

Modulation of summer monsoon sub-seasonal surface air temperature over India by soil moisture-temperature coupling

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सार – भारतीय ग्रीष्मकालीन मॉनसून वर्षा में अंतराल की अवधि से जुड़ी कुछ शुष्क मृदा स्थितियों के दौरान उप मौसमी गर्म धरातलीय पवन तापमान विसंगतियों पर मृदा की नमी के प्रभाव का अन्वेषण प्रेक्षणों का उपयोग करते हुए किया गया है। उप मौसमी समय श्रृंखला से जुड़े इस मृदा नमी-तापमान की प्रक्रिया को समझने के लिए धरातलीय सतह स्टेट के बहुनिर्देश विश्लेषण और द्वितीय भूमंडल मृदा आर्द्रता परियोजना (GSWP-2) से उपलब्ध फ्लक्स बहुत उपयोगी पाए गए हैं। इस विश्लेषण में मृदा नमी तापमान से संयोजित प्रतिदिन क्षेत्रों के रेखिकीय सहसंबंध के आधार पर नैदानिक परिकलन किए गए हैं। इससे पता चला है कि ग्रीष्म सतह वायु तापमान परिवर्तनशीलता भारतीय मॉनसून वृष्टि के अंतः मौसमी परिवर्तनशीलता से जुड़ी है जो कि धरातल जलवायु से संयोजित मृदा नमी परिवर्तनशीलता को नियंत्रित करती है। सुदृढ़ संयोजन मुख्यतः शुष्क मृदा स्टेट में परिवर्तनकाल के सम ग्रीष्मकालीन मॉनसून ऋतु में होता है, यह मध्य भारत से लेकर उत्तर-पश्चिमी भारत आर्द्र और शुष्क जलवायु के बीच होता है। इसके विपरीत समूचे ग्रीष्मकालीन मॉनसून ऋतु के दौरान पूर्वी भारत में आर्द्र और ऊर्जा सीमित वाष्पोत्सर्जन समय में यह संयोजन लगातार कमजोर होता है। प्रेक्षणों के आधार पर किए गए विश्लेषण भारतीय ग्रीष्मकालीन मॉनसून ऋतु के दौरान उप मौसमी शुष्क मृदा स्टेट और उष्ण स्थितियों के बीच सम्पर्क को समझने में बहुत सहायता प्रदान करते हैं। उपमौसमी और ऋतु की मॉनसून वर्षा के पूर्वानुमान के लिए प्रयोग किए गए मौसमी और जलवायु की मॉडल में धरातल-वायुमंडल अन्योन्य क्रियाओं के इन पक्षों का सही प्रदर्शन अनेक अनुप्रयोगों के लिए विशेषकर कृषि के लिए महत्वपूर्ण हो सकता है। इस अध्ययन में प्रयोग किए गए मृदा नमी तापमान से संयोजित नैदानिक मौसम और जलवायु मॉडल के निष्पादन का मूल्यांकन करने के लिए उपयोगी मीट्रिक होगी।

ABSTRACT. The influence of soil moisture on the sub-seasonal warmer surface air temperature anomalies during drier soil conditions associated with break spells in the Indian summer monsoon precipitation is explored using observations. The multi-model analysis of land surface states and fluxes available from the Second Global Soil Wetness Project (GSWP-2) are found useful in understanding the mechanism for this soil moisture-temperature coupling on sub-seasonal timescales. The analysis uses a soil moisture-temperature coupling diagnostic computed based on linear correlations of daily fields. It is shown that the summer surface air temperature variations are linked to intraseasonal variations of the Indian monsoon precipitation, which control the land-climate coupling by modulating the soil moisture variations. Strong coupling mainly occurs during dry soil states within the summer monsoon season over the transition zones between wet and dry climates of central to north-west India. In contrast, the coupling is weak for constantly wet and energy-limited evaporative regimes over eastern India during the entire summer monsoon season. This observational based analysis provided a better understanding of the linkages between the sub-seasonal dry soil states and warm conditions during the Indian summer monsoon season. A proper representation of these aspects of land-atmosphere interactions in weather and climate models used for sub-seasonal and seasonal monsoon forecasting could be critical for several applications, in particular agriculture. The soil moisture-temperature coupling diagnostic used in this study will be a useful metric for evaluating the performance of weather and climate models.

Key words – Sub-seasonal Indian monsoon precipitation, Soil moisture-temperature coupling, Surface air temperature variations.

1. Introduction

The Indian summer monsoon rainy season (June-September) is characterized by variations on a wide range of timescales across diurnal, synoptic, intraseasonal, interannual and decadal scales. The two principal months (July and August) of this season account for the maximum

contribution of nearly 75% of annual rainfall over most part of India (Raghavan, 1973). The strong intraseasonal variations during these principal months of the Indian summer monsoon in the form of active and break spells have been discussed for a long time (Ramamurthy, 1969; Raghavan, 1973; Krishnan *et al.*, 2000; Rajeevan *et al.*, 2010). The monsoon break spells tend to last for a week or

longer, while most active spells only last for 3-4 days (Rajeevan *et al.*, 2010). The surface air temperature increases rapidly during long intense breaks and a heat-trough type circulation gets established over the monsoon trough zone (Raghavan, 1973). For example, during the break spell of 4-17 July 2002 the day time maximum temperature anomaly exceeded 3 K for many days with magnitudes for the peak break days (12-15 July) exceeding 5 K over most parts of the Indo-Gangetic plains of north and east-central India (Rajeevan *et al.*, 2010). A significant increase in the incidence of prolonged monsoon-breaks has been observed during the recent decades in the months of July and August over India (Kumar *et al.*, 2009; Singh, 2013). The latest ensemble of climate models participating in the Coupled Model Intercomparison Project phase 5 (CMIP-5) also consistently projects significant increases in day-to-day rainfall variability during Indian summer monsoon season under unmitigated climate change (Menon *et al.*, 2013). This finding suggests that in future there is more possibility of break like conditions during monsoon season with longer periods of above normal surface air temperatures in wider area over India. This study explores a possible mechanism relating the contributions from soil moisture deficits during monsoon precipitation break spells in prolonging the above normal temperature for longer periods.

The role of soil moisture deficits in controlling summer daily surface air temperature variations has received considerable attention on a global scale (Koster *et al.*, 2006; Seneviratne *et al.*, 2010). The resulting global hot spots of soil moisture-temperature coupling include north-west India, and these regions agree with the observational analyses based on satellite-based estimates (Miralles *et al.*, 2012). In regional scales, such feedbacks between soil moisture and temperature have been shown to be relevant for the occurrence of hot days and the evolution of heat waves in transitional regions between wet and dry climate over Europe (Fischer *et al.*, 2007; Hirschi *et al.*, 2011) and United States (Durre *et al.*, 2000). The monthly distribution of average heat wave days experienced during the hot weather season (March-July) in India for the period 1961-2010 were found to be relatively more during the months of May and June (Pai *et al.*, 2013). These hot extremes over India occur under very dry soil conditions before the summer monsoon season, and hence are not found to be related to soil moisture deficits (Mueller and Seneviratne, 2012). The magnitude of the break monsoon warmer anomalies is smaller than during heat waves, but to our knowledge their relationship with sub-seasonal soil moisture deficits during Indian summer monsoon has never been investigated with observations over India.

