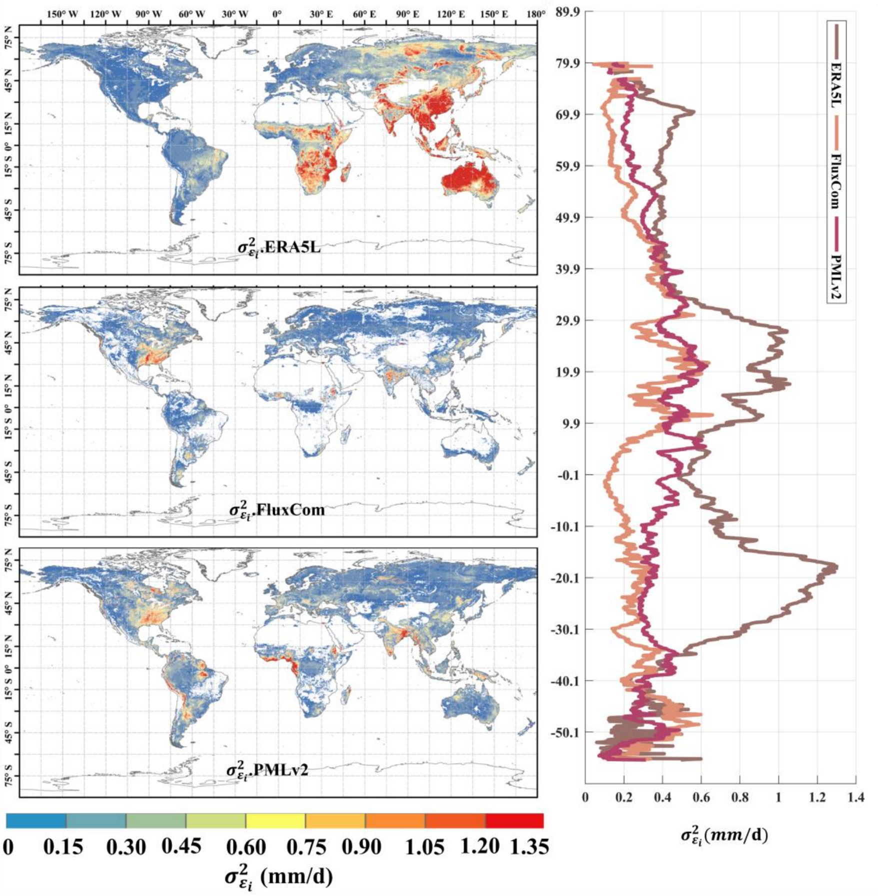

FIGURE.1 Global distribution of absolute error variances ($\sigma^2_{\varepsilon_i}$) of ERA5L, FluxCom, and PMLv2 using EIVD at 0.1° from 2001 to 2015, depicted alongside corresponding variation curves of average with latitude.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Figure 1 represents the random errors of the correlation products calculated using the EIVD method from 2001 to 2015 at 0.1°, where a non-zero ECC is assumed between FluxCom and PMLv2. The areas with missing values are due to the absence of data from either FluxCom or PMLv2 in those regions. The global random error variances (mean ± standard deviation) obtained using the EIVD method are as follows: ERA5L: 0.58 ± 0.53 mm/day, FluxCom: 0.12 ± 0.13 mm/day, PMLv2: 0.17 ± 0.14 mm/day. These results indicate that FluxCom performs best overall, while ERA5L performs the poorest. Regarding spatial distribution, regions with more significant random errors in ERA5L are mainly located in East Asia, Australia, and southern Africa. On the other hand, FluxCom and PMLv2 show relatively more considerable uncertainties in the southeastern United States. The latitude distribution reveals that ERA5L has the highest uncertainty, primarily in the vicinity of 20° to 30° north and south, consistent with its spatial distribution.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Open Access Earth System Science Data Discussions

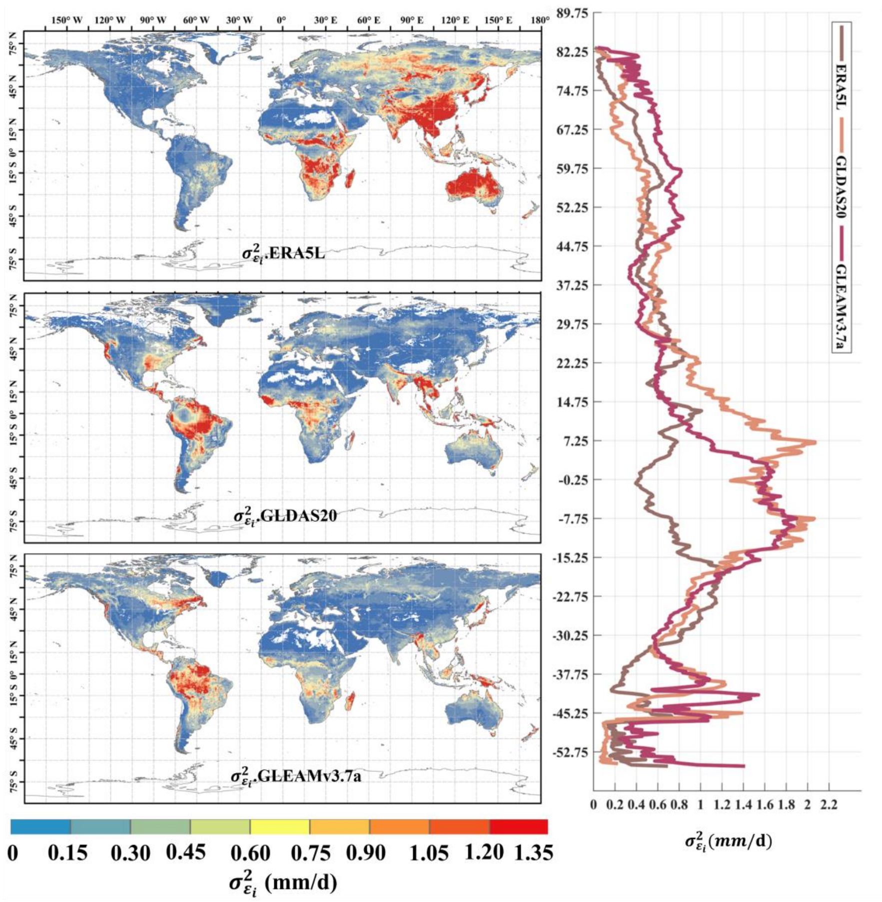

FIGURE.2 Global distribution of absolute error variances ($\sigma^2_{\varepsilon_i}$) of ERA5L, GLDAS2.0, and GLEAMv3.7a using EIVD at 0.25° from 1980 to 1999, depicted alongside corresponding variation curves of average with latitude.

The distribution of random error variance for ERA5L (0.59±0.58 mm/d), GLDAS2.0 (0.37±0.44 mm/d), and GLEAMv3.7a (0.38±0.36 mm/d) from 1980 to 1999 at 0.25° is shown in Figure 2. Here, we assumed a non-zero ECC between ERA5L and GLEAM. The ERA5L data was resampled from a 0.1° resolution to 0.25°, and its error distribution pattern is like that of the 0.1° resolution. It exhibits higher uncertainties in East Asia, Australia, and southern Africa. GLDAS and GLEAM exhibit relatively higher uncertainty over the southeastern United States and the Amazon Plain. GLDAS and GLEAM show similar performance among the three

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

products, while ERA5L performs relatively worse. Regarding the average distribution with latitude, ERA5L demonstrates a more even distribution, whereas GLDAS and GLEAM exhibit relatively higher uncertainties in tropical regions.

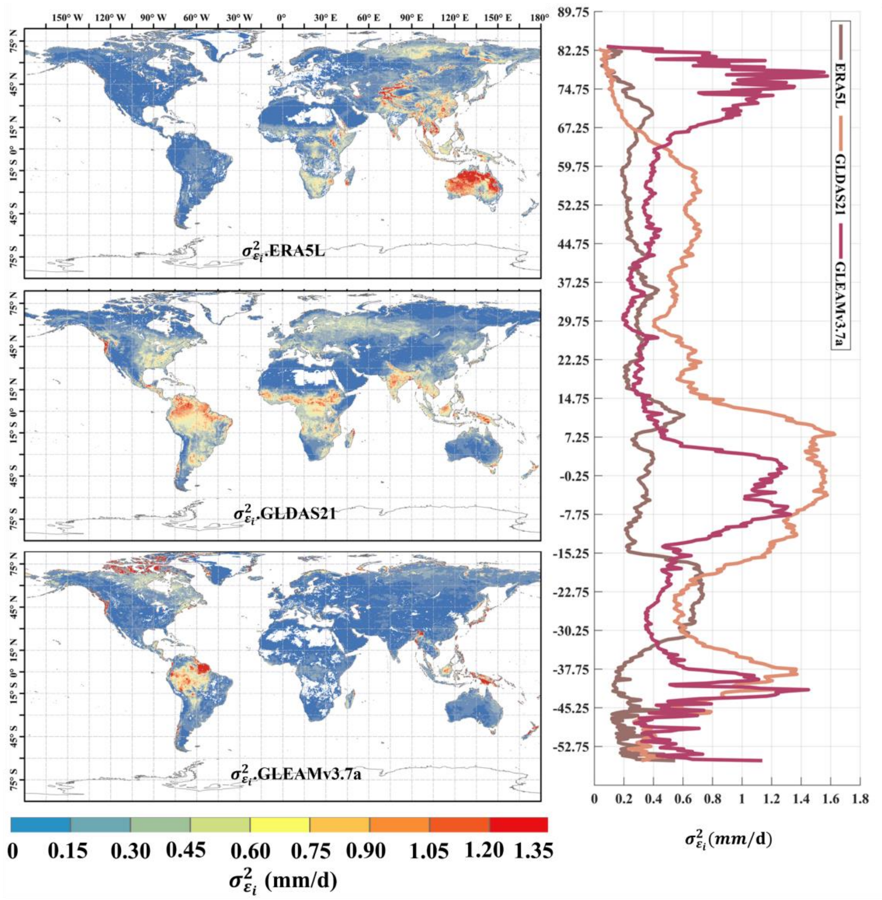

FIGURE.3 Global distribution of absolute error variances ($\sigma^2_{\varepsilon_i}$) of ERA5L, GLDAS2.1, and GLEAMv3.7a using EIVD at 0.25° from 2000 to 2022, depicted alongside corresponding variation curves of average with latitude.

In addition, Figure 3 presents the distribution of random error variance for ERA5L (0.32±0.33 mm/d), GLDAS2.1 (0.35±0.29 mm/d), and GLEAMv3.7a (0.38±0.36 mm/d) from 2000 to 2022 at a resolution of 0.25°. The non-zero ECC assumption was made between ERA5L and GLEAM. In this combination, ERA5L shows significantly lower errors than in previous periods, indicating improved ERA5L performance

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

during this time frame. However, ERA5L still exhibits more significant errors in the East Asia and Australia regions compared to the other two datasets. The overall errors for GLDAS and GLEAM have also decreased, but there are still random error variances exceeding 1.0 mm/d in the Amazon plain and Indonesia region. Regarding the latitudinal distribution, ERA5L shows relatively smooth changes, while GLDAS and GLEAM exhibit similar trends. However, GLEAM demonstrates a noticeable increase in errors near the Arctic.

For the analysis at a resolution of 0.1°, we also applied the IVD method to calculate the errors between ERA5L and PMLv2 for two time periods: 2000 and 2015 to 2020. Since the analysis of product errors is not the focus of this paper, we provide the results of the IVD in the appendix. Grids with higher random error variances correspond to smaller weights when calculating the weights. The weight distribution calculated at different time intervals is available in the appendix.

