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ISSN

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Publication Date

DOI

Copyright Information

Peer reviewed

CrossMark

ORIGINAL PAPER

Trends of precipitation extreme indices over a subtropical semi-arid area using PERSIANN-CDR

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Soroosh Sorooshian[2]

Abstract In this study, satellite-based daily precipitation estimation data from precipitation estimation from remotely sensed information using artificial neural networks (PERSIANN)-climate data record (CDR) are being evaluated in Iran. This dataset (0.25°, daily), which covers over three decades of continuous observation beginning in 1983, is evaluated using rain-gauge data for the period of 1998–2007. In addition to categorical statistics and mean annual amount and number of rainy days, ten standard extreme indices were calculated to observe the behavior of daily extremes. The results show that PERSIANN-CDR exhibits reasonable performance associated with the probability of detection and false-alarm ratio, but it overestimates precipitation in the area. Although PERSIANN-CDR mostly underestimates extreme indices, it shows relatively high correlations (between 0.6316–0.7797) for intensity indices. PERSIANN-CDR data are also used to calculate the trend in annual amounts of precipitation, the number of rainy days, and precipitation extremes over Iran covering the period of 1983–2012. Our analysis shows that, although annual precipitation decreased in the western and eastern regions of Iran, the annual number of rainy days increased in the northern and northwestern areas. Statistically significant negative trends are identified in the 90th percentile daily precipitation, as well as the mean daily precipitation from wet days in the northern part of the study area. The positive trends of the maximum annual number of consecutive dry days in the eastern regions indicate that the dry periods became longer in these arid areas.

1 Introduction

Precipitation is one of the most important components of the Earth's hydrologic cycle and the primary contributor to the water cycle. Understanding the temporal and spatial variability of precipitation at various scales is critical for addressing hydrologic hazards and managing water resources.

Such studies require reasonably accurate long-term, high-resolution, and consistent precipitation observations. Unfortunately, the quality (in terms of accuracy and spatial and temporal resolutions) of in situ precipitation observations is highly variable and dependent on the region. For example, based on global analyses by Groisman et al. (1999) and Frich et al. (2002) over a decade ago, there was (and still continues to be) very poor data coverage for most of Central and South America, Africa, and southern Asia. In addition, creating a consistent global precipitation dataset using observations obtained from different parts of the world cannot be easily merged due to the use of different methods (or indices) employed by different services and scientists (Karl et al. 1995; Zhai et al. 2005; Alexander and Arblaster 2009). The lack of such a long-term, high-resolution, comprehensive precipitation observation record at the global scale limits the ability of the scientific community to study extreme events. Recent progress in development of satellite-based precipitation

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observations has opened up the opportunity to fill this data gap. However, there will always be questions about the quality of any dataset obtained from new observation platforms. While in situ gauge and ground-based radar observations have their own limitations and their quality varies significantly from one region/country to another, they provide the basic needs of the forecast and application communities. Therefore, both the ground-based rainfall observations (gauge and radar) and the satellite-based estimates are the two sources that have their own pros and cons. The rain-gauge data are generally sparse-point measurements, measured in local time. In addition, these data are very limited over mountainous regions and deserts and are unavailable over the oceans. Moreover, rain-gauge observations vary from country to country and, for some regions, are highly limited due to the lack of proper organizational and observational infrastructures. On the other hand, satellite-based precipitation estimations provide global coverage at relatively fine spatiotemporal resolutions (Nguyen et al. 2014). These data are available over both the oceans and lands, and their potential advantage is particularly significant for regions where the gauge observations are limited (e.g., deserts or regions with varying topography). While these products are "best available" (Kidd and Huffman 2011) global estimates of precipitation, one major problem associated with such estimates is their biases when compared to ground-truth observations. Therefore, it is necessary to determine the validity and relative accuracy of these products in global and regional scales and in different parts of the world.

This study is intended to contribute to the evaluation of a newly released, three-decade-long, high-resolution, satellite-based precipitation dataset. Recently, the National Oceanic and Atmospheric Administration (NOAA) National Centers for Environmental Information (NCEI) released PERSIANN-CDR. This global dataset covers the period of 1983 to almost the present and at the daily temporal and 0.25° spatial resolution (Ashouri et al. 2015a). The usefulness of this high-resolution dataset for the study of extreme events and for the evaluation of regional hydroclimate models is among the many potential examples of its application. However, the user community expects some evidence of the relative accuracy of the PERSIANN-CDR dataset compared to in situ observations in different regions with different climates, geography, and topography. Comparisons and evaluations of satellite-based precipitation estimation products with in situ observations have been carried out for different spatial and temporal resolutions (Ebert et al. 2007; Tian and Peters-Lidard 2010; Kidd et al. 2012; Tian et al. 2009; Behrangi et al. 2011; AghaKouchak et al. 2011; Moazami et al. 2013; Katiraie-Boroujerdy et al. 2013; Ashouri et al. 2015b, among others). A number of

recent studies evaluating the quality of the PERSIANN-CDR dataset have already been initiated and reported for a number of geographic regions, including the USA and Australia (Ashouri et al. 2015a; Ashouri et al. 2016), China (Miao et al. 2015; Yang et al. 2016; Zhu et al. 2016), and over Malaysia (Tan et al. 2015). The results of these studies have been promising and encouraging enough to suggest the need for further evaluation over other regions of the world. This paper reports on the evaluation of PERSIANN-CDR over Iran.

This study has two parts. In the first part, the new "climate" satellite-based precipitation dataset, PERSIANN-CDR, is compared with an available condensed rain-gauge network over Iran. Although the satellite product is available from 1983, the rain-gauge dataset is available only for the period of 1998–2007; hence, the assessment is limited to this time period. The evaluation includes some categorical statistics and precipitation extreme comparisons. In the second part, PERSIANN-CDR data are used to calculate the trend in the annual amount of precipitation, the number of rainy days, and precipitation extremes, including mean daily precipitation on wet days, 90th percentile daily precipitation, annual maximum 1-day and 5-day consecutive precipitation amount, annual maximum number of days (and amounts) with more than 10- and 20-mm precipitation, and the annual maximum number of consecutive wet and dry days over Iran for the period of 1983–2012, for which the gauge network data are not available.