The sensitivity experiments using a global climate model had shown that the realistic representation of soil moisture anomalies over Eurasia was an important factor in the simulation of the Indian monsoon precipitation variability for two extreme years (Arpe *et al.*, 1998). The regional climate model studies that focused on soil moisture-precipitation feedbacks during Indian summer monsoon found that the changes in soil moisture is able to influence the precipitation by its control on local evapotranspiration, especially in the north western arid region than in the humid eastern region over India (Asharaf *et al.*, 2012; Asharaf and Ahrens, 2013). The stronger regional feedback over north-west India was attributed to the longer root zone soil moisture memory as well as evapotranspiration persistence (Asharaf and Ahrens, 2013). The atmospheric conditions in which the local land surface state affects convective precipitation during the monsoon season were found all over India about 25% of the time, mainly in break monsoon periods over wet regions that receive the majority of precipitation from convective storms (Tuinenburg *et al.*, 2011). In order for soil-moisture deficit to impact the surface-energy balance, and hence air temperature, in a given region, evapotranspiration needs to be soil moisture limited (Seneviratne *et al.*, 2010). This is the case in transitional regions between dry and wet climates, such as over the north-west India (Koster *et al.*, 2006; Seneviratne *et al.*, 2010). However a continental scale study using surface measurements showed that during the wet Indian summer monsoon the seasonal precipitation is larger than the potential evaporation, indicating that evaporation is energy limited during this season (Padmakumari *et al.*, 2013). But during long break spells in monsoon precipitation, the relatively drier soil conditions may limit evapotranspiration, allowing more available energy at the surface to be partitioned in to sensible heating, and thus inducing an increase in surface air temperature. Although such impact of soil moisture on near-surface air temperature is well documented in models and observations for seasonal meteorological droughts (Koster *et al.*, 2009), the importance of sub-seasonal soil moisture-temperature coupling in maintaining warmer surface air temperatures during monsoon breaks have not been addressed in earlier studies. A proper representation of these aspects of land-atmosphere interactions in weather and climate models used for subseasonal and seasonal monsoon forecasting could be critical for several applications, in particular agriculture (Seneviratne *et al.*, 2010).

The observational based investigation of soil moisture-temperature interactions are hampered due to lack of comprehensive global datasets of observed soil moisture, since ground observations are very limited in space (Seneviratne *et al.*, 2010). The satellite information

has been found valuable in studying the soil moisture-temperature coupling from an observational perspective and at the global scale. But these findings can be impacted by errors in the parameterizations of root-zone soil moisture as well as the uncertainties of the satellite observations (Miralles *et al.*, 2012). The output from land surface models driven with observation-based data is a useful alternative to derive global soil moisture datasets (Seneviratne *et al.*, 2010). The soil moisture simulated by the offline land surface models participating in the Second Global Soil Wetness Project (GSWP-2; Dirmeyer *et al.*, 2006) compares reasonably well with available observations, with the multi-model analysis generally outperforming the output from any single land surface model (Guo *et al.*, 2007). We show that the daily fields of root zone soil moisture and surface fluxes in the multi-model analysis from the GSWP-2 are useful to understand the role of soil moisture-temperature coupling in maintaining sub-seasonal warmer surface air temperature anomalies during drier soil conditions associated with break spells in the summer monsoon precipitation over parts of India.

The structure of this article is as follows: Section 2 describes the data used in this study as well as the methodologies used in the analysis. The results of analyzing the sub-seasonal spatio-temporal variations in land-atmosphere interactions during the summer monsoon season are presented in section 3. Finally, discussions of the main findings as well as the conclusions of this study are provided in section 4.

2. Data and methodology

The daily fields of land surface state variables and surface fluxes provided by the multi-model analysis from the Second Global Soil Wetness Project (GSWP-2; Dirmeyer *et al.*, 2006) on a 1° global grid over land for the period 1986-1995 are used. This multi-model analysis is generated by integrating a group of one-way uncoupled land surface models driven by the same observationally based near surface meteorology. The GSWP-2 used a hybrid forcing time series combining the observational and model (reanalysis) datasets of near-surface air temperature and specific humidity at 2 m, wind speed at 10 m, surface incident shortwave and long wave radiation, surface pressure and precipitation. This hybrid dataset is mostly based on reanalysis outputs, but key aspects of the forcing were scaled so that their long-term means agree with independent observational datasets. The precipitation data, in particular, were forced to agree with a rain gauge based dataset at the monthly time scale. The quality of the precipitation datasets that contributed to GSWP-2 might have been affected over Asia due to the fact that satellite information, with a large uncertainty over land, was used

to fill the gaps in this region with low rain gauge density (Koster *et al.*, 2011). However when compared with long term *in situ* soil moisture data over India, the multi-model analysis from GSWP-2 is found to simulate the phasing of the annual cycle, interannual variability, and magnitudes in observed soil moisture reasonably well (Guo *et al.*, 2007). The depth of the root zone differs among the participating land surface models in GSWP-2. This study uses the multi-model average root zone soil moisture provided by GSWP-2 (Dirmeyer *et al.*, 2006).

The observational datasets used in this study include the Asian Precipitation-Highly-Resolved Observational Data Integration Towards Evaluation of Water Resources (APHRODITE) gridded ($0.5^\circ \times 0.5^\circ$) daily surface air temperature (Yasutomi *et al.*, 2011) and rainfall (Yatagai *et al.*, 2012) for the period 1976-2005. The gridded ($1^\circ \times 1^\circ$) rainfall data set prepared by the India Meteorological Department (IMD; Rajeevan *et al.*, 2005) based on a weighted average of rain gauge observations is also used.

The intraseasonal variations in the Indian summer monsoon with significant precipitation fluctuations between the active and break spells are identified following Rajeevan *et al.* (2010) by averaging the daily precipitation over a core monsoon region (18.0° N to 28.0° N and 69.0° E to 88.0° E). The tropical convergence zone responsible for the large-scale rainfall during the summer monsoon fluctuates over this region during the peak monsoon months of July and August. The time series of the daily precipitation climatology is used for computing the daily anomalies during each year. The calculation of the daily anomalies by subtracting the daily climatology instead of the long term monthly or seasonal mean is justified because of the strong seasonality seen over the Indian subcontinent during summer monsoon season. The daily anomalies over the core monsoon zone are normalized by dividing with the respective daily standard deviation. The active (break) spell has been identified during July-August months as the period with normalized precipitation anomaly more (less) than +1.0 (-1.0) consecutively for three days or more. This methodology is applied to two observed precipitation datasets (APHRODITE and IMD) in order to bring out the robustness of this methodology and also to capture the observational uncertainty.