4.2. Site-scale evaluation and comparison

At the site scale, the performance of CAMELE was compared with FluxNet as the reference. In this subsection, Figure 4 and Table 3 correspond to each other, as they integrate data from 212 sites for all available periods, allowing for a comparative analysis of the performance of different products at different times. Similarly, Figure 5 and Table 4 correspond to each other, where different product metrics were calculated for each site, and the calculated metric results were subjected to statistical analysis.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

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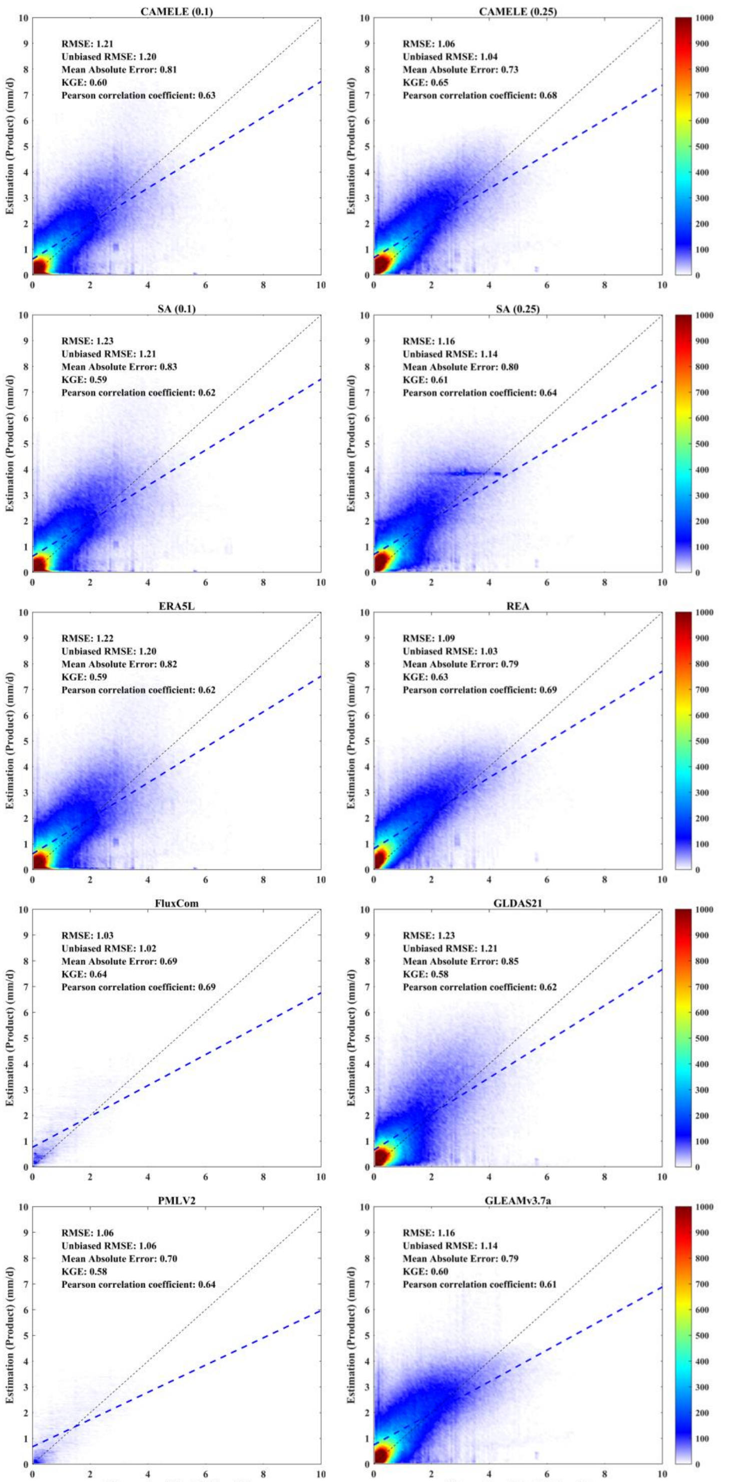


551

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Open Access Earth System Science Data Discussions

FIGURE.4 Scatter plots of product corresponding to the available period data from 212 FluxNet sites. The colorbar represents the density, with darker colors indicating higher concentration. The left and right columns present results for 0.1° and 0.25° resolutions, respectively, with "SA" indicating the results for simple average. Relevant statistical metrics are annotated in their respective figures.

The scatter plots in Figure 4 show that CAMELE performed well at both 0.1° and 0.25° resolutions. At 0.1° resolution, FluxCom and PMLv2 had fewer data points due to their original product being based on an 8-day average resolution, but overall, they showed the best performance. CAMELE exhibited a performance at a station scale like ERA5L. At 0.25° resolution, CAMELE performed similarly to the other datasets, with reasonable accuracy. Notably, there was an improvement in the KGE and R indices. The fitted line was closer to the 1:1 line, indicating a closer agreement with the observed values. Interestingly, the results obtained from the simple average were also acceptable, but SA (0.25°) had a large concentration of data points between (2-4 mm/d), which might be attributed to the inputs having a high concentration within that range. Theoretically, the simple average assumes that each product performs equally on each grid cell, which does not align with the actual situation.

Table.3 Average values of different metrics for CAMELE and other fusion schemes corresponding to the available period data from 212 FluxNet sites. The bolded sections indicate the schemes with the best performance in their respective metrics.

Product		RMSE (mm/d)	ubRMSE (mm/d)	MAE (mm/d)	KGE	R
0.1°-daily	**CAMELE**	1.21	1.20	0.81	**0.60**	0.63
	SA	1.23	1.21	0.83	0.59	0.62
	ERA5L	1.22	1.20	0.82	0.59	0.62
	FluxCom	**1.03**	**1.02**	**0.69**	0.64	**0.69**
	PMLv2	1.06	1.06	0.70	0.58	0.64
0.25°-daily	**CAMELE**	**1.06**	1.04	**0.73**	**0.65**	0.68
	SA	1.16	1.14	0.80	0.61	0.64
	REA	1.09	**1.03**	0.79	0.63	**0.69**

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

GLDAS21	1.23	1.21	0.85	0.58	0.62
GLEAMv3.7a	1.16	1.14	0.79	0.60	0.61

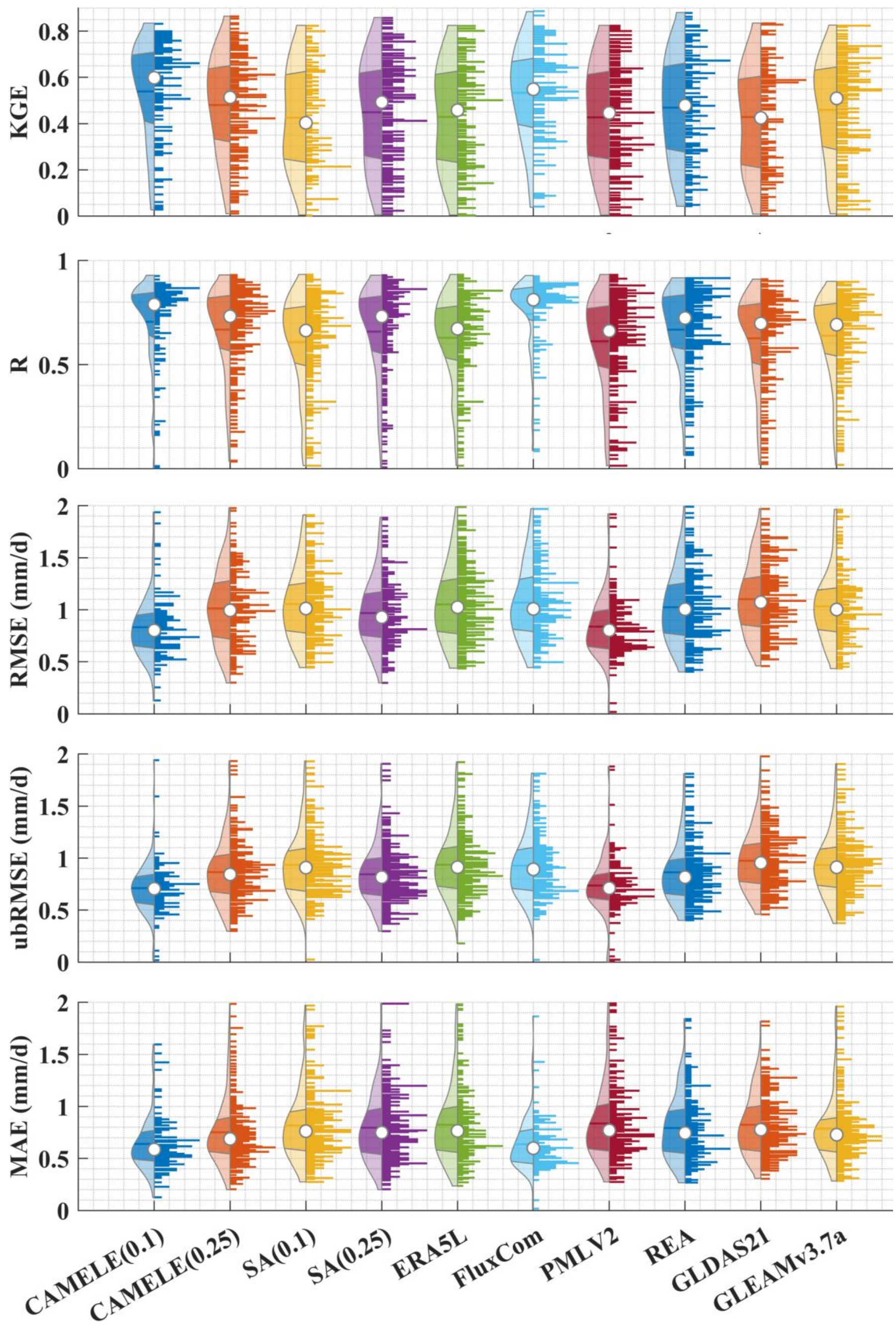
The information in Table 3 corresponds to Figure 4 and presents the results of various product indicators. The bolded parts indicate the products with the best corresponding indicators. The results indicate that CAMELE performed well at both 0.1° and 0.25° resolutions, mainly showing improvements in the KGE and R indicators. FluxCom exhibited the best performance; however, considering that this product utilized FluxNet sites for result calibration, this phenomenon is reasonable. In this study, we pooled the data from all 212 available periods at the stations as a reference without considering the differences between individual sites. This approach provided an initial validation of the reliability of CAMELE at all sites.

The information in Figure 5 corresponds to the data presented in Table 4, which involves the calculation of five indicators at each site, followed by statistical analysis of these indicators. From the distribution of the violin plots, it can be observed that a violin plot with a closer belly to 1 indicates better results in terms of the R and KGE indicators. CAMELE performs exceptionally well overall, closely resembling PMLv2 and FluxCom. On the other hand, the results obtained from Simple Average are relatively poorer. Regarding the RMSE, ubRMSE, and MAE indicators, a violin plot with a closer belly to 0 suggests more minor errors. CAMELE shows a significant improvement in performance at the 0.1° level. This indicates that the fusion method effectively reduces errors, aligning with the original intention of weight calculation.

Additionally, FluxCom and PMLv2 also exhibit minimal errors, which is expected considering their utilization of FluxNet sites for error correction. Furthermore, SA shows significantly larger errors. Although the simple average method can compensate for positive and negative errors between inputs in some instances, it can also lead to error accumulation, as evidenced by the results in the violin plots.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Open Access Earth System Science Data Discussions



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598 **Figure.5** Violin plots obtained by aggregating five different statistical indicators,

599 calculated separately for each site. In each violin plot, the left side represents the

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

distribution, with the shaded area indicating the box plot, the dot representing the mean, and the right side showing the histogram.

Table.4 Average values of indicators corresponding to different products, calculated based on the comprehensive results obtained for each site. The bolded sections indicate the schemes with the best performance in their respective metrics.