1.1 Study area and data

The study area, namely, the country of Iran, is located in the subtropical high-pressure belt region of the Middle East, spanning from 25–40° N latitude and 44–64° E longitude (Fig. 1). The northern and western regions of the country are mostly mountainous, while the central and eastern parts are primarily deserts. The satellite measurements (from 2003–2010) show that the hottest place in the world with 70.7° C (159.3° F) maximum temperature is located in the Lut Desert (Mildrexler et al. 2011). The location (between subtropical deserts and eastern Mediterranean areas) and the topography of Iran have primary roles in the precipitation regime. While the major parts of Iran receive only a few centimeters of precipitation each year, a narrow region along the Caspian Sea coastline has more than 1200 mm of annual precipitation. In mountainous areas, the annual precipitation varies from 200–700 mm. Most parts of the country experience water deficits on a permanent basis.

Daily precipitation data from more than 2100 rain gauges in Iran have been prepared by the Islamic Republic of the Iran Meteorological Organization (IRIMO) for the period of 1998–2007. Because satellite-

Fig. 1 Location and topography of the study area
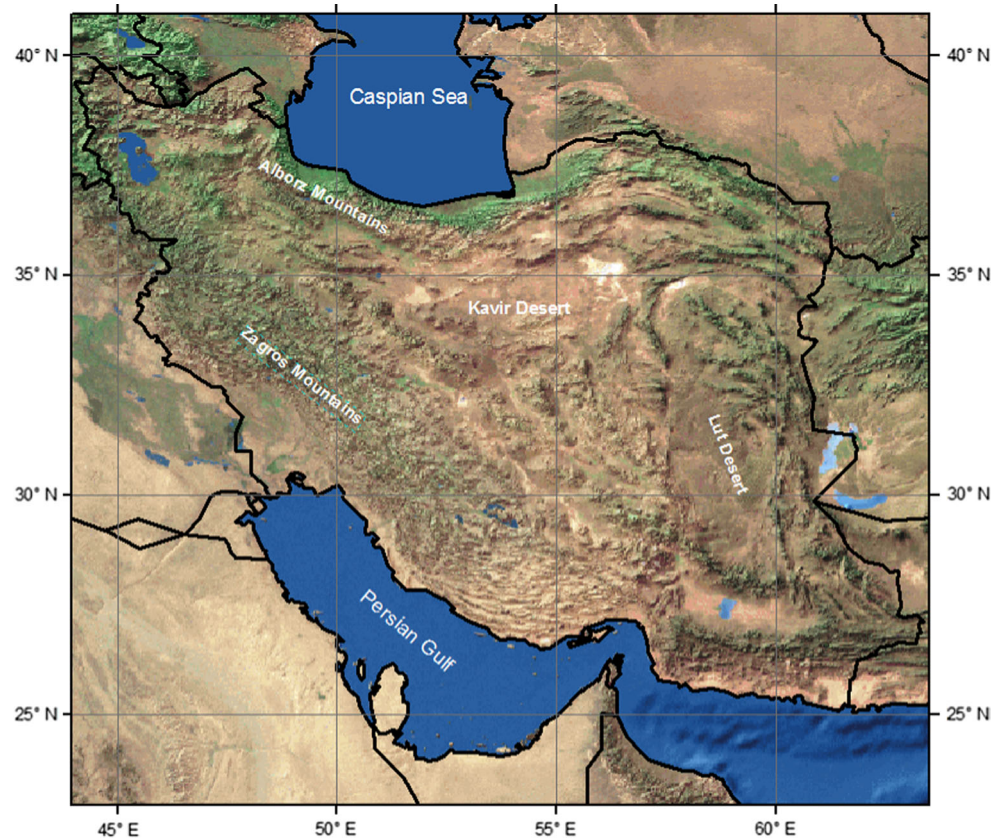
based datasets are available in 0.25° × 0.25° grid boxes, the study area was divided into similar grid boxes. Then, the daily precipitation was derived by calculating the average of the precipitation at the gauges that are located in each pixel (Katiraie-Boroujerdy et al. 2013). In order to avoid rain-gauge uncertainties, only the pixels that include at least three gauges are selected. Therefore, the gridded reference rain-gauge dataset includes 228 pixels. Figure 2 shows the distribution of the selected pixels over Iran. As can be seen, most of the pixels are distributed over the northern, southern, and western parts of Iran. The remainder of the country, which primarily includes desert regions with small amounts of precipitation throughout the year, is poorly covered by rain-gauge data.

Developed at the Center for Hydrometeorology and Remote Sensing (CHRS) at the University of California, Irvine, and maintained and distributed at the NCEI Climate Data Record Program, PERSIANN-CDR (Ashouri et al. 2015a) provides more than three decades of historical precipitation data at daily and 0.25° spatio-temporal resolutions for the latitude band of 60° S–60° N and the entire longitude. This product makes it feasible to study long-term historical variations in global precipitation at a higher resolution than previously possible. PERSIANN-CDR uses the global archive of the GridSat-B1 Infrared (Knapp et al. 2011) window from

geostationary earth orbit (GEO) satellites in the PERSIANN model (Hsu et al. 1997; Sorooshian et al. 2000) to generate three-hourly rainfall-rate estimates (1983-near present) at 0.25° spatial resolution. The estimates are then bias corrected using the Global
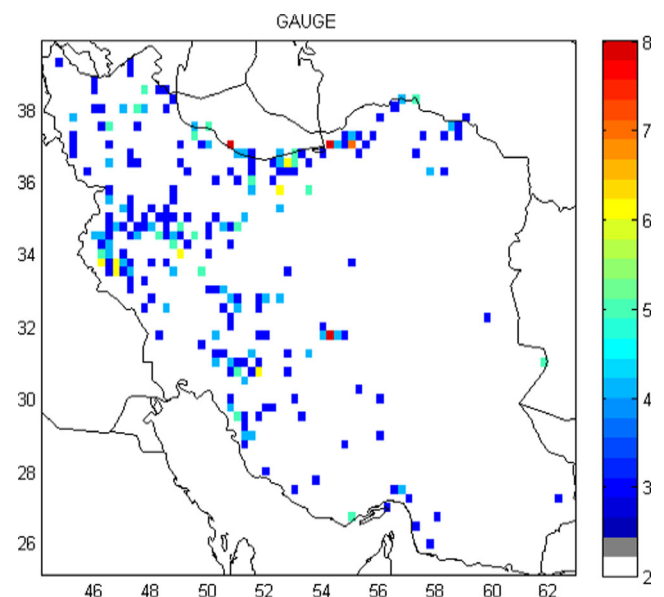
Fig. 2 The locations of pixels that include at least three gauges. The legend shows the number of rain gauges in each pixel

Precipitation Climatology Project (GPCP) monthly-precipitation product to maintain the consistency of the two products in monthly scale. PERSIANN-CDR is publicly available via ftp://eclipse.ncdc.noaa.gov/pub/cdr/persiann/files/ and gets updated to the most recent time on a quarterly basis.

