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Signatures of aerosol-induced decline in evapotranspiration over the Indo-Gangetic Plain during the recent decades

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सार – वाष्पन-वाष्पोत्सर्जन (ET) भूमि के ऊपर जलीय चक्र में जल अंतरण की प्राथमिक प्रक्रिया है और यह जल, ऊर्जा और कार्बन चक्रों से जुड़ा हुआ है। जबकि वैश्विक जलीय चक्र में हुई वृद्धि से वाष्पन-वाष्पोत्सर्जन और वर्षा के साथ उष्ण जलवायु के तीव्र होने की संभावना है तथापि जलवायु परिवर्तन के लिए वाष्पन-वाष्पोत्सर्जन के क्षेत्रीय पैमाने की प्रतिक्रिया का परिमाण और स्थानिक वितरण अनिश्चित बना हुआ है। इस शोध पत्र में हमने 1979-2008 के दौरान भारत के 23 स्टेशनों से वाष्पन-वाष्पोत्सर्जन के स्व स्थाने प्रेक्षणों का विश्लेषण प्रस्तुत किया है, जो दर्शाता है कि भारत के गांगेय क्षेत्र (IGP) के आर्द्र उप-क्षेत्रों में वार्षिक वाष्पन-वाष्पोत्सर्जन में लगभग 9% की कमी आई है। उच्च-विभेदन वाले जलवायु मॉडल सिमुलेशन और प्रेक्षित जलवायु डेटासेट से अतिरिक्त विश्लेषण, आईजीपी में मॉनसून वर्षा और मृदा-नमी स्तर में कमी की पृष्ठभूमि में, वाष्पन-वाष्पोत्सर्जन की कटौती को तेज करने में एयरोसोल-प्रेरित सौर-किरण को धीमा करने की भूमिका को सहयोग करता है।

ABSTRACT. Evapotranspiration (ET) is the primary process of water transfer in the hydrological cycle over land and is linked to water, energy and carbon cycles. While the global hydrological cycle is expected to intensify in a warming climate with enhanced ET and precipitation, the magnitude and spatial distribution of regional scale response of ET to climate change remains uncertain. Here we present an analysis of in-situ observations of ET from 23 stations in India during 1979-2008, which shows that the annual ET has declined by about 9% over the humid sub-regions of the Indo-Gangetic Plain (IGP). Additional analysis from high-resolution climate model simulations and observed climate datasets lend support to the role of aerosol-induced solar-dimming in intensifying ET reductions, in a background of decreasing monsoon precipitation and soil-moisture levels, over the IGP.

Key words – Evapotranspiration (ET), Indo-Gangetic Plain (IGP), Aerosol.

1. Introduction

Evapotranspiration (ET) is a fundamental component of the global water and energy cycles and plays a key role in influencing land surface water resource availability and partitioning of net radiation (Wang and Dickinson, 2012; Douville *et al*., 2021). Water returned to the atmosphere through ET accounts for nearly 60% of the annual global land precipitation (Oki and Kanae, 2006). Although the strength of the global-mean hydrological cycle is expected to increase with warming more slowly as compared to near-surface mixing ratio (Betts, 1998; Held and Soden, 2006), ET over land areas is constrained by net radiation predominantly in energy-limited regimes and by soil-moisture predominantly in water-limited regimes (Kumar *et al*., 2013; Greve *et al*., 2014; Miralles *et al*., 2016). This implies that the relative contribution of ET from land surface to the global water budget assumes greater significance in a warming world (Miralles *et al*., 2014; Greve *et al*., 2019). It is observed that the global terrestrial annual ET has increased since the early 1980s due to increasing atmospheric water demand and vegetation greening (Douville *et al*., 2021). While there is high confidence that the ET trend can be partly attributed to anthropogenic forcing, there are discrepancies among independent studies in quantifying the magnitude of change in the global terrestrial ET and the associated spatial and temporal patterns (Zhang *et al*., 2016; Pan *et al*., 2020; Douville *et al*., 2021; Liu *et al*., 2021). Quantifying the spatio-temporal variations of ET is crucial for partitioning of energy and water at the Earth's surface required for reliable assessments of the impacts of climate change on hydrology and agriculture (Sellers, 1997); and evaluation of the hydrological sensitivities of weather and climate extremes such as heat-waves and droughts (Seneviratne, 2012; Seneviratne *et al*., 2006, 2010; Sheffield and Wood, 2008; Sheffield *et al*., 2012; Ganeshi *et al*., 2020).

Pan evaporation observations over India indicate a significant decreasing trend during the period 1979-2010, which has apparent linkages to decreased surface wind speeds and increased solar dimming by anthropogenic aerosols (Padmakumari *et al*., 2013). Unlike pan evaporation, actual evapotranspiration is a complex hydrological process which is controlled by soil moisture availability, as well as climatic factors. Regional variations in ET are determined by considering the limiting drivers of ET, such as soil moisture and net radiation (Roderick and Farquhar, 2004; Teuling *et al*., 2009). Jung *et al*. (2010) analyzed global monthly ET data for a relatively short period 1998-2008, based on integration of point wise ET measurements from a few FLUXNET observation sites and satellite remote sensing information and noted a declining trend in global annual ET. Furthermore, estimations of ET variability using offline models and CMIP5 coupled models indicate an overall reduction of ET over the tropics during the period 1951-2005 (Douville *et al*., 2013).

