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Evapotranspiration Over the Indian Region: Implications of Climate Change and Land Use/Land Cover Change

Garima Singh and Sudhir Kumar Singh†
K. Banerjee Center of Atmospheric and Ocean Studies, University of Allahabad, Prayagraj, 211002, India
†Corresponding author: Sudhir Kumar Singh; sudhirinjnu@gmail.com

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ABSTRACT

Evapotranspiration (ET) plays a significant role in climatic studies, directly influencing the hydrological cycle, energy balance equation, and surface vegetation. ET comprises three components: bare soil or ground evaporation, evaporation, and transpiration, in which vegetation removes water influenced by food grain production. In turn, soil moisture availability depends on precipitation characteristics over land, surface net radiation, and wind speed are the major climatic factors that together determine the magnitude of ET. This controls moisture availability in the lower troposphere, hence atmospheric stability, chances of cloud formation, and precipitation. Though the study of evapotranspiration is important for determining agricultural water consumption and analyzing drought situations, there is a lot of uncertainty in its accurate estimation. Land use/Land cover changes (LULCC) occurring throughout the Indian subcontinent have been found to affect the characteristics of low to moderate rainfall events and surface temperature extremes (Halder et al. 2016). A global warming scenario will change the hydrological cycle, and the impact of anthropogenic factors has also necessitated the need to understand the mechanisms that control changes in ET over India. In this study, we want to analyze the relationship between transpiration and the Normalized Difference Vegetation Index (NDVI) and investigate the relationship between canopy interception with respect to NDVI all over the Indian region. Attempts have been made to assess the impact of changes in climate and LULC on ET and its three components over the Indian region from 1981 till the present time. The monsoon season increases precipitation, and soil evaporation is found to increase at first, along with an increase in NDVI followed by canopy evaporation and transpiration. It is noted that changes in precipitation and LULCC across the Indian subcontinent have contributed significantly to changes in ET in different seasons. As variability in surface net radiation also plays an important role in controlling changes in total ET, it is being investigated.

INTRODUCTION

Global climate, as well as that over the Indian region, has been changing since the last century due to natural and anthropogenic factors, per the IPCC Fifth Assessment Report (IPCC) AR5 (Stocker et al. 2013). Significant global warming has resulted in rapid intensification of the hydrological cycle with adverse impacts on ecosystems and agricultural and water resources worldwide. In a regional context, modeling studies suggest that unprecedented changes have occurred, varying in terms and trend of average daily value and extreme (Both the maximum and the minimum) surface air temperature and heavy and very heavy precipitation (Halder et al. 2016). Cloudiness and associated changes in the incoming shortwave radiation, atmospheric humidity, aerosols, heat and cloud waves, and droughts (Rohini et al. 2016, Rajeevan & Nayak, 2017) over the Indian land parts in the last few decades. Understanding the mechanism inherent in such changes over India, particularly in terms of precipitation, soil moisture, runoff, evapotranspiration, and surface temperature, contributes to an accurate evaluation of the state of the surface weather in the area present Anthropocene and estimating better and improved model projections of the future climate under different radiative forcing (Stocker et al. 2013) scenarios.

A combination of evaporation and transpiration is known as evapotranspiration, evaporation is a process in which water moves from the liquid state to back into the atmospheric water vapor, and transpiration is a process in which loss of water vapor through open leaf stomata. Under sunny, warm weather, the amount of water lost through evaporation is higher than in cool, cloudy weather. Solar radiation absorbs the solar radiation, and heat radiated by the earth increases the temperature of the air. ET increases with the temperature, and molecular water gains more energy, move faster, and escapes more quickly. Solar radiation (Warmer water evaporates faster as the air temperature is increased by solar energy in addition to heating the air, the sun also causes the rate of evaporation to increase due to the warmth) and wind draws in drier air, which improves the evaporation rate (since humid air is blown away by the wind). ET decreases with increasing humidity (because the air already has high moisture content as a result, excess moisture will not be able to accumulate). An ET rate is typically measured in millimeters (mm) per unit of time, and it expresses the amount of water lost per unit of time from a cropped surface over several time frames, such as an hour, a day, a month, a decade, or even a growing season.

The need to attain self-sustainability in food grain production led to the Indian green revolution in the 20th century. However, large-scale increases in agricultural practices and irrigation activity resulted in declination in surface and groundwater in northern India (Rodell et al. 2009). Such activities also altered the surface temperature variability on the northern Indian subcontinent (Roy et al. 2007). On the other hand, studies also show that rapid deforestation and an increase in crop cover fraction over the Indian region has resulted in surface temperature changes on a daily and extreme basis and rainfall distribution and intensity (Halder et al. 2016).