The accumulation of daily precipitation for rain-gauge data in Iran begins from 15 UTC; thus, to synchronize the satellite product with rain-gauge data, the three-hourly PERSIANN-CDR data are aggregated to obtain daily precipitation. In order to reduce the uncertainties in the analyses, a 2.5-mm/day threshold is considered for daily precipitation calculation for both datasets, and every daily precipitation amount less than 2.5 mm/day is considered as zero. It should be mentioned that the evaluation time period is limited to 1998–2007, the longest time period for which that rain-gauge dataset is available. The 30-year trend analyses time period is 1983–2012 when only PERSIANN-CDR data are available.

2 Methods

2.1 Evaluation

To evaluate the performance of PERSIANN-CDR, the categorical statistics are calculated for daily precipitation as a first step. The categorical statistics (Wilks 2006) used in this study are the probability of detection (POD), the false-alarm ratio (FAR), and the bias (BIAS). In brief, the POD represents how often the satellite product detects rainfall correctly, the FAR shows how often the satellite product indicates precipitation when it did not occur, and the BIAS represents the ratio of total satellite-based product precipitation alarm to rain-gauge precipitation alarm, i.e., "ground-truth" (Katiraie-Boroujerdy et al. 2013). The best score (perfect estimation) for POD and BIAS is one, and the best score for FAR is zero. The mean annual amount and number of rainy days for both datasets for selected pixels are compared. The categorical statistics are applied to PERSIANN-CDR (CDR) and the gauge-reference (GAUGE) daily precipitation data. It is noteworthy that rain-gauge data is considered to be the "ground-truth."

In the second step, in order to evaluate how well this satellite dataset can monitor the extreme precipitation events, ten standard extreme indices, introduced by the World Climate Research Program (WRCP) on Climate and Ocean: Variability, Predictability and Change (CLIVAR), are used (Karl et al. 1999; Peterson et al. 2001). A list of these extreme indices is provided in Table 1. The extreme precipitation indices are in three categories.

The extreme indices are calculated for the gauge-reference dataset and PERSIANN-CDR for 228 pixels that include at least three gauges (shown in Fig. 2). The analyses are performed for 1998–2007, where both datasets are available. Then, the annual means of these indices are calculated at each pixel. Finally, the scatter plots, correlation coefficients, and the root-mean-square error (RMSE) are derived between GAUGE and PERSIANN-CDR for these annual means.

2.2 Trend analysis

The trend analysis is applied only to PERSIANN-CDR data that are available from 1983–2012. The Kendall tau (Sneyers 1990) is used to determine the trends in the annual precipitation, the number of annual rainy days, and the ten extreme indices (Table 1) time series for Iran (spanning from 25–40° N latitude and 44–64° E longitude). The non-parametric Mann-Kendall test is used to evaluate the significance of the trends at 90 % confidence interval. This test does not assume any special distribution in the data series and is robust to the effect of the outliers in the data (Lanzante 1996). This test has been widely used in climate change analyses (Karl and Knight 1998; Klein Tank et al. 2006; Alexander et al. 2006).

Table 1 Extreme precipitation indices used in the analysis (Miao et al. 2015)

Category	ID	Definition	Unit
Intensity indices	SDII	Mean daily precipitation from annual wet days	mm/day
	RR90p	The 90th percentile of annual precipitation on wet days	mm/day
	Rx1d	Annual maximum 1-day precipitation	mm/day
	Rx5d	Annual maximum 5-day consecutive precipitation	mm/5 days
Absolute threshold indices	R20 mm	Annual number of days when precipitation ≥20 mm	Days
	R10 mm	Annual number of days when precipitation ≥10 mm	Days
	R20 mmTOT	Annual total precipitation when daily precipitation ≥20 mm	mm
	R10 mmTOT	Annual total precipitation when daily precipitation ≥10 mm	mm
Wet and dry spell indices	CWD	Annual largest number of consecutive days with daily precipitation ≥2.5 mm	Days
	CDD	Annual largest number of consecutive days with daily precipitation <2.5 mm	Days
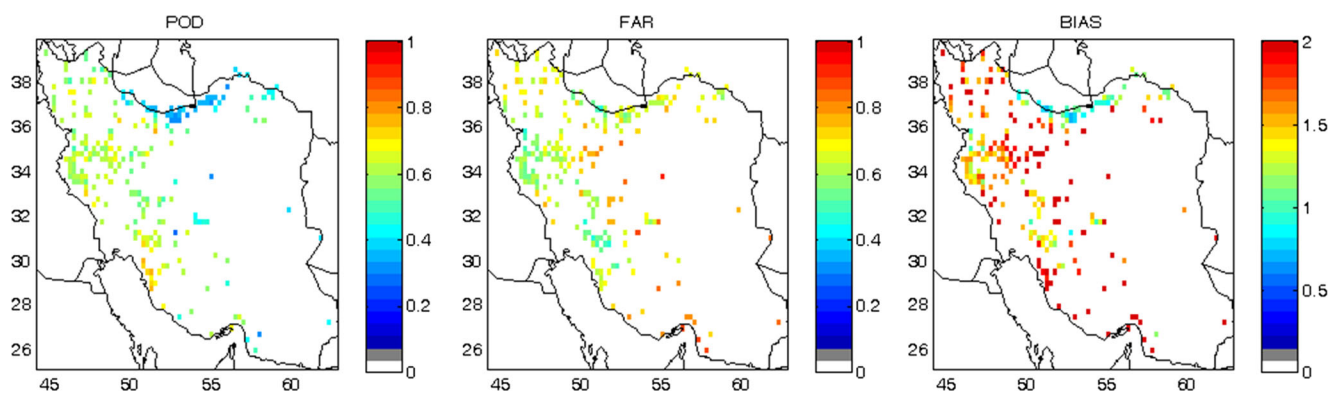
**Fig. 3** The results of categorical statistics for daily precipitation

3 Results

### 3.1 Results of evaluation analyses

In this section, the daily precipitation time series from both CDR and GAUGE datasets, after implementing a 2.5-mm/day threshold for the 228 pixels (Fig. 2) that include at least three gauges for the period 1998–2007, are used. The results of categorical statistics are shown in Fig. 3. As shown, PERSIANN-CDR has reasonable POD results in most pixels. On the other hand, it shows a poor performance in the coast of the Caspian Sea (especially the eastern part), which is in agreement with previous analyses for most satellite products (Moazami et al. 2013; Katiraie-Boroujerdy et al. 2013). PERSIANN-CDR shows high BIAS (about two) in many pixels (except in the humid regions in the northern area of the country). The FAR is dominantly higher in pixels that are located in the central and southeastern parts of Iran, which are dry regions. This means PERSIANN-CDR overestimates rainy days in dry regions.