While taking note of the above, it is also realized that regional-specific information on long-term changes in ET is limited particularly over the Indian sub-continent - a region that is dominated by a strong seasonal cycle of monsoon precipitation. By analyzing terrestrial ET derived from satellite over the period 1983-2006, Goroshi *et al*. (2017) noted a significant decreasing trend of ET over India, particularly over the northeastern Indian forest regions, parts of Western Ghats and areas over Orissa and Chhattisgarh, although the causes for this observed long-term decrease of ET are not well understood. In this context, a notable study by Murthy *et al*., 2014 investigated the radiative effects of aerosols on ET using *in-situ* observations over a tropical Indian station (Ranchi, 85.3° E, 23.5° N, 650 m AMSL) located in the humid southeastern end of the Indo-Gangetic basin. By estimating the aerosol direct radiative forcing (ARF) from instantaneous observations of global radiation and aerosol optical depth (AOD) during winter, pre-monsoon and monsoon seasons, the authors reported that aerosols over this station can reduce visible radiation by 27%, latent heat flux by 14% and sensible heat flux by 16%, relative to their observed values (Murthy *et al*., 2014). Precipitation observations over the Indian region show a statistically significant long-term decreasing trend in the June-September (JJAS) seasonal monsoon rainfall since the mid-20th century (Ramanathan *et al*., 2005; Guhathakurta and Rajeevan, 2008; Bollasina *et al*., 2011; Krishnan *et al*., 2013, 2016; Rajendran *et al*., 2012; Singh *et al*., 2014; Roxy *et al*., 2015; Ramarao *et al*., 2015; Kulkarni *et al*., 2020; Ayantika *et al*., 2021), followed by an apparent recovery of the monsoonal rains since 2003 (Jin and Wang, 2017; Hari *et al*., 2020). Evidence from several studies point to the role of enhanced Northern Hemisphere anthropogenic aerosol emissions in driving the decrease of Indian monsoon precipitation during the second half of the 20th century (Ramanathan *et al*., 2005; Bollasina *et al*., 2011; Ganguly *et al*., 2012; Polson *et al*., 2014; Krishnan *et al*., 2016, 2020; Undorf *et al*., 2018; Ayantika *et al*., 2021). While aerosols regulate ET mainly by reducing direct solar radiation and improving diffuse radiation (Murthy, 2014), aerosol-induced reduction in surface solar insolation coupled with weakened monsoon winds can cause marked reductions in evaporative fluxes over the South Asian monsoon region and adjoining oceanic areas (Ayantika *et al*., 2021).

Despite the aforementioned studies, a comprehensive understanding of the aerosol radiative effects on ET and ecosystem processes remains inadequate and is an important research topic for ongoing and future investigations (Zhou *et al*., 2021). Lack of observations of land surface hydrological variables limits our knowledge of ET variability over the Indian region, while model-based ET products (*e.g*., Global Land Evaporation Amsterdam Model - GLEAM) have large uncertainties in ET over humid regions with high aerosol concentrations (Liu *et al*., 2016; Pan *et al*., 2020). Given these considerations, the present study aims to understand the response of ET over the Indian region to climate change by analyzing available ground-based ET station observations from the India Meteorological Department (IMD) together with high-resolution global climate experiments.

2. Datasets, methodology and model details

2.1. *Datasets used*

Daily ET and surface air temperature observations from 23 stations distributed widely over the Indian region are analyzed for the period 1979-2008. The ET observations are part of a network of 40 lysimeters (33 weighing type and 7 volumetric type) stations established by the IMD to measure ET in plant environments for different crops in each major soil climatic regime (http://www.imdagrimet.gov.in/node/314). Out of the 40 stations, long-term observational data are available at 23 stations for the period 1979-2008 (Table 1). The

TABLE 1

Table of the locations of 23 ET measurement stations used in this study

S. No.	Station Name	Latitude (degrees)	Longitude (degrees)	% data available
1.	Bari-Bramana (BBN)	32.65	74.90	89
2.	Ludhiana (LDN)	30.93	75.86	75
3.	Pantnagar (PNT)	29.00	79.50	71
4.	New Delhi (NDLI)	28.66	77.16	72
5.	Jodhpur (JDP)	26.29	73.02	74
6.	Lucknow (LKN)	26.87	80.93	83
7.	Varanasi (VNS)	25.39	83.05	71
8.	Banswara (BSW)	23.55	74.45	73
9.	Kanke (RNC)	23.28	85.32	70
10.	Rajkot (RJK)	22.28	70.80	85
11.	Anand (AND)	22.58	72.92	80
12.	Raipur (RPR)	21.26	81.59	71
13.	Shyamkuntha (SKT)	21.93	86.76	83
14.	Akola (AKL)	20.70	77.03	90
15.	Bhubaneshwar (BWN)	20.25	85.86	86
16.	Rahuri (RHI)	19.40	74.65	79
17.	Parbhani (PRB)	19.26	76.78	80
18.	Solapur (SLP)	17.06	75.90	82
19.	Rajahmundy (RJY)	17.00	81.76	70
20.	Dharwad (DHR)	15.43	75.12	78
21.	Bellary (BLY)	15.15	76.85	78
22.	Bangalore (BNG)	13.00	77.62	78
23.	Kovilpatti (KVP)	9.19	77.88	89

percentage availability of monthly ET data at these 23 stations exceeds 70% during the period 1979-2008. To account for data gaps, we have also utilized the multi-model monthly mean ET based on the Global Land Data Assimilation System (GLDAS) dataset, which is derived from multiple off-line land surface models driven by observations and bias-corrected reanalysis fields, so that the multi-model estimates from GLDAS serve as physically consistent reference datasets of land surface fluxes and state. Also used in this study are five different gridded precipitation datasets based on rain-gauge measurements (IMD, UDEL, GPCC, CRU and APHRODITE) (Table 2) along with potential evapotranspiration (PET) data from the Climatic Research Unit (CRU TS3.10; Harris *et al*., 2014) for computing aridity index (see Methods) over India for the period 1951-2008. The PET calculation is based on a variant of the Penman-Monteith formula as recommended by FAO (http://www.fao.org/docrep/x0490e/x0490e06.htm) and is based on the physical principles of energy balance and is considered to be more appropriate, especially over wet surface as compared to empirically based formulations that usually consider the effects of temperature and/or radiation only (Scheff and Frierson, 2015; Huang *et al*., 2016).

2.2. *Methodology*

It is noted that there are some data gaps in the IMD lysimeter evapotranspiration data. To fill the data gaps and generate continuous data, we first calculated monthly anomalies at each station by subtracting the seasonal cycle. In addition, we computed monthly anomalies of ET using the GLDAS dataset interpolated to the station