3. Results

The changing characteristics of the intraseasonal variations in precipitation and surface air temperature during the Indian summer monsoon are diagnosed using observational based gridded analyses. The frequency of break days during July and August months identified

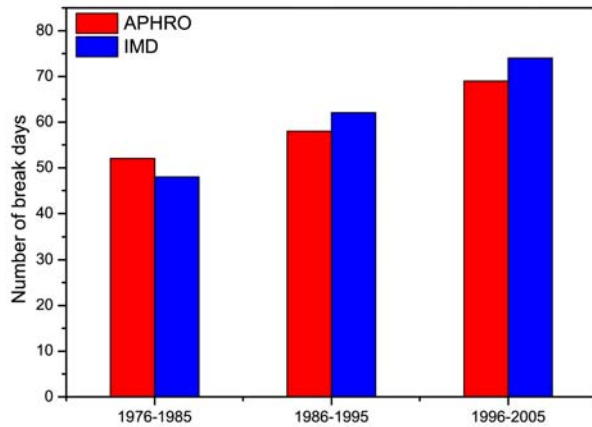


Fig. 1. The frequency of the break days in the two observed precipitation datasets (APHRODITE and IMD) during the recent three decades (1976-1985, 1986-1995, 1996-2005)

using the APHRODITE and IMD precipitation datasets show a gradual increase for the recent three consecutive decades (1976-1985, 1986-1995, 1996-2005; Fig. 1). This finding is consistent with the earlier results of Kumar *et al.* (2009) and Singh (2013), and confirms that the method used to identify break spells in this study are robust. Fig. 2 shows the APHRODITE daily mean surface air temperature averaged over the monsoon zone during July-August for a drought year 1987 (bars) and the respective 10 year (1986-1995) climatology (thick line). It is seen that the surface air temperature increased rapidly during the break spells (filled bars) in 1987. The above normal temperatures are also found to persist for more days after each break spell with anomalies exceeding 1 K.

The spatial distribution of the daily detrended APHRODITE surface air temperature anomalies composited for break days in the recent three decades are shown in Fig. 3. The statistical significance of the composited break temperature anomalies are evaluated following Krishnan *et al.* (2000) using the Student's *t*-test for unequal variances (Press *et al.*, 1992). The null hypothesis assumes that the composited break anomalies are not statistically significant. The break composite temperature anomalies that are statistically significant at 95% level for the Student's *t*-test are only plotted in Fig. 3. The area of warm anomalies above 0.5 K are seen to be extending from east coast to north India during 1980s [Fig. 3(a)]. This region widens and appears to cover more area over the west coast and parts of peninsular India during 1990s [Fig. 3(b)], and further expands during 2000s [Fig. 3(c)]. The small region with peak warm anomalies of magnitude above 1.5 K seen over north-central India in 1990s also expands into more parts of central India during 2000s. The difference plot for the consecutive decades clearly shows that the surface air temperatures during monsoon break period in 1990s are in

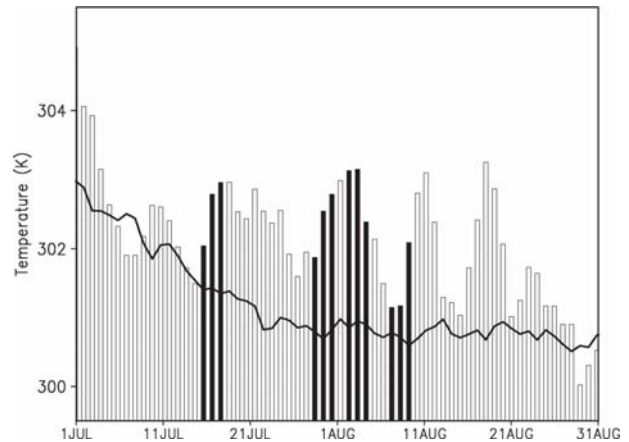
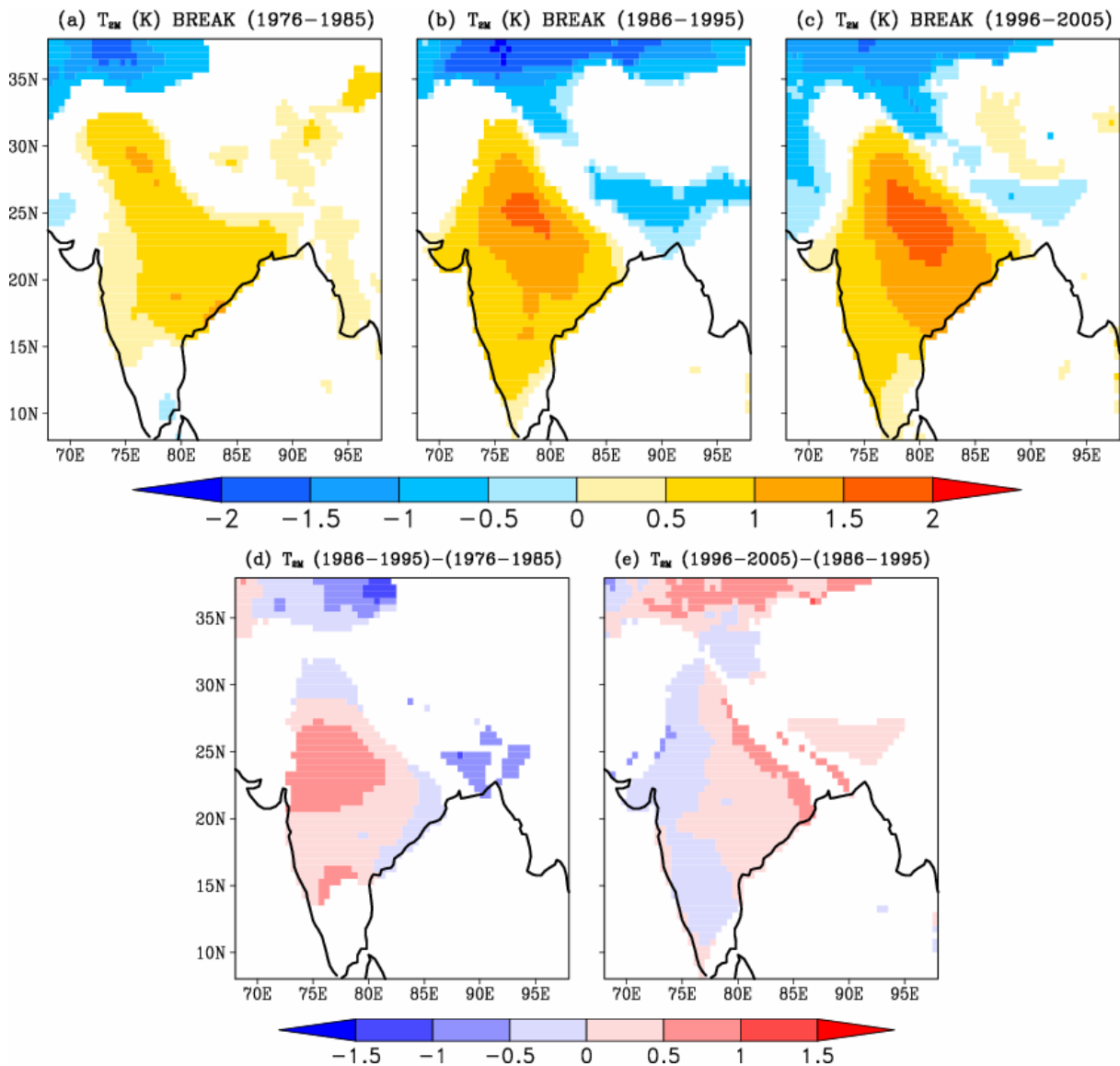


