EVALUATION OF THE HYDROCLIMATOLOGICAL VARIABLES DERIVED FROM GLDAS-1, GLDAS-2 AND MERRA-2 IN MEXICO

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ABSTRACT

In this study, we evaluate the accuracy of three datasets comprising products from global land data assimilation systems (GLDAS-1, GLDAS-2) and reanalysis (MERRA-2). Results from the three products are compared against in-situ observations from the Mexican network of streamflow gauges and climatic stations. For clarity, quality of the *in-situ* information is revised through the revision of homogeneity of ground observations. The evaluation of hydroclimatic variables was carried out for both, absolute values and its variability. The latter was computed using standardized indexes. Results show in general, that the absolute precipitation derived from MERRA-2 (land surface diagnostics) product supply the best fit with the ground observations. However, the reported skill of the GLDAS-2 with regards to the precipitation was nearly as good as the one of MERRA-2. On the other hand, comparisons of total runoff estimated by the three products against *in-situ* measurements, showed a significant decrease in skill. In summary, this work will show the ability of global free sources of information to derive adequate hydroclimatic variables needed in the simulation of hydrological processes and water balance studies. This is especially important in developing countries where data may be scarce.

Keywords: Datasets evaluation; GLDAS; Hydroclimatological variables; MERRA; Mexico

1 INTRODUCTION

In the last decades, the rapid growth of the world population makes necessary the constant search for new water sources. Unfortunately, in many regions of the world, especially in developing countries, the density of streamflow gauges and climatic stations is limited. This situation hinders the utilization of this data for large scale analysis, *e. g.* for drought monitoring. In contrast, data from remote sensors and land surface models has been show a great advance in the last twenty years. Indeed, the combination of both data sets (*in situ* and remotely sensed) in addition to data assimilation techniques, offers an attractive alternative to determine changes in the water cycle at national and global scales. Datasets derived from these products has the additional advantage of pass through a process of validation and quality control before being published which reduces the inconsistencies in its data (Damberg and AghaKouchak, 2014).

Several studies have demonstrated the applicability of these sources of information of variables such as precipitation (e. g., Sorooshian et al., 2011), soil moisture (*e. g.*, Cashion *et al.*, 2005; Entekhabi *et al.*, 2004) and evapotranspiration (*e. g.*, Allen *et al.*, 2007; Anderson *et al*., 2011). In Mexico, recent applications of these source can be found in the estimation of the precipitation associated to tropical cyclones (Breña-Naranjo *et al.*, 2015), pan evaporation (Breña-Naranjo *et al.*, 2016) and the analysis of droughts through the Standardized Precipitation Index (de Jesús *et al*., 2016). It is anticipated that the use of remote sense derived data for models calibration, forecast assessment and improvements in short-term forecasts will grow in the future (Beven, 2012).

Disregarding the technique of data collection, verifying the quality of time series is of critical importance in all numerical analysis that uses this type of timely records. It is due to that the accuracy of the results of every computation depends in a great portion on the degree in which the input data reflects the variable it represents. Having that in mind, an assessment of the hydrometeorological variables of different products of data assimilation has been carried out.

2 METHODOLOGY

The precision of hydrometeorological fields from three different global datasets was evaluated against ground-based observations in the territory of Mexico. The datasets evaluated were: the Global Land Data Assimilation System, version 1 and 2 (GLDAS-1 and GLDAS-2; Noah model); and the Modern-Era Retrospectiva Analysis for Research and Applications, version 2 (MERRA-2) (their main characteristics are shown in **Table 1**). More than 1 300 electronic files of hydrological and atmospheric fields were compiled from the web site of the Goddard Earth Sciences Data and Information Services Center (GES DISC; http://disc.sci.gsfc.nasa.gov).

It was evaluated the efficiency of the products to represent the absolute magnitude of precipitation and runoff measured by ground observations. Besides, the variability of the mentioned variables was assessed by mean of the standardized indexes of precipitation and runoff (SPI and SRI), following the procedure proposed by McKee *et al.* (1993), commonly used in drought analysis.

Table 1. Features of analyzed datasets.

Name	Temporal coverage	Spatial resolution	Temporal resolution
GLDAS_NOAH10_M (v1; Noah model)	1979-01-01 to present	1.00 × 1.00°	1 month
GLDAS_NOAH10_M (v2; Noah model)	1948-01-01 to present	1.00 × 1.00°	1 month
MERRA-2 tavgM_2d_lnd_Nx	1980-01-01 to present	0.50 × 0.625°	1 month

2.1 Data sources

2.1.1 Global Land Data Assimilation System (GLDAS)

The GLDAS (Rodell et al., 2004) products were developed by the NASA's Goddard Space Flight Center (GSFC). It consists in datasets of fields of land surface states and fluxes generated by diverse land surface models (LSM) forced with satellite- and ground-based observational data products using data assimilation techniques. The LSM driven by GLDAS are Mosaic (Koster and Suarez, 1996), Noah (Chen *et al.*, 1996), Community Land Model (CLM; Dai *et al.*, 2003) and the Variable Infiltration Capacity model (VIC; Liang *et al.*, 1994).