Product		RMSE (mm/d)	ubRMSE (mm/d)	MAE (mm/d)	KGE	R
0.1°-daily	**CAMELE**	**0.83**	**0.71**	0.64	**0.54**	0.71
	SA	1.05	0.93	0.82	0.43	0.61
	ERA5L	1.05	0.94	0.82	0.43	0.63
	FluxCom	1.07	0.93	**0.64**	0.53	**0.74**
	PMLv2	0.84	0.74	0.84	0.43	0.61
0.25°-daily	**CAMELE**	**1.03**	0.87	**0.75**	**0.49**	**0.67**
	SA	0.97	**0.84**	0.80	0.45	0.66
	REA	1.02	0.86	0.80	0.47	0.67
	GLDAS21	1.10	0.97	0.83	0.43	0.63
	GLEAMv3.7a	1.03	0.93	0.79	0.46	0.64

Table 4 presents the average values of different metrics in Figure 5, boldly highlighting the optimal products corresponding to each metric. It can be observed that CAMELE exhibits significant improvements in performance at a resolution of 0.1°, particularly in terms of the error metrics RMSE and ubRMSE, surpassing other products. This further confirms the effectiveness of our fusion scheme in reducing product errors. Additionally, although the performance of CAMELE at a resolution of 0.25° is comparable to other products, there is still a slight decline compared to its performance at 0.1°. This can be attributed partly to the inherent errors in the input products and partly to the decreasing representativeness of FluxNet, which serves as the reference at the 0.25° grid. Nevertheless, we can still consider CAMELE to have good accuracy.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Open Access Earth System Science Data Discussions

Figure.6 Heatmap of five indicators calculated separately for each site, classified by PFTs. The top right corner indicates the number of sites corresponding to each type.

Table.5 Optimal product corresponding to different PFTs under various statistical indicators against observations from FluxNet sites

<table>
<tr><th>IGBP (n-sites)</th><th>RMSE (mm/d)</th><th>ubRMSE (mm/d)</th><th>MAE (mm/d)</th><th>KGE</th><th>R</th></tr>
<tr><td>CRO (20)</td><td rowspan="4">CAMELE</td><td>CAMELE</td><td rowspan="3">CAMELE</td><td>PMLv2</td><td>CAMELE</td></tr>
<tr><td>CSH (3)</td><td>PMLv2</td><td>FluxCom</td><td rowspan="3">FluxCom</td></tr>
<tr><td>DBF (26)</td><td rowspan="2">CAMELE</td><td>REA</td></tr>
<tr><td>DNF (1)</td><td>FluxCom</td><td>CAMELE</td></tr>
</table>

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

<table>
<tr><td>EBF (15)</td><td rowspan="2"></td><td rowspan="7"></td><td>CAMELE</td><td>GLEAM</td><td rowspan="2"></td></tr>
<tr><td>ENF (49)</td><td rowspan="2">FluxCom</td><td rowspan="2">CAMELE</td></tr>
<tr><td>GRA (39)</td><td>PMLv2</td><td>CAMELE</td></tr>
<tr><td>MF (9)</td><td rowspan="6">CAMELE</td><td>CAMELE</td><td>REA</td><td rowspan="6">FluxCom</td></tr>
<tr><td>OSH (13)</td><td rowspan="2">FluxCom</td><td rowspan="2">CAMELE</td></tr>
<tr><td>SAV (9)</td></tr>
<tr><td>SNO (1)</td><td>CAMELE</td><td>REA</td></tr>
<tr><td>WET (21)</td><td>PMLv2</td><td rowspan="2">FluxCom</td><td rowspan="2">CAMELE</td></tr>
<tr><td>WSA (6)</td><td>CAMELE</td></tr>
</table>

Furthermore, we classified 212 sites according to PFTs and analyzed the statistical indicators of different PFTs corresponding to each site. The results are represented in Figure 6 as a heatmap, and the corresponding optimal products for other PFTs sites are marked in Table 5. The results show that CAMELE performs the best in almost all PFTs categories, as indicated by various indicators. While on sites where other products perform better, CAMELE's indicators are comparable to the optimal products, albeit slightly inferior. This indicates that our fusion approach effectively combines the advantages of different products, resulting in superior fusion results across different vegetation types.

In summary, using the filtered daily-scale data from 212 FluxNet sites as a reference, we conducted a benchmark analysis with CAMELE and demonstrated its good fit with the observed data. Additionally, by comparing the performance of different products at each site, we further illustrated that CAMELE exhibits similar or slightly improved accuracy and minor errors compared to existing products.

4.3. Global comparison of multi-year average and linear trend

This section will compare the multi-year average daily-scale evapotranspiration distributions and their linear trends between CAMELE and other products at resolutions of 0.1° and 0.25°. Due to the varying available periods of different products, the results presented here are based on calculations using data from all available periods, and the corresponding periods are indicated in each figure.

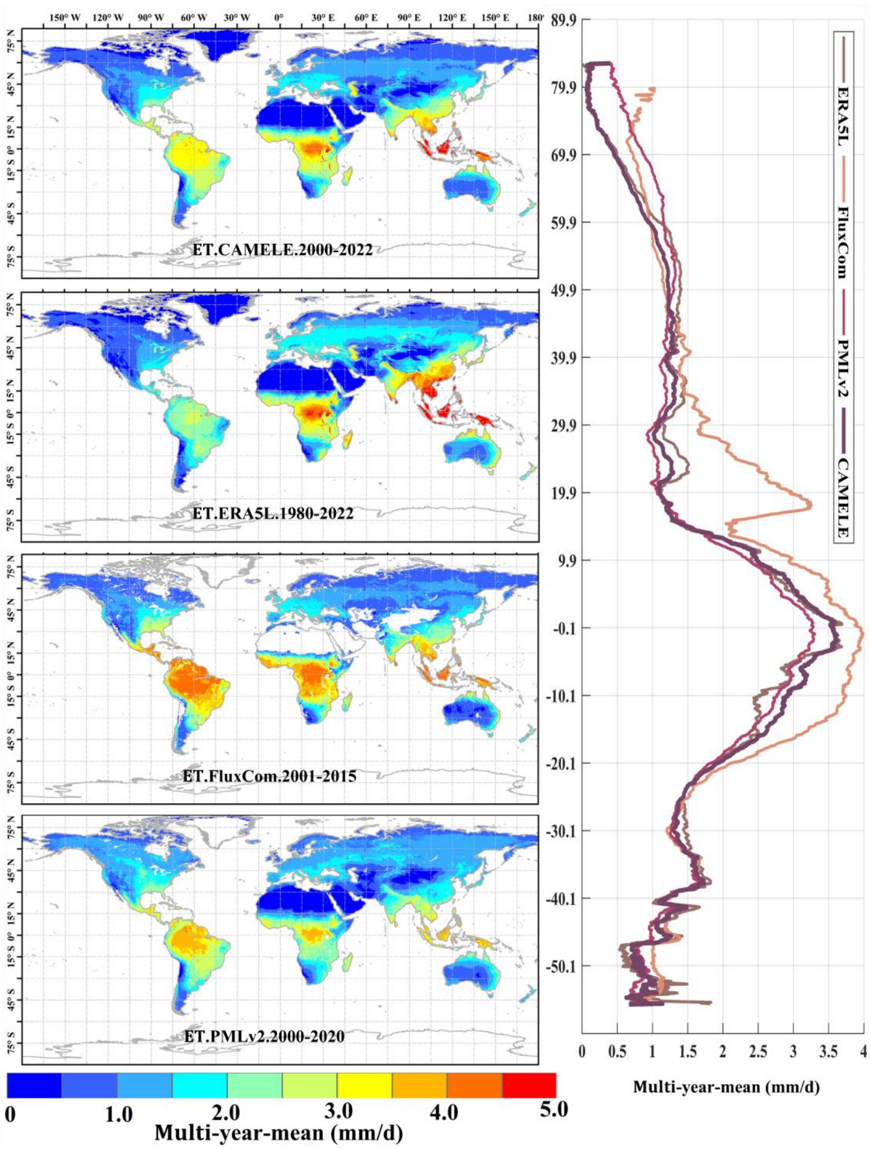

FIGURE.7 Global distribution of multi-year daily average ET at 0.1° for CAMELE, ERA5L, FluxCom, and PMLv2, depicted alongside corresponding variation curves of average with latitude.

The results in Figure 7 indicate significant differences in the multi-year daily average distribution of global evapotranspiration (ET) among different products. Specifically,

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

ERA5L shows noticeably higher values in East Asia than other products, while FluxCom and PMLv2 exhibit higher values in the Amazon rainforest and southern Africa regions. This distribution pattern is consistent with the error results obtained from the EIVD calculation, indicating that these products possess certain uncertainties in the regions. In terms of the latitudinal distribution pattern, except for FluxCom, which displays distinct fluctuations, the variability among the other products is relatively similar. This suggests that despite spatial differences among the different products, they maintain consistency in the overall quantity.

Figure 8 presents the results with a resolution of 0.25°. It can be observed that compared to the 0.1° distribution, the spatial distribution of annual average evapotranspiration (ET) is more consistent among different products at 0.25°, showing larger ET values in tropical regions. The main differences are concentrated in the Amazon rainforest and the Congo Basin, where GLEAM and GLDAS results are higher than REA's. REA utilizes MERRA2 as input data, while GLDAS and GLEAM have weights of approximately close to 1/3 each (Lu et al., 2021). Therefore, the distribution of REA falls between GLDAS and GLEAM, which is understandable. The latitude variation plots show that the results from each product are very close, providing additional evidence for the reliability of CAMELE.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

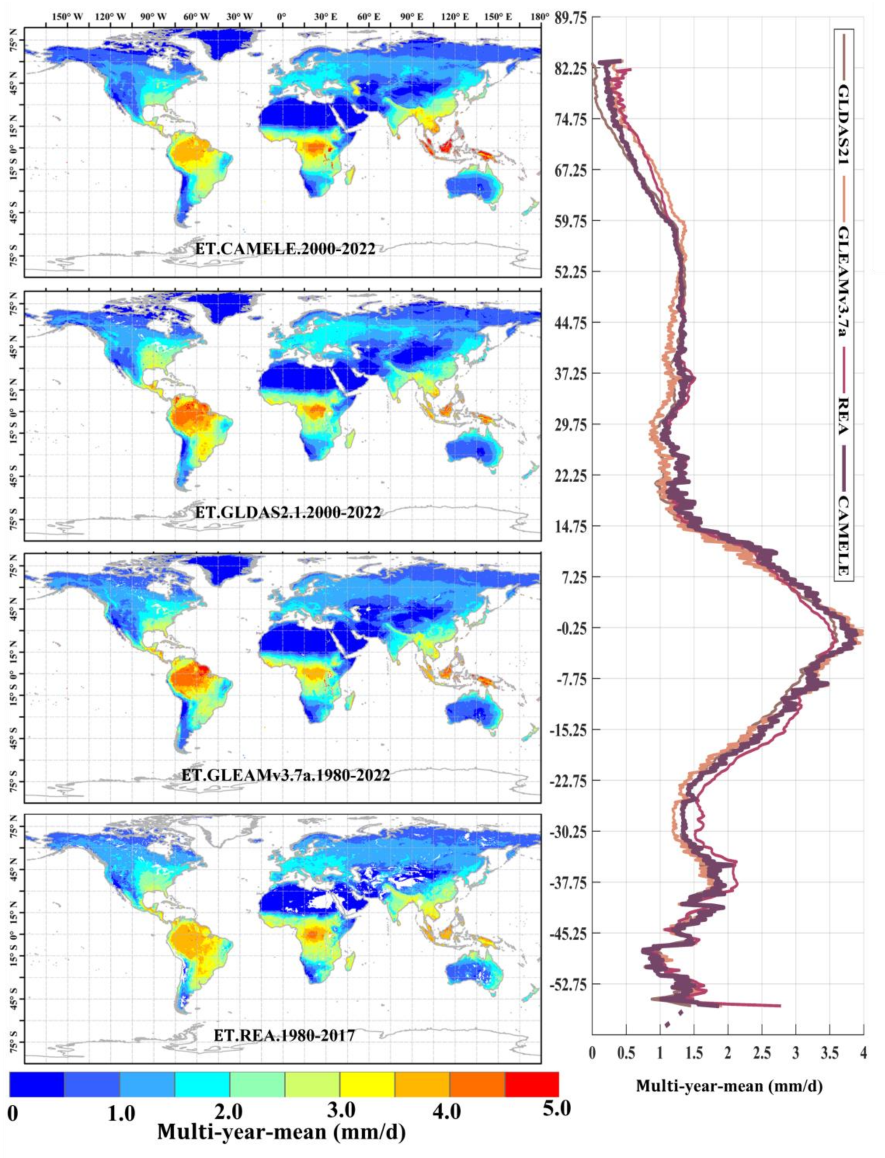

FIGURE.8 Global distribution of multi-year daily average ET at 0.25° for CAMELE, GLDAS2.1, GLEAMv3.7a, and REA, depicted alongside corresponding variation curves of average with latitude.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