Fig. 2. The daily surface air temperature (APHRODITE) area averaged over the core monsoon region during Jul-Aug months for year 1987 (bars) and the 10 year (1986-1995) climatology (line). The filled bars are the break days during 1987

general warmer than in 1980s by about 0.5 K over the central and parts of peninsular India with an area to the north-west warmer by about 1K [Fig. 3(d)]. The region of break period warming in 2000s shifts from the area in 1990s and is found to extend from the east-central to the Indo Gangetic plains over India [Fig. 3(e)]. This analysis using detrended daily data excludes the impact of global warming on regional temperature and hence indicates the role of local feedbacks such as land-atmosphere interactions in maintaining higher break monsoon temperatures over a wider region in recent decades.

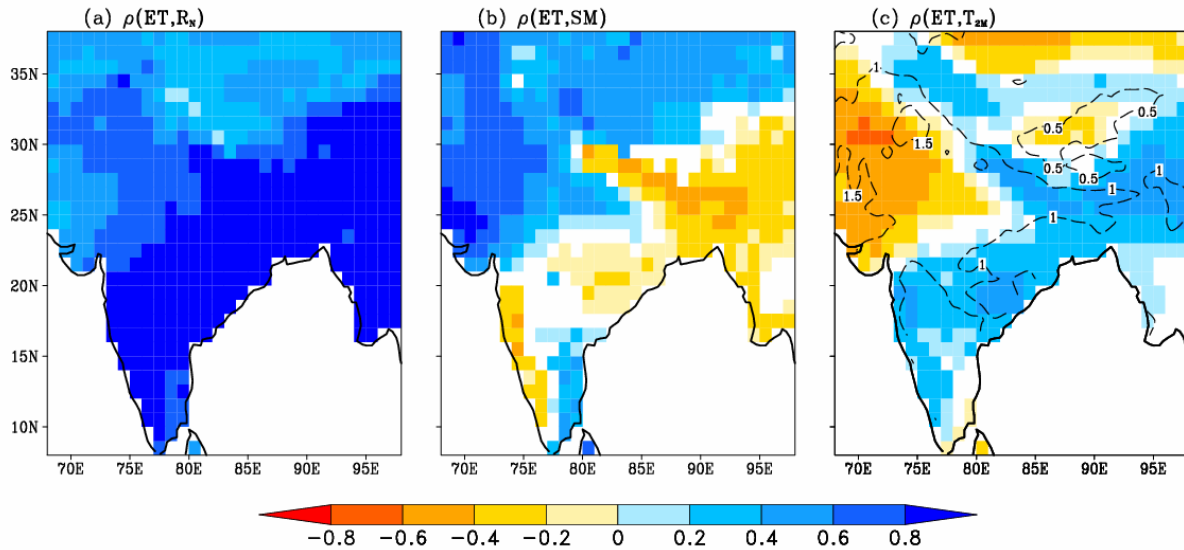
The daily fields of root zone soil moisture and surface fluxes available in the multi-model analysis from the GSWP-2 during the 10 year period (1986-1995) are used in conjunction with the daily APHRODITE surface air temperature to identify the probable regions of strong soil moisture-temperature coupling over India in July and August months. The earlier studies found the hot-spot regions of land-atmosphere coupling with strong impacts of soil moisture on temperature and precipitation only in the transition climate zones between dry and wet areas (Koster *et al.*, 2006). This is the result of a high sensitivity of evapotranspiration to soil moisture together with a high temporal variability of the evapotranspiration in these regions (Guo *et al.*, 2006; Seneviratne *et al.*, 2010). The correlation in time is used as an indirect estimate of coupling for these relationships for which causality has been established although this diagnostic cannot demonstrate the links of causality (Teuling *et al.*, 2009; Seneviratne *et al.*, 2010; Miralles *et al.*, 2012). Fig. 4 shows the regions with statistically significant correlation of GSWP-2 daily mean evapotranspiration with its two main drivers, surface net radiation [Fig. 4(a)] and root zone soil moisture during July-August [Fig. 4(b)]. The



Figs. 3(a-e). The observed (APHRODITE) daily July-August 2m air temperature (T_{2M} , K) anomalies (computed from detrended time series) composited for the Indian monsoon break days during the recent three decades (a) 1976-1985, (b) 1986-1995 and (c) 1996-2005. The difference in the break composite anomalies between the consecutive decades (d) b minus a, and (e) c minus b. Break composite anomalies exceeding the 95% level of significance are shaded

spatial distribution reveals the existence of two dominant evapotranspiration regimes over India during these principal monsoon precipitation months. The central and peninsular India with wet soil conditions under the influence of monsoon precipitation show an energy limited evapotranspiration regime with relatively higher positive correlation with net radiation [Fig. 4(a)] than with soil moisture [Fig. 4(b)]. This finding that most parts of India is energy limited during summer monsoon season is also supported by a continental scale study using surface

measurements (Padmakumari *et al.*, 2013). In these regions where soil moisture is abundant but available energy is the limiting factor it is even found that sub-regionally the correlation of evapotranspiration with soil moisture is negative [Fig. 4(b)] because high (low) net radiation increases (decreases) evapotranspiration, drawing down (retaining) soil moisture. Such negative relationship between GSWP-2 soil moisture and evapotranspiration in energy limited evapotranspiration regimes has been discussed earlier (Dirmeyer, 2011). A



Figs. 4(a-c). Correlation of GSWP-2 daily mean evapotranspiration (ET) during July-August months with: (a) surface net radiation (R_N), (b) root zone soil moisture (SM) and (c) observed (APHRODITE) 2m air temperature (T_{2M}). Correlation values with statistical significance exceeding 95 % are shaded. Standard deviation of ET is contoured in (c) at 0.5 mm d^{-1} intervals

soil moisture limited evapotranspiration regime characterized by relatively higher positive correlation with soil moisture than with net radiation is seen over the north-west India, indicating that variations in soil moisture control the variations in evapotranspiration over this region [Fig. 4(b)]. This suggests that the evapotranspiration is largely determined by the degree of soil moisture deficit over this semi-arid region, and not by the availability of net radiative energy at the surface, as was also discussed by Koster *et al.* (2009). The strength of land-atmosphere coupling will not only depend on the positive relationship between evapotranspiration and soil moisture, but also on the connection of evapotranspiration with surface air temperature and precipitation (Guo *et al.*, 2006; Seneviratne *et al.*, 2010). The correlation of evapotranspiration with temperature have been applied both to observational and model data as an indirect estimate of soil moisture-temperature coupling (Seneviratne *et al.*, 2010). Fig. 4(c) shows the regions with statistically significant correlation of GSWP-2 daily mean evapotranspiration during July-August with daily APHRODITE surface air temperature. The evapotranspiration and temperature tend to correlate positively in regions with abundant soil moisture availability because they both depend on net radiation. This diagnostic shows high negative correlation in the soil moisture limited region over north-west India where a strong dependency of evapotranspiration on soil moisture was also found [Fig. 4(b)]. The temporal variability of evapotranspiration [Fig. 4(c); contours] is also found to

be relatively larger suggesting that strong soil moisture-temperature coupling take place over this region in north-west India during the principal monsoon months. This region was also identified as a hot spot of strong soil moisture-temperature coupling in the multi-modelling study of Koster *et al.* (2006), and fit well the definition of transitional climate zones (Seneviratne *et al.*, 2010). This analysis confirms the significant control of soil moisture on observed surface air temperature over north-west India during summer monsoon in 1990s.