Version 1 of this product (GLDAS-1) was discontinued on December 2016 and has been sustitued by Version 2 (GLDAS-2), launched in 2012 which solves some issues reported in the datasets of the first version. These issues include a problem of granularity of adjacent grid cell maxima and minima precipitation for 2001 onward when the disaggregated CPC's CMAP precipitation fields are used, which affects all the results of all LSM. Also, GLDAS-2 solves unnatural trends found in GLDAS-1 due to multiple switches of data sources over it records by using long term climatology from the Global Meteorological Forcing Dataset from Princeton University and observational based forcing. Datasets are available in a 3-hourly and monthly time resolution starting on January of 1948 to present with spatial resolutions of 0.25 and 1.00°.

2.1.2 Modern-Era Retrospective Analysis for Research and Applications (MERRA)

MERRA (Rienecker *et al.*, 2011) uses the Goddard Earth Observing System, version 5 (GEOS-5), and its data assimilation system (DAS) to generate an atmospheric reanalysis, which combines temporally and spatially irregular observations to generate gridded meteorological datasets. It's native spatial resolution its of 1/2° of latitude by 2/3° longitude.

The second version of MERRA (MERRA-2), published in 2014, can use the newer microwave sounders and hyperspectral infrared radiance instruments, among other instruments (Ostrenga, 2015). This study evaluates the subproduct MERRA-Land 2, which consists exclusively in the land component of MERRA-2 (*i. e.*, the application of MERRA-2 uncoupled of the atmospheric model to generate fields of terrestrial hydrology). Datasets of this product are available from January 1980 to present with an hourly and monthly temporal resolution.

2.1.3 National Climate Database

The National Climate Database contains historic records from more than 6 000 climatologic stations located over all the territory of Mexico, from which more than 3 000 are currently operative. It is public and available for consult and download through the CLICOM System platform (http://clicom-mex.cicese.mx), supported by the Ensenada Center for Scientific Research and Higher Education (CICESE). The stations record in a daily basis at 8:00 a. m. (local time) the maximum and minimum temperature in the last 24 hours, and the accumulated values of precipitation and evaporation (Miranda Alonso *et al.*, 2006).

2.1.4 National Database of Surface Water

The National Database of Surface Water (BANDAS), supported and updated by the Mexican Institute of Water Technology (IMTA), integrate more than 2 200 stream gauges in natural streams and irrigation channels. The records compile information of daily, monthly and annual mean flow, sediment flow and water level. Datasets are updated about every three years (Solís-Alvarado *et al.*, 2015) and are available in ftp://ftp.conagua.gob.mx/Bandas.

2.1.5 Set of stations and gauges used

The criteria adopted to select the climatological stations used in this evaluation was based in two main aspects: (i) the extent of the record of precipitation is equal or greater than 30 years, and (ii) they span in all the country to include all the clime types in the territory (*i. e.*, dry, temperate and tropical).

In contrast to the selection of climatologic stations, criteria to choose stream gauges for the evaluation carried out here was stricter because this variable is much more sensible to the anthropogenic influence, such as changes in land use or vegetal cover in the gauged basin or because of the construction of controls, like dams, water abstraction, etc. Therefore, there were selected stream gauges with records that accomplish following criteria: (i) extent of record equal or greater than 30 years; (ii) its time series is homogeneous; and (iii) its time series is independent.

Homogeneity was checked by mean of three statistical tests: the von Neumann Ratio test (von Neumann, 1941), the Bayesian test (Chernoff and Zacks, 1964) and the Cumulative Deviation test (Buishand, 1982). If two out of the three tests indicated no homogeneity of a given time series, it was excluded from the analysis. Moreover, independency (randomness) of time series was tested using the technique of autocorrelation (Machiwal and Jha, 2012).

The set of gauge station that formed part of the evaluation carried out here consists in five climatological stations and five stream gauges. Tables 2-3 and Figure 1 show the location and identification fields of all the stations.

Table 2. Climatological stations used to evaluate the precipitation field of GLDAS-2 and MERRA-2.

ID	Name	Basin	Lat [°]	Lon [°]	Alt [m]
C-01004	Cañada Honda	Río Verde Grande	22.0008	–102.1989	1 925
C-02033	Mexicali	Bacanora-Mejorada	32.6633	–115.4678	3
C-06003	Callejones	Río Coahuayana	18.8156	–103.6342	30
C-07168	Tonalá	Mar Muerto	16.0842	–93.7439	55
C-30068	Los Ídolos	Río Jamapa y otros	19.4083	–96.5164	100

Table 3. Stream gauges used to evaluate the runoff field of GLDAS-2 and MERRA-2.