TABLE 2

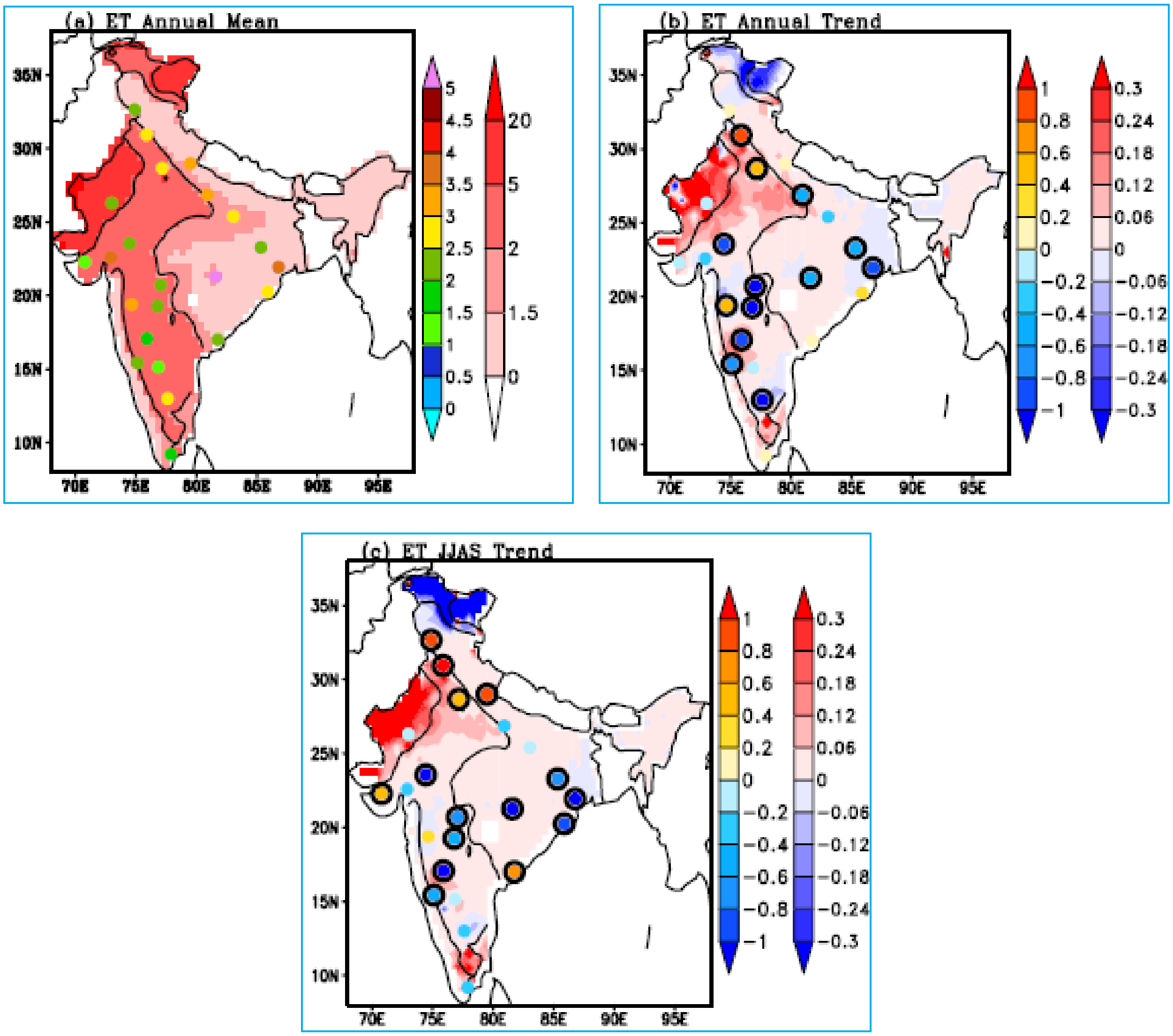
The details of the precipitation datasets used in this study

Data set	Resolution	Reference
IMD (India Meteorological Department)	Daily, 0.25° × 0.25°	Pai *et al*. (2013)
UDEL (University of Delaware)	Monthly, 0.5° × 0.5°	Legates and Willmott (1990)
GPCC (Global Precipitation Climatology Centre)	Monthly, 0.5° × 0.5°	Schneider *et al*. (2014)
CRU (Climatic Research Unit)	Monthly, 0.5° × 0.5°	Harris *et al*. (2014)
APHRODITE (Asian Precipitation – Highly - Resolved Observational Data Integration Towards Evaluation of water resources)	Daily, 0.5° × 0.5°	Yatagai *et al*. (2012)

location. The ET anomalies from the GLDAS dataset were later used to fill the data gaps in the station observations. The monthly mean ET dataset (1979-2008), without data gaps, is constructed by superposing the climatological mean ET at each station location on the corresponding monthly anomaly time series. Before superposition of the climatological mean on the anomalies, we multiplied the GLDAS anomalies by a scaling factor which is the ratio of the standard deviations of the station data and the GLDAS data. This normalization is performed considering the differences in standard deviations between the station observations and the interpolated GLDAS dataset. Linear trends in ET are computed for the annual and summer monsoon season. The statistical significance of the linear trends is tested using Student's t test at 95 % level. The aridity index (AI) representing the terrestrial aridity of a region indicates the degree of climatic dryness and is computed as the ratio of annual mean PET to the annual mean precipitation (P) (Holdridge, 1967; Middleton and Thomas, 1997; Feng and Fu, 2013; Scheff and Frierson, 2015). For the present study, AI is computed using five different precipitation data sets (Table 2) and an ensemble mean is considered in the analysis to account for the uncertainty among rainfall data sets (Kim *et al*., 2015). All the datasets have been interpolated onto a common 0.5 × 0.5 latitude-longitude grid for inter-comparison. The analysis grid has been selected to coincide with that of IMD land grid points over India. The regions with different AI values are classified as hyper-arid ($AI > 20$); arid ($5 < AI \leq 20$); semiarid ($2 \leq AI < 5$); dry sub-humid ($1.5 \leq AI < 2$) and humid ($AI < 1.5$). Note that 8 stations falling under dry-sub humid and humid regions of Indo-Gangetic plains (IGP) and central India based on AI [< 1.5; Fig. 1(a)] are considered as humid (HUM) and the remaining 15 stations falling under arid and semi-arid regions are considered as semi-arid (SAR) in the analysis. The semi-arid region is decided based on the mean observed AI values and the region 80.0°-89.0° E, 21.0°-28.0° N covering the IGP and Central India is considered as humid for the analysis of climate model simulations.

