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Assessment of Satellite Based Evapotranspiration Products at Regional Scale over Landscape of Pakistan

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Abstract: Satellite based Evapotranspiration (ET) products are being used at a global scale for ET estimation and mostly providing a reliable opportunity in in-situ data-sparse region. GLDAS, GLEAM & MODIS are currently used state-of-the-art satellite ET products. They provide wide and continuously available datasets with large spatio-temporal coverage. Availability of accurate & reliable ET information is a prerequisite for many hydro-meteorological applications such as water resource management, irrigation scheduling, crop yield estimation, and drought predictions; hence, this research work was carried out to evaluate the accuracy and applicability of MODIS, GLEAM & GLDAS in diverse regions of Pakistan. ET estimates obtained from these products were compared with gauge data on monthly temporal scale, and seasonal (spring, autumn, summer, and winter) scale in four diverse climatic zones using six performance metrics namely root mean square error, standard deviation, linear correlation coefficient, index of agreement, Nash-Sutcliffe efficiency and statistical bias. The results showed that (1)- GLEAM is a competitive ET estimation product and it gave promising ET estimates in the dry regions as well as in hilly and mountainous terrain of Pakistan. (2)- Seasonal analysis resulted that GLEAM was best suitable product in case of spring, summer & autumn, whereas MODIS provide better agreement in case of winter. On the other hand, GLDAS was ranked 2nd in case of all seasons. (3)- By considering zones based analysis it was noted that GLEAM performed better as compared to other ET products in all zones, whereas GLDAS & MODIS ranked 2nd and 3rd respectively. (4)- The overall performance of GLEAM is very convincing and it was concluded that it can be a feasible satellite product for most of the areas of Pakistan. Furthermore, error component (systematic & random) estimation can be a step further evaluation of GLDAS & GLEAM.

Keywords: Evapotranspiration, Satellite-Based ET Products, Performance Metrics, Climatic Zones

1. Introduction

Evapotranspiration (ET) is referred as the sum of evaporation process from the land and the transpiration process from the plants. ETo is ET from the reference surface not short of water [2]. However, ETa is the actual ET from heterogeneous surface [12]. ET measurement is considered a very critical process. It is because it has a huge role in the connection of the energy cycles, carbon, and hydrological cycles. Therefore, it is very important to have reliable information related to ET for different bio-geophysical activities such as meteorological, agriculture, hydrological and forestry field. But, it is important note that getting the accurate information on evapotranspiration can be very challenging. It is because it is controlled by some complex interactions among heterogeneous vegetation condition, atmospheric feedback and soil moisture availability.

Many networks related to large scale eddy covariance and the ground-based methods can provide some good estimation for ET on local level [3]. But these methods have some uncertainties and scientific limitations because of the errors which are caused by the mismatch of scale, time consuming and costly instruments installation and low density of network.

Droughts and floods which are increasing each and every day have gained special focus in Pakistan due to the great causalities and monetary loses. It is affecting the country socially and economically. The main reason is climate change and global warming which are causing these extreme weather events [17]. In the year 2019, Pakistan is ranked as the eighth most vulnerable country for the climate change. In 2020, it has gained fifth position all over the world. Therefore, it is very important for the country to do some climate change research which includes crop yield or hydrological models, ecological or drought forecasting, and water cycle. That is why, accuracy in the estimation of ET at the temporal and regional scale is very important and critical for the country [6].

Correct measurement of evapotranspiration is very challenging because it depends on the connection of vegetation conditions, soil moisture and many other things [7].

There are many ground based measurements implemented over the past few past years to estimate the amount of ET. These methods could be divided into 2 different categories which are Eco physical techniques (e.g. stable isotopes, sap flow sap and open top chamber) and micro-meteorological estimations (e.g. Eddy covariance system, Bowen Ratio and Scintiliometry). These can give a suitable and good measurement and estimation for evapotranspiration on the local level. But it is important to note that there are some uncertainties and scientific restriction in these methods while demonstrating the spatiotemporal changes in the ET at the global and regional scales [11].