ID	Name	Basin	Lat [°]	Lon [°]
S-09067	San Bernardo	Río Mayo	27.4124	–108.8833
S-12428	Bolaños	Río Bolaños	21.8278	–103.7851
S-24301	Tepehuaje	Río San Juan	25.4961	–99.7675
S-29006	Jesús Carranza II	Río Jaltepec	17.3915	–95.0529
S-36039	La Flor	Río Aguanaval	25.0923	–103.3248

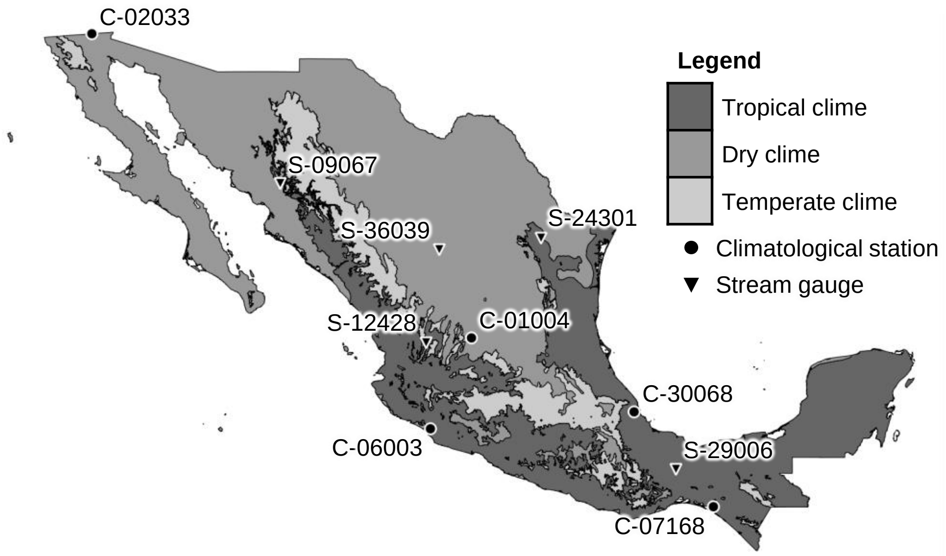

Figure 1. Location of the stations and gauges used in the analysis.

2.2 Efficiency criteria used

The mathematical measures conducted to assess the perform of the evaluated products were the coefficient of determination (r^2), the Nash-Sutcliffe efficiency (E) and the index of agreement (d). The coefficient of determination estimates the combined dispersion against the single dispersion of the observed and predicted series (Krause *et al.*, 2005). It is computed by the following expression:

$$r^2 = \left(\frac{\sum_{i=1}^{n}(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^{n}(O_i - \bar{O})^2}\sqrt{(P_i - \bar{P})^2}} \right)^2 \quad [1]$$

where O are the ground-based observations and P are the values from the assessed data assimilation products. The values of r^2 range from 0 to 1. A value of 0 means that there is no correlation at all, while a value of 1 means that the dispersion of the prediction is equal to that of the observation. Typically, values greater than 0.5 are considered acceptable (Moriasi *et al.*, 2007).

The Nash-Sutcliffe efficiency is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance (Nash and Sutcliffe, 1970) computed using the following equation:

$$E = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad [2]$$

where O are the ground-based observations and P are the values from the assessed data assimilation products. E ranges between $-\infty$ and 1.0, with $E = 1$ being the optimal value. Values between 0 and 1 are generally considered as acceptable levels of performance (Krause *et al.*, 2005; Moriasi *et al.*, 2007).

Finally, the index of agreement (d) is a standardized measure of the degree of model prediction error. It is defined by the following expression:

$$d = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad [3]$$

where O are the ground-based observations and P are the values from the assessed data assimilation products. The values d range between 0 and 1, where 0 means no correlation at all and 1 means perfect fit.

2.3 Time series variability

The efficiency of the products to represent the variability of precipitation and runoff was evaluated based on the standardized indexes, widely used in drought analysis. This approach assesses the difference between a given value and the long term mean of its variable, divided by the standard deviation. The Standardized Precipitation Index (SPI) was first proposed by McKee *et al.* (1993). After that, other authors have been applied its methodology for other variables. That is the case of the Standardized Runoff Index (SRI; Shukla and Wood, 2008), used in this analysis to evaluate the runoff variable. In the present work, it has been applied the modification in the computation of standardized indexes proposed by Farahmand and AghaKouchak (2015), which consists in a non-parametric computation, defining the frequency of the values in the time series by mean of a plotting formula with the following form (Gringorten, 1963):

$$\mathrm{p}(x_i) = \frac{i - 0.44}{n + 0.12} \quad [4]$$

where $p(x_i)$ is the probability correspondant to the ith of n ordered observations. Once obtained the value of p, the standardized index (SI) is defined as (Farahmand and AghaKouchak, 2015):

$$\mathrm{SI} = \phi^{-1}(p) \quad [5]$$

where ϕ is the standard normal distribution function and p is the probability derived from Equation [4].

The SI is computed for a time scale (averaging moving window) that can be of $ts = 1, 3, 6, 12$ months, etc. In each case, the dataset for the computation of the index is the entire time series of a given variable, and each element of the dataset is the sum of the ts previous months.