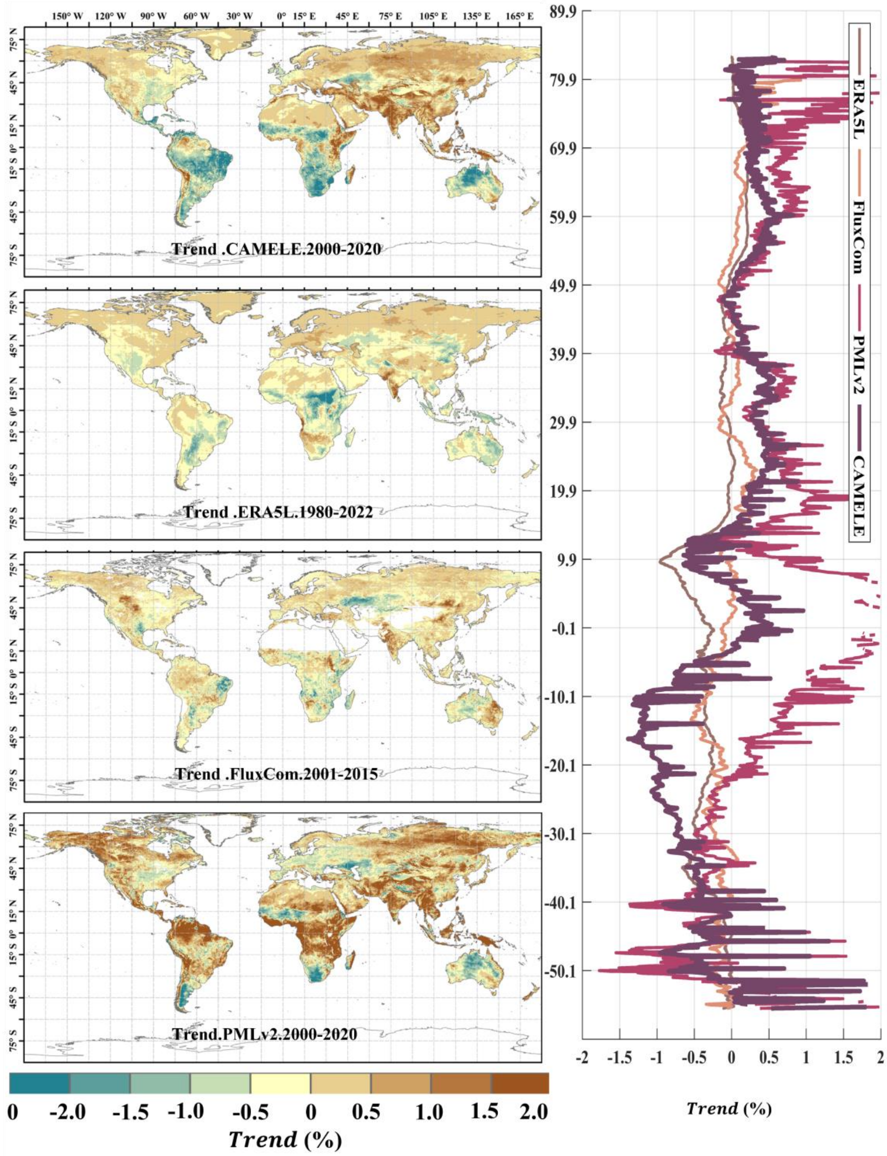

FIGURE.9 Global distribution of multi-year linear trend at 0.1° for CAMELE, ERA5L, FluxCom, and PMLv2, depicted alongside corresponding variation curves of average with latitude.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

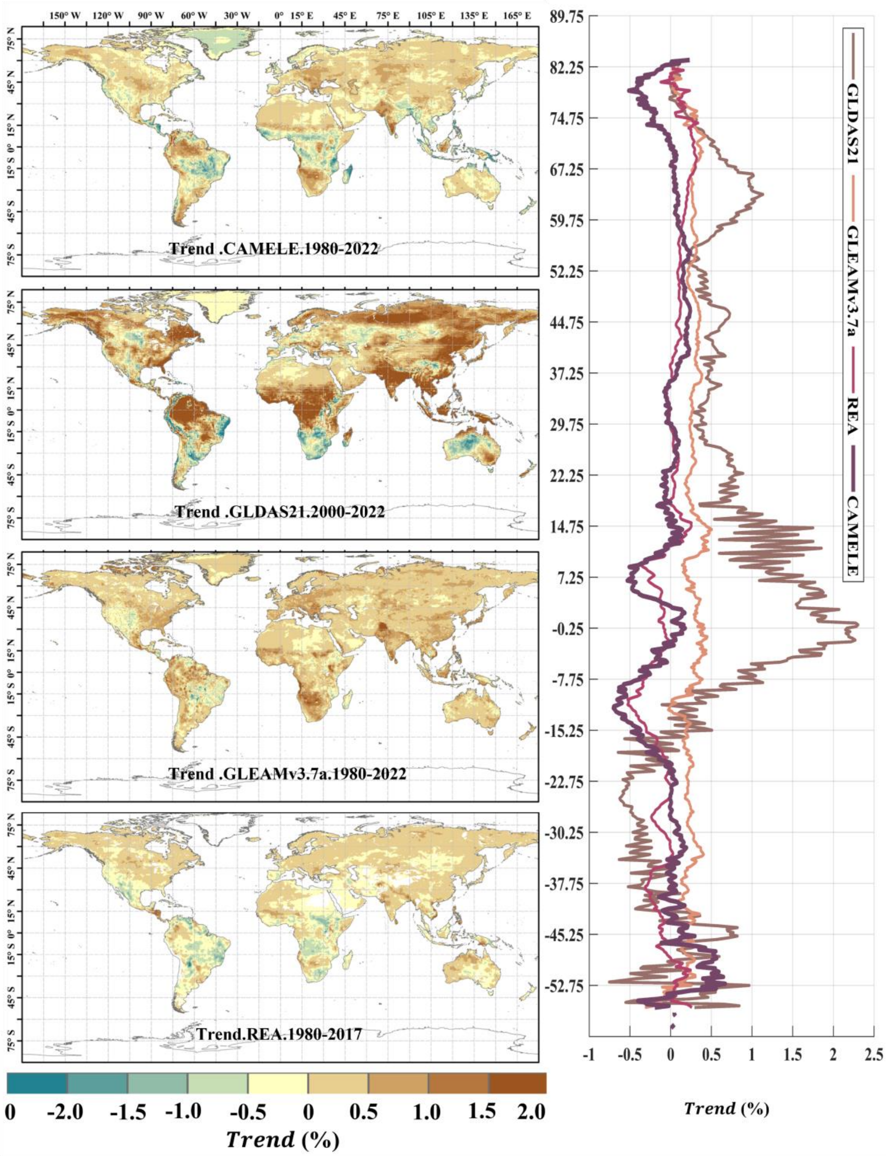

FIGURE.10 Global distribution of multi-year linear trend at 0.25° for CAMELE, GLDAS2.1, GLEAMv3.7a, and REA, depicted alongside corresponding variation curves of average with latitude.

Figures 9 and 10 present the linear trends of multi-year daily scale evapotranspiration (ET) calculated for different products at resolutions of 0.1° and 0.25°, respectively. The corresponding latitude-dependent variations of the rate of change are shown on

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

the right side. It can be observed that the differences in linear trends among the different products are more significant than the multi-year averages, and in some regions, they even exhibit opposite trends. For example, at 0.1° resolution, PMLv2 shows a global increase of 1.0% in ET in most regions, while the results from CAMELE, ERA5L, and PMLv2 indicate a slight decrease in ET in the Amazon rainforest, southern Africa, and northwestern Australia. Among them, CAMELE exhibits a more pronounced decreasing trend. At 0.25° resolution, except for GLDAS2.1, which shows an apparent global increase in ET, the results from CAMELE, GLEAMv3.7a, and REA indicate more minor variations in global ET.

To calculate the linear trend more reasonably, we focused on the available years for different products without uniformly applying the same time range, as this could introduce specific impacts on the comparison of results. Furthermore, it can be observed that the linear trend obtained at 0.25°is milder than that of 0.1°. The grid size and the characteristics of the data itself influence this.

5. Discussion

5.1. Impact of underlying assumptions in collocation analysis

The collocation analysis system relies on several fundamental assumptions, namely: (i) Linearity: a linear regression model that describes the relationship between the true signal and the datasets; (ii) Stationarity: the unconditional joint probability distribution of the signal and the random error of estimates remains unchanged when shifted in time; (iii) Error Orthogonality: independence between the random error of estimates (e.g., evapotranspiration product) and the true signal (assumed unknown true evapotranspiration value); and (iv) Zero Error Cross-Correlation: independence between random errors of relevant datasets. Additionally, potential error autocorrelation must be considered when incorporating the lag-1 [day] series into the triplet (Kim et al., 2021b; Dong et al., 2020a, 2019). Numerous studies have

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

examined the validity of these assumptions and their impact on the outcomes if violated (Tsamalis, 2022; Duan et al., 2021; Gruber et al., 2020). Thus, we will provide a concise and accurate account of the implications resulting from breaches of these assumptions.

The linearity assumption shapes the error model by including additive and multiplicative biases and zero-mean random error. Although some studies have explored the application of a nonlinear rescaling technique (Yilmaz and Crow, 2013; Zwieback et al., 2016), those efforts are primarily limited to soil moisture signals and often fail to accurately represent the true signal unless all datasets share a similar signal-to-noise ratio (SNR). However, it is worth noting that after rescaling processes, such as cumulative distribution function (CDF) matching or climatology removal, the resulting time series (anomalies) are often considered linearly related to the truth since higher-order error terms are removed. Therefore, the linear error model remains a robust implementation, though it has the potential for improvement through rescaling techniques.

Regarding violating the stationarity assumption, the evapotranspiration signal does not strictly adhere to this characteristic. However, by collocating triplets with similar magnitude variations, the influence of this violation is minimized. Nonetheless, disparities in climatology between datasets can still arise for various reasons (Su and Ryu, 2015). Several proposed alternatives aim to address this issue, such as removing the climatology of inputs (Stoffelen, 1998; Yilmaz and Crow, 2014; Draper et al., 2013) and subsequently analyzing the random error variance of the anomalies (Dong et al., 2020b). Nevertheless, obtaining a reliable estimation of climatology proves challenging in practice.

The assumption of error orthogonality assumes independence between random error and true signal, i.e., $\sigma_{\varepsilon_i\Theta} = 0$. A few studies have examined this assumption. Yilmaz and Crow (2014) investigated such violations using four in situ sites and concluded that the impact is negligible since rescaling mitigates or compensates for bias.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Additionally, non-orthogonality results in non-zero error cross-correlation (ECC), although the latter is considered more important. Vogelzang et al. (2022) also investigated this violation recently and demonstrated minimal second-order impact. Non-zero ECC conditions introduce more substantial bias in the results compared to other violations mainly due to two reasons: (1) they cannot be mitigated by rescaling; (2) they cannot be compensated even with equal magnitude for all inputs; and (3) they have been frequently reported in recent studies for various variables (Li et al., 2018, 2022; Gruber et al., 2016b). Gruber et al. (2016a) proposed the extended collocation method, which effectively addresses the ECC of selected pairs. Moreover, the EIVD method adopts the error cross-correlation framework. In the following section, we will analyze the ECC between pairs.