Increasing development of the satellite-based models in some past few years which made things easy to get the temporal and spatial variability of the evapotranspiration from the regional to global scales and continental scales. But there are still many levels of uncertainties on the basis of input parameterization, structural assumptions and theories. [8].

Huge efforts have been made for making the large-scale reanalysis ET products and long term continuous through the combination of remotely sensed vegetation index and ground based meteorological indexes. There are many global evapotranspiration products that are continuously and widely available datasets with huge coverage of spatio-temporal such as MERRA, GLEAM, GLDAS and MOD16 [11].

Satellite datasets give proper information on the hydrological parameters and variables all over the world for different locations and areas where the in-situ observations are available in limited amount. [16]. There are many studies that show that satellite-based ET products are based on regions and it gives different amount of accuracy for different regions.

Although remote sensing ET models can provide relatively accurate spatial distributions of instantaneous ET, it is usually only employed under clear sky conditions and at an instantaneous scale [10]. Therefore, it is important to do proper evaluation of this data by comparing it to the gauge observations that are available before the application.

This study provides a comprehensive insight on the quality and comparison of three globally available Evapotranspiration (ET) Products which in results prove to be beneficial for the hydro-meteorological community and regional water users on the basis of climatic conditions and major landscape over long-time scales. Therefore, this study can be very helpful to deal with climate change challenges in an effective way.

2. Study Area

The study area (Figure 1) is Pakistan which is a developing country. It is located between the 61°E–77°E (longitude) and 23.5°N–37°N (latitude). The geographical area of Pakistan is 796096 km^2 with the ranges from zero to 8611m. Because of the change in environmental conditions and the wide vegetation types across the regional ET estimations, there are large uncertainties of evapotranspiration products when compared with ground-based measurements [14]. The landscape of Pakistan is diverse. There is snow peaked mountains in the north of the county. In the central region, there is plain area and deserts. That is why, there is prominent change in the average annual precipitation in various regions of the country [13]. In Pakistan, the profile of ET has been observed and analyzed for cropping seasons on a long-term basis. For this, the climate data related to wind speed, mean relative humidity, minimum & maximum temperatures for the past few years are used to study [4]. Climate change can affect the agriculture and also the weather patterns of Pakistan significantly. There are many studied that showing agreement with this statement in the context of global warming and climate change [15].

3. Research Methodology

For this study, two sorts of data are collected. First are the ground-based measurements. This type of data is measured on ground by different methods like Lysimeters, Water Balance etc. under the vicinity of Pakistan Government. The second type of data is collected from satellite based evapotranspiration products which includes three products; MODIS (Moderate Resolution Imaging Spectroradiometer version-16A2), GLDAS (Global Land Data Assimilation System version-2.1) & GLEAM (Global Land Evaporation Amsterdam Model version-3.3b). This type of satellite data is readily available specifically on NASA LANDSAT websites to be downloaded and use in research & other useful purposes. They have widely and continuously available datasets [1]. The details of these satellite products have been given in (table 1).

Evapotranspiration data of 30 selected gauge stations (Figure 1) across the whole country for the period of 10 years (2009-2018) was obtained from Pakistan Meteorological Department [PMD], University of Agriculture, Faisalabad (UAF) & National Engineering Services Pakistan [NESPAK]. Some other data for verification purposes has also been taken which includes

1. Temperature Data;
2. Wind Speed;
3. Sunshine Hours;
4. Relative Humidity.

There are very few researches related to the reduction of ET uncertainties for the applied conditions in hydrological filed [5]. That is why, this study will focus on accessing the performance of three satellite-based evapotranspiration products which are MODIS, GLDAS and GLEAM.

Data from satellite evapotranspiration products i-e from

GLEAM, GLDAS and MODIS available at NASA Landsat websites were downloaded in NETCDF and HDF files formats respectively. Verification of data is done by the opening files of HDF in HDF Viewer & that of NETCDF in panoply software. The rate for ET is usually showed in millimeters as mm per unit time. The time unit in this could be a month, decade, day, an hour or even an entire year [9].