Results of the standardized indexes of the variables derived from the products were compared to those obtained from the ground observations. In all cases, it has been used the SI with time scale of one month (*i. e.*, SPI_{01} and SRI_{01}).

3 RESULTS

3.1 Precipitation data

The site in which precipitation magnitude is better reproduced is the station C-07168 (Tonalá; with $r^2 = 0.89$, $E = 0.84$ and $d = 0.95$), followed by the station C-06003 (Callejones; with $r^2 = 0.84$, $E = 0.81$ and $d = 0.94$), both in the coasts of the Pacific Ocean, in the southern territory of Mexico. In both cases, the most accurate product is MERRA-2. In contrast, the site with worst fit measures is the station C-02033 (Mexicali; with best measures of $r^2 = 0.41$, $E = 0.35$ and $d = 0.78$), where the three products evaluated show dispersions and efficiencies below the acceptable range of values. **Table 4** and **Figure 2** show the results of the evaluation of the precipitation magnitude derived from the data assimilation products.

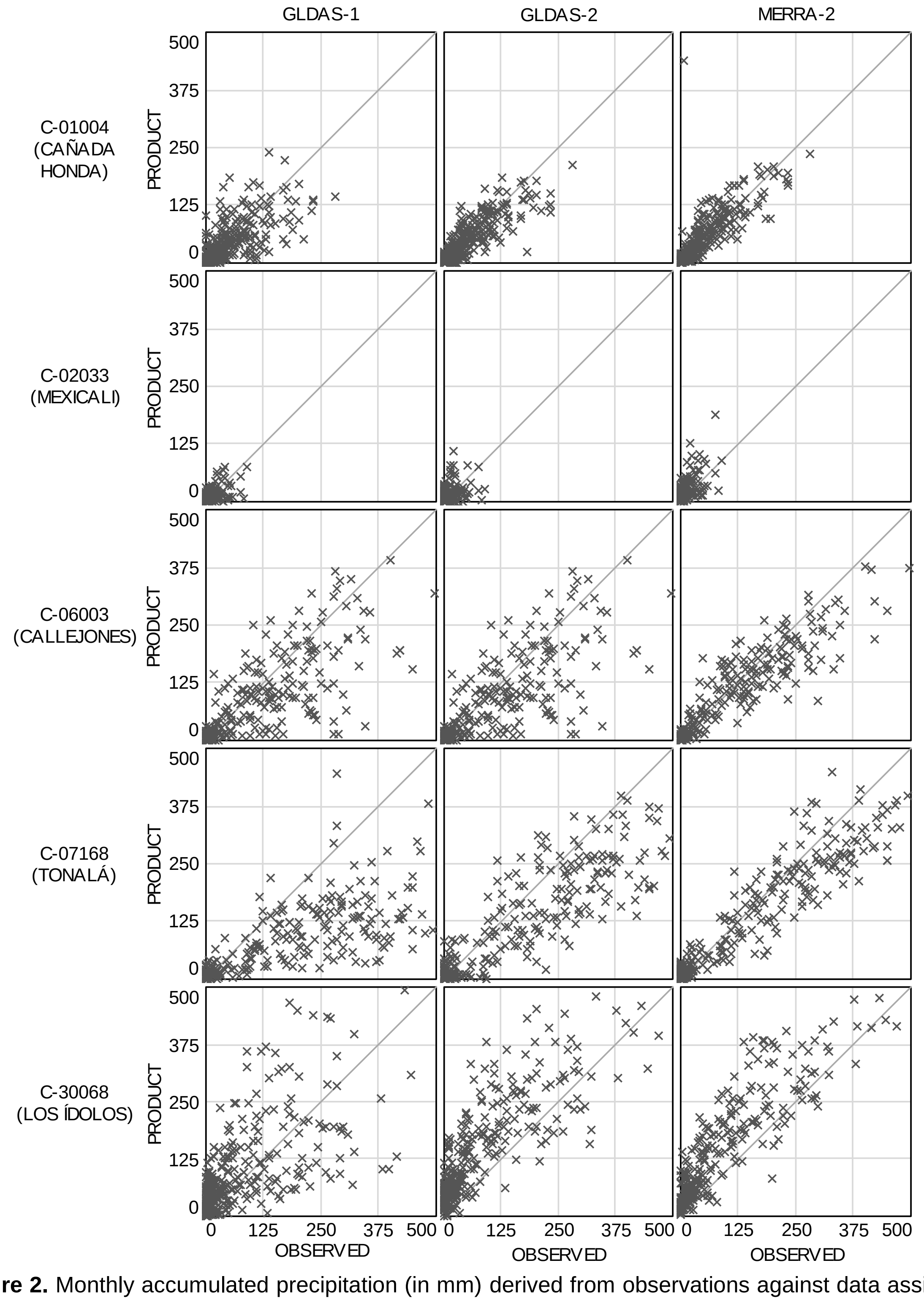

Figure 2. Monthly accumulated precipitation (in mm) derived from observations against data assimilation products. Gray line indicates perfect agreement.