5.2. Analysis of error cross-correlation

This study assumes non-zero ECC (Error-Correction Coefficient) conditions exist between FluxCom and PMLv2 at 0.1° and between ERA5L and GLEAM at 0.25°. However, non-zero ECC conditions were also possible between other pairs. Therefore, we presented the EIVD-based ECC results of various pairs.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

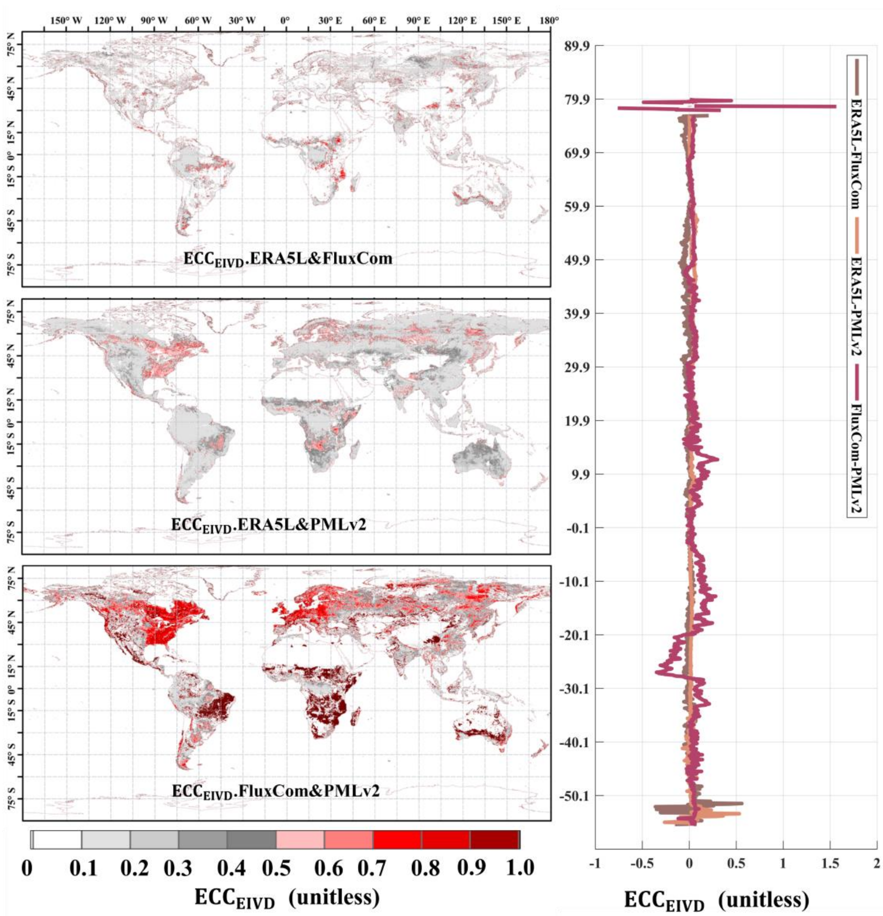

FIGURE.11 Global Distribution of estimated error cross-correlation (ECC) between ERA5L, FluxCom, and PMLv2 pairwise using EIVD alongside relevant variation curves of average with latitude.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

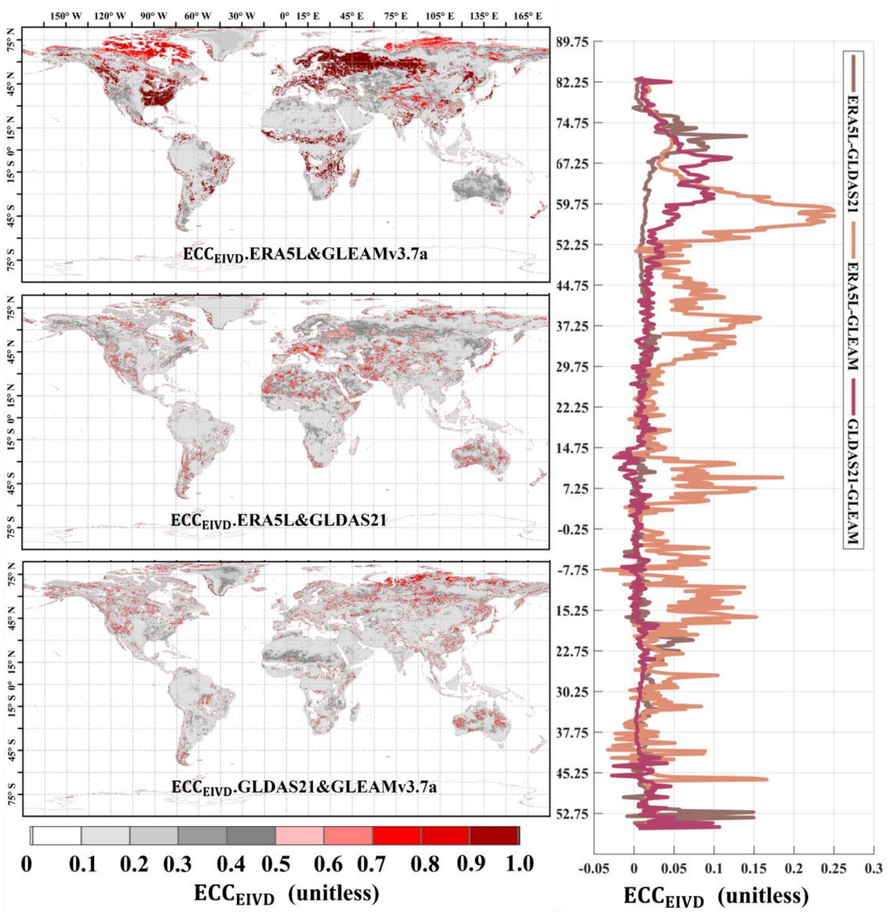

FIGURE.12 Global Distribution of estimated error cross-correlation (ECC) between ERA5L, GLEAMv3.7a, and GLDAS21 pairwise using EIVD alongside relevant variation curves of average with latitude.

As depicted in Figure 11 and Figure 12, at a resolution of 0.1°, the Error-to-Covariance (ECC) values of FluxCom and PMLv2 were notably higher than those of ERA5L-FluxCom and ERA5L-PMLv2. The global average ECC value for FluxCom-PMLv2 was 0.16, and regions with high ECC values were identified in the eastern United States, most of Europe, and the western Amazon, areas densely covered by measurement sites. Since both FluxCom and PMLv2 incorporated corrections based on FluxNet measurement sites, there is likely some overlap between the sites used by both products in the high ECC regions. This partially explains the shared source of random errors between the two datasets.

The global error correlations of GLEAM-GLDAS and ERA5L-GLDAS are relatively low. The random error of ERA5L correlates with that of GLEAM, primarily in arid regions such as the Sahara Desert, Northwest China, and central Australia, where the average ECC exceeds 0.20. The global average ECC of ERA5L-GLEAM is approximately 0.14. A higher error correlation is observed for ERA5L-GLEAM, with a mean ECC value of 0.26, which is expected since meteorological information from ECMWF is reanalyzed for both datasets. However, ECC values for GLEAM-GLDAS and ERA5L-GLDAS are generally low globally, supporting the assumption of zero ECC for these two pairs.

Our findings highlight the significant impact of Error Cross Correlation (ECC) between FluxCom-PMLv2 and ERA5L-GLEAM at 0.1° and 0.25° resolutions, respectively. Mathematically, when a triplet exhibits a high ECC value (>0.3) between two sets, it indicates a preference for the remaining independent product as the "better" one, potentially leading to an underestimation of its error variance. However, it is essential to note that the overall ECC values for other pairs are relatively small, suggesting that the zero ECC assumptions can be considered valid for these pairs across most areas. Therefore, these assumptions are unlikely to affect the relevant results of uncertainties significantly. Nevertheless, we have considered the non-zero ECC condition between FluxCom-PMLv2 and ERA5L-GLEAM in this study, as it requires careful consideration.

5.3. Comparison of different fusion schemes

In this section, we conducted comparisons in three aspects: (1) comparing the performance of CAMELE at different resolutions; (2) comparing the performance of different change fusion schemes, explicitly changing the input products' versions (GLDAS21 to GLDAS22, GLEAMv3.7a to v3.7b); and (3) comparing the

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

performance of the results obtained without considering the ECC impact.

We compared the results of three schemes in the fusion process at a resolution of 0.25°. The first combination consisted of ERA5L, GLDAS22, and GLEAMv3.7a (Comb1). The second input combination consisted of ERA5L, GLDAS22, and GLEAMv3.7b (Comb2). The third input combination consisted of ERA5L, GLDAS2.1, and GLEAMv3.7b (denoted as Comb3). These three combinations used for comparison corresponded to the period from February 2003 to December 2022. The combination assuming zero ECC (Zero-ECC) had the same inputs as CAMELE at both resolutions.

Table 6 Average metrics for CAMELE and other fusion schemes at all sites. The bolded sections indicate the schemes with the best performance in their respective metrics.

Product	RMSE (mm/d)	ubRMSE (mm/d)	MAE (mm/d)	KGE	R
CAMELE (0.1)	**0.83**	**0.71**	**0.64**	**0.54**	**0.71**
CAMELE (0.25)	1.03	0.87	0.75	0.49	0.67
Comb1	1.20	0.95	0.94	0.43	0.68
Comb2	1.19	0.94	0.93	0.44	0.69
Comb3	1.05	0.90	0.80	0.47	0.69
Zero-ECC (0.1)	1.06	0.91	0.80	0.44	0.60
Zero-ECC (0.25)	1.26	1.03	0.99	0.38	0.61

According to the information in the table, CAMELE (0.1°) results were superior in all indicators. Firstly, when comparing the performance of CAMELE at resolutions of 0.1° and 0.25°, it was observed that the fused product performed slightly worse at the 0.25° resolution. This could be attributed to the variations in the input products. Additionally, the representative of FluxNet sites at the 0.25° resolution decreased, leading to degraded statistical indicators.

Furthermore, when comparing the results of different fusion schemes, mainly focusing on the differences between CAMELE and Comb1 to Comb3 at the 0.25° resolution, CAMELE performed better regarding error metrics (RMSE, ubRMSE,

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

MAE). The differences in fitting metrics (KGE, R) were insignificant, indicating that the choice of fusion scheme primarily affected the errors of the fusion results. The relatively poor performance of other fusion schemes could be due to the lack of consideration for non-zero ECC. For example, GLEAMv3.7b and GLDAS2.2 employed the satellite data from MODIS, introducing random error homogeneity between the two datasets.