Proper daily estimate of evapotranspiration of each point from the panoply software has been observed. Extraction of the ET data was carried out using Arc GIS Software & recorded in the Microsoft excel.

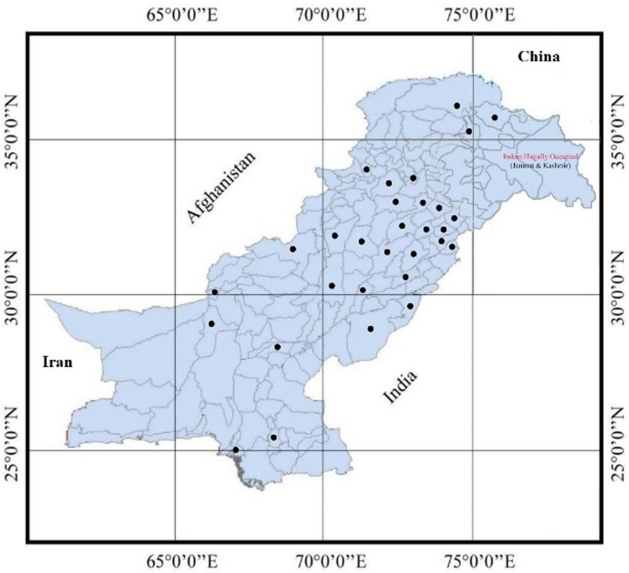

Figure 1. *Study Area, Pakistan.*

4. Comparison

Comparison of the data was carried out at monthly timescale based upon:

4.1. Climatic Zones

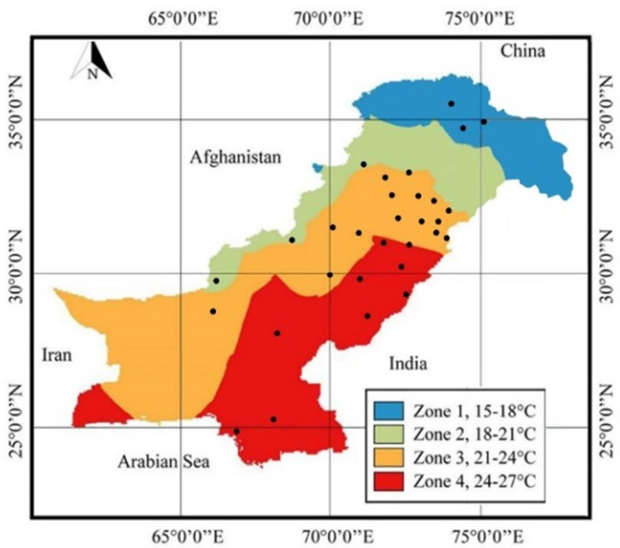

Figure 2. *Climatic Zones, Pakistan.*

On the basis of data collected over the time period of 30 years, the average annual temperature of sixty stations in the area of study, climate zoning of the Pakistan was done with the usage of GIS. Four different zones were selected across the study area (Figure 2).

4.2. Seasonal Variations

a) Winter (from December to February);
b) Spring (from March to May);
c) Summer (June-August);
d) Autumn (September-November).

The evapotranspiration data which is obtained from the various ET products like GLDAS, GLEAM & MODIS will be compared with each other individually and also compared with the ground based data by using six performance metrics which are:

1. *Bias* [Statistical Measure]
2. *ST. Dev* [Standard Deviation]
3. *RMSE* [Root Mean Square Error]
4. R^2 [Correlation Coefficient]
5. *IOA* [Index of Agreement]
6. *NSE* [Nash-Sutcliffe Efficiency]

The details of Performance Metrics including their symbols, formula units, ranges & ideal values have been given in (Table 2).

5. Results

5.1. Zones Based Performance Evaluation

Zonal Averages of the performance metrics for MODIS, GLEAM, and GLDAS given in (table 3) & shown in (Figure 3) indicates that GLEAM gives overall better performance than other two products metrics giving better correlation coefficient (R^2) and better agreement (IOA) on almost all zones. RMSE & BIAS values also shows that GLEAM shows less degree of errors and uncertainties. NSE shows that GLEAM show better efficiency than other two products. Overall, GLEAM outperformed than other two products.