Figure 4 shows the spatial distribution of mean annual precipitation in the study pixels for the period of 1998–2007. Based on the results from the GAUGE data, the strip along the coast of the Caspian Sea, as well as some parts of the mountainous areas in the western part of the country (i.e., the Zagros Mountains), are the wettest regions. On the contrary, the central and eastern parts are identified as the driest areas. As shown in Fig. 4, PERSIANN-CDR underestimates annual precipitation over the Caspian Sea coastline and some parts west of the Zagros Mountains, while it overestimates annual precipitation over the northwest regions over the Zagros Mountains. In fact, PERSIANN-CDR divides Iran into two parts: the eastern part, which is completely dry (both the northern and southern sections) and the western part, which is moderately humid (both the northern and southern sections).

The annual average of the number of rainy days for the period of 1998–2007 for both datasets is represented in Fig. 5. PERSIANN-CDR overestimates the mean annual number of rainy days in the northwest region of the
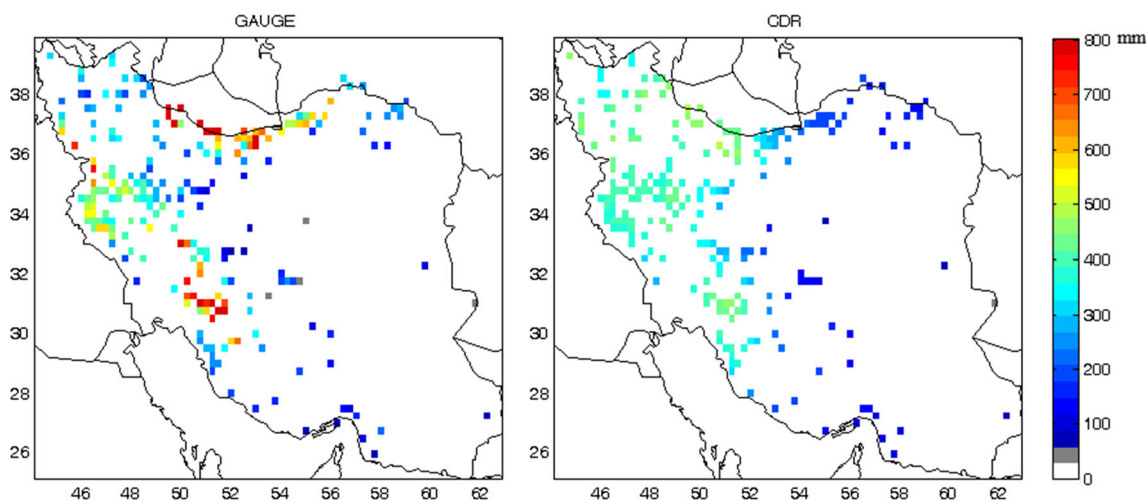
Fig. 4 Mean annual precipitation over Iran
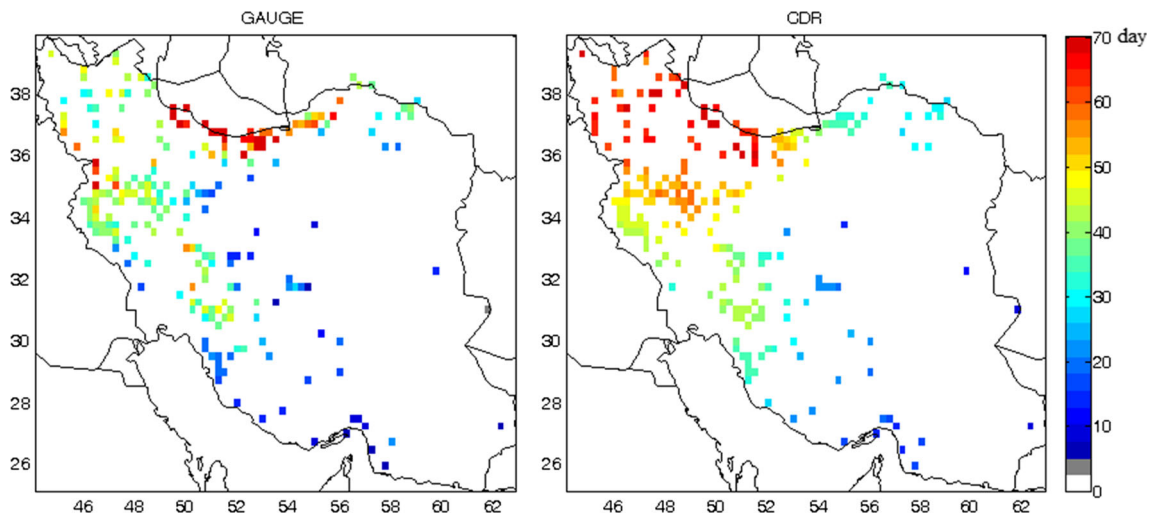
**Fig. 5** The mean annual number of rainy days in Iran

country. In addition, it underestimates the mean annual number of rainy days in the eastern parts of the Caspian Sea coastline.

Figure 6 shows the correlation coefficients between GAUGE and PERSIANN-CDR daily precipitation (1998–2007). PERSIANN-CDR has considerable correlation of coefficients for the western parts of the Zagros Mountains. The smallest correlation coefficients are identified on the coast of the Caspian Sea. The previous studies (Katiraie-Boroujerdy et al. 2013; Moazami et al. 2013) show that most satellite products have poor performances over this area.