The role of sub-seasonal dry soil conditions associated with break spells of monsoon precipitation in prolonging the above normal temperature for longer periods by modulating the soil moisture-temperature coupling is further analysed. The wet and dry soil conditions during July and August months over India are identified using the root zone soil moisture in the multi-model analysis from the GSWP-2 during the 10 year period (1986-1995), by applying a methodology similar to that used for identification of the active and break spells in monsoon precipitation. Fig. 5 shows the time series of core monsoon zone area averaged normalized daily anomalies of root zone soil moisture (red line) and the GSWP-2 precipitation forcing (black line) during July-August months of each year. The days with wet and dry soil conditions are highlighted with red dots in each panel of Fig. 5. It may be noted that the reanalysis based GSWP-2 precipitation forcing, which is adjusted to agree with a low resolution rain gauge based dataset at monthly time

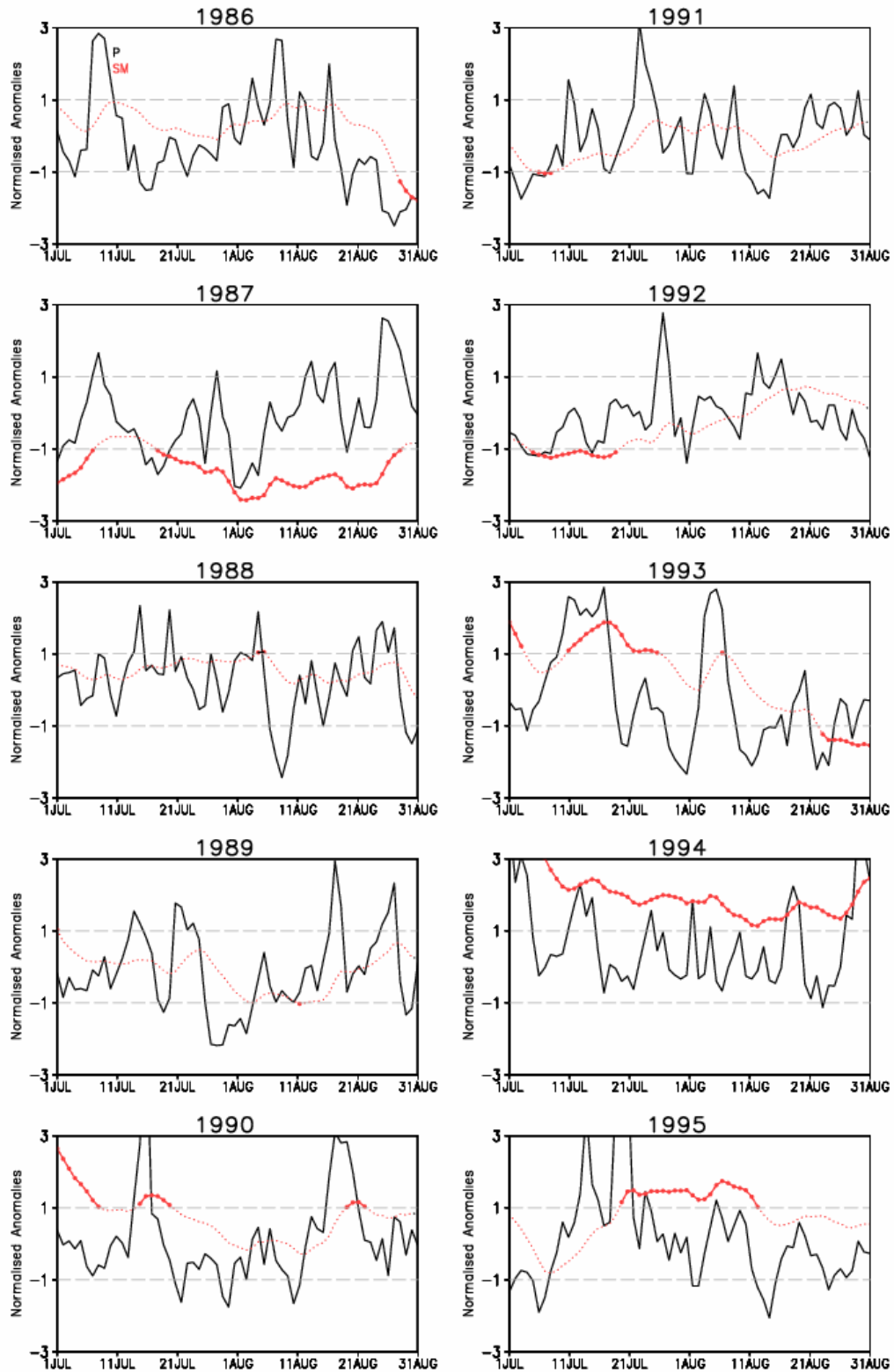
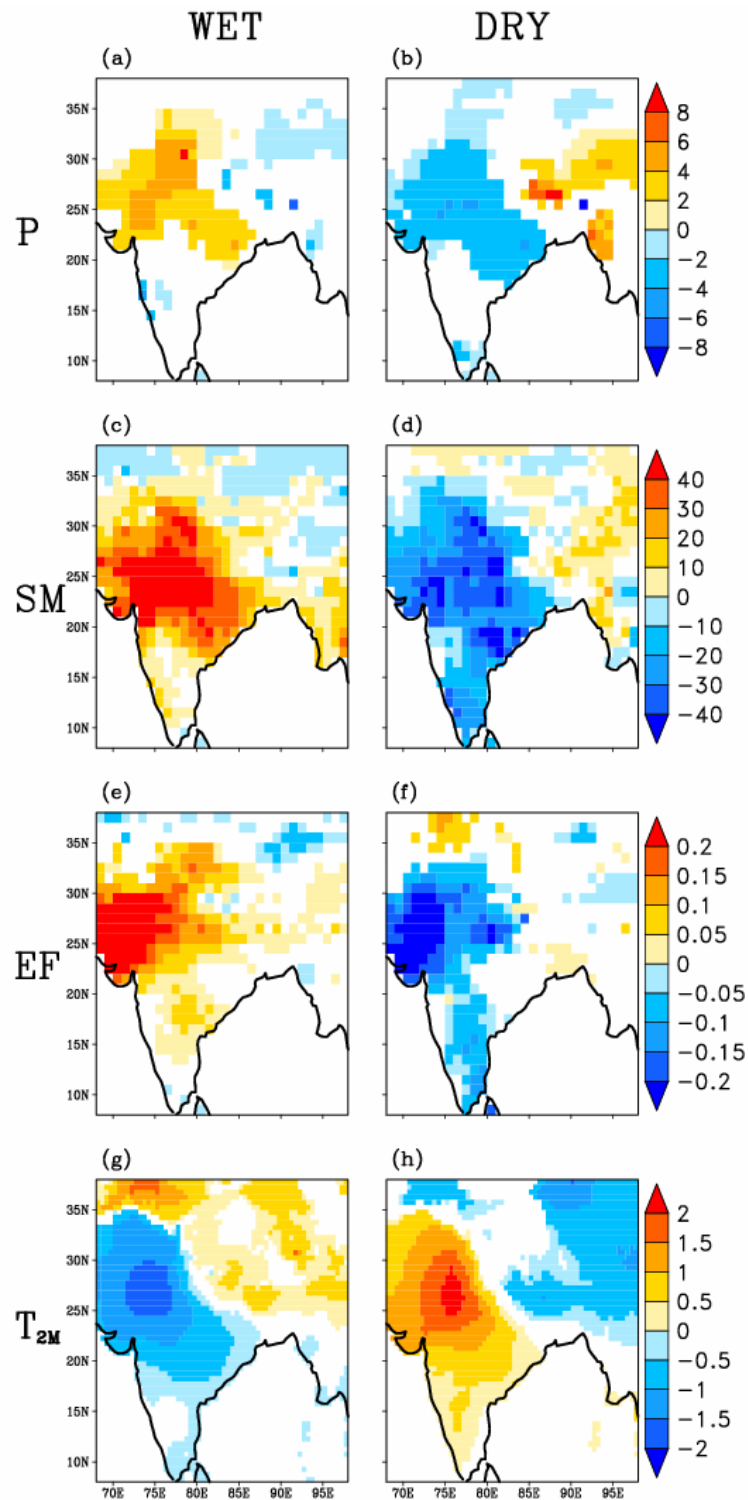
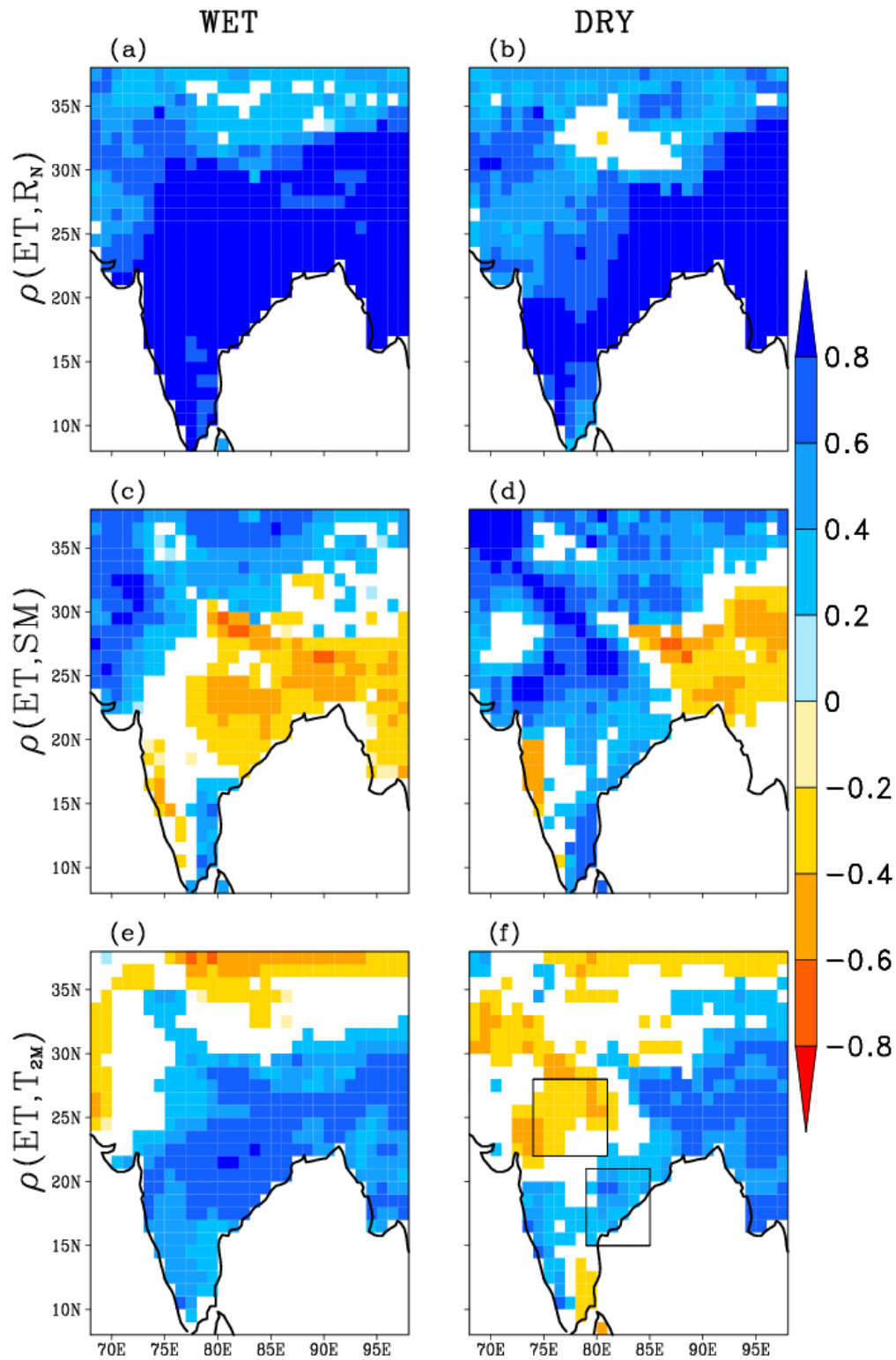


Fig. 5. Temporal evolution of normalized daily anomalies of selected GSWP-2 fields area averaged over the core monsoon zone during July-August months for each year during 1986 to 1995: (red dotted line) root zone soil moisture (SM) and, (black line) precipitation (mm d^{-1}) forcing. The bold red dots are the days with wet and dry soil state