2.3. *Models and experiments*

To understand the response of land ET over the Indian region to anthropogenic radiative forcings, we use climate change simulations from the Laboratoire de Meterologie Dynamique (LMDZ; where Z stands for zoom) variable resolution global climate model having enhanced resolution (~35 km) over South Asian region (Sabin *et al*., 2013). These long-term simulations have been used for attribution studies on the observed changes in South Asian monsoon precipitation and land-surface hydrological response to climate change (Krishnan *et al*., 2016; Ramarao *et al*., 2015). The high-resolution LMDZ climate simulations consist of two long-term simulations with and without anthropogenic forcing for the period (1886-2005). The first one is a historical experiment (HIST) which uses both natural (*e.g*., volcanoes and solar variability) and anthropogenic forcing (*e.g*., greenhouse gases (GHG), aerosols evolution estimated from transport models, land use and land cover changes etc.). The second one is a historical natural experiment (NAT) based only on natural forcing (*e.g*., volcanoes and solar variability). The monthly bias adjusted sea surface temperature (SST) and sea-ice from the CMIP5 experiments with the coarser resolution atmosphere-ocean coupled GCM run from Institut Pierre Simon Laplace (IPSL-CM5A-LR) are used as boundary forcing for LMDZ experiments. Further details of model experiments are given in Krishnan *et al*., 2016 and Ramarao *et al*., 2015. While the HIST and NAT simulations are for the period (1886-2005), the present analysis is focused during the second half of the 20th century (1951-2005) which was associated with a



Figs. 1(a-c). Long-term mean (mm day^{-1}) and trend [mm d^{-1} (30yr)$^{-1}$] of ET over IMD stations. Mean and trend of aridity are shaded. ET and aridity data is for the period 1979-2008 (a) Long-term annual mean (b) Trends for the annual mean (c) Trends for the summer monsoon season. Stations with trend values exceeding the 95% statistical significance based on Students t test are outlined with a circle. Semi-arid regions have mean aridity between 2 and 5 and are demarcated by the solid black line. Mean aridity for humid and dry sub-humid regions is less than 2. Decreasing trends in ET can be noted over most of the stations. Aridity increases are prominent over the semi-arid regions

significant reduction (~7%) in monsoon precipitation over India (Krishnan *et al.*, 2016, 2020; Ramarao *et al.*, 2015). An important aspect of the high-resolution LMDZ simulation is that it adequately captures the mean surface water balance between (P-R) and ET over the Indian subcontinent (Ramarao *et al.*, 2015).

In addition to the LMDZ simulations, we have also analyzed results of sensitivity experiments (Ayantika *et al.*, 2021) from the Indian Institute of Tropical Meteorology Earth System Model (IITM-ESMv2), one of the models that participated in the Coupled Model Intercomparison Project Phase 6 (CMIP6) experiments. Details about the model and its different components are available in Swapna *et al.*, 2018 and Ayantika *et al.*, 2021. Earlier studies using the IITM-ESMv2 have investigated the response of the South Asian monsoon to volcanic aerosols (Singh *et al.*, 2020) and anthropogenic GHG and aerosols (Ayantika *et al.*, 2021). The IITM-ESMv2 sensitivity experiments consists of three 50-year simulations, *viz.*, (AER, GHG and COMB) of the IITM-ESMv2 with different combinations of CO_2 and anthropogenic aerosols held fixed to the pre-industrial conditions and present-day (2005) conditions. The AER experiment is a 50-year simulation uses the anthropogenic aerosol properties for the year 2005, while the CO_2

concentration is fixed to the pre-industrial value. The GHG experiment uses the CO_2 concentration corresponding to 2005 (379 ppmv), with fixed pre-industrial natural aerosols. The combined forcing experiment (COMB) is a 50-year simulation using the elevated CO_2 concentration and anthropogenic forcing corresponding to the year 2005. More details of the experiments are available in Ayantika *et al*. (2021).

3.1. *Observed changes in ET over India*

In this section, we present an analysis of observed changes in ET and aridity index (AI) over the Indian subcontinent. Since India is a region with pronounced seasonal cycles, the analysis is carried out for the annual mean and for the wet summer monsoon season (June-September). Fig. 1 shows the spatial variation of the climatological mean and trends of AI (shading) and ET based on the IMD station observations during 1979-2008. The distribution of AI indicates arid regions over the northwestern desert area surrounded by a semi-arid region which extends from northern India to the southern peninsula of India (regions shown in black contour). The semi-arid regions are margined with dry sub-humid regions on the eastern side. The AI spatial distribution depicts wet, humid regions along the narrow Western Ghats, sub-regions of Indo Gangetic plains, central India and northeastern parts of the country. The classification of these sub-regions is based on the mean aridity index (AI) value (see methods for further details). The annual mean ET for the selected stations ranges from 1.0 - 5.0 mm d^{-1} [Fig. 1(a)], with higher mean values for the stations over dry sub-humid and humid parts of central India and along the Indo-Gangetic plains and relatively lower values of mean ET for the stations over semi-arid regions of South peninsula and the western parts of India. The spatial distribution of trends in annual mean ET depicts significant negative trends over most of the stations in Central and Peninsular India [Fig. 1(b)], while a few stations over north and northwest India show positive trends. Although the reasons for the increasing ET trends over northwest India are not adequately clear, they may have apparent links to global warming and/or the increased irrigation in the region (Shah *et al*., 2019). It is important to notice that most of the stations show decreasing trends in annual mean ET; while the aridity trends (shaded) are stronger over the semi-arid region than those over the humid region of central India. Since AI is a good indicator of the degree of water deficiency at a given location (Fu and Feng, 2014), the contending decrease of the annual ET and increase of AI over the semi-arid regions suggests that the annual trends in ET at the surface are largely controlled by water availability changes over these regions [Fig. 1(b)]. Further, it is important to note that the spatial distribution of ET trends for the JJAS monsoon season bears resemblance with that of the annual trends with moderate deviations [Fig. 1(c)].