5.2. Performance Evaluation at Seasonal Scale

Products GLEAM, GLDAS and MODIS were also properly evaluated at the seasonal scales. It was evaluated all the thirty stations that are selected using the estimations monthly basis.

For the representation of the graphical overview for the performances of the each evapotranspiration products in various seasons, clustered columns are made for this part. The tip shows the average or median amount, air-bar shows the spread of data around mean value and no overlapping means different values than other product which is conclusive.

(Figure 4) shows the Clustered Columns for Root Mean Square Error, Correlation Coefficient, Nash Sutcliffe Efficiency, Standard Deviation, BIAS and Index of Agreement of GLDAS, GLEAM and MODIS for various seasons such as (a) winter, (b) spring, (c) summer and (d) autumn.

In winter, the RMSE value of GLEAM for performance metrics is usually slightly greater than the other two products. However, the value of standard deviation of MODIS is higher than the other two products in winter. In summer, standard deviation value of GLDAS is higher than the other two. In autumn, the overall performance of MODIS is worse than other two ET Products.

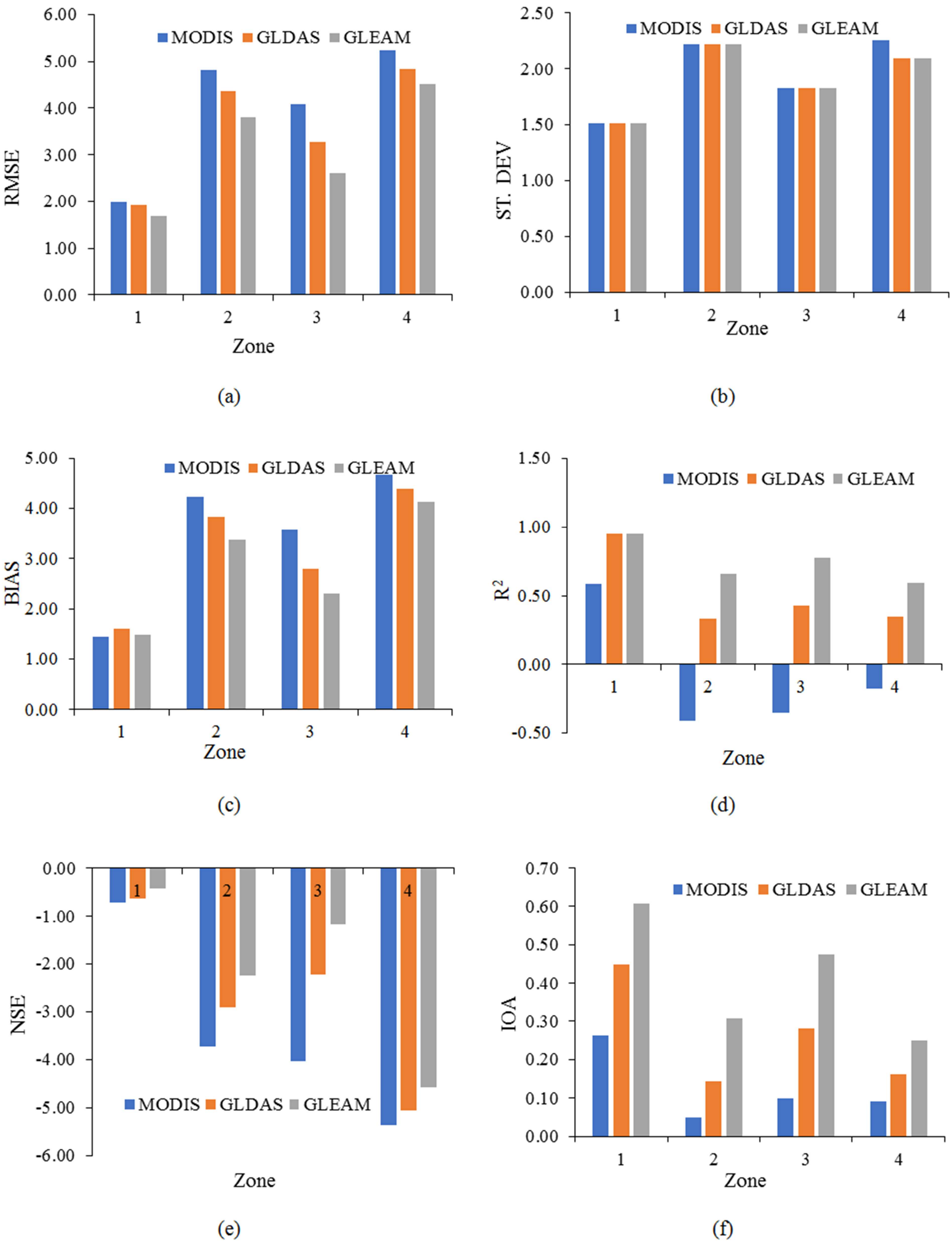

Figure 3. *Bar Charts of the Performance Metrics Obtained By Comparing the Monthly Average ET Estimates of Satellite Products with Gauge Data in All Four Zones.*