Changes in near-surface and low to mid-tropospheric atmospheric variables can occur through changing fluxes near the surface and state variables such as soil moisture. Net surface net radiation (NRAD) is a component of the hydrological cycle broken down into sensible, latent heat fluxes by soil moisture. Changes in the different components of the hydrologic cycle mentioned before are linked thermodynamically and dynamically (Seneviratne et al. 2012). Spatiotemporal and vertical changing circumstances in the distribution of clouds and aerosols bring about alterations in the net surface radiation (NRAD) that contributes significantly to determining the surface fluxes of moisture and heat. Therefore, to understand long-term variability in ET and its effect on the surface climate throughout India in a changing climate scenario and anthropogenic land use/ land cover (LULC) change, there is a need for a detailed investigation of all the components.

So far, very few studies have investigated the characteristics and causes of changes in global ET or that over India. One of the factors for that is the lack of accurate data and high uncertainty in the estimation of ET. Land use/ Land cover changes (LULCC) occurring throughout India in the form of conversion of forest cover into agriculture or bare land have been found to affect the characteristics of low to moderate rainfall events and surface temperature extremes (Halder et al. 2016). Furthermore, under a global warming scenario, the hydrological cycle would change. The impact of various anthropogenic factors has also necessitated an urge to understand the factors that control ET characteristics in India. Goroshi et al. (2017) analyzed the spatial seasonal trend of ET all over India from 1983-2006. For the forest region, they observed decreasing trend of ET. An analysis of the seasonal trend shows a declining trend during summer monsoons and post-monsoons, and the northeast monsoon and premonsoon period, the trend has been increasing. Goroshi et al. (2017) calculate the correlation between ET and some climatic factors (soil moisture, precipitation, temperature, and insolation). They found a positive correlation in ET related to rainfall and soil moisture in arid semi-arid regions. An inverse correlation is also seen between ET and temperature in the dry areas of western India. Chattopadhyay and Hulme (1996) analyzed the pan evaporation and potential evapotranspiration, India's time series for various stations, and seasonal analysis for all over India in both short term (15 years) and long term (32 years). They find a diminished trend in pan evaporation and potential evapotranspiration all over India. Lin et al. (2018) analyzed the spatiotemporal trend of global vegetation and its connection with some anthropogenic forces (GHG) and the influences of ENSO, AO, and AMO on vegetation with the help of NDVI. This analysis showed an increasing trend Throughout Europe and other land areas. In high northern latitudes, NDVI is influenced by temperature. Still, in dry and semi-arid regions, it's influenced by water, and East and southern Asia, as well as the Amazon, is influenced by radiation. Previous studies analyzed Climate change as a local driver of vegetation change. The climate is determined by precipitation, radiation, and temperature. Temperature dominates in arid and semi-arid zones; Tropical rainforests are the only areas where radiations are the limiting factor. This study aimed to examine the long-term mean and inter-annual variation of vegetation cover and ET components over the Indian region and their relationship.

Study Area

India is located in the tropics 6°-38°N; 68°-98°E. Its vegetation and ecosystems are known for their diversity and climatic variability. The climate of India is divided into four seasons. The southwest monsoon season lasts from June to September, the post-monsoon season lasts from October to November, the winter season lasts from December to February, and the pre-monsoon season lasts from March to May. The southwest monsoon season brings warm and humid weather. The country receives 80% of its annual rainfall during this time. This is a cold and dry period during the northeast monsoon; however, significant amounts of rain recorded in the southeast of the country are primarily dry and moderately

