Effects of spring land cover change on early Indian summer monsoon variability

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Abstract. Effects of land cover change over the Indian subcontinent during the preceding March through May (MAM) on early Indian summer monsoon (ISM) rainfall were examined using the Normalized Difference Vegetation Index (NDVI) and Global Precipitation Climatology Project precipitation for the period of 1982~2003. MAM NDVI anomalies have increased significantly in western and northern India. NDVI anomalies are correlated with the decreasing trend of early ISM rainfall. Decreasing rainfall originates from the decreased land-sea thermal contrast, which is due to the decreasing trend of July sensible heat flux in central and northern India. This is related to the increase in the preceding MAM NDVI anomalies because early ISM rainfall is significantly and negatively correlated with the standardized principal component of the first leading empirical orthogonal function for the preceding MAM NDVI anomalies. Also, composite differences of early ISM rainfall for the five years of highest and of lowest MAM NDVI anomalies demonstrate that early ISM rainfall is significantly less for the years of highest MAM NDVI anomalies. Composite differences of wind vectors and divergence in the upper level also support the conclusion that the weak early Indian summer monsoonal circulation is due to the increase in land cover during the preceding spring, which would promote an increase in latent heat flux and a decrease in sensible heat flux thereby favoring a reduced horizontal temperature gradient.

1. Introduction

The most prominent regions of irrigation are clearly correlated with areas of intensive food production: southeastern China and, especially, the Indo-

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Gangetic Plain [*Gordon et al.*, 2005]. India is the most important irrigated region of the world [*Shiklomanov*, 1997], and its irrigation withdrawals represent 80~90% of all water use in India [*Douglas et al.*, 2006].

Several studies have analyzed the impact of irrigation on regional climate, especially in the U.S. [e.g., *Adegoke et al.*, 2003; *Moore and Rojstaczer*, 2001; *Chase et al.*, 1999; *Barnston and Schickedanz*, 1984] and India [e.g., *Douglas et al.*, 2006; *de Rosnay et al.*, 2003; *Lohar and Pal*, 1995]. *de Rosnay et al.* [2003] conducted two two-year simulations, forced by the 1987~88 International Satellite Land Surface Climatology Project (ISLSCP) data sets, with and without irrigation over the Indian Peninsula. They pointed out that irrigation is a major component of the hydrological processes and the water cycle. *Douglas et al.* [2006] investigated the changes across India in vapor and energy fluxes between pre-agricultural and contemporary agricultural land cover, indicating a dramatic influence of dry-season (January through May) agriculture on atmospheric moisture and energy fluxes in comparison with that of wet-season (July through December). *Lohar and Pal* [1995] showed that the effect of irrigation on pre-Indian summer monsoon precipitation over southwest Bengal at a station in Kharagpur (22.2 °N, 87.3 °E). In their study, the increase in soil moisture as a result of irrigation hinders the development and intensity of sea-breeze circulation. The result may, therefore, lead to diminished rainfall over the region during the pre-monsoon period.

In our study, we examine the effects of land cover change over a more general Indian summer monsoon (ISM) region, i.e., 5~30°N and 70~90°E (see Fig. 1a), because the changes in water cycle and fluxes due to land cover change over a large enough area can impact on the changes in monsoonal circulation [e.g., *Douglas et al.*, 2006; *Fu et al.*, 2004; *Chase et al.*, 2003]. Since July is the month of the highest ISM rainfall, we determine July ISM variability due to land cover change using the Normalized Difference Vegetation Index (NDVI). The present study aims to address the following questions: 1) Are there significant recent changes in the land cover over the Indian subcontinent during the pre-ISM season (i.e., March through May), and in early ISM rainfall; and 2) what is the impact of land cover change on early ISM variability? Changes in Asian summer monsoon due to weakening of summer monsoon precipitation have been examined [e.g., *Wang and Ding*, 2006; *Chase et al.*, 2003]. Thus, this study could help to explain the changes in the behavior of the Asian summer monsoon system by demonstrating that vegetation influences the regional climate, including the monsoon system.