Moreover, when comparing the fusion effects with and without considering non-zero ECC conditions, it was evident that considering ECC information could effectively improve the performance of the fused product, which further demonstrated the reliability and advantages of the fusion method employed in this study.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

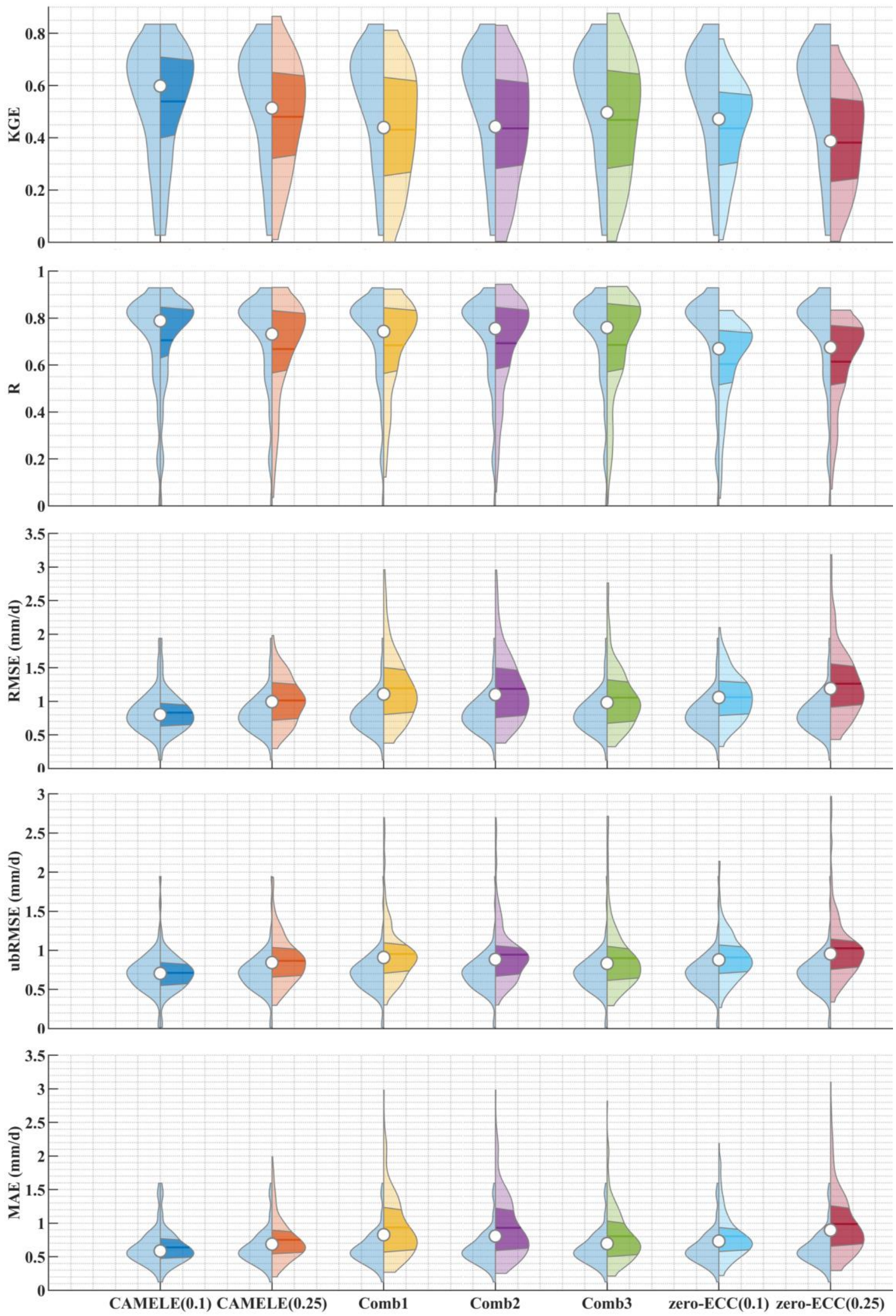

Figure 13 Violin plot comparing KGE, R, RMSE, ubRMSE and MAE of CAMELE with other fusion schemes. The right half of each violin plot represents the

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

distribution, with shaded areas indicating the box plot, where the horizontal line corresponds to the median and the dot represents the mean. The left half represents the results of CAMELE (0.1°) for comparison.

We further provided violin plots for different metrics, comparing the results of each fusion scheme to CAMELE (0.1°). The results indicated that the fusion schemes adopted were significantly superior to other schemes based on the distribution of results for all metrics across all sites. Regarding KGE and R, CAMELE's results were concentrated near 1 for most sites. Regarding RMSE, ubRMSE, and MAE, their results were concentrated below one mm/d. The results in the plots also suggested that CAMELE performed slightly worse at 0.25° compared to 0.1° but still outperformed the combination results of Comb1 to Comb3. Additionally, comparing CAMELE and the zero-ECC scheme in the plots further highlighted the importance of considering non-zero ECC conditions.

6. Conclusion

This study used a collocation-based approach for merging data considering non-zero conditions. We successfully generated a long-term daily CAMELE evapotranspiration (ET) product at resolutions of 0.1° (2000 to 2020) and 0.25° (1980 to 2022) by integrating five widely used datasets: ERA5L, FluxCom, PMLv2, GLDAS, and GLEAM. The key findings of our study are as follows:

1. Collocation analysis methods proved to be a reliable tool for evaluating ET products without a reference dataset. This approach shows promising potential for error characterization, especially in regions with limited data availability or on a global scale. The evaluation results provided valuable insights into the data merging process.
2. Compared to five input products, REA, and simple average, the CAMELE product performed well when evaluated against FluxNet flux tower data. Although it may not have been the best in all metrics, the overall performance was satisfactory.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

The result showed Pearson correlation coefficients (R) of 0.63 and 0.65, root-mean-square errors (RMSE) of 0.81 and 0.73 mm/d, unbiased root-mean-square errors (ubRMSE) of 1.20 and 1.04 mm/d, mean absolute errors (MAE) of 0.81 and 0.73 mm/d, and Kling-Gupta efficiency (KGE) of 0.60 and 0.65 on average over resolutions of 0.1° and 0.25°, respectively.

3. For different plant functional types (PFTs), the CAMELE product outperformed the five input products, REA, and simple average in most PFTs. Although FluxCom and PMLv2 performed slightly better than CAMELE at some PFT sites, considering that both utilized FluxNet sites for product calibration, it indirectly demonstrates the excellent performance of CAMELE.
4. When utilizing the error information derived from collocation analysis for merging, it is crucial to consider the potential presence of non-zero error compensation conditions (ECC). Comparing the merging schemes with and without considering non-zero ECC, it was found that considering ECC improves the accuracy of the merging process. Additionally, when using collocation analysis, it is necessary to identify which products may have ECC in advance, providing more effective support for data merging and obtaining more accurate product error information.

In conclusion, our proposed collocation-based data merging approach demonstrates the promising potential for merging ET products. The resulting CAMELE product exhibited good overall performance at site-based and regional scales, meeting the requirements for more detailed research. Furthermore, further evaluation of the merged product in specific regions is necessary to improve its accuracy. In future studies, dynamic weights could be computed by considering suitable merging periods for different products to enhance the quality of the merged product, and more sophisticated combination schemes could be explored to improve accuracy.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Author Contribution

C.L. conceived and designed the study, collected and analyzed the data, and wrote the manuscript. H.Y participated in the study design, provided intellectual insights, and reviewed the manuscript for important intellectual content. Z.L. and W.Y provided substantial input in the study design and data interpretation and revised the manuscript. Z.T., J.H., and S.L. guided the research process and critically reviewed the manuscript. All authors have read and approved the final version of the manuscript.

Competing interests

The authors declare that they have no conflict of interest.

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Data and code availability

The datasets utilized in this research can be accessed through the links provided in the Dataset Section. The CAMELE products are available via https://doi.org/10.5281/zenodo.5704736 (Li et al., 2023a). The data is distributed under a Creative Commons Attribution 4.0 License. Additionally, we provide example MATLAB codes to read and plot CAMELE data and employ IVD and EIVD methods to merge the inputs. Please refer to the latest version., 202306.

Reference

Baker, J. C. A., Garcia-Carreras, L., Gloor, M., Marsham, J. H., Buermann, W., da Rocha, H. R., Nobre, A. D., de Araujo, A. C., and Spracklen, D. V.: Evapotranspiration in the Amazon: spatial patterns, seasonality, and recent trends in observations, reanalysis, and climate models, Hydrology and Earth System Sciences, 25, 2279–2300, https://doi.org/10.5194/hess-25-2279-2021, 2021.

Barraza Bernadas, V., Grings, F., Restrepo-Coupe, N., and Huete, A.: Comparison of the performance of latent heat flux products over southern hemisphere forest ecosystems: estimating latent heat flux error structure using in situ measurements and the triple collocation method, International Journal of Remote Sensing, 39, 6300–6315, 2018.

Bates, J. M. and Granger, C. W.: The combination of forecasts, Journal of the Operational Research Society, 20, 451–468, 1969.

Chen, Z., Zhu, Z., Jiang, H., and Sun, S.: Estimating daily reference evapotranspiration based on limited meteorological data using deep learning and classical machine learning methods, Journal of Hydrology, 591, https://doi.org/10.1016/j.jhydrol.2020.125286, 2020.

De Lannoy, G. J., Houser, P. R., Verhoest, N. E., Pauwels, V. R., and Gish, T. J.: Upscaling of point soil moisture measurements to field averages at the OPE3 test site, Journal of Hydrology, 343, 1–11, 2007.

Deng, X., Zhu, L., Wang, H., Zhang, X., Tong, C., Li, S., and Wang, K.: Triple Collocation Analysis and In Situ Validation of the CYGNSS Soil Moisture Product, IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 16, 1883–1899, https://doi.org/10.1109/jstars.2023.3235111, 2023.

Dong, J. and Crow, W. T.: An Improved Triple Collocation Analysis Algorithm for Decomposing Autocorrelated and White Soil Moisture Retrieval Errors, Journal of Geophysical Research: Atmospheres, 122, 13,081-13,094, https://doi.org/10.1002/2017jd027387, 2017.

Dong, J., Crow, W. T., Duan, Z., Wei, L., and Lu, Y.: A double instrumental variable method for geophysical product error estimation, Remote Sensing of Environment, 225, 217–228, https://doi.org/10.1016/j.rse.2019.03.003, 2019.

Dong, J., Wei, L., Chen, X., Duan, Z., and Lu, Y.: An instrument variable based algorithm for estimating cross-correlated hydrological remote sensing errors, Journal of Hydrology, 581, 124413, https://doi.org/10.1016/j.jhydrol.2019.124413, 2020a.

Dong, J., Lei, F., and Wei, L.: Triple Collocation Based Multi-Source Precipitation Merging, Frontiers in Water, 2, https://doi.org/10.3389/frwa.2020.00001, 2020b.

Dong, J., Crow, W. T., Chen, X., Tangdamrongsub, N., Gao, M., Sun, S., Qiu, J., Wei, L., Gao, H., and Duan, Z.: Statistical uncertainty analysis-based precipitation merging (SUPER): A new framework for improved global precipitation estimation, Remote Sensing of Environment, 283, 113299, https://doi.org/10.1016/j.rse.2022.113299, 2022.

Dorigo, W. A., Scipal, K., Parinussa, R. M., Liu, Y. Y., Wagner, W., De Jeu, R. A., and Naeimi, V.: Error characterisation of global active and passive microwave soil moisture datasets, Hydrology and Earth System Sciences, 14, 2605–2616, 2010.

Draper, C., Reichle, R., de Jeu, R., Naeimi, V., Parinussa, R., and Wagner, W.: Estimating root mean square errors in remotely sensed soil moisture over continental scale domains, Remote Sensing of Environment, 137, 288–298, 2013.

Duan, Z., Duggan, E., Chen, C., Gao, H., Dong, J., and Liu, J.: Comparison of traditional method and triple collocation analysis for evaluation of multiple gridded precipitation products across Germany, Journal of Hydrometeorology, https://doi.org/10.1175/JHM-D-21-0049.1, 2021.

ECMWF, S. P.: In IFS documentation CY40R1 Part IV: Physical Processes, ECMWF: Reading, UK, 111–113, 2014.

Ershadi, A., McCabe, M. F., Evans, J. P., Chaney, N. W., and Wood, E. F.: Multi-site evaluation of terrestrial evaporation models using FLUXNET data, Agricultural and Forest Meteorology, 187, 46–61, https://doi.org/10.1016/j.agrformet.2013.11.008, 2014.

Feng, Y., Cui, N., Zhao, L., Hu, X., and Gong, D.: Comparison of ELM, GANN, WNN and empirical models for estimating reference evapotranspiration in humid region of Southwest China, Journal of Hydrology, 536, 376–383, https://doi.org/10.1016/j.jhydrol.2016.02.053, 2016.

Gan, R., Zhang, Y., Shi, H., Yang, Y., Eamus, D., Cheng, L., Chiew, F. H., and Yu, Q.: Use of satellite leaf area index estimating evapotranspiration and gross assimilation for Australian ecosystems, Ecohydrology, 11, e1974, 2018.