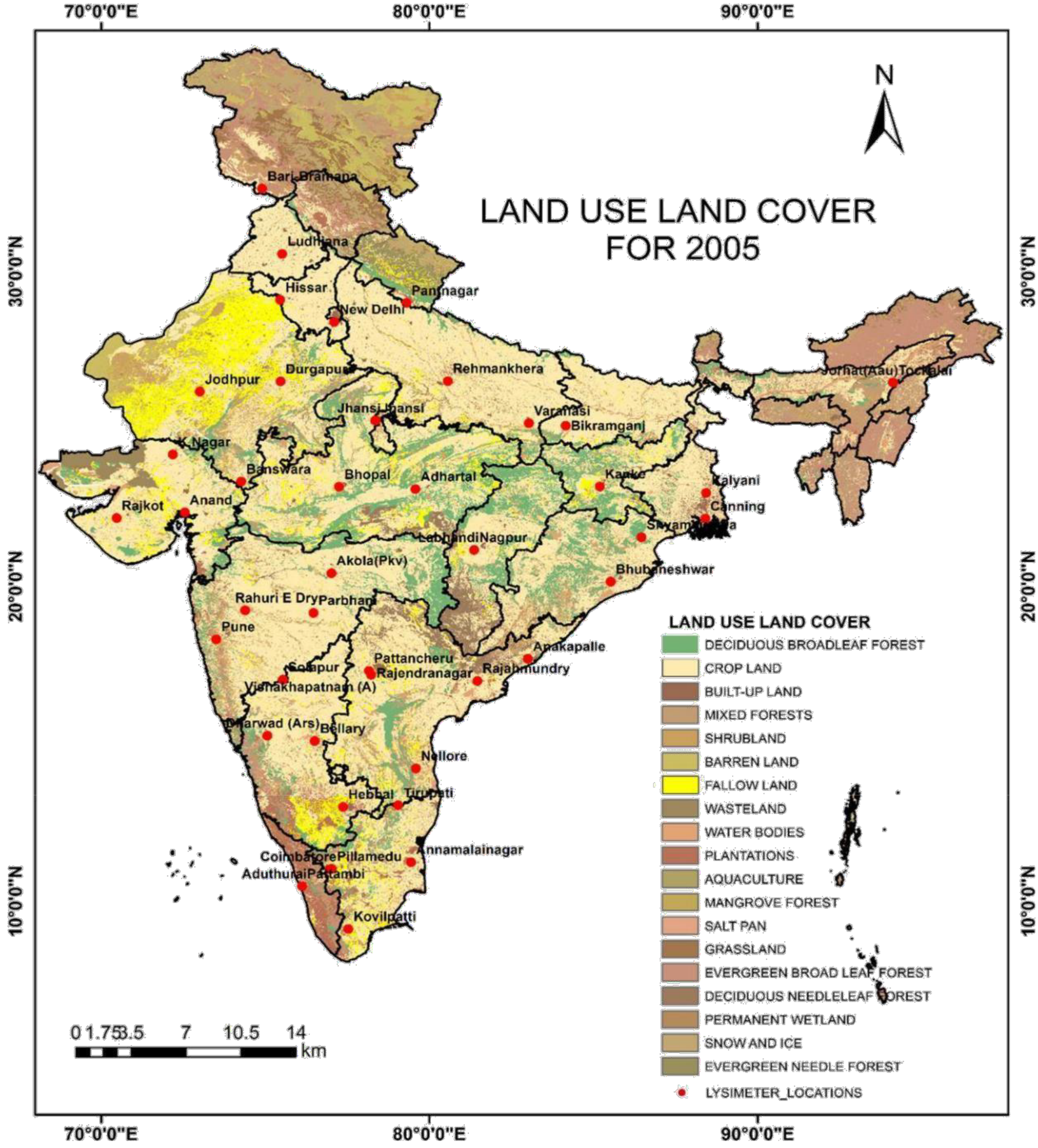

Fig. 1: Land use land cover types derived for 2005 (Roy et al. 2015, Meiyappan et al. 2016). Lysimeter sites in India are indicated in red circles.

warm during the two inter-monsoonal periods. A typical annual temperature varies by latitude, with humid regions experiencing 25°C and arid regions experiencing 45°C. Throughout the country, the latitudinal zonation of vegetation is caused by climate variability. The country's most common vegetation types are broadleaf forests, mixed forest types, grasslands, short woods and meadows, and desert steppe cover the deserts and semi-desert regions (Fig. 1).

The country is divided into 29 states and seven union territories. As of 2021, there are 748 districts within states and territories. In terms of population, There are 1.38 billion people in India, among the world's second-largest population. Agriculture provides the primary source of income for over 70% of rural households.

MATERIALS AND METHODS

In the absence of in-situ ET observations, we have used meteorological observation-driven global reanalysis data on ET for this study.

Normalized Difference Vegetation Index (NDVI)

The NDVI estimates the amount of light absorbed by vegetation over the land's surface. NASA Goddard Space Flight Center provides future NDVI updates and this NDVI log. This www provides NDVI data in various spatial and temporal resolutions. The data version of the current www page is the monthly average data for 1-degree longitude and latitude.

We calculated net CDF for this data and calculated the mean and the standard deviation for (the 1981-2001 AVHRR) from the NASA platform (http://research.jisao.Washington.edu) and the Moderate Resolution Imaging Spectroradiometer (MODIS, 2002-2015). Definitions of NDVI: A ratio between the reflected solar energy an incident leaf receives in the red spectrum band through the chlorophyll and the reflected solar energy reflected through the spongy mesophyll the plant emits near-infrared light. It is calculated as:

$$NDVI = NIR\text{-}RED/NIR+RED$$

The measurement of crop production has been based on an integrated series of NDVI during the growing season and how these affect the overall health and growth of the plant, water stress, and photosynthetic activity.