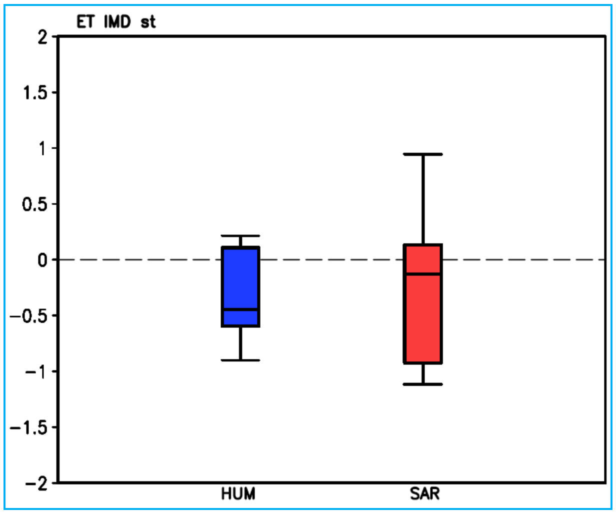
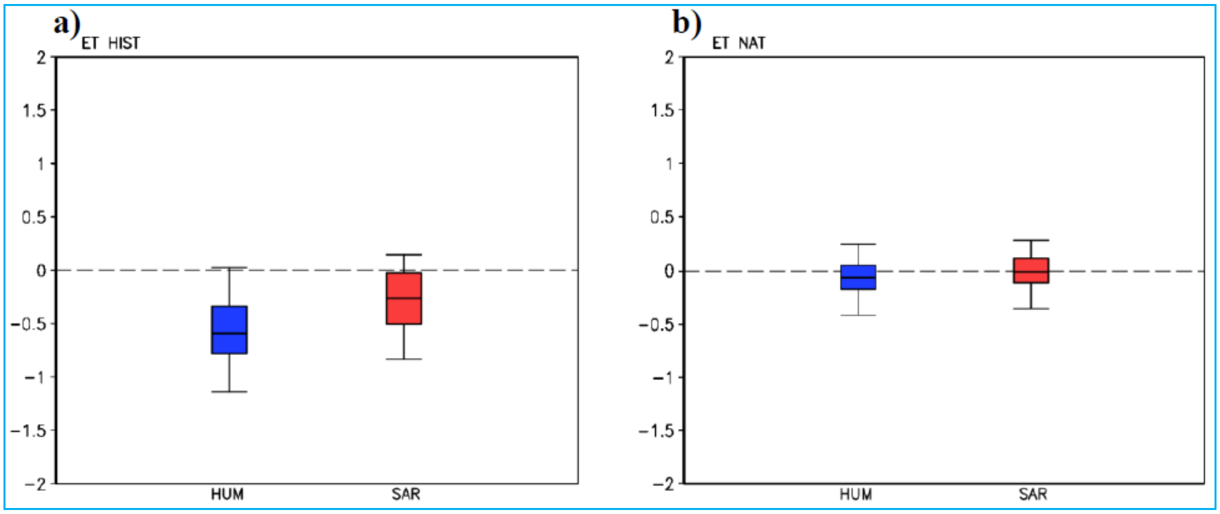


Fig. 2. Box-whisker diagram of trends in observed annual mean ET for the Humid (blue) and Semi-arid (red) stations during 1979-2008. Linear trends of ET are first calculated at each station prior to computing the percentiles. The central line (black) within each box represents the median (mean) value of the stations. The top and bottom of each box shows the 75th and 25th percentiles and the top and bottom of each whisker display the 95th and 5th percentile values in the ensemble, respectively. Decreasing trend of ET for the humid and semi-arid stations are evident from the negative median values. Also note that the spread of trends is relatively smaller for the humid stations as compared to the semi-arid stations

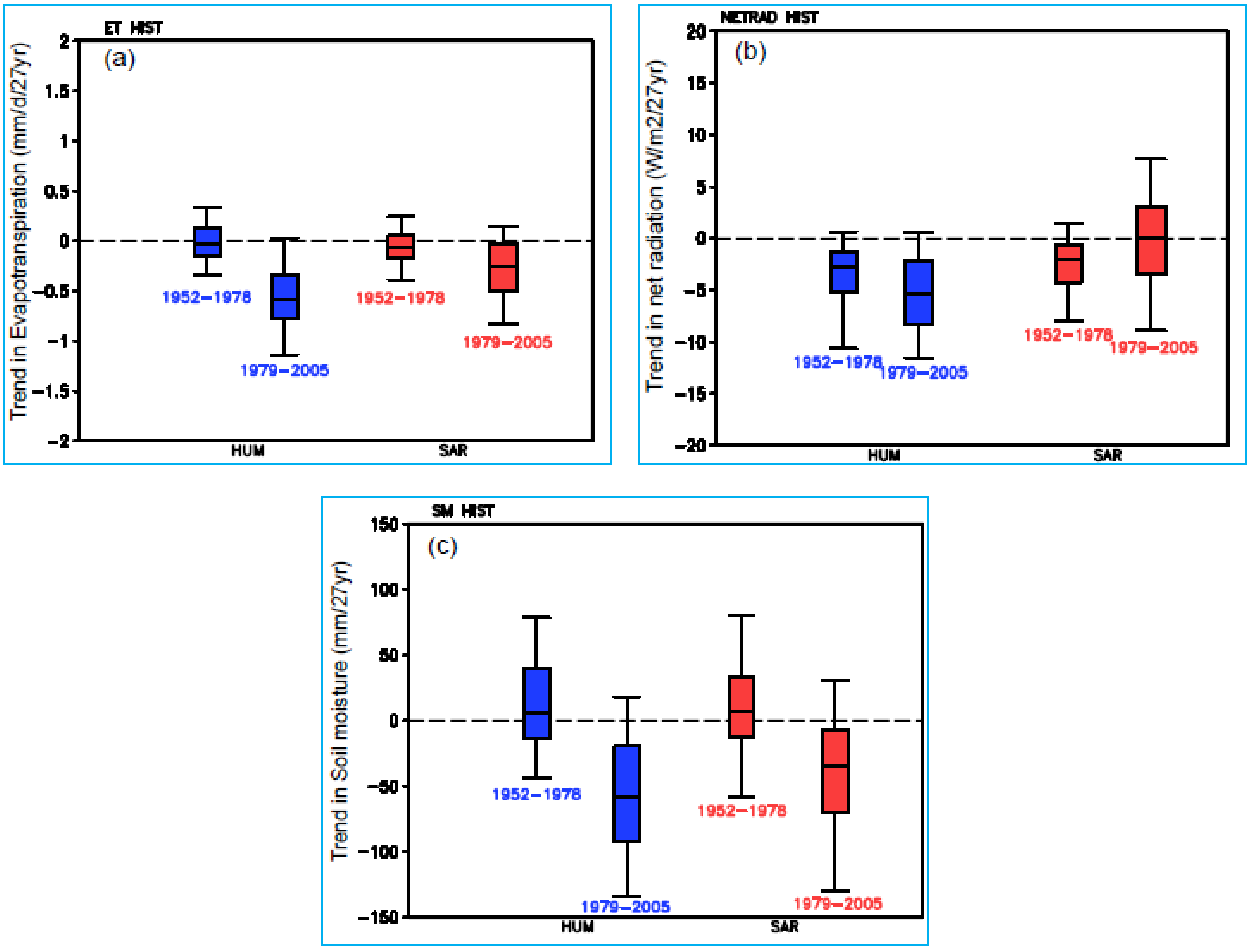
The distribution of observed annual trends in ET for the station measurements over the humid (HUM) and semi-arid (SAR) regions of India during the period 1979-2008, is shown in Fig. 2 as box-whisker plots. The figure indicates that the median (*i.e*., second quartile Q2) is highly negative for HUM (blue) than that for SAR (red). The third quartile (Q3) shows positive trends in ET for both the HUM and SAR regions. However, the inter-quartile range and the variability of top 25% of stations over SAR is large indicating a larger spread among the stations. From the above discussion, it is clear that most of the stations over India exhibit declining trends in the annual mean ET during 1979-2008. It is also noted that the trends in annual mean ET, when averaged over the HUM and SAR stations account for a decline of about 9% and 11%, respectively.