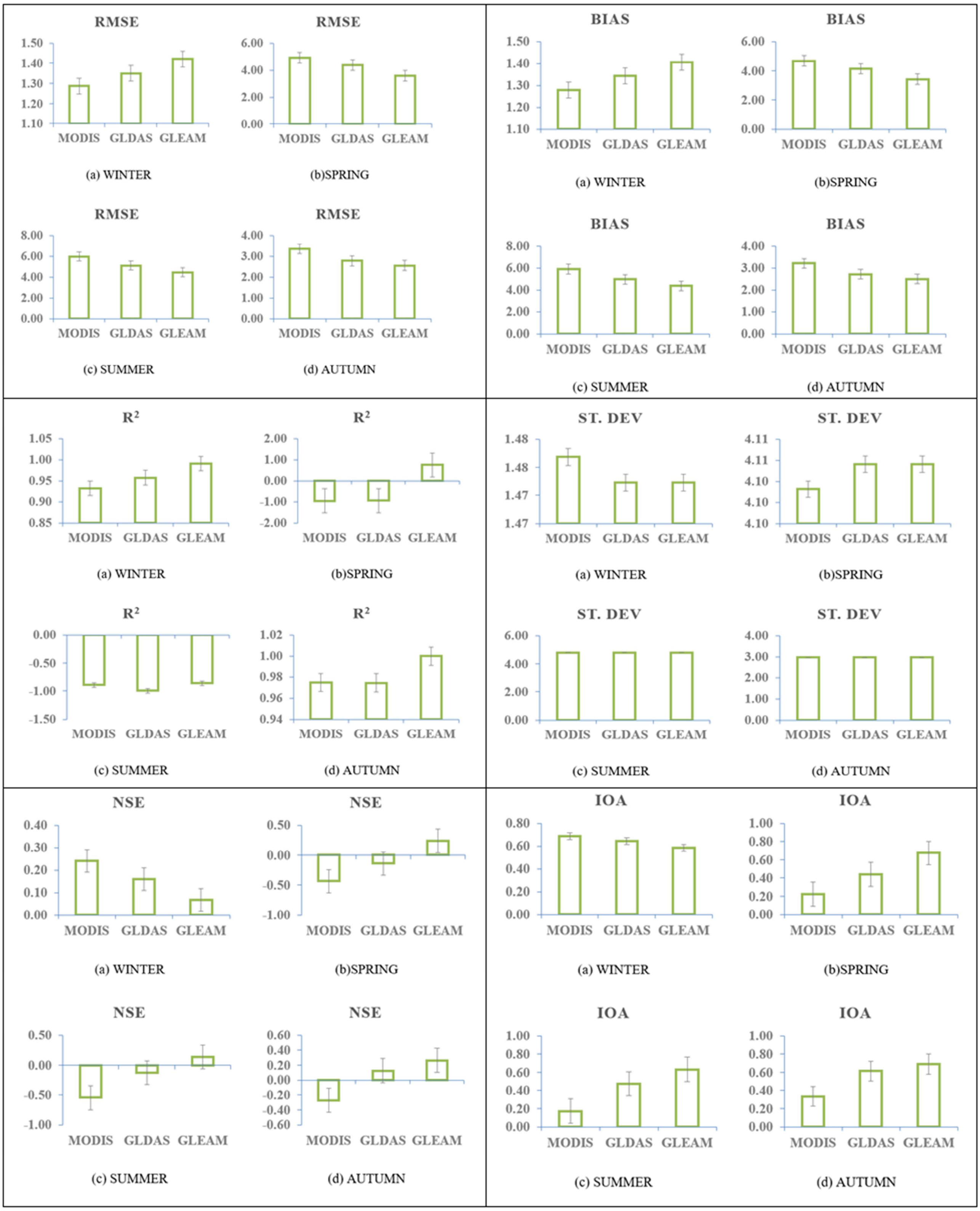

Figure 4. *Clustered Columns for Root Mean Square Error, Correlation Coefficient, Nash Sutcliffe Efficiency, Standard Deviation, BIAS and Index of Agreement of GLDAS, GLEAM and MODIS for various seasons such as (a) winter, (b) spring, (c) summer and (d) autumn.*

Table 1. *Details of Satellite Data.*

Product	Version	Spatial Resolution	Temporal Resolution	Time Period
Global Land Data Assimilation System (GLDAS)	GLDAS V2.1	0.25°×0.25°	Monthly	2009-2018
Moderate Resolution Imaging Spectro-radiometer [MODIS]	MOD16A2	0.1°×0.1°	8 daily	2009-2018
Global Land Evaporation Amsterdam Model [GLEAM]	GLEAM v3.3b	0.25°×0.25°	Daily	2009-2018

Table 2. *Formulas of Performance Metrics, Their Ranges, and Ideal Values.*

Performance Metrics	Symbol	Formulas	Perfect Value	Units	Remarks
Stats Measure	BIAS	$\frac{1}{n}\sum_{i=1}^{n}(E_i - M_i)$	near to 0	Same as ET	mm/d
Root Mean Square Error	RMSE	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_i - M_i)^2}$	0.2-0.5	Same as ET	mm/d