GLDAS 2.0

Monthly evapotranspiration and its components (transpiration, bare soil evaporation, and canopy evaporation) data (1981-2010; at 0.25 x 0.25 resolution) from the NASA Global Land Data Assimilation System. Princeton's meteorological forcing inputs are entirely used in Version 2.0 (Goroshi et al. 2017); Trend analysis of evapotranspiration over India: Observed from long-term satellite measurements). We are using these data sets to study evapotranspiration and its components. (https://disc.gsfc.nasa.gov/uui/datasets/GLDAS_NOAH025_M_V2.0/)

GPCP 2.2

From January 1979 to the present, the Global Precipitation Climatology Project (GPCP) version 2 monthly precipitation analysis is available at 2.5° latitude * 2.5° longitude resolution. We calculated NetCDF for this data, mean, standard deviation, and long-term changes, including the trend of seasonal precipitation (mm.day^{-1}) over India for 1981-2015. At NASA Goddard Space Flight Center's Mesoscale Atmospheric Processes Laboratory - Atmosphere, the GPCP combined precipitation data were calculated as part of the GEWEX program.

GrADS (Grid Analysis and Display System), Earth science data can easily be accessed, manipulated, and visualized with GrADS. GrADS has 2 data models to handle gridded and station data. GRADS uses a five-dimensional data environment with four conventional dimensions (longitude, latitude, vertical altitude, and time) and one optional fifth dimension for grids, which is typically not used but could be used for ensemble applications. The GrDAS is open-source software, and FORTRAN programming has been used to perform different analyses. Long-term means characteristics and interannual variability of the climate, vegetation, and ET data have been analyzed. Correlation and regression analysis were performed to understand how climate and anthropogenic variables relate to evapotranspiration.

RESULTS AND DISCUSSION

The boreal summer monsoon season, comprising of the month approximately 80% of India's annual precipitation, occurs from June to September. (Fig. 2) Mean and long-term changes, including the trend of seasonal precipitation in mm.day^{-1} over India). The southwest monsoon season begins in June and ends in September. For the Indian Subcontinent, the southwest monsoon is a major rainy season. The summer monsoon period is when the southwest monsoon holds off over the country. This is the time when nearly 80% of the Indian rainfall occurs. Maximum rainfall during the season reaches the western ghats, parts of central and eastern India, the foothills of the Himalayas, and the northeastern region. The southwest monsoon arrives by the end of May over the southern tip of the peninsula. During the beginning of the monsoon season, there is an explosive increase in rainfall. As the storm progresses inland, By mid-July, it has covered the whole country. By the beginning of September, it starts to pull away from the extreme northwest, gradually moving southward. Because of its location on the eastern (eastward) side of the western ghats, Tamil Nadu is considered a rain shadow region. It rains most often over the southernmost part of the state.