All products show an acceptable skill to reproduce the precipitation in tropical climate regions. Conversely, it has been found a poor perform of the precipitation fields of all products in the climatological station located in a dry climate region (C-02033, Mexicali). These findings can be interpreted as that local precipitations (climatological station time series) have better agreement to major values of precipitation in tropical clime regions, while the opposite is found in dry clime regions.

The precipitation variability showed a similar pattern, with better fit measures in the station C-01004 (Cañada Honda; with $r^2 = 0.53$, $E = 0.31$ and $d = 0.84$). As in the case of the absolute magnitude, all the products were showed the worst perform in the station C-02033 (Mexicali; with $r^2 = 0.33$, $E = -0.43$ and $d = 0.71$).

Table 4. Fit measures of the variable of precipitation derived from the data assimilation products.

Station	GLDAS-1			GLDAS-2			MERRA-2		
	r^2	E	d	r^2	E	d	r^2	E	d
C-01004	0.52	0.51	0.82	0.71	0.71	0.90	0.73	0.70	0.92
C-02033	0.41	0.35	0.78	0.19	–0.29	0.62	0.46	–0.71	0.73
C-06003	0.67	0.63	0.87	0.79	0.78	0.94	0.84	0.81	0.94
C-07168	0.56	0.26	0.69	0.77	0.65	0.87	0.89	0.84	0.95
C-30068	0.45	0.23	0.80	0.68	0.22	0.83	0.80	0.47	0.89

Products show poorer skills in reproducing precipitation variability than its absolute magnitude. Nevertheless, it is interesting to notice that, when analyzing the SPI of greater time scales derived from the data assimilation products, the efficiency of the data from GLDAS-2 and MERRA-2 improve significantly (see **Figure 3**). This effect suggests that, although short-term (one month) fluctuations of precipitation are not well reproduced, precipitation fields of these products are capable of reproduce acceptably well the mid- and long-term variability (as of three months accumulated precipitation).