Linear correlation coefficient	R^2	$\frac{n(\sum E-M)-(\sum E)(\sum M)}{\sqrt{[n\sum E^2-(\sum E)^2][n\sum M^2-(\sum M^2]}}$	up to 1	Unit Free Value	Negative value also possible
Standard Deviation	St Dev	$\sqrt{\frac{1}{n}\sum_{i=1}^{n}(E_i - \overline{E})^2}$	2SD	Same as ET	mm/d
Nash Sutcliffe Efficiency	NSE	$1 = \frac{\sum_{i=1}^{n}(E_i-M_i)^2}{\sum_{i=1}^{n}(E_i-\overline{E})^2}$	up to 1	%	Negative value also possible
Index of Agreement	IOA	$1 - \frac{\sum(E_i-M_i)^2}{\sum(\lvert E_i-\overline{Mi}\rvert+\lvert M-\overline{Mi}\rvert)^2}$	0 to 1	Unit Free Value	Ratio B/w Errors

Table 3. *The Zonal Averages of the Performance Metrics of MODIS, GLEAM, and GLDAS for the Four Zones at the Monthly Timescale.*

BIAS				**RMSE**			
Zone	**MODIS**	**GLDAS**	**GLEAM**	**Zone**	**MODIS**	**GLDAS**	**GLEAM**
1	1.44	1.61	1.48	1	1.98	1.93	1.69
2	4.22	3.83	3.37	2	4.81	4.37	3.80
3	3.57	2.79	2.30	3	4.09	3.26	2.60
4	4.67	4.38	4.14	4	5.25	4.82	4.50