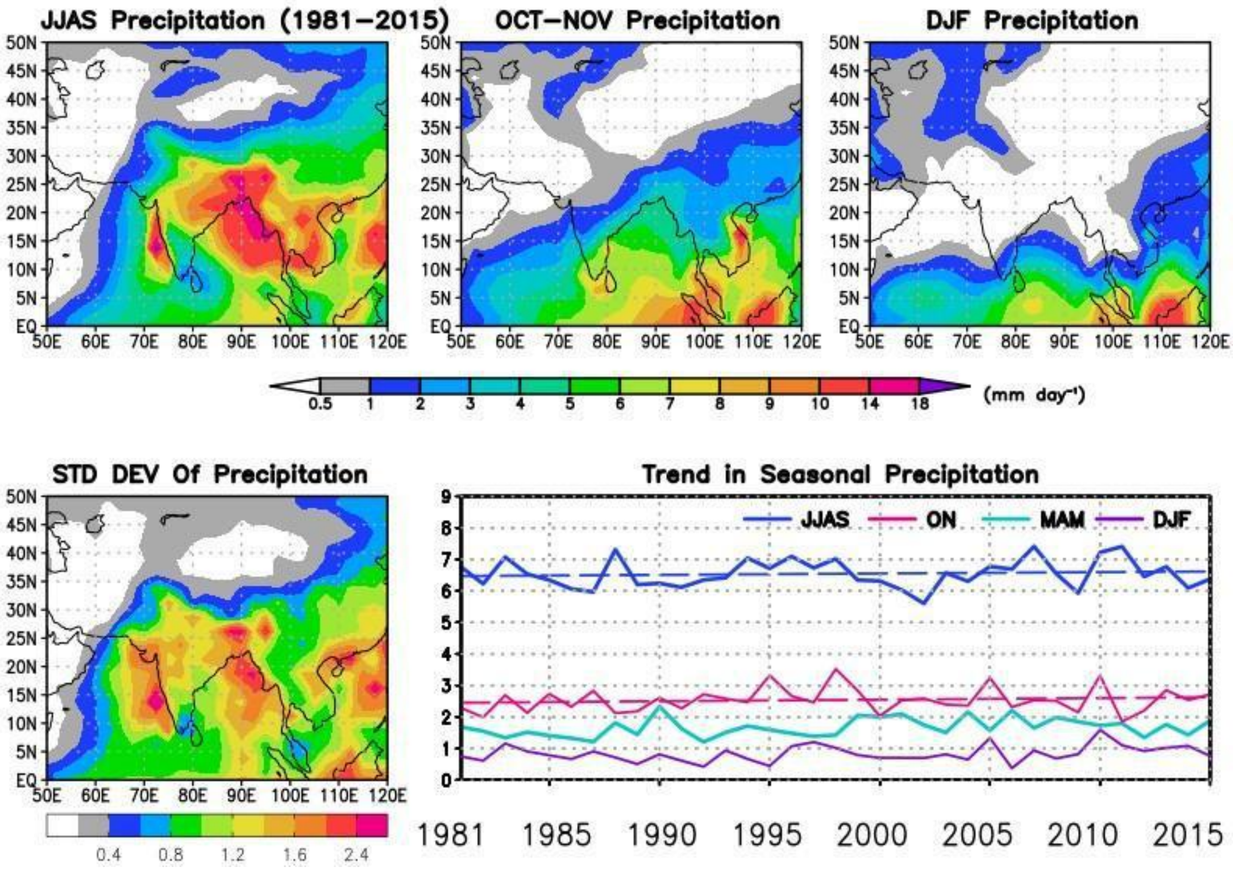

Fig. 2: (Top) Mean, (bottom) interannual standard deviation and long–term changes, including the trend of seasonal precipitation ($mm.day^{-1}$) over India.

Fig. 3 shows an analysis of the mean seasonal distribution of ET over three seasons - southwest summer monsoon season (June to September), Post monsoon season (October to November), and northeast monsoon (December to February) for the study period 1981-2015. During different seasons, different spatial patterns can be observed in India. The average ET during the southwest summer monsoon was 1.8 $mm.day^{-1}$ but ranged from 1 to 3.2 $mm.day^{-1}$ in more than a third of the pixels in the country. ET was more significant than 1 $mm.day^{-1}$. During JJAS, the highest amounts of ET were seen when crops (Indo - Gangetic plains, eastern peninsula) and forests prospered, topsoil moisture was adequate, and the weather was ideal. The magnitude of the ET further grew during the autumn or mid-fall season (October-November) and reached its maximum level in all parts of the country. ET was more than 1.6 $mm.day^{-1}$ in more than 80% of pixels, an average of 2.2 $mm.day^{-1}$. In addition to this high ET, most deciduous vegetation had peak growth during this time; soil moisture was adequate, and the weather was congenial. The ET varied between 0-3.4 $mm.day^{-1}$ during DJF, with an average of 1.2 $mm.day^{-1}$. This season, more than 30% of pixels showed ET<1 $mm.day^{-1}$. A deciduous forest experiencing leaf fall, low crop production, dry weather, and little rain during the northeast winter monsoon are the primary causes of the low magnitude of the season. However, ET was high (1-1.6 $mm.day^{-1}$) in the Indo-Gangetic plains and Tamil Nadu compared with other agricultural areas in the country. It was caused mainly by the peak growth stages of winter crops.

Fig. 4 shows the inter-seasonal variations and trends in ET over India during three seasons (JJAS, ON, DJF) over 30 years (1981-2010). ET increases during the northeast winter monsoon season. Meanwhile, a decreasing trend was observed during the summer southwest monsoon and the fall post-monsoon. ET was higher during the northeastern winter monsoon during the past decade due to improved management of cropping in India's arid and semi-arid regions through irrigation and crop intensity. Due to higher aerosol loads and cloudiness, there has been an increase in solar dimming over major parts of India, and southwest monsoon and post-monsoon activity have decreased over the past years (Padmakumari & Goswami 2010).