Gentine, P., Massmann, A., Lintner, B. R., Hamed Alemohammad, S., Fu, R., Green, J. K., Kennedy, D., and Vilà-Guerau de Arellano, J.: Land–atmosphere interactions in the tropics – a review, Hydrology and Earth System Sciences, 23, 4171–4197, https://doi.org/10.5194/hess-23-4171-2019, 2019.

Gruber, A.: Estimation of error structures in remotely sensed soil moisture data sets, Wien, 2016.

Gruber, A., Su, C., Crow, W. T., Zwieback, S., Dorigo, W., and Wagner, W.: Estimating error cross-correlations in soil moisture data sets using extended collocation analysis, Journal of Geophysical Research: Atmospheres, 121, 1208–1219, 2016a.

Gruber, A., Su, C.-H., Zwieback, S., Crow, W., Dorigo, W., and Wagner, W.: Recent advances in (soil moisture) triple collocation analysis, International Journal of Applied Earth Observation and Geoinformation, 45, 200–211, https://doi.org/10.1016/j.jag.2015.09.002, 2016b.

Gruber, A., Dorigo, W. A., Crow, W., and Wagner, W.: Triple Collocation-Based Merging of Satellite Soil Moisture Retrievals, IEEE Trans. Geosci. Remote Sensing, 55, 6780–6792, https://doi.org/10.1109/TGRS.2017.2734070, 2017.

Gruber, A., Scanlon, T., van der Schalie, R., Wagner, W., and Dorigo, W.: Evolution of the ESA CCI Soil Moisture climate data records and their underlying merging methodology, Earth System Science Data, 11, 717–739, https://doi.org/10.5194/essd-11-717-2019, 2019.

Gruber, A., De Lannoy, G., Albergel, C., Al-Yaari, A., Brocca, L., Calvet, J. C., Colliander, A., Cosh, M., Crow, W., Dorigo, W., Draper, C., Hirschi, M., Kerr, Y., Konings, A., Lahoz, W., McColl, K., Montzka, C., Muñoz-Sabater, J., Peng, J., Reichle, R., Richaume, P., Rüdiger, C., Scanlon, T., van der Schalie, R., Wigneron, J. P., and Wagner, W.: Validation practices for satellite soil moisture retrievals: What are (the) errors?, Remote Sensing of Environment, 244, 111806, https://doi.org/10.1016/j.rse.2020.111806, 2020.

Gupta, H. V., Kling, H., Yilmaz, K. K., and Martinez, G. F.: Decomposition of the mean squared error and NSE performance criteria: Implications for improving hydrological modelling, Journal of hydrology, 377, 80–91, 2009.

Han, S. and Tian, F.: A review of the complementary principle of evaporation: from the original linear relationship to generalized nonlinear functions, Hydrology and Earth System Sciences, 24, 2269–2285, https://doi.org/10.5194/hess-24-2269-2020, 2020.

Hao, Y., Baik, J., and Choi, M.: Combining generalized complementary relationship models with the Bayesian Model Averaging method to estimate actual evapotranspiration over China, Agricultural and Forest Meteorology, 279, 107759, https://doi.org/10.1016/j.agrformet.2019.107759, 2019.

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D., Simmons, A., Soci, C., Abdalla, S., Abellan, X., Balsamo, G., Bechtold, P., Biavati, G., Bidlot, J., Bonavita, M., Chiara, G., Dahlgren, P., Dee, D., Diamantakis, M., Dragani, R., Flemming, J., Forbes, R., Fuentes, M., Geer, A., Haimberger, L., Healy, S., Hogan, R. J., Hólm, E., Janisková, M., Keeley, S., Laloyaux, P., Lopez, P., Lupu, C., Radnoti, G., Rosnay, P., Rozum, I., Vamborg, F., Villaume, S., and Thépaut, J.: The ERA5 global reanalysis, Quarterly Journal of the Royal Meteorological Society, 146, 1999–2049, https://doi.org/10.1002/qj.3803, 2020.

Hoareau, N., Portabella, M., Lin, W., Ballabrera-Poy, J., and Turiel, A.: Error characterization of sea surface salinity products using triple collocation analysis, IEEE Transactions on Geoscience and Remote Sensing, 56, 5160–5168, 2018.

Jia, Y., Li, C., Yang, H., Yang, W., and Liu, Z.: Assessments of three evapotranspiration products over China using extended triple collocation and water balance methods, Journal of Hydrology, 614, 128594, 2022.

Jiang, C. and Ryu, Y.: Multi-scale evaluation of global gross primary productivity and evapotranspiration products derived from Breathing Earth System Simulator (BESS), Remote Sensing of Environment, 186, 528–547, 2016.

Jiang, C., Ryu, Y., Fang, H., Myneni, R., Claverie, M., and Zhu, Z.: Inconsistencies of interannual variability and trends in long-term satellite leaf area index products, Glob Chang Biol, 23, 4133–4146, https://doi.org/10.1111/gcb.13787, 2017.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Jiang, C., Guan, K., Pan, M., Ryu, Y., Peng, B., and Wang, S.: BESS-STAIR: a framework to estimate daily, 30 m, and all-weather crop evapotranspiration using multi-source satellite data for the US Corn Belt, Hydrology and Earth System Sciences, 24, 1251–1273, https://doi.org/10.5194/hess-24-1251-2020, 2020.

Jung, M., Koirala, S., Weber, U., Ichii, K., Gans, F., Camps-Valls, G., Papale, D., Schwalm, C., Tramontana, G., and Reichstein, M.: The FLUXCOM ensemble of global land-atmosphere energy fluxes, Sci Data, 6, 74, https://doi.org/10.1038/s41597-019-0076-8, 2019.

Khan, M. S., Liaqat, U. W., Baik, J., and Choi, M.: Stand-alone uncertainty characterization of GLEAM, GLDAS and MOD16 evapotranspiration products using an extended triple collocation approach, Agricultural and Forest Meteorology, 252, 256–268, https://doi.org/10.1016/j.agrformet.2018.01.022, 2018.

Kim, S., Pham, H. T., Liu, Y. Y., Marshall, L., and Sharma, A.: Improving the Combination of Satellite Soil Moisture Data Sets by Considering Error Cross Correlation: A Comparison Between Triple Collocation (TC) and Extended Double Instrumental Variable (EIVD) Alternatives, IEEE Transactions on Geoscience and Remote Sensing, 59, 7285–7295, https://doi.org/10.1109/tgrs.2020.3032418, 2021a.

Kim, S., Sharma, A., Liu, Y. Y., and Young, S. I.: Rethinking satellite data merging: from averaging to SNR optimization, IEEE Transactions on Geoscience and Remote Sensing, 60, 1–15, 2021b.

Knoben, W. J. M., Freer, J. E., and Woods, R. A.: Technical note: Inherent benchmark or not? Comparing Nash–Sutcliffe and Kling–Gupta efficiency scores, Hydrology and Earth System Sciences, 23, 4323–4331, https://doi.org/10.5194/hess-23-4323-2019, 2019.

Koster, R. D., Liu, Q., Reichle, R. H., and Huffman, G. J.: Improved Estimates of Pentad Precipitation Through the Merging of Independent Precipitation Data Sets, Water Resources Research, 57, https://doi.org/10.1029/2021wr030330, 2021.

Leuning, R., Zhang, Y., Rajaud, A., Cleugh, H., and Tu, K.: A simple surface conductance model to estimate regional evaporation using MODIS leaf area index and the Penman-Monteith equation, Water Resources Research, 44, 2008.

Leuning, R., Zhang, Y. Q., Rajaud, A., Cleugh, H., and Tu, K.: Correction to "A simple surface conductance model to estimate regional evaporation using MODIS leaf area index and the Penman-Monteith equation," Water Resources Research, 45, https://doi.org/10.1029/2008wr007631, 2009.

Li, B., Rodell, M., Kumar, S., Beaudoing, H. K., Getirana, A., Zaitchik, B. F., Goncalves, L. G., Cossetin, C., Bhanja, S., Mukherjee, A., Tian, S., Tangdamrongsub, N., Long, D., Nanteza, J., Lee, J., Policelli, F., Goni, I. B., Daira, D., Bila, M., Lannoy, G., Mocko, D., Steele-Dunne, S. C., Save, H., and Bettadpur, S.: Global GRACE Data Assimilation for Groundwater and Drought Monitoring: Advances and Challenges, Water Resour. Res., 55, 7564–7586, https://doi.org/10.1029/2018WR024618, 2019a.

Li, C., Tang, G., and Hong, Y.: Cross-evaluation of ground-based, multi-satellite and reanalysis precipitation products: Applicability of the Triple Collocation method

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

across Mainland China, Journal of Hydrology, 562, 71–83, https://doi.org/10.1016/j.jhydrol.2018.04.039, 2018.

Li, C., Yang, H., Yang, W., Liu, Z., Jia, Y., Li, S., and Yang, D.: Error Characterization of Global Land Evapotranspiration Products: Collocation-based approach, Journal of Hydrology, 128102, 2022.

Li, C., Liu, Z., Yang, W., Tu, Z., Han, J., Sien, L., and Hanbo, Y.: CAMELE: Collocation-Analyzed Multi-source Ensembled Land Evapotranspiration Data, , https://doi.org/10.5281/zenodo.8047038, 2023a.

Li, X., Gentine, P., Lin, C., Zhou, S., Sun, Z., Zheng, Y., Liu, J., and Zheng, C.: A simple and objective method to partition evapotranspiration into transpiration and evaporation at eddy-covariance sites, Agricultural and Forest Meteorology, 265, 171–182, https://doi.org/10.1016/j.agrformet.2018.11.017, 2019b.

Li, X., Zhang, W., Vermeulen, A., Dong, J., and Duan, Z.: Triple collocation-based merging of multi-source gridded evapotranspiration data in the Nordic Region, Agricultural and Forest Meteorology, 335, 109451, https://doi.org/10.1016/j.agrformet.2023.109451, 2023b.

Lian, X., Piao, S., Huntingford, C., Li, Y., Zeng, Z., Wang, X., Ciais, P., McVicar, T. R., Peng, S., Ottlé, C., Yang, H., Yang, Y., Zhang, Y., and Wang, T.: Partitioning global land evapotranspiration using CMIP5 models constrained by observations, Nature Clim Change, 8, 640–646, https://doi.org/10.1038/s41558-018-0207-9, 2018.

Liang, S., Cheng, J., Jia, K., Jiang, B., Liu, Q., Xiao, Z., Yao, Y., Yuan, W., Zhang, X., Zhao, X., and Zhou, J.: The Global Land Surface Satellite (GLASS) Product Suite, Bulletin of the American Meteorological Society, 102, E323–E337, https://doi.org/10.1175/bams-d-18-0341.1, 2021.

Lin, C., Gentine, P., Huang, Y., Guan, K., Kimm, H., and Zhou, S.: Diel ecosystem conductance response to vapor pressure deficit is suboptimal and independent of soil moisture, Agricultural and Forest Meteorology, 250, 24–34, 2018.

Loveland, T. R., Zhu, Z., Ohlen, D. O., Brown, J. F., Reed, B. C., and Yang, L.: An analysis of the IGBP global land-cover characterization process, Photogrammetric engineering and remote sensing, 65, 1021–1032, 1999.

Lu, J., Wang, G., Chen, T., Li, S., Hagan, D. F. T., Kattel, G., Peng, J., Jiang, T., and Su, B.: A harmonized global land evaporation dataset from model-based products covering 1980–2017, Earth System Science Data, 13, 5879–5898, https://doi.org/10.5194/essd-13-5879-2021, 2021.

Ma, N., Szilagyi, J., and Jozsa, J.: Benchmarking large-scale evapotranspiration estimates: A perspective from a calibration-free complementary relationship approach and FLUXCOM, Journal of Hydrology, 590, https://doi.org/10.1016/j.jhydrol.2020.125221, 2020.