The results of the evaluation of extreme indices are presented in Table 2 and Figs. 7–9. Table 2 shows the correlation of coefficients and RMSEs of the extreme indices comparison between GAUGE and PERSIANN-CDR. In these figures, the annual means of all extreme indices for GAUGE (the horizontal axis) versus the PERSIANN-CDR

(the vertical axis) for the 228 pixels are shown. Although we cannot compare the RMSEs (because those have different scales), the correlation of coefficients for intensity indices is higher than the correlation of coefficients of absolute-threshold indices. As shown in Fig. 7, PERSIANN-CDR underestimates the intensity indices. In addition, the results for these indices given in Table 2 show that the correlation coefficients and RMSEs are considerable. As presented in this figure, the agreement between GAUGE and PERSIANN-CDR for Rx5d in comparison with Rx1d depicts that this climate-satellite product can capture the maximum 5 days of accumulation better than the maximum 1-day precipitation.

Figure 8 shows the evaluation results for the *absolute-threshold extreme indices*. This figure and Table 2 show that PERSIANN-CDR underestimates the absolute-threshold indices, especially in wet areas. As shown, PERSIANN-CDR has higher correlation coefficients and less RMSEs for R20 mm and R20 mmTOT than for R10 mm and R10 mmTOT.
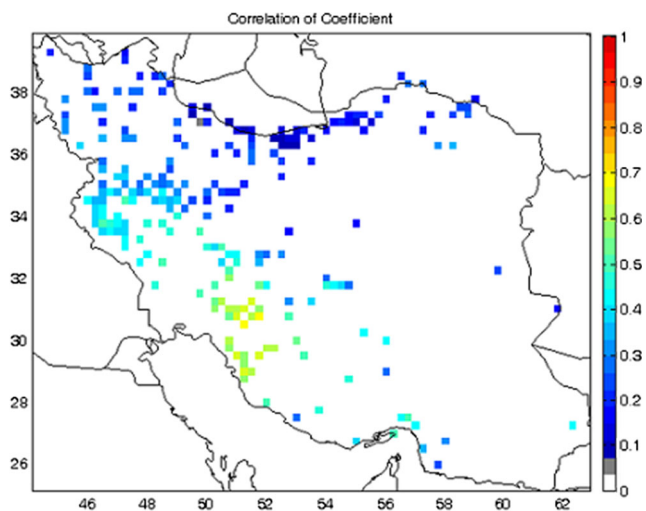
Fig. 6 The correlation coefficients between GAUGE and PERSIANN-CDR daily precipitation time series

Table 2 Correlation coefficients (R) and root-mean-square error (RMSE) of extreme indices comparison between GAUGE and other datasets

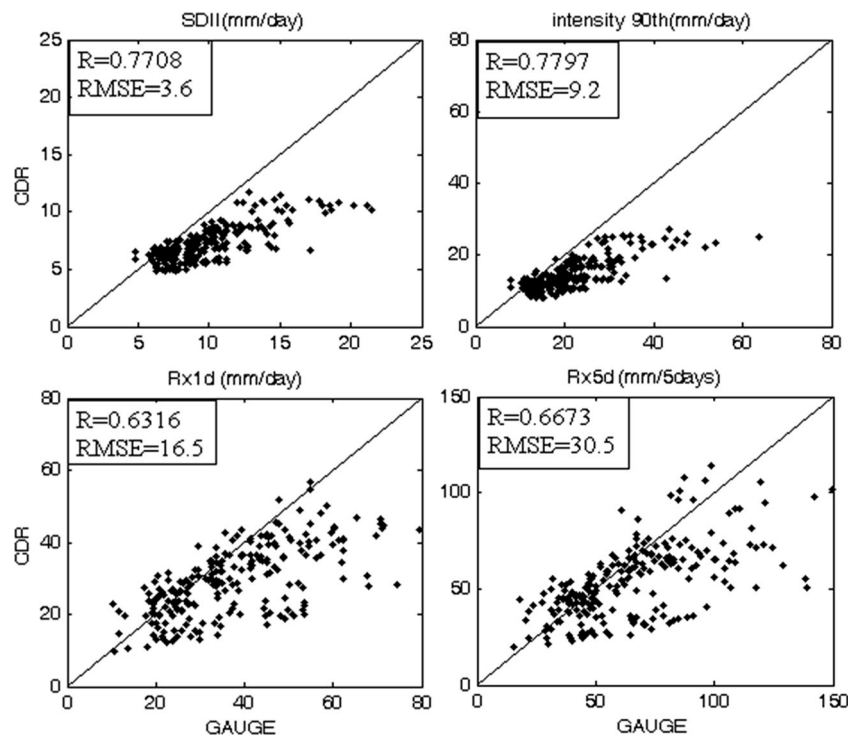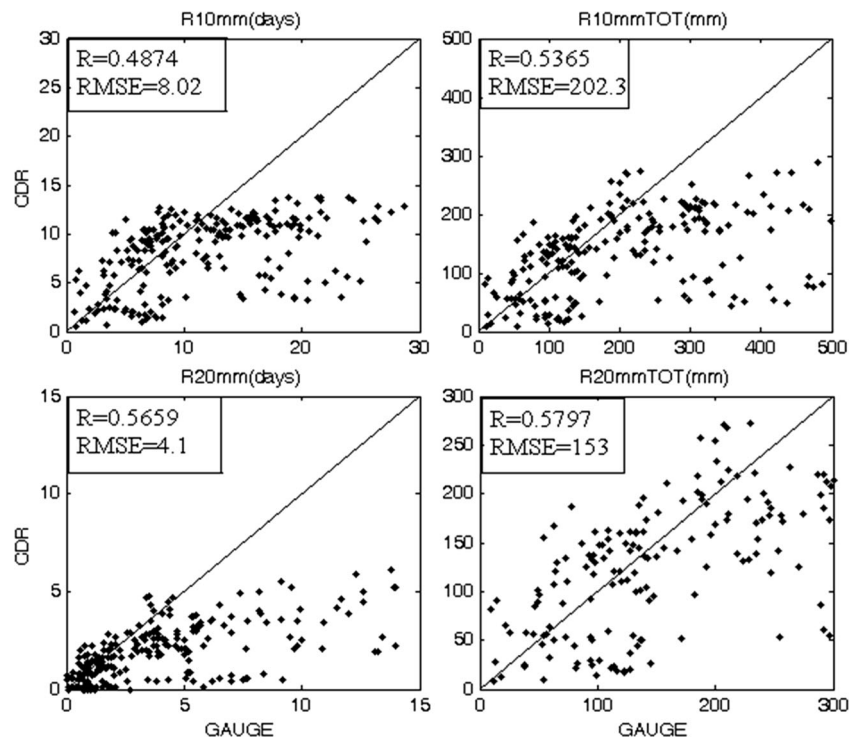| Category	ID	R	RMSE
Intensity indices	SDII	0.7708	3.6 mm/day
	RR90p	0.7797	9.2 mm/day
	Rx1d	0.6316	16.5 mm/day
	Rx5d	0.6673	30.5 mm/5 days
Absolute threshold indices	R20 mm	0.4874	8.02 days
	R10 mm	0.5365	202.3 days
	R20 mmTOT	0.5659	4.1 mm
	R10 mmTOT	0.5797	153 mm
Wet and dry spell indices	CWD	0.4285	1.2 days
	CDD	0.8358	38.3 days