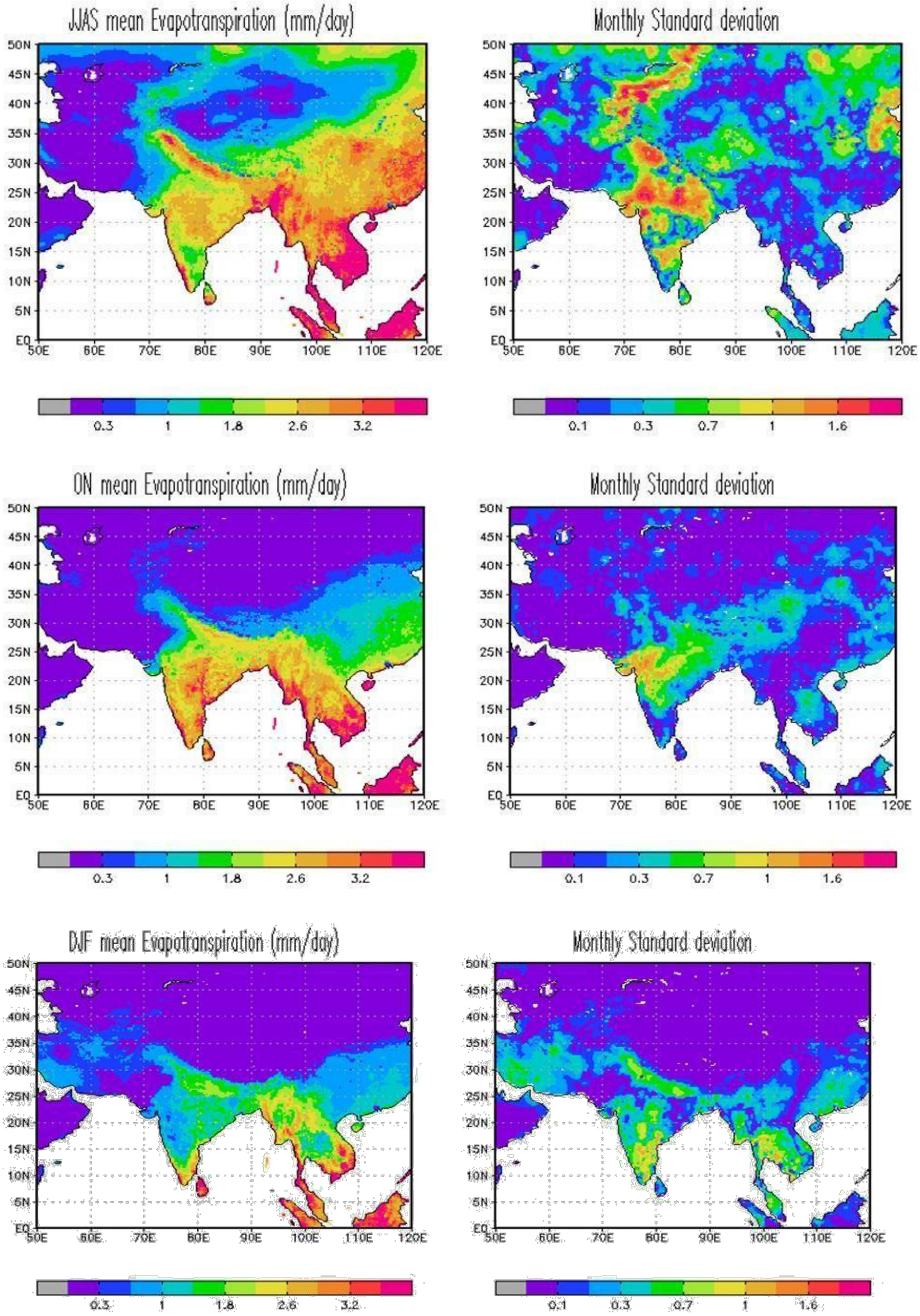

Fig. 3: (Left) Mean and (right) interannual standard deviation of monsoon (June- September), post-monsoon (October – November), and winter season (December-February) evapotranspiration (mm.day^{-1}) over India.