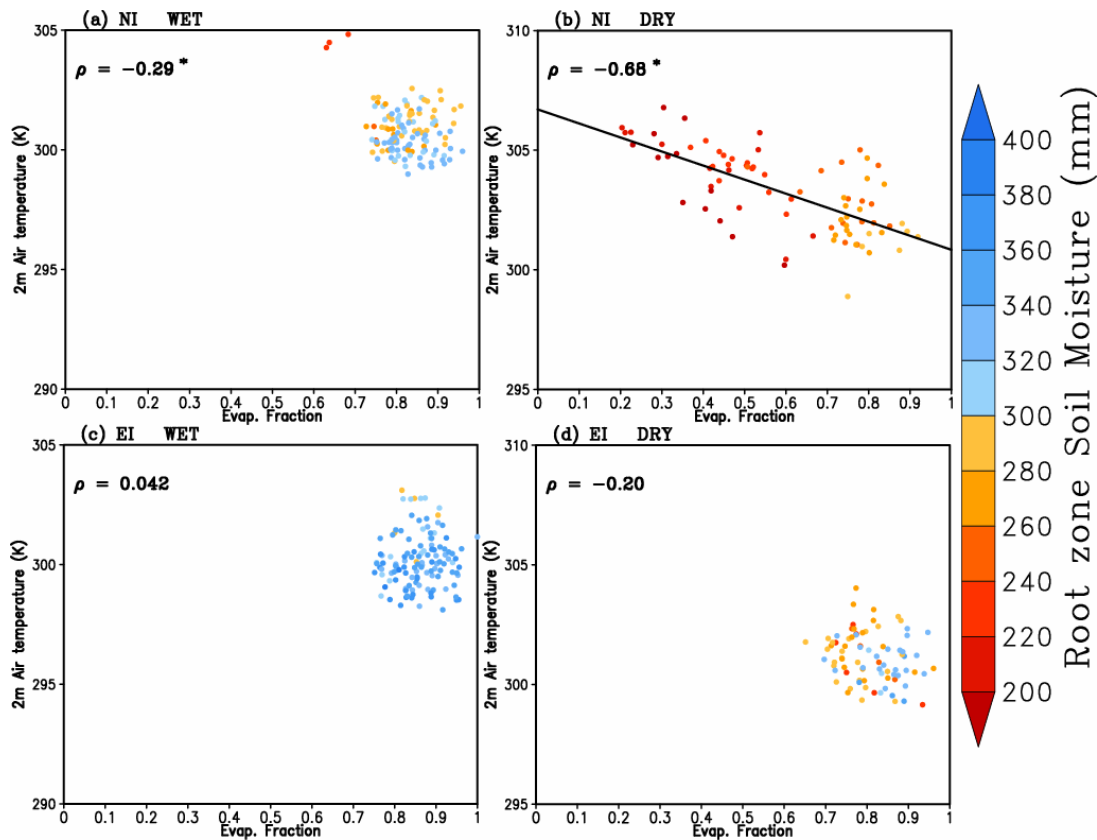
Figs. 6(a-h). Daily anomaly composites for (left panels) wet and (right panels) dry conditions during July-August months for GSWP-2: (a, b) Precipitation (P; mm d⁻¹), (c, d) root zone soil moisture (SM; mm), (e, f) evaporative fraction (EF), and (g, h) the corresponding daily anomaly composite for observed (APHRODITE) 2m air temperature (T_{2M}; K). Anomalies are computed using the daily climatology for the 10-year (1986-1995) period. Composite anomalies exceeding the 95% level of significance are shaded



Figs. 7(a-f). Correlation of GSWP-2 daily mean composites of evapotranspiration (ET) for (left panels) wet and (right panels) dry soil conditions during July-August months with: (a, b) surface net radiation (R_N), (c, d) root zone soil moisture (SM) and (e, f) observed (APHRODITE) 2m air temperature (T_{2M}). Correlation values with statistical significance exceeding 95 % are shaded

scale (Koster *et al.*, 2011), is found to have significant bias over the monsoon zone in some years when the daily precipitation during July and August months are compared with the high resolution rain gauge based dataset prepared by IMD. However, these datasets compare closely over the semi-arid region in north-west India (figure not shown) where strong soil moisture-temperature coupling was found during principal monsoon months [Fig. 4(c)]. Fig. 5 shows that in most years the dry soil conditions exist for longer periods than the break spells in monsoon precipitation (*e.g.*, year 1987). The GSWP-2 land state variables and surface fluxes are composited for the wet (123 days) and dry (80 days) soil conditions identified during the 10 year period in order to explore the role of sub-seasonal dry soil states in maintaining above normal surface air temperatures. Fig. 6 shows the spatial distribution of the statistically significant daily anomalies of the GSWP-2 precipitation forcing, root zone soil moisture, evaporative fraction (the ratio of surface latent heat flux to the available energy for evapotranspiration) and surface air temperature for the wet (left panels) and dry (right panels) soil composites. The GSWP-2 precipitation anomalies for wet [Fig. 6(a)] and dry [Fig. 6(b)] soil conditions in general indicate characteristics of active (break) spells during monsoon with above (below) normal values over the core monsoon zone. The positive precipitation anomaly over northeast India in the dry soil composite [Fig. 6(b)] is similar to that reported by Ramamurthy (1969) to be in association with the sub-seasonal northward shift of the monsoon trough to the foothills of the Himalaya during monsoon break spells. However a small region of positive precipitation anomaly over Tamilnadu in southeastern peninsular India during break spells reported in earlier studies is not correctly depicted in the GSWP-2 precipitation forcing dataset. This improper representation of sub-seasonal precipitation patterns may have introduced some regional bias in the soil moisture simulated by the GSWP-2 land surface models. However to the best of our knowledge the soil moisture products in the multi-model analysis from GSWP-2 are the best available dataset to investigate the daily spatial variations of soil state over India (Guo *et al.*, 2007). The wet and dry GSWP-2 root zone soil moisture anomaly composites indicate a sub-seasonal transformation from a wetter [Fig. 6(c)] to drier [Fig. 6(d)] than normal soil state over the core monsoon region. However the statistically significant anomalous evaporative fraction is confined to the west-central India [Figs. 6(e&f)] and suggests that in wet soil state the contribution of available energy at the surface to evapotranspiration is larger [Fig. 6(e)], while the drier soil conditions limits evapotranspiration [Fig. 6(f)], allowing more energy to be partitioned in to sensible heating. The surface air temperature over this region also consistently varies from below to above normal values for