R^2				***St Dev***			
Zone	**MODIS**	**GLDAS**	**GLEAM**	**Zone**	**MODIS**	**GLDAS**	**GLEAM**
1	0.59	0.95	0.95	1	1.51	1.51	1.51
2	-0.41	0.33	0.66	2	2.22	2.22	2.22
3	-0.35	0.43	0.78	3	1.83	1.83	1.83
4	-0.17	0.35	0.60	4	2.26	2.10	2.10

NSE				**IOA**			
Zone	**MODIS**	**GLDAS**	**GLEAM**	**Zone**	**MODIS**	**GLDAS**	**GLEAM**
1	-0.72	-0.62	-0.42	1	0.26	0.45	0.61
2	-3.73	-2.90	-2.24	2	0.05	0.14	0.31
3	-4.03	-2.22	-1.17	3	0.10	0.28	0.47
4	-5.37	-5.06	-4.57	4	0.09	0.16	0.25

5.3. Spatial Maps

The spatial maps of GLDAS, GLEAM and MODIS that of four seasons and their average annual mean value are given below:

5.4. GLDAS

Range of ET observed from this satellite product lies between a little below 0 to more than 2 mm/day. Spatial Maps of GLDAS shows more ET values (almost 1-2 mm/day) in upper Punjab areas while it shows less value in Sindh area (less than 1 mm/day) in almost all seasons. It gives somewhat realistic and near to ground based values. (Figure 5) shows Spatial Maps of GLDAS.

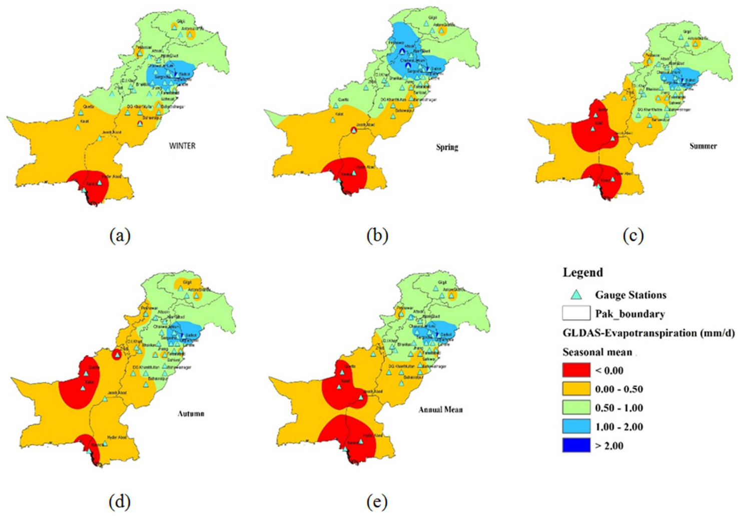

Figure 5. *Spatial Maps GLDAS (a) winter, (b) spring, (c) summer, (d) autumn, (e) Annual Mean.*

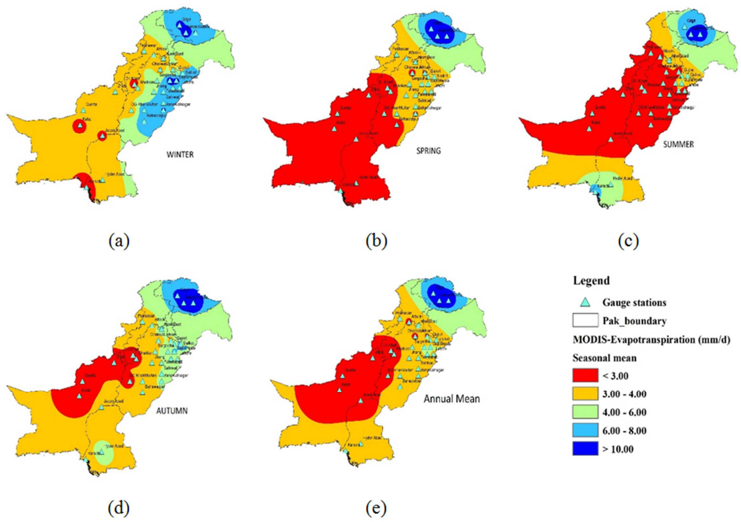

Figure 6. *Spatial Maps MODIS (a) winter, (b) spring, (c) summer, (d) autumn, (e) Annual Mean.*