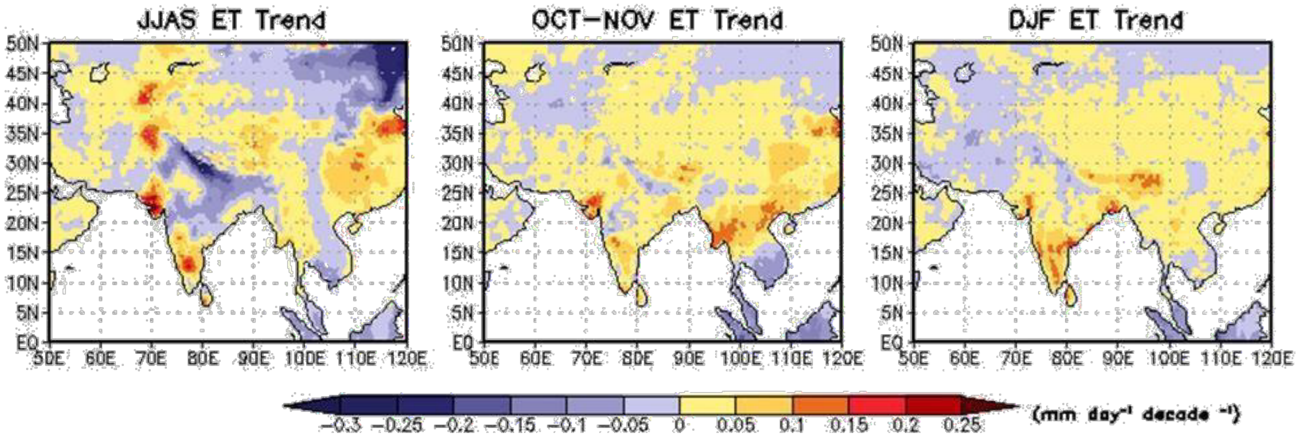

Fig. 4: Trend (1981-2010) in total evapotranspiration (ET, mm.day^{-1}decade) over India.

For the summer season, the NDVI chart showed less than 0.3 in most places and more than 0.3 in the northeast. However, the northwest and western ghats had a low vegetation index, around 0.15, compared to other areas of the country. Fig. 5 shows the vegetation cover has recovered over many parts of the country (southwest monsoon), varying from 0.1 (northwest part) to a maximum of 0.5 (northeast part). The vegetation pattern changes from hot weather to the southwest monsoon season. The two branches of the monsoon trough merge in the region for more rainfall across India, resulting in fairly widespread vegetation conducive to better harvesting. The eastern ghats and eastern parts of the Deccan plateau have NDVI values of 0.4, possibly attributed to the southwest monsoon currents along the Arabian sea and the Bay of Bengal. It is a slower process that the monsoon withdraws from northwest India and leaves the rest of the country by the end of November. By October, the northeast winds cause the northeast monsoon to develop over the peninsula's southern half. Monsoon retreat usually follows the withdrawal of the southwest monsoon. Thus the impact of retreat season on vegetation cover can be seen in the western ghats as NDVI increases above 0.4, whereas at the time of southwest monsoon season, it is below 0.4. Tamil Nadu and Kerala receive rain during this season (Fig. 2), leading to good vegetation in some western ghats. In general, NDVI data showed a positive trend in the country. India's northeastern region of India, namely the Assam region and surrounding area climate, is always wet and humid, and the vegetation index is always the highest (NDVI > 0.6). In parts of India, the NDVI has gradually decreased by winter (DJF). Parts of the western ghats and the Gangetic plains are experiencing reduced vegetation (NDVI < 0.3). The northwest part of the country is covered in deserts and semi-arid regions with a vegetation index of under 0.2. In parts of the Gangetic plains, there is low vegetation (NDVI<0.3); in the northeast, the NDVI is highest over the country and is more than 0.6.

The spatial pattern of NDVI and ET during the monsoon season also appears to follow that of rainfall, which is quite expected. However, ET's components, bare soil evaporation, transpiration, and canopy evaporation, follow different spatial patterns in different months. Interestingly, there is much difference in the spatial pattern of interannual variability of the monthly parameters over the Indian region. It can be inferred that vegetation characteristics (e.g., NDVI) and other climatic factors, such as precipitation and air temperature, also determine the variability of monthly ET over the Indian region. This has been further quantified based on correlation and regression analyses.

On the contrary, precipitation received during the pre-monsoon season (March through May) is relatively low except during severe thunderstorm events (Nor'westers) occurring over the eastern region. Monthly and seasonal temperatures are the highest during this season. As a result, the evaporative demand of the atmosphere is very high. The relative impact of the three components on total ET is characteristically different than that observed during the summer monsoon. The relative contribution of soil evaporation to ET is stronger in northern Indian states, whereas agriculture is mainly supported by irrigation activity. Though the sources of NDVI datasets before and after the year 2000 are different, one can notice significant changes not only in the spatial distribution of NDVI but also in precipitation and temperature. Our analysis has revealed interesting facets of the relationship between climatic variables and NDVI with ET during the decades before and after 2000.