3.2. *Changes in limiting factors of ET*

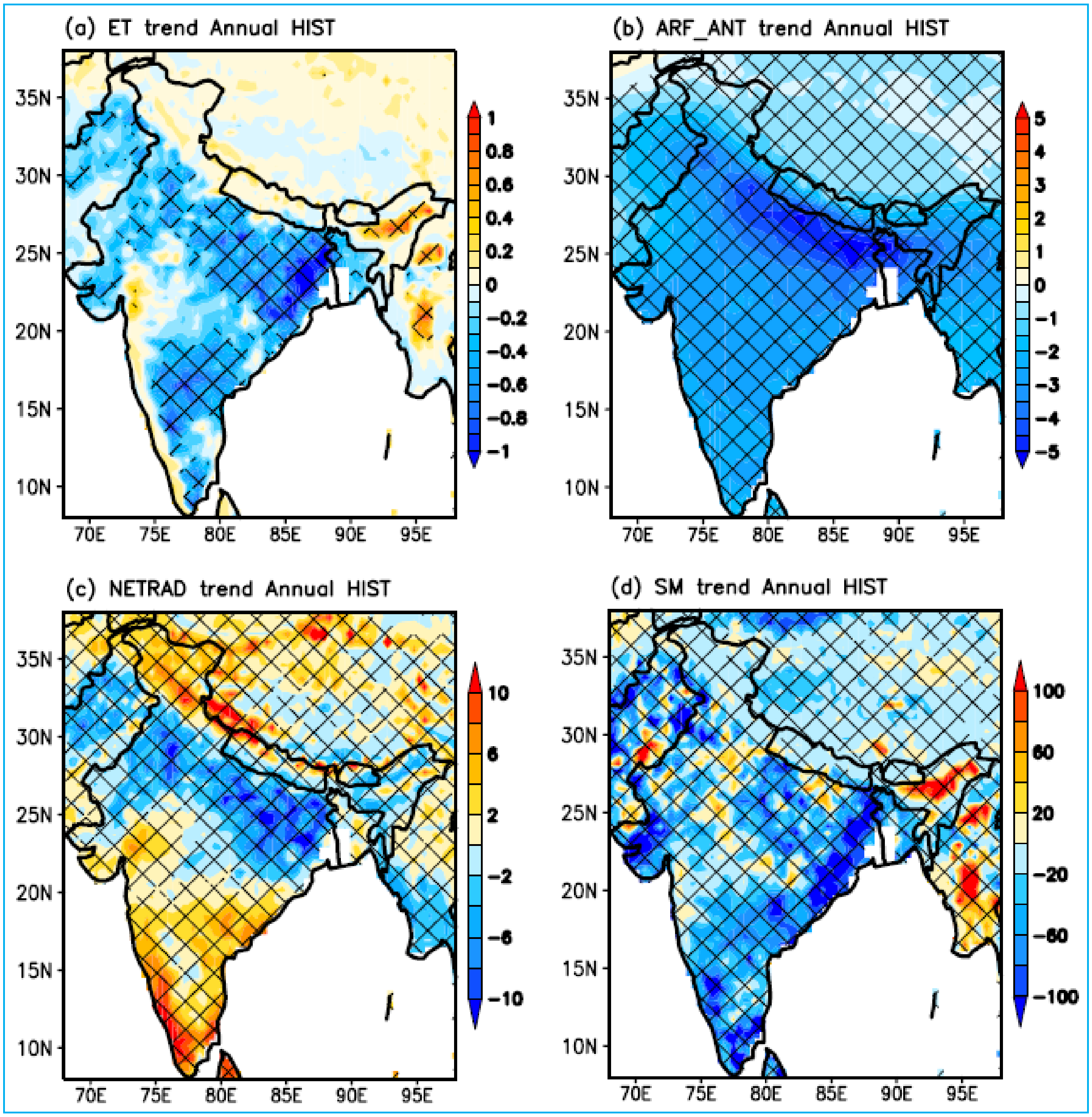
In order to draw further insights into the observed decrease of ET and the role of various limiting factors in



Figs. 3(a&b). Comparison of trends in LMDZ model simulated annual mean ET for the HUM (blue) and SAR (red) regions during 1979-2005 between (a) HIST and (b) NAT simulations, plotted as box and whisker diagrams