2. Data and Methodology

NDVI data available from NOAA/AVHRR [*Tucker et al.*, 2005; http://iridl.ldeo.columbia.edu/expert/SOURCES/.UMD/.GLCF/.GIMMS/.NDVIg/.global/ndvi/streamrescale/-999/setmissing_value/dods] are used as an index for land cover change. NDVI is the unitless difference between infrared

and visible reflectance normalized by their sum. The mean precipitation (mm/day) derived from the Global Precipitation Climatology Project version 2 (GPCP) [*Adler et al.*, 2003] is used to calculate July ISM rainfall. In order to determine the influences of land cover change during the preceding spring on the thermal and dynamic conditions during the early summer, we use surface sensible heat flux [SHF (W/m^2)], latent heat flux [LHF (W/m^2)], 2m-temperature (K), upper level wind vector (m/s) and divergence (s^{-1}) calculated with mean 200 hPa *u*- and *v*-winds (m/s) from National Centers for Environmental Prediction-National Center for Atmospheric Research (NCEP) reanalysis [*Kalnay et al.*, 1996].

Spatial resolutions (longitude × latitude) of these datasets are 1°×1° for NDVI (converted from 0.073°× 0.073°) and 2.5°×2.5° for GPCP and NCEP. NDVI data started in July 1981 and are only available through December 2003, so we examine 22 years, from 1982 to 2003. Seasonally averaged values of March through May (MAM) are defined as the pre-ISM season, and July as the month of early ISM. Maximum rainfall is in July and is about one third of all ISM rainfall for June through September based on 1982~2003.

The first leading empirical orthogonal function (EOF 1) and its corresponding standardized principal component 1 (PC 1) of MAM NDVI anomalies are used to examine land cover change in the Indian subcontinent and to calculate the index of land cover change. The standardized PC 1 is defined as the PC 1 time series multiplied by the area-averaged value of the first eigenvector over the Indian subcontinent and then divided by its standard deviation. We examine the spatial distributions of regression trends of NDVI, SHF, LHF, 2m-temperature, and rainfall with time (22 years). The spatial pattern of July ISM rainfall correlated with the standardized PC 1 of MAM NDVI anomalies is used to determine the relationship between land cover change during the preceding spring and early ISM rainfall. In order to check the consistency with the correlation pattern, we use the composite analysis of rainfall, 200 hPa wind vector, and 200 hPa divergence for the five highest (1997, 1998, 1999, 2001 and 2002) and the five lowest (1983, 1985, 1987, 1988 and 1989) years of MAM NDVI anomalies over the Indian subcontinent. In all statistical analyses, significant regions at the 90% are contoured.

3. Results

3.1. Changes in spring land cover

The spatial distributions of EOF 1 of MAM NDVI anomalies show the same positive sign in eigenvectors over the Indian subcontinent with the relatively higher values in the central western and northeastern regions (Fig. 1a). The variance of the EOF 1 accounts for 24% of the total variance. The time series of the corresponding standardized PC 1 for 1982~2003 show an increasing trend (Fig. 1b). This result is consistent with the 1982~2003 regression

trend of MAM NDVI, which significantly increases in the western and northern regions (Fig. 1c). These significant changes of NDVI are clearly related to the areas of irrigation [*Chase and Lawrence*, in review] not only in northern India, i.e., the Indo-Gangetic Plain [*Gordon et al.*, 2005], but also in central India, i.e., the Krishna River Basin [*Ahmed et al.*, 2006; *Biggs et al.*, 2006]. We take the standardized PC 1 as an index for land cover change during the pre-ISM season to examine the effects of land cover change on early ISM variability shown in section 3.3.
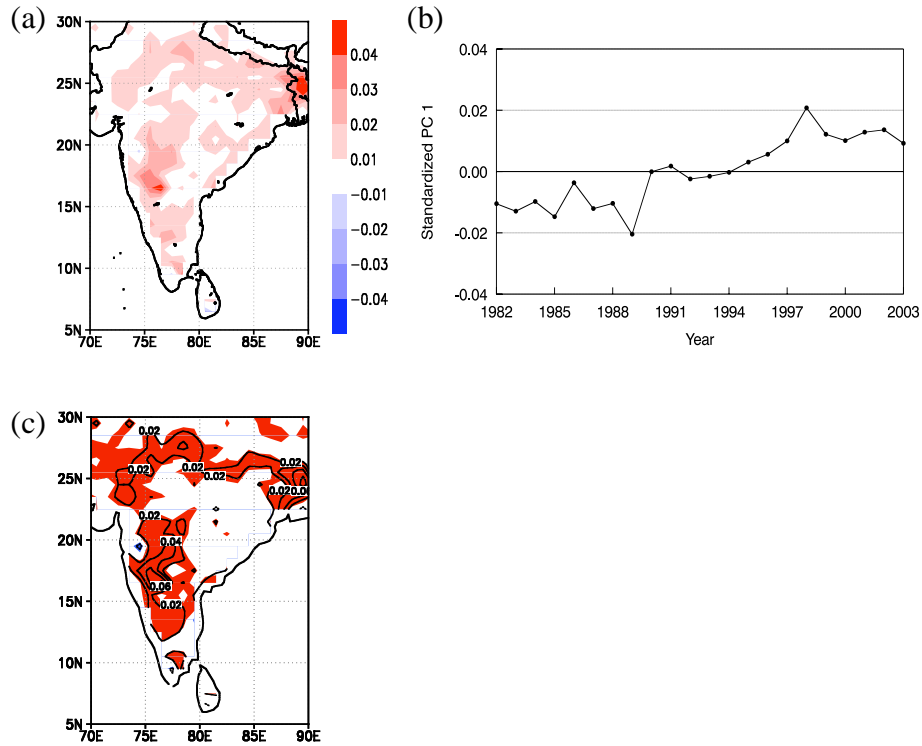