Majozi, N. P., Mannaerts, C. M., Ramoelo, A., Mathieu, R., Nickless, A., and Verhoef, W.: Analysing surface energy balance closure and partitioning over a semi-arid savanna FLUXNET site in Skukuza, Kruger National Park, South Africa, Hydrology and Earth System Sciences, 21, 3401–3415, https://doi.org/10.5194/hess-21-3401-

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

2017, 2017.

Martens, B., Miralles, D. G., Lievens, H., van der Schalie, R., de Jeu, R. A. M., Fernández-Prieto, D., Beck, H. E., Dorigo, W. A., and Verhoest, N. E. C.: GLEAM v3: satellite-based land evaporation and root-zone soil moisture, Geoscientific Model Development, 10, 1903–1925, https://doi.org/10.5194/gmd-10-1903-2017, 2017.

McColl, K. A., Vogelzang, J., Konings, A. G., Entekhabi, D., Piles, M., and Stoffelen, A.: Extended triple collocation: Estimating errors and correlation coefficients with respect to an unknown target, Geophysical Research Letters, 41, 6229–6236, https://doi.org/10.1002/2014gl061322, 2014.

Ming, W., Ji, X., Zhang, M., Li, Y., Liu, C., Wang, Y., and Li, J.: A Hybrid Triple Collocation-Deep Learning Approach for Improving Soil Moisture Estimation from Satellite and Model-Based Data, Remote Sensing, 14, https://doi.org/10.3390/rs14071744, 2022.

Miralles, D., De Jeu, R., Gash, J., Holmes, T., and Dolman, A.: Magnitude and variability of land evaporation and its components at the global scale, Hydrology and Earth System Sciences, 15, 967–981, 2011.

Miralles, D. G., Gentine, P., Seneviratne, S. I., and Teuling, A. J.: Land-atmospheric feedbacks during droughts and heatwaves: state of the science and current challenges, Ann N Y Acad Sci, 1436, 19–35, https://doi.org/10.1111/nyas.13912, 2019.

Mu, Q., Zhao, M., and Running, S. W.: Improvements to a MODIS global terrestrial evapotranspiration algorithm, Remote sensing of environment, 115, 1781–1800, 2011.

Muñoz-Sabater, J., Dutra, E., Agustí-Panareda, A., Albergel, C., Arduini, G., Balsamo, G., Boussetta, S., Choulga, M., Harrigan, S., Hersbach, H., Martens, B., Miralles, D. G., Piles, M., Rodríguez-Fernández, N. J., Zsoter, E., Buontempo, C., and Thépaut, J.-N.: ERA5-Land: a state-of-the-art global reanalysis dataset for land applications, Earth Syst. Sci. Data, 13, 4349–4383, https://doi.org/10.5194/essd-13-4349-2021, 2021.

Pan, S., Pan, N., Tian, H., Friedlingstein, P., Sitch, S., Shi, H., Arora, V. K., Haverd, V., Jain, A. K., Kato, E., Lienert, S., Lombardozzi, D., Nabel, J. E. M. S., Ottlé, C., Poulter, B., Zaehle, S., and Running, S. W.: Evaluation of global terrestrial evapotranspiration using state-of-the-art approaches in remote sensing, machine learning and land surface modeling, Hydrology and Earth System Sciences, 24, 1485–1509, https://doi.org/10.5194/hess-24-1485-2020, 2020.

Park, J., Baik, J., and Choi, M.: Triple collocation-based multi-source evaporation and transpiration merging, Agricultural and Forest Meteorology, 331, 109353, 2023.

Pastorello, G., Trotta, C., Canfora, E., Chu, H., Christianson, D., Cheah, Y. W., Poindexter, C., Chen, J., Elbashandy, A., Humphrey, M., Isaac, P., Polidori, D., Reichstein, M., Ribeca, A., van Ingen, C., Vuichard, N., Zhang, L., Amiro, B., Ammann, C., Arain, M. A., Ardo, J., Arkebauer, T., Arndt, S. K., Arriga, N., Aubinet, M., Aurela, M., Baldocchi, D., Barr, A., Beamesderfer, E., Marchesini, L. B., Bergeron, O., Beringer, J., Bernhofer, C., Berveiller, D., Billesbach, D., Black, T. A., Blanken, P. D., Bohrer, G., Boike, J., Bolstad, P. V., Bonal, D., Bonnefond, J. M., Bowling, D. R., Bracho, R., Brodeur, J., Brummer, C., Buchmann, N., Burban, B., Burns, S. P., Buysse, P., Cale, P., Cavagna, M., Cellier, P., Chen, S., Chini, I., Christensen, T. R., Cleverly, J., Collalti, A., Consalvo, C., Cook, B. D., Cook, D., Coursolle, C., Cremonese, E., Curtis, P. S., D'Andrea, E., da Rocha, H., Dai, X., Davis, K. J., Cinti, B., Grandcourt, A., Ligne, A., De Oliveira, R. C., Delpierre, N., Desai, A. R., Di Bella, C. M., Tommasi, P. D., Dolman, H., Domingo, F., Dong, G., Dore, S., Duce, P., Dufrene, E., Dunn, A., Dusek, J., Eamus, D., Eichelmann, U., ElKhidir, H. A. M., Eugster, W., Ewenz, C. M., Ewers, B., Famulari, D., Fares, S., Feigenwinter, I., Feitz, A., Fensholt, R., Filippa, G., Fischer, M., Frank, J., Galvagno, M., et al.: The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data, Sci Data, 7, 225, https://doi.org/10.1038/s41597-020-0534-3, 2020.

Priestley, C. H. B. and TAYLOR, R. J.: On the assessment of surface heat flux and evaporation using large-scale parameters, Monthly weather review, 100, 81–92, 1972.

Restrepo-Coupe, N., Albert, L. P., Longo, M., Baker, I., Levine, N. M., Mercado, L. M., da Araujo, A. C., Christoffersen, B. O., Costa, M. H., Fitzjarrald, D. R., Galbraith, D., Imbuzeiro, H., Malhi, Y., von Randow, C., Zeng, X., Moorcroft, P., and Saleska, S. R.: Understanding water and energy fluxes in the Amazonia: Lessons from an observation-model intercomparison, Glob Chang Biol, 27, 1802–1819, https://doi.org/10.1111/gcb.15555, 2021.

Ribal, A. and Young, I. R.: Global Calibration and Error Estimation of Altimeter, Scatterometer, and Radiometer Wind Speed Using Triple Collocation, Remote Sensing, 12, https://doi.org/10.3390/rs12121997, 2020.

Rodell, M., Houser, P., Jambor, U., Gottschalck, J., Mitchell, K., Meng, C.-J., Arsenault, K., Cosgrove, B., Radakovich, J., and Bosilovich, M.: The global land data assimilation system, Bulletin of the American Meteorological society, 85, 381–394, 2004.

Sheffield, J., Goteti, G., and Wood, E. F.: Development of a 50-Year High-Resolution Global Dataset of Meteorological Forcings for Land Surface Modeling, Journal of Climate, 19, 3088–3111, https://doi.org/10.1175/JCLI3790.1, 2006.

Stoffelen, A.: Toward the true near-surface wind speed: Error modeling and calibration using triple collocation, Journal of Geophysical Research: Oceans, 103, 7755–7766, https://doi.org/10.1029/97jc03180, 1998.

Su, C.-H. and Ryu, D.: Multi-scale analysis of bias correction of soil moisture, Hydrology and Earth System Sciences, 19, 17–31, 2015.

Su, C.-H., Ryu, D., Crow, W. T., and Western, A. W.: Beyond triple collocation: Applications to soil moisture monitoring, Journal of Geophysical Research: Atmospheres, 119, 6419–6439, https://doi.org/10.1002/2013jd021043, 2014.

Sun, J., McColl, K. A., Wang, Y., Rigden, A. J., Lu, H., Yang, K., Li, Y., and Santanello, J. A.: Global evaluation of terrestrial near-surface air temperature and specific humidity retrievals from the Atmospheric Infrared Sounder (AIRS), Remote Sensing of Environment, 252, https://doi.org/10.1016/j.rse.2020.112146, 2021.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Towner, J., Cloke, H. L., Zsoter, E., Flamig, Z., Hoch, J. M., Bazo, J., Coughlan de Perez, E., and Stephens, E. M.: Assessing the performance of global hydrological models for capturing peak river flows in the Amazon basin, Hydrology and Earth System Sciences, 23, 3057–3080, https://doi.org/10.5194/hess-23-3057-2019, 2019.

Tsamalis, C.: Clarifications on the equations and the sample number in triple collocation analysis using SST observations, Remote Sensing of Environment, 272, https://doi.org/10.1016/j.rse.2022.112936, 2022.

Twine, T. E., Kustas, W., Norman, J., Cook, D., Houser, Pr., Meyers, T., Prueger, J., Starks, P., and Wesely, M.: Correcting eddy-covariance flux underestimates over a grassland, Agricultural and forest meteorology, 103, 279–300, 2000.

Vogelzang, J., Stoffelen, A., and Verhoef, A.: The Effect of Error Non-Orthogonality on Triple Collocation Analyses, Remote Sensing, 14, 4268, 2022.

Wu, K., Ryu, D., Nie, L., and Shu, H.: Time-variant error characterization of SMAP and ASCAT soil moisture using Triple Collocation Analysis, Remote Sensing of Environment, 256, https://doi.org/10.1016/j.rse.2021.112324, 2021.

Yilmaz, M. T. and Crow, W. T.: The optimality of potential rescaling approaches in land data assimilation, Journal of Hydrometeorology, 14, 650–660, 2013.

Yilmaz, M. T. and Crow, W. T.: Evaluation of Assumptions in Soil Moisture Triple Collocation Analysis, Journal of Hydrometeorology, 15, 1293–1302, https://doi.org/10.1175/JHM-D-13-0158.1, 2014.

Yilmaz, M. T., Crow, W. T., Anderson, M. C., and Hain, C.: An objective methodology for merging satellite- and model-based soil moisture products, Water Resources Research, 48, n/a-n/a, https://doi.org/10.1029/2011wr011682, 2012.

Yin, G. and Park, J.: The use of triple collocation approach to merge satellite- and model-based terrestrial water storage for flood potential analysis, Journal of Hydrology, 603, https://doi.org/10.1016/j.jhydrol.2021.127197, 2021.

Yin, L., Tao, F., Chen, Y., Liu, F., and Hu, J.: Improving terrestrial evapotranspiration estimation across China during 2000–2018 with machine learning methods, Journal of Hydrology, 600, https://doi.org/10.1016/j.jhydrol.2021.126538, 2021.

Zhang, Y., Leuning, R., Hutley, L. B., Beringer, J., McHugh, I., and Walker, J. P.: Using long-term water balances to parameterize surface conductances and calculate evaporation at 0.05 spatial resolution, Water Resources Research, 46, 2010.

Zhang, Y., Kong, D., Gan, R., Chiew, F. H. S., McVicar, T. R., Zhang, Q., and Yang, Y.: Coupled estimation of 500 m and 8-day resolution global evapotranspiration and gross primary production in 2002–2017, Remote Sensing of Environment, 222, 165–182, https://doi.org/10.1016/j.rse.2018.12.031, 2019.

Zhao, M., Liu, Y., and Konings, A. G.: Evapotranspiration frequently increases during droughts, Nature Climate Change, 1–7, 2022.

Zhu, G., Li, X., Zhang, K., Ding, Z., Han, T., Ma, J., Huang, C., He, J., and Ma, T.: Multi-model ensemble prediction of terrestrial evapotranspiration across north China using Bayesian model averaging, Hydrological Processes, 30, 2861–2879, https://doi.org/10.1002/hyp.10832, 2016.

https://doi.org/10.5194/essd-2023-226
Preprint. Discussion started: 17 July 2023

Open Access Earth System Science Data Discussions

Zwieback, S., Su, C.-H., Gruber, A., Dorigo, W. A., and Wagner, W.: The impact of quadratic nonlinear relations between soil moisture products on uncertainty estimates from triple collocation analysis and two quadratic extensions, Journal of Hydrometeorology, 17, 1725–1743, 2016.