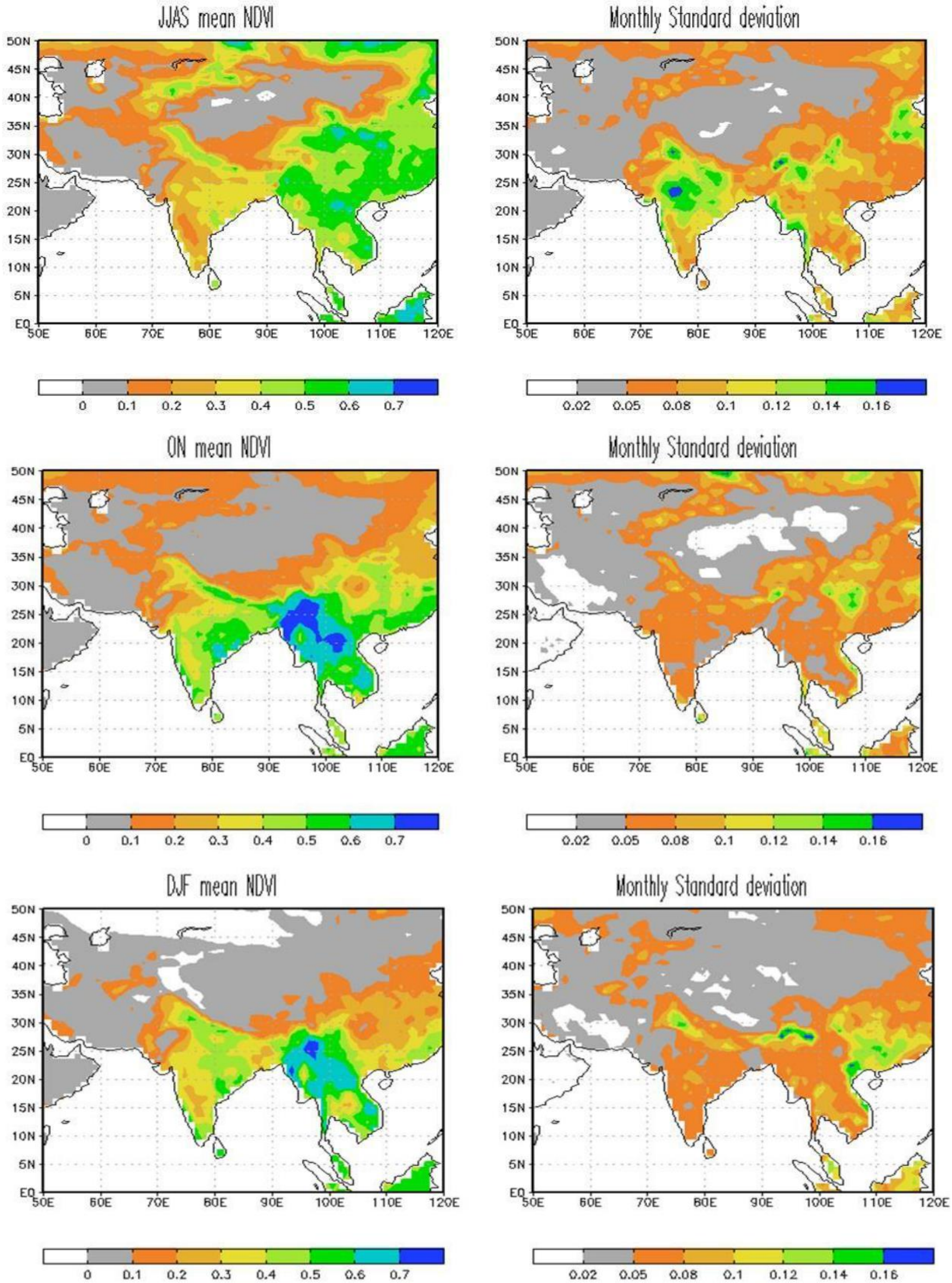

Fig. 5: (Left) Mean and (right) inter-annual standard deviation of the monsoon season (June-September), the post-monsoon season (October-November), and the winter season (December-February) NDVI over India.

CONCLUSION

A study has been conducted to investigate the impact of climate change and LULC on ET and its three components (evaporation, transpiration, and canopy interception) over the Indian region from 1981 till the present time. It is noted that there is a distinct difference in the characteristics of vegetation and climate and three components of ET and their relationship during the premonsoon seasons, as brought out by detailed statistical analysis and tests of significance. The monsoon season increases precipitation, and canopy evaporation increases along with NDVI, followed later by transpiration variability in surface net radiation, controlled by cloud cover, aerosols, and surface albedo changes, which also play an important role in controlling total ET. At the same time, ground evaporation is strongly correlated with precipitation. In this analysis, we find out 1. With increased precipitation during the monsoon season, soil evaporation is found to increase at first, along with an increase in NDVI, followed by canopy evaporation and transpiration. 2. It is noted that changes in precipitation and LULCC over the Indian region have contributed significantly to the changes in ET in different seasons. 3. As variability in surface net radiation also plays an important role in controlling changes in total ET, it is being investigated.

Another is suggested that further detailed study on the daily time scale with in-situ and remote sensing data can bring more interesting insight regarding these processes. An attempt is further made to demonstrate the impact of climatic changes and ET on food grain production over the Indian region.

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