Figure 9 shows the scatter plots of the maximum annual dry and wet period extreme indices. As shown, satellite data have good agreement with GAUGE to show the annual largest number of consecutive dry days (CDD).
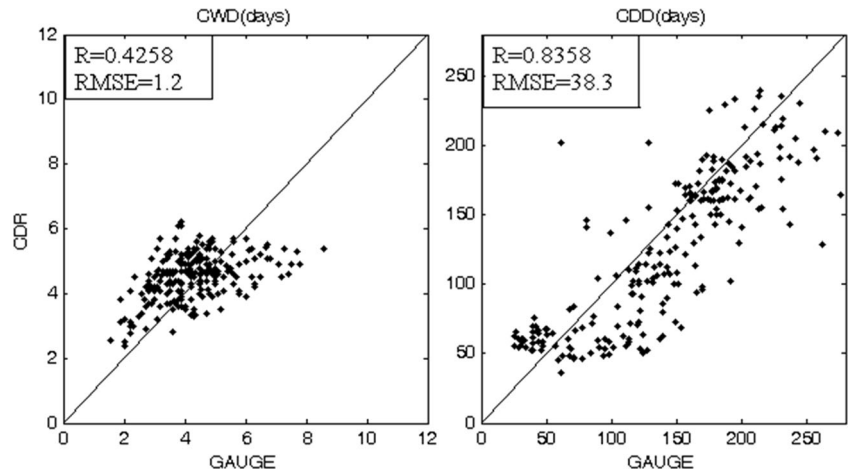
3.2 Results of the trend analyses

After the evaluation phase, in order to determine the trend sign and significance (90 %) of annual precipitation, the

Fig. 9 Same as Fig. 7, but for two maximum annual dry and wet period extreme indices (Table 1)


number of annual rainy days, and the ten extreme indices (Table 1) for the period of 1983–2012 (the gauge network is not available), the Mann-Kendall test (Sneyers 1990) is used. In this phase of the study, (0.25° latitude × 0.25° longitude) PERSIANN-CDR data time series, which covers Iran for the period 1983–2012, is used.

Figures 10–12 show the results of PERSIANN-CDR trends for the amount of annual precipitation, rainy days, and extreme indices. In these figures, the significant (90 %) positive trends are shown in red, significant (90 %) negative trends are shown in blue, and no significant trends are shown in white.