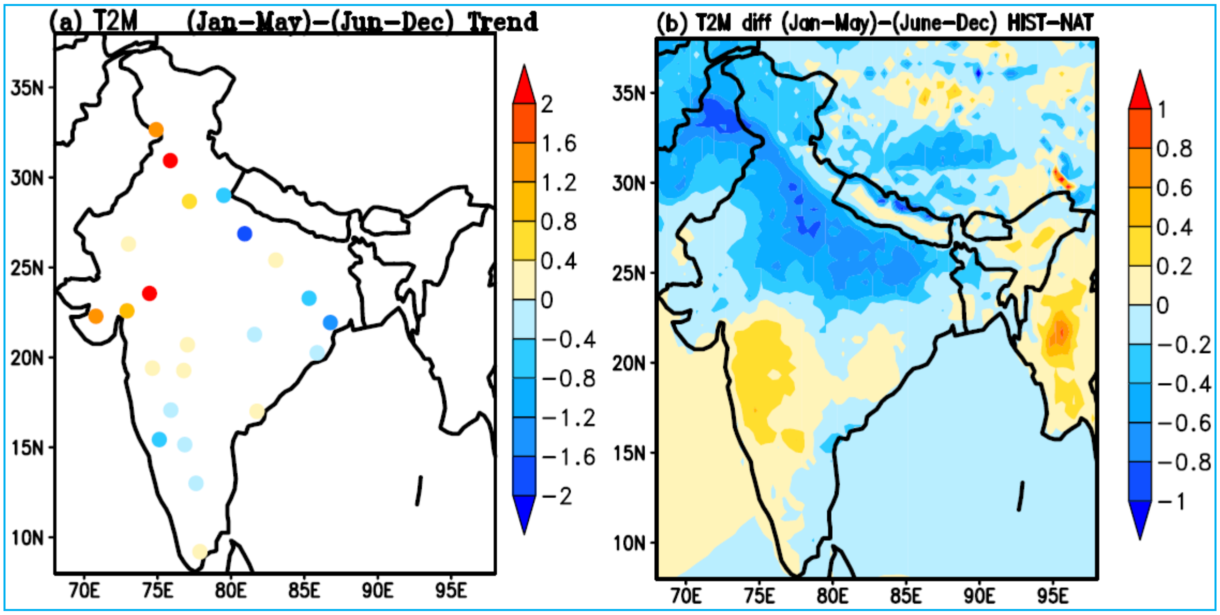


Figs. 4(a-c). Comparison of trends in annual mean parameters between the periods (1952-1978) and (1979-2005) from the HIST simulation (a) ET [mm day^{-1} [27 years]$^{-1}$] (b) Net radiation at the surface (Wm^{-2} [27 years]$^{-1}$) and (c) Soil moisture (mm [27 years]$^{-1}$). Trends for the humid and semi-arid regions are shown in blue and red colors respectively. Trends are expressed as change over 27 year period. The time periods are selected such that the recent period nearly matches with that of observations



Figs. 5(a-d). Spatial maps of linear trends in annual mean (a) ET (mm/d), (b) aerosol radiative forcing at surface (Wm^{-2}), (c) net radiation at surface (Wm^{-2}) and (d) soil moisture (mm) from LMDZ HIST simulation during 1979-2005. Units are expressed as change over the period 1979-2005. Trend values exceeding the 95% level of statistical significance based on Student's *t* test are hatched

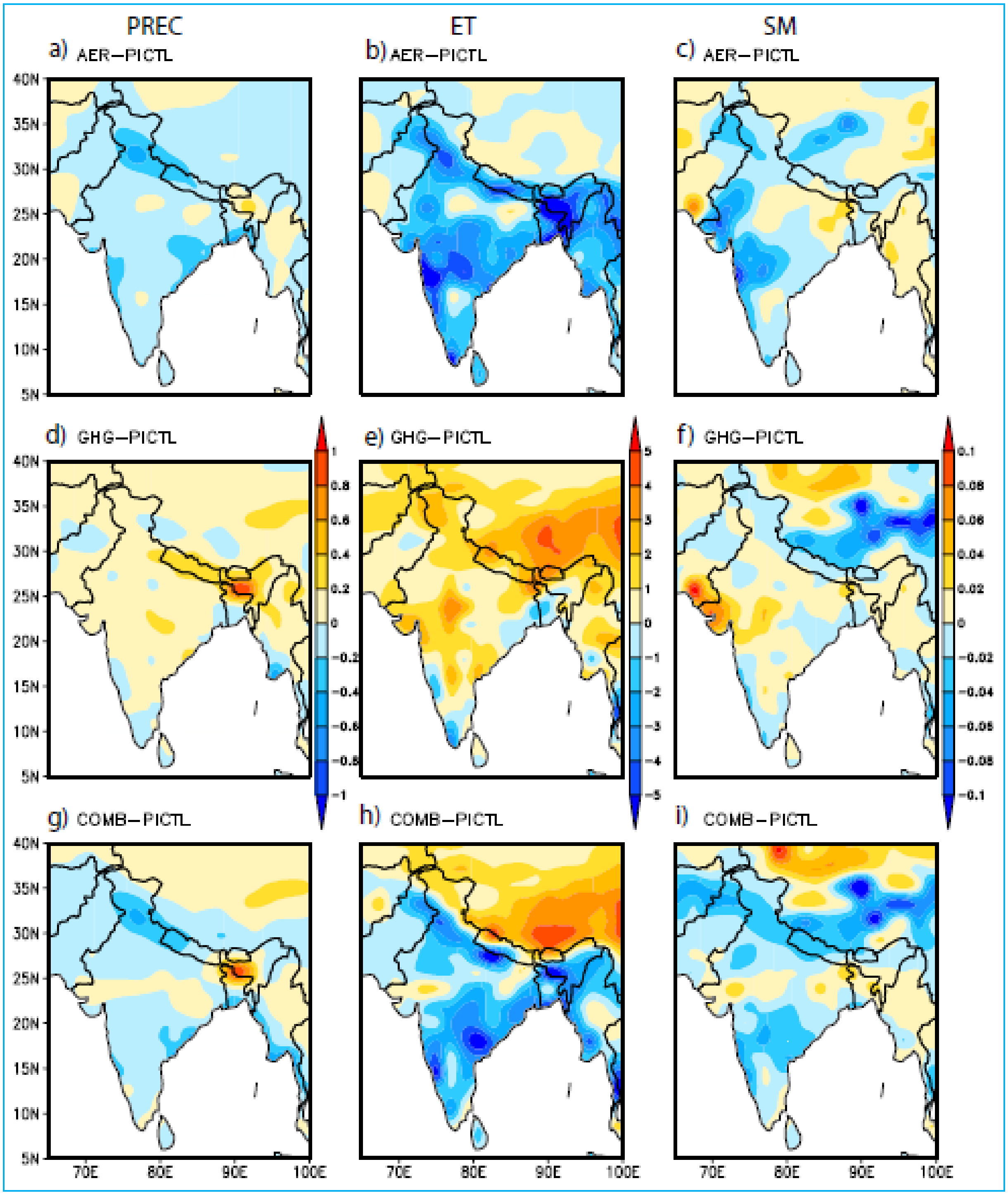
controlling the trends in ET over the Indian land region, we analyzed the annual trends in ET, net radiation at surface, soil moisture and aerosol radiative forcing at surface over semi-arid and humid regions covering the IGP and Central India (80.0°-89.0° E, 21.0°-28.0° N) from the high-resolution climate change simulation experiments (HIST and NAT) of the LMDZ model. A comparison of the distribution of the simulated annual ET trends during 1979-2005 based on the HIST and NAT experiments, for the HUM and SAR regions, is shown in Fig. 3(a). It can be seen that the medians of the box-whisker plots display negative values in the HIST experiment, similar to observations (Fig. 1) for both the HUM and SAR regions; whereas the trends are weak in the NAT experiment over both the regions [Fig. 3(b)]. Further, we have noted that the time-series of the