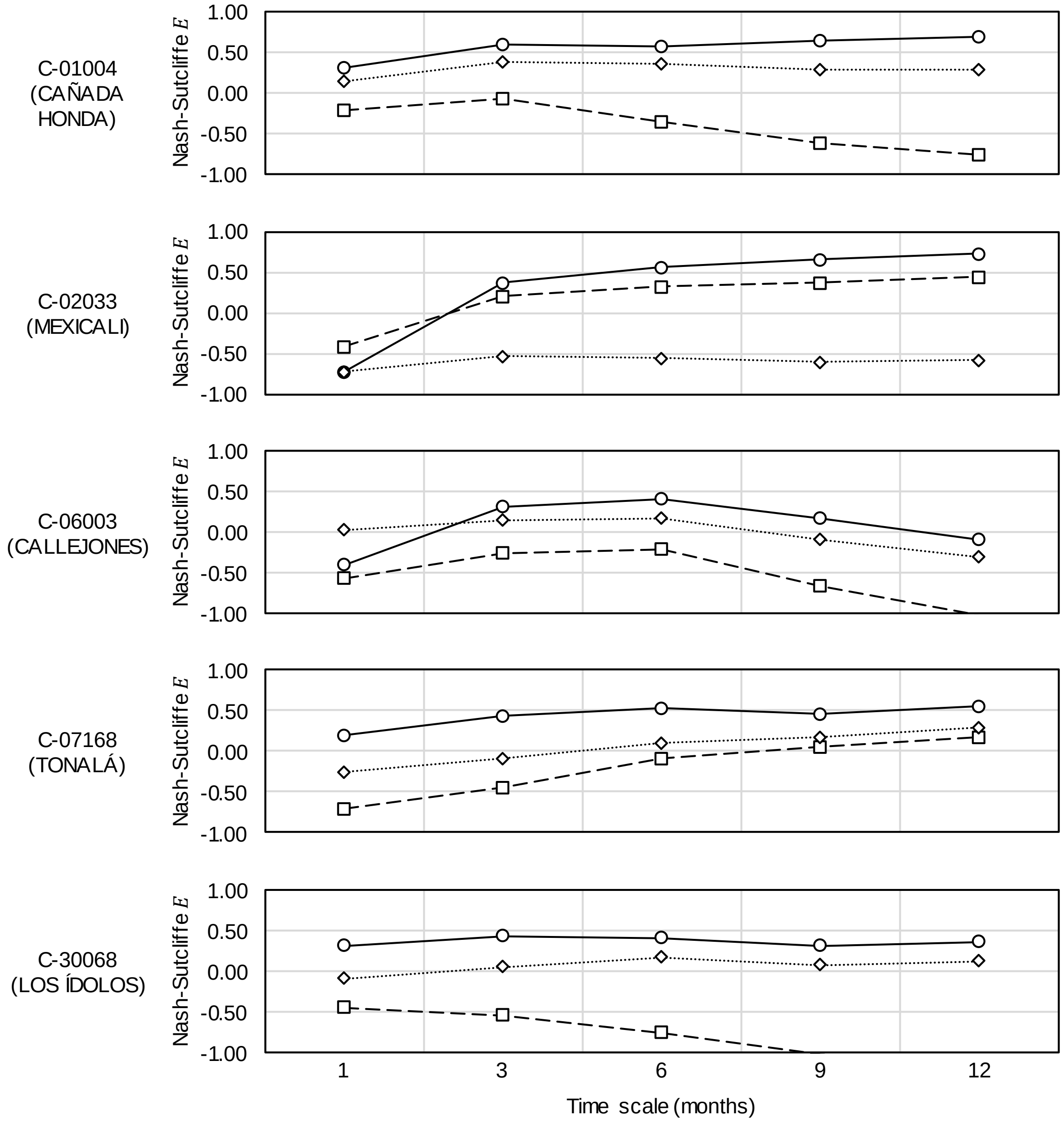

Figure 3. Variation of the Nash-Sutcliffe efficiency (E) of the Standardized Precipitation Index (SPI) of the assimilation data products evaluated as a function of the time scale of computation.

3.2 Streamflow

In general terms, all products exhibit poorer skills of its runoff fields compared to its precipitation fields. This was expected as the runoff fields are outcome of the LSM applied in each product, in contrast to the precipitation values which are remote sense based observations. **Table 5** and **Figure 2** show the results of the evaluation of the data assimilation products for the variable of runoff.

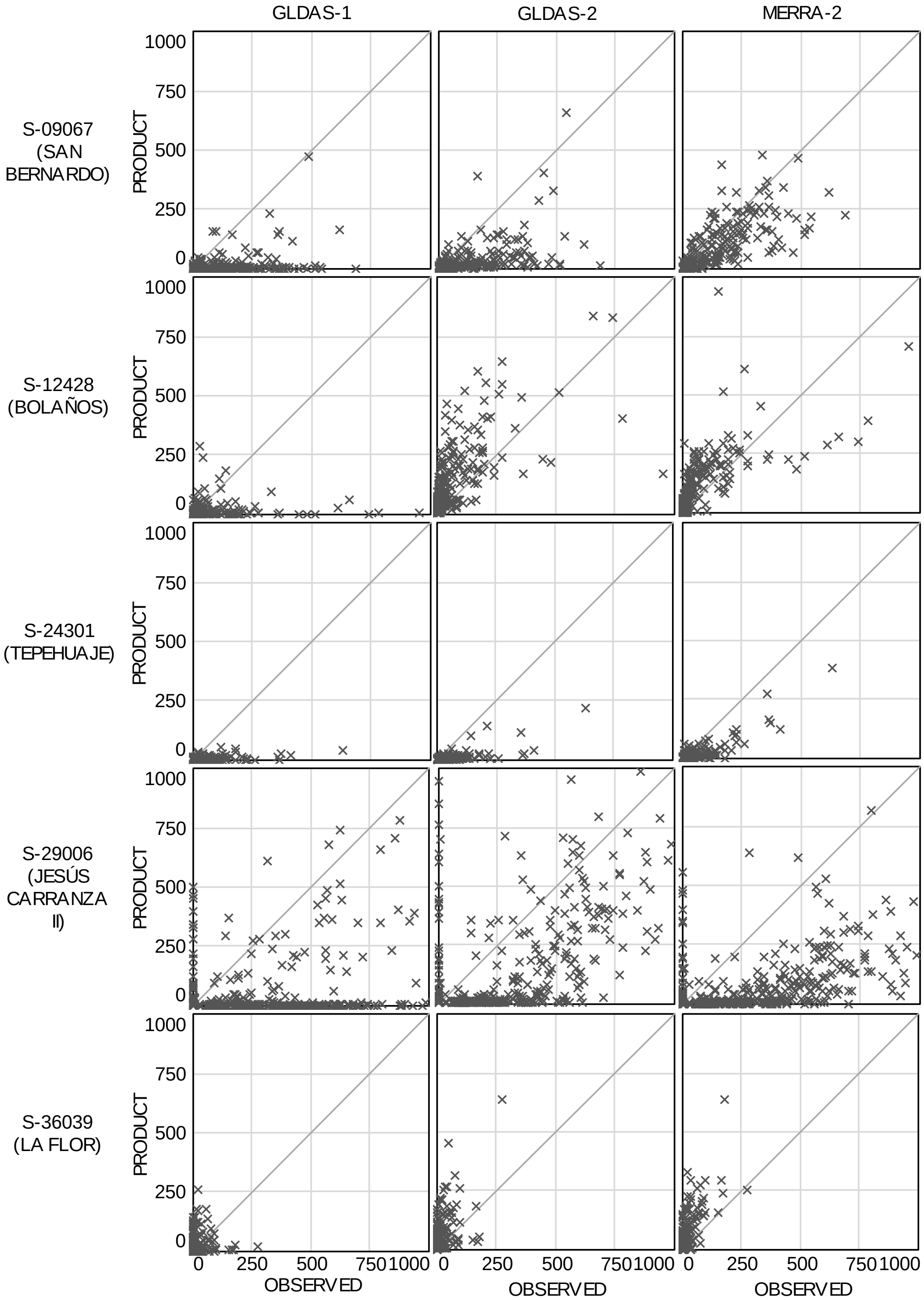

Figure 4. Monthly accumulated runoff (in hm³) derived from observations against data assimilation products. Gray line indicates perfect agreement.