Fig. 10 The annual rainy days, precipitation amount, CDD, and CWD significant (90 %) trends based on PERSIANN-CDR data
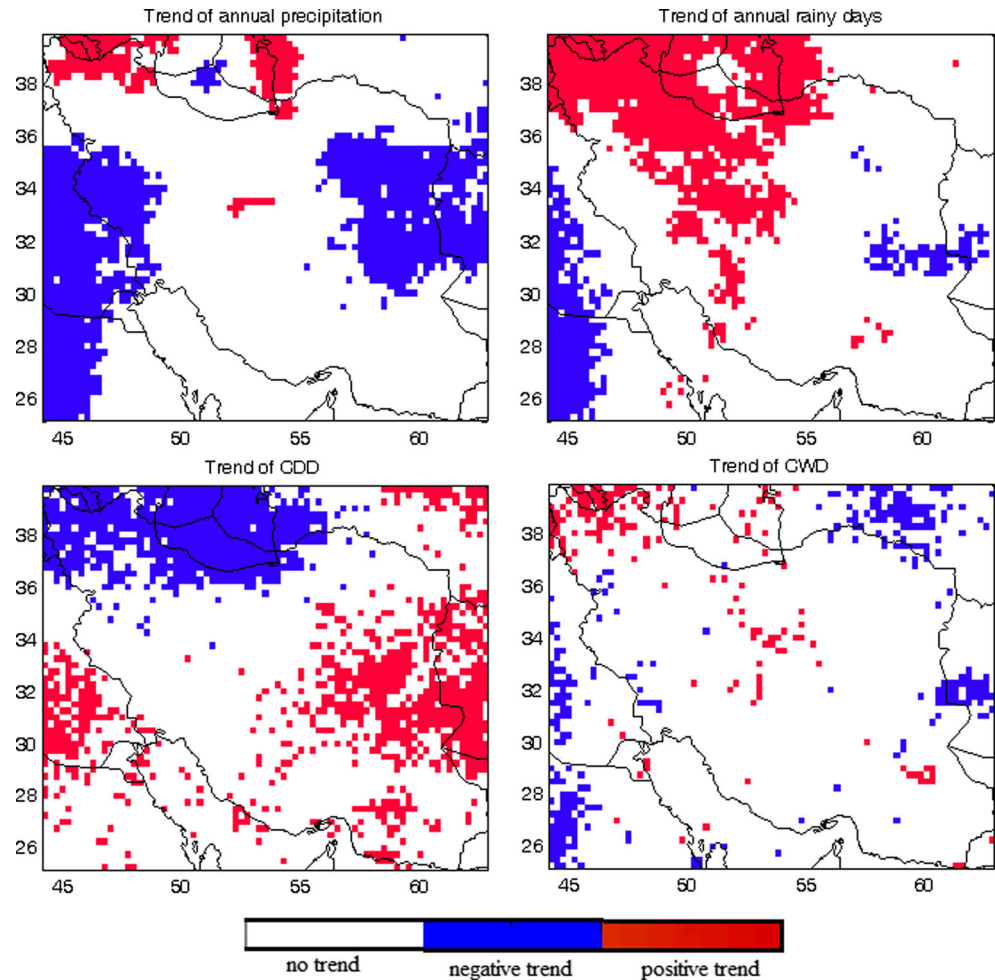
Fig. 11 Same as Fig. 10, but for the 90th percentile, mean daily precipitation from wet days (SDII), Rx1d, and Rx5d
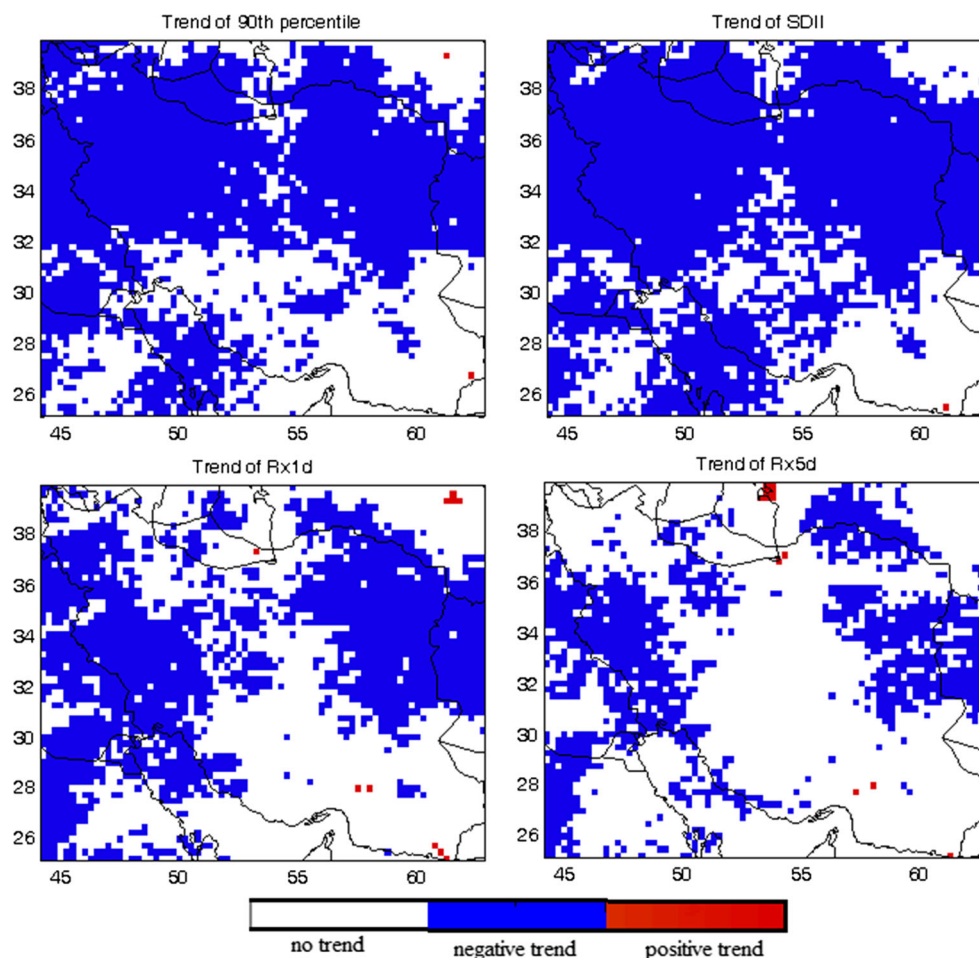
As shown in Fig. 10, the annual precipitation decreased in the western and eastern regions. On the other hand, the annual precipitation increased significantly in a small area in the northwestern portion of the country, in a few pixels in the central region (a dry area), and in a few pixels east of the Caspian Sea.

The number of annual rainy days (Fig. 10) increased primarily in the northern and northwest sections of Iran, as well as in some eastern parts of the Zagros Mountains toward the central areas. The results show that the maximum annual dry period (CDD) decreased in the northern and the northwestern regions, which coincided with the positive trend in the number of annual rainy days in these regions. On the other hand, positive CDD trends in the eastern region and some sparse pixels in the southern and central parts show that the dry periods became longer in these arid areas. There are positive trends in annual wet periods in a few pixels in northwestern Iran, which is in agreement with positive trends in annual rainy days in this area. However, a few continuous pixels in the northwest show significant positive trends for CWD, but there are only some individual pixels in

different parts of the country that show significant trends (positive or negative) in the number of consecutive wet days. Hence, there is no available evidence that shows areal trends for this index in Iran.

With respect to the 90th percentile and the mean daily precipitation from wet days (SDII), the results show negative significant trends for these extreme indices, which is dominant for the most parts (especially for the northern half).

Figure 11 also shows the significant negative trends in the Rx1d and Rx5d indices for the western and eastern regions of Iran that are more spatially extended for Rx1d.

Figure 12 shows significant decreasing trends in the eastern and western regions for annual-absolute thresholds (R10 mm, R10 mmTOT, R20 mm, and R20 mmTOT), which are dominant for heavier precipitations. The dominant significant (90 %) negative trends of annual absolute thresholds (R10 mm, R10 mmTOT, R20 mm, and R20 mmTOT) and the 90th percentile, SDII, Rx1d, and Rx5d in most parts of Iran (shown in Figs. 11–12) indicate that the frequency and amount of the heavy precipitation have decreased.