Fig. 1. (a) EOF 1 (23.98% Var.) and (b) the corresponding standardized PC time series of MAM NDVI anomalies for 1982~2003 over India, i.e., 5~30°N and 70~90°E. Anomalies are area-weighted values. (c) Spatial distribution of 1982~2003 regression trend of MAM NDVI (NDVI/ decade). Significant regions at the 90% are shaded in red for increasing and in blue colors for decreasing trends.

3.2. Changes in July heat energy and rainfall

Fig. 2a shows that SHF in the central and northern regions decreases, especially in the Indo-Gangetic Plain. This trend may be related to the increase in MAM NDVI due to intense irrigation, which results in decreased SHF. The spatial distribution of the regression trend of July 2m-temperature (Fig. 2b) is similar to that of July SHF. This result is consistent with previous studies, which showed that an increased SHF allows warmer surface temperature [e.g., *Xue*, 1997; *McGuffie et al.*, 1995; *Shukla et al.*, 1990; *Lean and Warrilow*,

1989]. July 2m-temperature significantly decreases in northern India and increases in the Bay of Bengal. These trends in 2m-temperature can cause a decrease in heat contrast of land and sea, and thus may cause the variability of July ISM rainfall. Fig. 2c shows that July ISM rainfall significantly decreases on the central Indian subcontinent and increases on the northern Bay of Bengal. The trend of early ISM rainfall on the land is different from that on the ocean, which may be related to land cover change. Thus, the decrease in early ISM rainfall over the Indian subcontinent could be related to the decreased land-sea heat contrast due to the decrease in SHF, which may be a result of the increase in MAM NDVI and irrigation, both which would act to favor an increase in LHF (see Fig. 2d) and a decrease in SHF.

In order to examine consistency between the results from NCEP and from other dataset, we compare the spatial distributions of the regression trends of SHF, LHF, and 2m-temperature from NCEP reanalysis with those from NCEP- Department of Energy (DOE) Atmospheric Model Intercomparison Project (AMIP-II) reanalysis [*Kanamitsu et al.*, 2002]. The spatial correlation values between the trends of July SHF, LHF, and 2m-temperature from NCAR and those from NCEP-DOE AMIP-II over X-Y domain (including 144 grid cells) are 0.36, 0.48, and 0.36, respectively, which are significant at 99%.
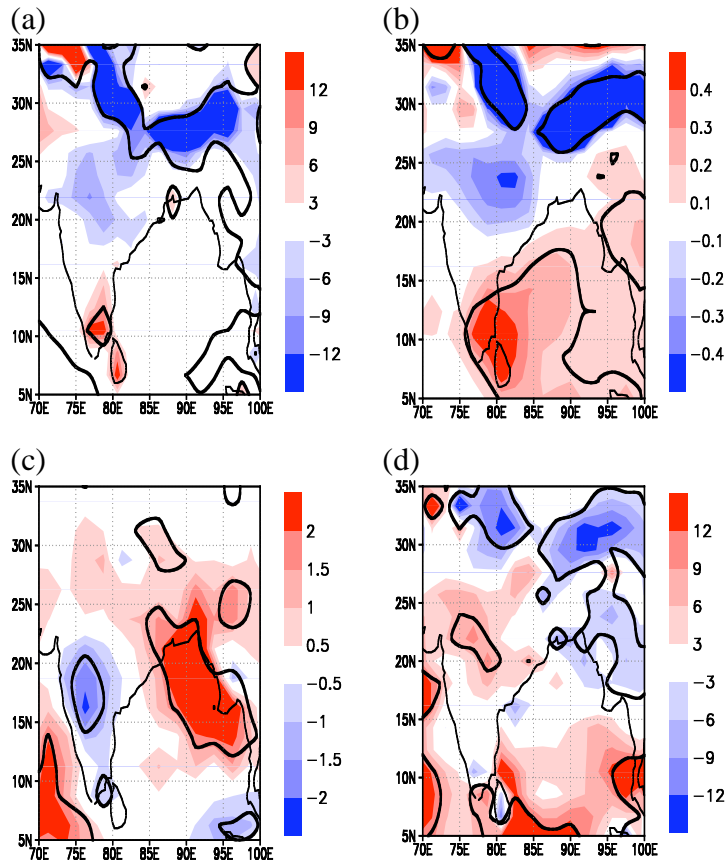
Fig. 2. Spatial distributions of 1982~2003 regression trends of (a) July SHF [(W/m^2)/ decade], (b) July 2m-temperature [K/ decade], (c) July rainfall [(mm/day)/ decade], and (d) July LHF [(W/m^2)/ decade]. Significant regions at the 90% are contoured.