In the same way as in precipitation fields, MERRA-2 presented the best skills to reproduce the absolute magnitude of runoff. Best efficiency of this product was found in the gauge S-09067 (San Bernardo; with $r^2 = 0.62$, $E = 0.56$ and $d = 0.84$), followed by gauge S-24301 (Tepehuaje; with $r^2 = 0.74$, $E = 0.49$ and $d = 0.78$). On the contrary, worst qualified absolute magnitude of data assimilation products was the gauge S-29006 (Jesús Carranza II; with best measures of $r^2 = 0.31$, $E = -0.09$ and $d = 0.71$).

Concerning to gauge S-29006, it highlights in the scatterplot that data assimilation products tends to significantly subestimate the recorded runoff. Its scatterplot (in **Figure 4**) shows several cases in which the products brought zero values, while the observed values reach up to 750 hm³. In this regard, station S-29006 shows a significant subsuperficial component of the observed runoff reflected in the presence of baseflow all the year around (see **Figure 5**), not detected in other gauge stations. According to these results, the models applied by the evaluated data assimilation products failed to reproduce this type of flow, which causes their comparatively low values.

Table 5. Fit measures of the variable of runoff derived from the data assimilation products.

Station	GLDAS-1			GLDAS-2			MERRA-2		
	r^2	E	d	r^2	E	d	r^2	E	d
S-09067	0.12	–0.25	0.48	0.28	0.03	0.59	0.62	0.56	0.84
S-12428	0.01	–0.11	0.25	0.54	0.30	0.82	0.00	–128.26	0.02
S-24301	0.19	–0.14	0.33	0.49	0.11	0.53	0.74	0.49	0.78
S-29006	0.15	–0.66	0.57	0.31	–0.09	0.71	0.24	–0.47	0.55
S-36039	0.01	–1.29	0.30	0.29	–3.98	0.53	0.19	–16.92	0.31

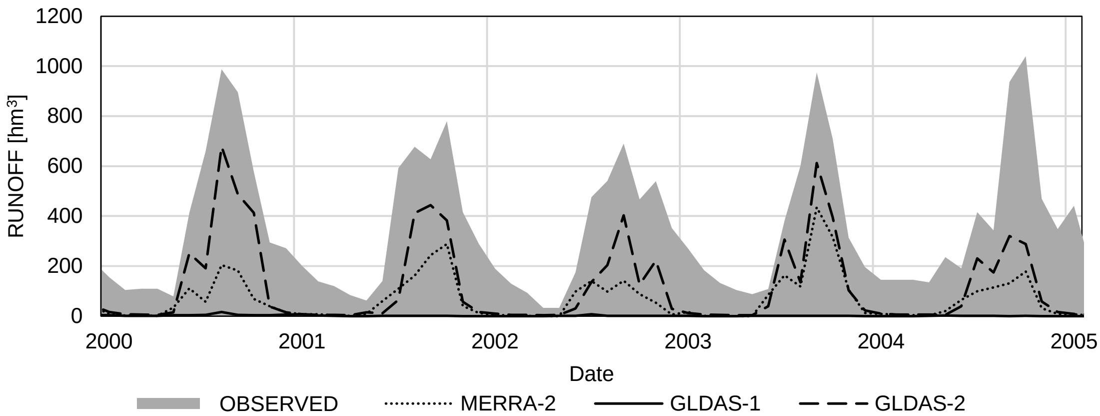

Figure 5. Time series of monthly accumulated runoff in the gauge station S-29006 (Jesús Carranza II) in the period 2000-2005.

This represents the most critical limitation of the data assimilation products derived datasets. Additional analysis would help to confirm this finding and locate its most affected area in the country.

In the other hand, data assimilation products exhibit a poor efficiency in reproduce the runoff variability. In all cases, fit measures gave less than required to be considered acceptable. Nevertheless, three gauge sites present measures moderately good. This is the case of stations S-24301 (Tepehuaje; with $r^2 = 0.43$, $E = 0.27$ and $d = 0.81$), S-09067 (San Bernardo; with $r^2 = 0.41$, $E = 0.34$ and $d = 0.80$) and S-36039 (La Flor; with $r^2 = 0.30$, $E = 0.04$ and $d = 0.74$). In all of them with the best product results derived from MERRA-2.

The use of different time scales in the computation of the Standardized Runoff Index (SRI) exhibit a slightly better agreement between observed runoff variability and data assimilation products derived runoff variability (see **Figure 6**). However, it does not represent a significant improvement in perform of the products in the gauge site S-29006 (Jesús Carranza II).