Fig. 12 Same as Fig. 10, but for annual absolute-threshold extreme indices
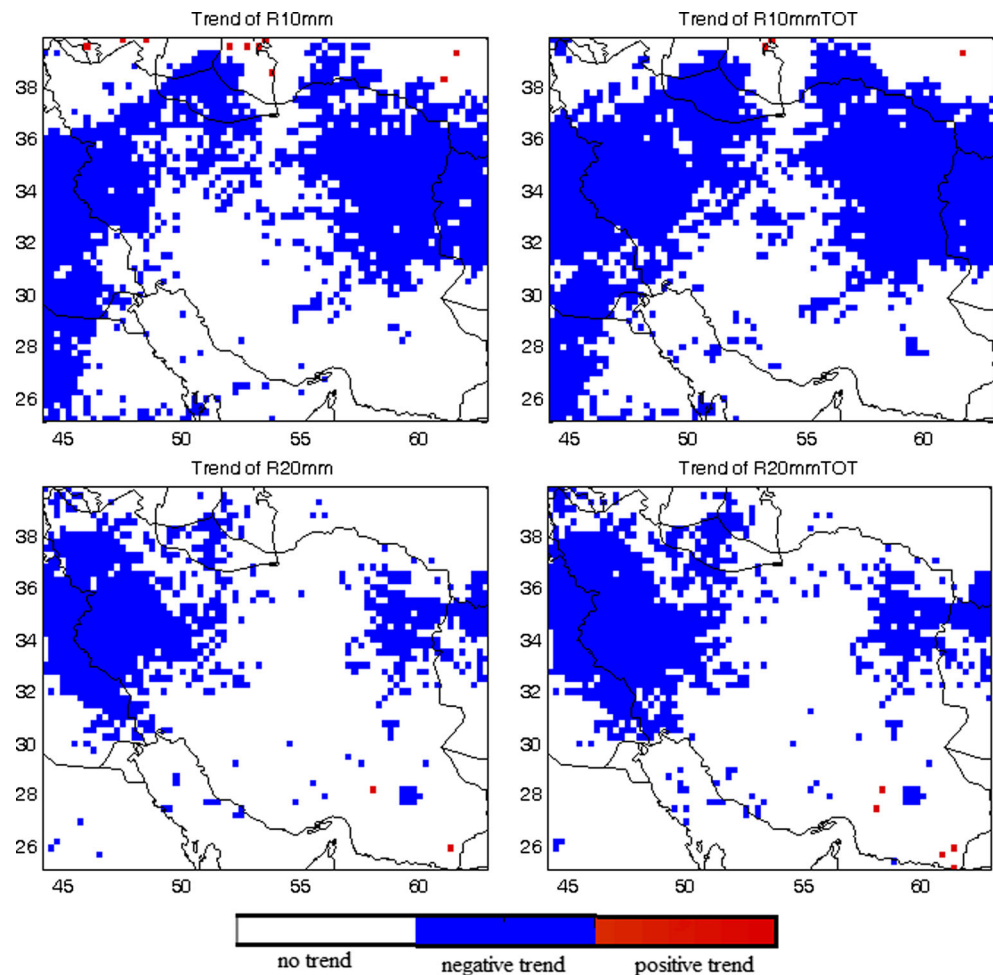
4 Conclusions

PERSIANN-CDR is a high-resolution, satellite-based, daily precipitation dataset that provides 0.25° rainfall estimates from 1983-present. In this study, we (1) evaluated the performance of a newly developed precipitation climate data record, called PERSIANN-CDR, in reproducing extreme precipitation indices from 1998–2007 over Iran and (2) investigated the trend in annual amounts of precipitation, the number of rainy days, and precipitation extremes for 1983–2012 over the same region. In the first phase of the study, ten standard extreme indices introduced by CLIVAR and WMO are used (Table 1). The daily threshold precipitation considered 2.5 mm/day for both datasets. The evaluation analysis was applied to 228 pixels (0.25° × 0.25° grid boxes) that included at least three gauges (Fig. 2).

The results of categorical statistics show that PERSIANN-CDR has considerable POD in most pixels but also high BIAS. Its performance in the coast of the Caspian Sea is less than satisfactory, but is comparable to previously reported results for other satellite products over this area (Moazami et al. 2013; Katiraie-Boroujerdy et al. 2013).

Climatologically and in terms of average annual precipitation, Iran is divided into two parts: the dry (east) and wet (west), and results show that PERSIANN-CDR underestimates the precipitation over the mountainous area (the Zagros Mountains) and the low-elevation regions of the coastal Caspian Sea area. On the other hand, PERSIANN-CDR overestimates the mean annual number of rainy days in the northwest region.

The results of the evaluation of extreme indices show that, while the PERSIANN-CDR has reasonable correlation coefficients for scatter plots, it underestimates intensity indices, especially for wet pixels. It must be mentioned that some of these 228 selected pixels are located in the humid coastal region of the Caspian Sea (poor performance by satellite products) and have considerable affect on these calculations.

PERSIANN-CDR underestimates mean daily precipitation from annual wet days (SDII) and the intensity of the 90th percentile. The agreement between GAUGE and PERSIANN-CDR for Rx5d in comparison with Rx1d depicts that this dataset can capture the maximum 5-day accumulation better than the maximum 1-day precipitation. PERSIANN-CDR shows good agreement with GAUGE in terms of the

annual largest number of consecutive dry days (CDD). However, it underestimates the absolute (number and amount) threshold daily precipitation (R10 mm, R20 mm, R10 mmTOT, and R20 mmTOT).

Among the current high-resolution, satellite-derived precipitation products, only PERSIANN-CDR provides high spatio-temporal precipitation data (0.25° and daily) for the past three decades. Thus, it fits well for a suite of long-term trend studies. In the second phase of the study, PERSIANN-CDR data over the time period of 1983–2012 were used to investigate the potential trends in annual amount, number of rainy days, and the ten extreme indices over Iran. The Mann-Kendall test was used to determine the significance (90 %) trends. The results show negative annual precipitation trends in the western and eastern regions of the country. On the other hand, the results show positive trends of rainy days in the northern and the northwestern areas. The results also show negative significant trends for the 90th percentile in the northern part of the area. The spatial pattern of trends for mean daily precipitation from wet days (SIDD) is similar to that for the 90th percentile. The positive trends of the maximum annual dry period (CDD) in the east and some sparse pixels in the southern and central parts are apparent. This shows that the dry periods became longer in these arid areas. A few sparse pixels show negative or positive significant trends of the maximum annual wet period (CWD). There are significant decreasing trends in the eastern and western regions for annual absolute thresholds (R10 mm, R10 mmTOT, R20 mm, and R20 mmTOT), which are dominant for heavier precipitation events.

Similar to any other satellite-based precipitation products, PERSIANN-CDR's improvement is an ongoing project. It is noteworthy that not only would satellite-derived precipitation data need continuous monitoring for improvement, the reference datasets (in this study, GAUGE data) against which satellite products are compared require careful control on their quality. Rain-gauge data have inherent limitations: they are sparse-point measurements which limit their application for high-resolution gridded analysis. Such measurements might be significantly incorrect, specifically in remote and mountainous regions. These effects can lead to significant differences between satellite products and ground-based measurements.

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