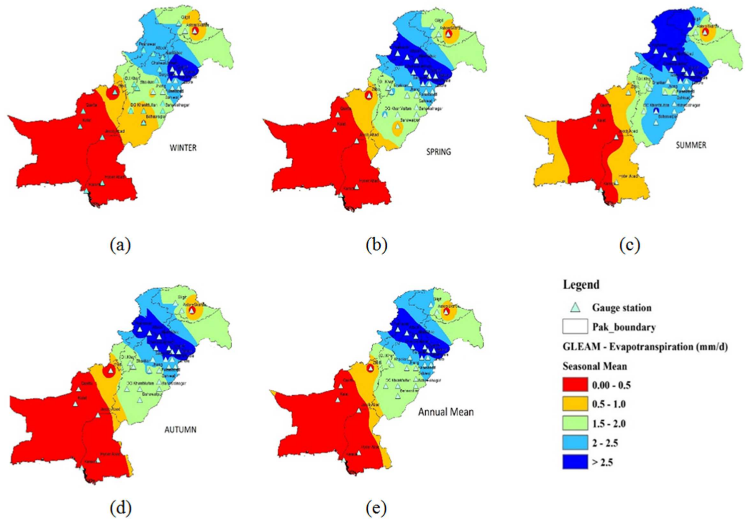

Figure 7. *Spatial Maps GLEAM (a) winter, (b) spring, (c) summer, (d) autumn, (e) Annual Mean.*

5.5. MODIS

Range of ET observed from this satellite product lies between 3 to 9 mm/day. Spatial Maps of MODIS shows more ET values in upper Khyber Pakhtunkhwa areas (6-8 mm/day) in almost all seasons while it shows less value in lower Punjab, upper Sindh and Baluchistan areas (3-5 mm/day) specifically in spring and summer. Therefore, these values are not close to ground based values. (Figure 6) shows Spatial Maps of MODIS.

5.6. GLEAM

Range of ET observed from this satellite product lies between 0 to a little more than 2.5 mm/day. Spatial Maps of GLEAM shows more ET values in upper Punjab & Khyber Pakhtunkhwa areas (2-2.5 mm/day) while it shows less value in Sindh and Baluchistan areas (less than 1 mm/day) in almost all seasons. It gives very realistic and near to ground based values. (Figure 7) shows Spatial Maps of GLEAM.

6. Conclusion

Different Evapotranspiration (ET) products having different spatio-temporal resolution at continental and global scale have been developed by using commonly available satellite imagery and ground based observation. However, the developed ET products have large uncertainties that limits their operational hydro meteorological applications, especially in water scarce regions where water consumption is increasing. Hence, this study attempted to evaluate the performance of three widely available products namely GLEAM, GLDAS & MODIS in diverse regions of Pakistan. Based on overall analysis, it was resulted that: in zones based analysis GLEAM performed better as compared to other ET products in all zones, whereas GLDAS & MODIS ranked 2nd and 3rd respectively. GLEAM performed consistently better with least error whereas GLDAS and MODIS showed comparatively high uncertainties over all dry as well as humid regions.

Seasonal analysis resulted that GLEAM was best suitable product in case of spring, summer & autumn, whereas MODIS provide better agreement in case of winter. On the other hand, GLDAS was ranked 2nd in case of all seasons.

Overall performance of GLEAM Product was better than other Products. This study reveals that in future GLEAM can be used as an effective tool for evapotranspiration estimation in poorly gauged areas of Pakistan especially in zone 3 and zone 4, which are dry areas. Performance of GLEAM can be enhanced by merging its ET estimates with other state-of-the-art satellite products or by applying ensemble algorithm.

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