Figs. 6(a&b). (a) Linear trend in the seasonal difference in temperature over IMD stations and (b) seasonal difference in temperature between HIST and NAT simulations of LMDZ during 1951-2005. The seasonal difference is computed as the difference between seasons Jan-may and Jun-Dec

simulated ET from the NAT experiment does not exhibit any significant long-term trend (figure not shown), as compared to the HIST experiment. This result suggests that the simulated long-term decreasing trend of ET over the Indian region in HIST is influenced by anthropogenic forcing and cannot be explained by natural forcing alone. Furthermore, a comparison of the trends in annual ET between the HUM (blue) and SAR (red) regions shows relatively larger negative trends over HUM as compared to the SAR region, with stronger declines of ET during the second half (1979-2005) than the first half (1952-1978). The distribution of trends in annual net radiation and soil moisture also show consistent declining trends over the HUM region ET with stronger declines during the second half than the first half [Figs. 4(b&c)]. It may be noted that the SM trends show larger spread than the net radiation trends over the HUM region. Over the SAR region, we note a strong decline in the SM trends during the recent period, although net radiation doesn't indicate a prominent signal [Fig. 4(c)]. The declining trends in ET over the SAR region during the recent 2-3 decades in the HIST simulation appear to be linked to reductions in SM, whereas the declining trends in ET over the HUM region are additionally influenced by decrease of net radiation. It is interesting to note that the model simulation captures stronger trends in aerosol radiative forcing over Indo-Gangetic Plains [Fig. 5(b)], which is referred in the literature as an “aerosol hotspot” with high aerosol concentration through the year (Ramanathan *et al*., 2007; Lau *et al*., 2009; Sanap *et al*., 2014 and many others). The simulated radiative forcing due to aerosols over the Indian region is negative at the surface during the period 1951-2005 (figure not shown). The spatial patterns of annual trends of ET, aerosol radiative forcing at surface, net radiation and SM during 1979-2005 from the HIST simulation point to the role of anthropogenic aerosol radiative forcing in driving ET reductions over the humid IGP and the central Indian region through decrease of surface solar insolation (Fig. 5).

Anthropogenic aerosol loading over the North Indian Ocean, South and Southeast Asia is dominant during the boreal winter and spring seasons (Ramanathan *et al*., 2001). Given this seasonality of the regional aerosol loading, we examined the temperature changes over the subcontinent between the dry season (Jan-May) and rest of the year (Jun-Dec), following Krishnan and Ramanathan (2002) in order to derive additional insights about the regional influence of the anthropogenic aerosols. This approach of separating the seasonally asymmetric temperature response is based on the premise that the temperature trends due to the greenhouse gas (GHG) forcing are not seasonally dependent and as a result, differencing the temperatures for the two seasons factors out the GHG forcing (Krishnan and Ramanathan, 2002). The linear trend in the seasonal difference (Jan-May) minus (Jun-Dec) of surface air temperature over the IMD stations for the period 1979-2008 is shown in Fig. 6(a). A decreasing trend in the seasonal difference of observed temperatures can be noted over the stations located in the



Figs. 7(a-i). Spatial maps of changes in JJAS precipitation, evapotranspiration and soil moisture for different IITM-ESM sensitivity experiments relative to PICTL (a, b, c) AER, (d, e, f) GHG, (g, h, i) COMB

humid areas of central India and IGP [Fig. 6(a)], which is physically consistent with surface air temperature cooling due to reduced insolation at the surface. We also compared the seasonal difference (Jan-May) minus (Jun-Dec) of the simulated surface temperature using the HIST and NAT experiments. For this, we first computed the seasonal difference separately for the HIST and NAT experiments and later compared them by taking the difference (HIST minus NAT) between the two experiments [Fig. 6(b)]. The negative anomalies over the IGP in Fig. 6(b) clearly point to stronger decrease of the dry season temperatures in the HIST experiment relative to NAT, which is consistent with the observed signal in surface air temperatures [Fig. 6(a)] and ET [Fig. 1(b)]. The above results indicate that the ET reduction over humid sub-regions of the IGP and central India, observed during the recent decades, is apparently linked to the reduced availability of solar radiation at surface. The positive anomalies over the drier regions of northwest India in Fig. 6(a) are more complex to interpret given that this region has experienced significant irrigation changes, during the latter part of the 20th century, which appear to have altered the regional land surface hydrological processes (Shah *et al*., 2019) and will need separate investigation.

To further strengthen the interpretation and attribution of ET changes over the Indian region, we also examined the results from the IITM-ESMv2 sensitivity experiments (Ayantika *et al*., 2021), which includes 3 experiments, *viz*., AER, GHG and COMB, respectively. The simulated ET from these 3 sensitivity experiments is compared with the pre-industrial control (PI-CTL) simulation of IITM-ESMv2. We examined the changes in precipitation, ET and soil moisture for the AER, GHG and COMB experiments relative to PI-CTL (Fig. 7). In congruence with earlier studies, it can be noted that the AER and COMB simulations show a decrease in monsoon precipitation over the Indian landmass resulting in reduction of soil moisture and widespread decrease of ET over the region. In contrast, the GHG experiment shows enhanced soil moisture and ET in response to enhanced monsoon precipitation. Interestingly, both the AER and COMB experiments show prominent decreases in soil moisture and ET over central and peninsular Indian region, which are attributable to anthropogenic aerosol-induced reductions in solar insolation at the earth’s surface (Fig. 4 in Ayantika *et al*., 2021). Based on the overall analysis of this study, which includes *in situ* observations and climate model experiments (high-resolution LMDZ model and IITM-ESMv2), it is inferred that anthropogenic aerosol forcing have significantly influenced the observed decrease of ET over the humid sub-regions of the IGP during the last 3-4 decades.

4. Summary

A detailed analysis of ET observations from 23 stations over India shows a significant decreasing trend in ET (~10%) over most stations in central and peninsular India during 1979-2008. It is noted that the trends in ET over stations located in the semi-arid regions are controlled by changes in the hydrological cycle (P-ET), as indicated by the aridity index, whereas the weaker aridity changes over the humid sub-regions of the IGP indicate the role of other limiting factors of ET in controlling the long-term trends. Results from the climate model experiments (high-resolution LMDZ and the IITM-ESMv2) indicate that the radiative forcing due to anthropogenic-aerosol emissions has significantly influenced the decrease of Indian summer monsoon precipitation since the mid-20th century, in turn causing reductions in soil moisture and ET over the humid sub-regions of the IGP. Additionally, the model simulations suggest that the declining trends in ET are stronger during recent 27 year period (1979-2005), as compared to the first half (1952-1978). The present results reveal that the strong decrease of ET over the humid sub-regions of IGP and central India in the recent 2-3 decades are attributable to decreased radiation at the surface by anthropogenic aerosols. The present results have implications for the regional agricultural and water resource sectors.

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