4 CONCLUSIONS

Based on the results of the present analysis, it can be stated that precipitation and runoff fields derived from the product GLDAS-1 are inefficient in represent the hydrologic conditions of the ten analyzed sites in the territory of Mexico, while MERRA-2 emerges as the assimilation data product with the best performance metrics, given that it acceptably reflects, the dispersion and magnitude of these indicators, comparatively to *in situ* observations.

GLDAS-2 appear as a good alternative as well. Nevertheless, at the time of writing this paper the update of its datasets is intermittent. Which puts it at a disadvantage compared to MERRA-2 if it is meant to be used in a monitoring system.

The efficiency of the products in represents the runoff is not as good as it is for the precipitation variable. The most important limitation found in the evaluated products is the estimation of the subsuperficial flow in their land surface models. This limitation could hinder its application hich may significant affect the use of these data sources in watersheds with high presence of tuis kind of flow.

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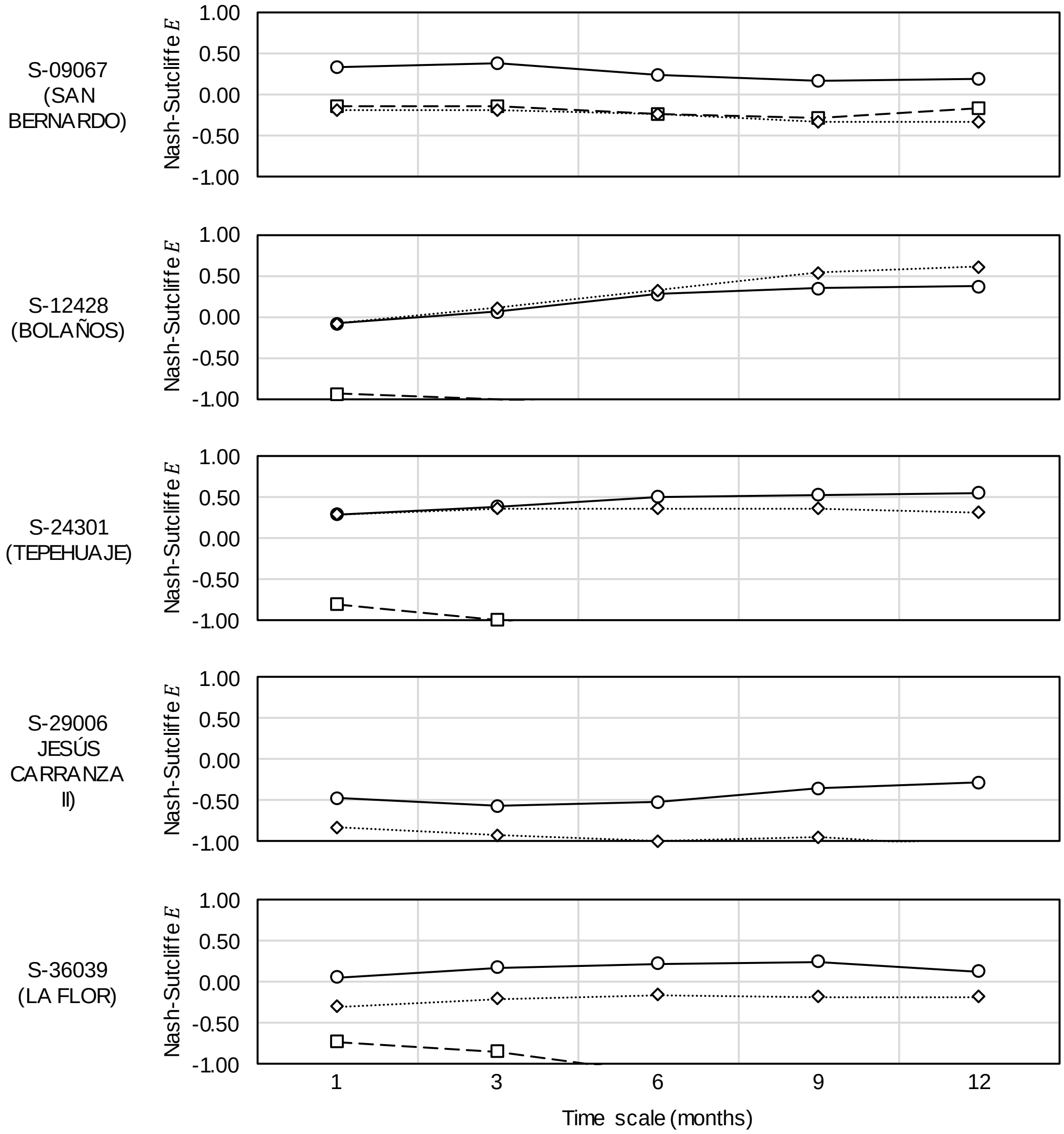

Figure 6. Variation of the Nash-Sutcliffe efficiency (E) of the Standardized Runoff Index (SRI) of the assimilation data products evaluated as a function of the time scale of computation.

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