### 3.3. Effects of spring land cover change on early ISM variability

In order to determine the relationship between land cover change during the preceding MAM and early ISM variability, we examine the spatial correlation pattern of July rainfall with the PC 1 of MAM NDVI anomalies. July ISM rainfall is negatively correlated with the PC 1 of MAM NDVI anomalies in the Indian subcontinent, and positively correlated in the northern Bay of Bengal (see Fig. 3a). The spatial distribution of the correlation pattern is similar to that of the regression trend in July rainfall shown in Fig. 2c. To check if the significant correlations are due to the trends, July rainfall and the PC 1 of MAM NDVI anomalies are detrended by performing a linear regression with time as the independent variable, and then correlation analysis is performed. In the detrended correlation pattern (Fig. 3b), there still exists significant negative correlation in the Indian subcontinent, even though the significant positive correlation in the northern Bay of Bengal disappears. The spatial correlation value between Fig. 3a and b over X-Y domain is 0.63, which is significant at 99%. Thus, the correlation analysis supports the conclusion that the decrease in July ISM rainfall over the Indian subcontinent for 1982~2003 is significantly related to the increase in the preceding MAM NDVI anomalies.
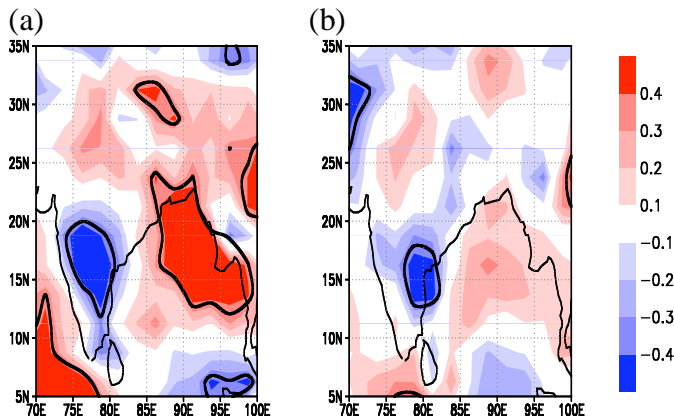
Fig. 3. (a) Correlation patterns of July rainfall with the standardized PC 1 of MAM NDVI anomalies. (b) As in (a), but after detrending. Significant regions at the 90% are contoured.

The composite difference of July rainfall for the five years of highest and of lowest MAM NDVI anomalies over India shows lower rainfall anomalies over the Indian subcontinent for the five years of highest MAM NDVI anomalies (Fig. 4a). This result is consistent with a negative correlation between July ISM rainfall on the land and preceding MAM NDVI anomalies shown in Fig. 3a and b. In Fig. 4b, the composite difference of July 200 hPa wind vector shows more westerly anomalies for the five years of highest MAM NDVI anomalies. It represents fewer easterly wind anomalies in the upper troposphere and also a weaker July ISM, because the climatological upper level wind during the ISM season (June through September) is easterly (not shown