the wet [Fig. 6(g)] and dry [Fig. 6(h)] soil conditions respectively, indicating a strong control of soil moisture in inducing these sub-seasonal temperature changes. The modulation of this soil moisture-temperature coupling through the sub-seasonal changes in the evapotranspiration regimes during wet and dry soil conditions is further analysed. Figs. 7(a-f) shows the regions with statistically significant correlation of GSWP-2 daily mean evapotranspiration with net radiation [Figs. 7(a&b)] and root zone soil moisture [Figs. 7(c&d)] composited for wet (left panels) and dry (right panels) soil conditions. The wet soil composite show energy limited evapotranspiration regime covering wider regions over India than that found earlier for the principal monsoon months [Fig. 4(a)], characterized by high positive correlation with net radiation [Fig. 7(a)] and too low or negative correlation with soil moisture [Fig. 7(c)]. The energy limited regime is found even in the dry soil composite over some parts of west and east India [Fig. 7(b)]. The positive correlation of evapotranspiration with soil moisture during dry soil condition is found to be moderate over central region, and increases toward the north-west India [Fig. 7(d)]. These regions indicate soil moisture limited evapotranspiration regime with relatively low correlation of evapotranspiration with net radiation [Fig. 7(b)]. The statistically significant high negative correlation between GSWP-2 evapotranspiration and APHRODITE temperature for dry soil composite [Fig. 7(f)] further confirms the potential for strong soil moisture temperature coupling over north-west India. However this diagnostic for coupling strength show remarkable regional contrast, with positive correlation between evapotranspiration and temperature seen in some parts of west and east coasts of India with abundant soil moisture availability even during dry soil conditions [Fig. 7(f)]. In order to compare the regional soil moisture temperature coupling, we have chosen two sub-regions over north (NI; 74° E - 81° E; 22° N - 28° N) and east India (EI; 79° E - 85° E; 15° N - 21° N). These sub-regions are marked in Fig. 7(f). The NI region with strong coupling during dry soil states consists of a predominantly arid to semiarid environment and is generally characterized by scanty precipitation during Indian summer monsoon season. In contrast, the EI region lies always in the energy limited evapotranspiration regime discussed earlier, which receives heavy and frequent precipitation during the monsoon season. Fig. 8 shows the scatter plots of daily fields of GSWP-2 evaporative fraction and APHRODITE temperature area averaged over the NI and EI regions for each day of wet (left panels) and dry (right panels) soil conditions identified over the core monsoon zone during July-August for the 10-year (1986-1995) period. The regional averages of the GSWP-2 root zone soil moisture (colored dots) for the two regions are varying over time in both soil states, but of



Figs. 8(a-d). Scatter plots of daily fields of GSWP-2 evaporative fraction (EF) versus observed (APHRODITE) 2m air temperature (T_{2M} ; K) area averaged over the (a, b) northern India (NI; 74° E - 81° E; 22° N - 28° N) and (c, d) eastern India (EI; 79° E - 85° E; 15° N - 21° N) for each day of (left) wet and (right) dry soil conditions identified over the core monsoon zone during July-August months for the 10-year (1986-1995) period. The colors represent the root zone soil moisture (mm). The correlation between the EF and T_{2M} is denoted at the top-right corner of each panel with an asterisk indicating 95% statistical significance

larger magnitude in NI region [Figs. 8(a&b)]. The impact of reduced soil moisture over NI on increasing surface air temperature is found to be mediated through large decreases of evaporative fraction for the dry soil composite [Fig. 8(b)]. This negative relationship between evaporative fraction and temperature with temporal correlation of -0.64 is statistically significant at 95% confidence level. The seasonally wet EI region does not indicate such linear relationships for both soil composites [Figs. 8(c&d)], and hence does not impact the air temperature even when dry soil conditions exist over the core monsoon zone. Thus the spatial variations in the soil moisture temperature coupling strength over India during the summer monsoon season can be attributed to the regionally wet and dry climatic conditions. On the other hand the enhanced coupling over the north-west India during sub-seasonal dry soil states is related to a transformation in to soil moisture limited evapotranspiration regime.

4. Discussion

This study investigated the potential feedbacks from land surface state to atmosphere using simple diagnostics based on temporal correlations. It was shown that this methodology, which was used globally for diagnosing the summer season soil moisture control on air temperature and precipitation, can be applied to observations for understanding the importance of soil moisture-temperature coupling in modulating the Indian summer monsoon surface air temperature. The stable atmospheric condition during break spells in monsoon precipitation is found to favor increasing control by the local energy balance and subsequently the surface sensible heat flux becomes the driver of air temperature. These conditions enable a positive feedback from land over regions where soil moisture deficit increases as a consequence of the high atmospheric demand of water and decreases in evaporative cooling leading to a further rise in air

temperature. These linkages between dry and warm conditions are well documented in the literature and are extensively reviewed by Durre *et al.* (2000). These relationships were also found by modeling studies that have postulated a possible impact of soil moisture deficit on hot extremes over Europe (Fischer *et al.*, 2007; Hirschi *et al.*, 2011). This mechanism of sub-seasonal enhanced soil moisture-temperature coupling is found to modulate the warmer anomalies in surface air temperature over the semi-arid north-west India during dry soil conditions within Indian summer monsoon season.

The presence of a spatial gradient in evapotranspiration regimes over India found in this study during July-August months is consistent with the results demonstrated earlier using regional climate model simulations over Indian sub-continent for summer monsoon season (Asharaf *et al.*, 2012; Asharaf and Ahrens, 2013) and with observation-driven multi-model estimates from GSWP-2 over European continent in summer time (Teuling *et al.*, 2009). The earlier investigation by Asharaf *et al.* (2012) of soil moisture-precipitation feedback processes during Indian summer monsoon through soil moisture perturbation simulations with a regional climate model had found that the simulations initialized with decreased soil moisture content yield an increase in the sensible heat fluxes and warming of the earth's surface, which results in a stronger land-sea contrast in the northwestern parts of India and intensification of moisture advection from the Arabian Sea to this region. Our observational based analyses also reveals that over north-west India during dry soil states in sub-seasonal time scales within the Indian summer monsoon season, sensible heating increases, inducing warmer surface air temperature anomalies. Thus more studies are needed to understand the effects of these observed sub-seasonal processes on atmospheric dynamics and its role in influencing the precipitation over this region.

The daily temporal resolution of the GSWP-2 land state variables and surface fluxes allowed the study of coupling at the sub-seasonal time scales relevant for warmer anomalies related to break spells in Indian monsoon precipitation. The decadal record length was useful to analyze the climatological means of land-atmospheric coupling during peak monsoon months. However the lack of such reliable datasets for multi-decadal periods hampered the investigation of the role of land-atmosphere interactions in the observed increases in break monsoon period warm anomalies over India in recent decades.

5. Conclusion

In conclusion, this study represents the first attempt to link sub-seasonal summer soil moisture coupling on near-surface air temperature over India using the multi-model analysis from the GSWP-2. Our results show that the summer temperature variations are linked to intraseasonal variations of the Indian monsoon precipitation, which control the land-climate coupling by modulating the soil moisture variations. Strong coupling mainly occurs over the transition zones between wet and dry climates of central to north-west India. In contrast, the coupling is weak over remaining regions over India with constantly wet and energy-limited evaporative regimes during the entire summer monsoon season. This observation-based analysis, by taking into account the respective period of the summer monsoon season where soil moisture is most likely to be limiting over some parts of India, suggests a broader relevance of soil moisture-atmosphere coupling than could be assumed from the past modeling studies (Koster *et al.* 2006). This finding is decisive, since climate change is already causing changes in the sub-seasonal characteristics of Indian summer monsoon precipitation, indicating that in future there is more likelihood of break like conditions, and the associated soil moisture deficits may contribute to prolong the warmer surface air temperature anomalies for longer periods in a wider area over India. The soil moisture-temperature coupling diagnostic used in this study will be a useful metric for evaluating the performance of weather and climate models used for subseasonal and seasonal monsoon forecasting as the skill associated with soil moisture could be critical for several applications, in particular agriculture.

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