here). The significant smaller upper level divergence anomalies in southern India for the five years of highest MAM NDVI anomalies represents the weakened Indian summer monsoonal convergence in the lower level. The composite analyses, therefore, show that the changes in the preceding MAM NDVI can affect the Indian monsoonal circulation during the early summer, and also the weakening of the early ISM is related to the increase in land cover activity during the preceding spring.
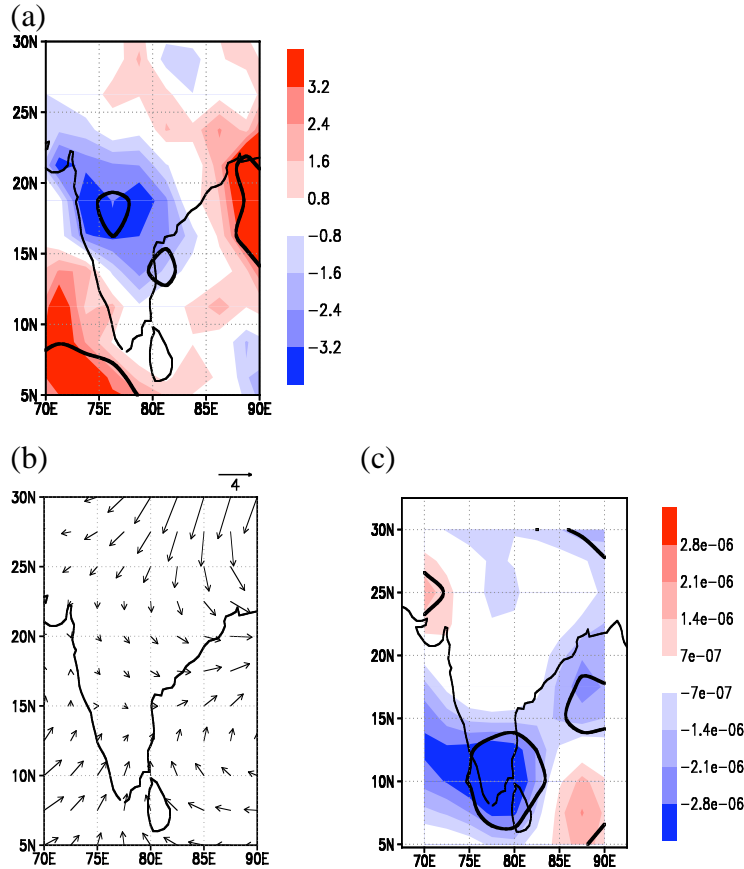
Fig. 4. Composite differences of (a) July rainfall (mm/day), (b) July 200 hPa wind vector (m/s), and (c) July 200 hPa divergence (s^{-1}) for the five years of highest and of lowest MAM NDVI anomalies over the India. Significant regions at the 90% are contoured.

4. Conclusions and Remarks

For 1982~2003, there is significant increase in NDVI during the pre-ISM season over the India subcontinent. The significant change is clearly related to the areas of irrigation not only in the traditional agricultural regions, i.e., the Indo-Gangetic Plain, but also in the recently irrigated regions, i.e., the Krishna River Basin. Both changes, increased soil moisture and increased vegetation and land cover, would favor an increase in LHF and a decrease in SHF. For the same period, early ISM rainfall significantly decreases on the Indian sub-

continent. As the reason for the significant decrease in early ISM rainfall, we demonstrate a decreased land-sea heat contrast due to the decrease of SHF in central and northern India, which dominates any increased instability due to increased atmospheric moisture. The recent decrease in early ISM rainfall is highly related to land cover change during the preceding spring, because early ISM rainfall is significantly and negatively correlated with the preceding MAM NDVI anomalies. Composite analysis of rainfall, 200 hPa wind vector, and 200 hPa divergence shows that the early ISM is weaker for the years having more vegetation activity during the pre-ISM season.

Changes in Asian summer monsoon precipitation [e.g., *Wang and Ding*, 2006; *Chase et al.*, 2003] can be related to land cover change over the Asian continent. To examine the general relationships between Asian summer monsoon variability and land cover change, the other Asian monsoon systems, e.g., East Asian summer monsoon, which can be affected by land cover change over Asian continent including China, Mongolia, Southeast Asia, and India, should be considered in a further study. The study of the dynamical mechanisms between land cover change during the pre-ISM season and early ISM variability should be investigated using surface heat fluxes calculated from observational datasets (e.g., Surface Energy Balance Algorithm for Land approach [*Ahmad et al.*, 2006]). Climate model simulation could also support an elucidation of these mechanisms, and also a validation of the relation between spring land cover change and early ISM variability shown in this study.

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