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Changes in moisture and energy fluxes due to agricultural land use and irrigation in the Indian Monsoon Belt

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Changes in moisture and energy fluxes due to agricultural land use and irrigation in the Indian Monsoon Belt

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[1] We present a conceptual synthesis of the impact that agricultural activity in India can have on land-atmosphere interactions through irrigation. We illustrate a "bottom up" approach to evaluate the effects of land use change on both physical processes and human vulnerability. We compared vapor fluxes (estimated evaporation and transpiration) from a pre-agricultural and a contemporary land cover and found that mean annual vapor fluxes have increased by 17% (340 km^3) with a 7% increase (117 km^3) in the wet season and a 55% increase (223 km^3) in the dry season. Two thirds of this increase was attributed to irrigation, with groundwater-based irrigation contributing 14% and 35% of the vapor fluxes in the wet and dry seasons, respectively. The area averaged change in latent heat flux across India was estimated to be 9 Wm^{-2}. The largest increases occurred where both cropland and irrigated lands were the predominant contemporary land uses. **Citation:** Douglas, E. M., D. Niyogi, S. Frolking, J. B. Yeluripati, R. A. Pielke Sr., N. Niyogi, C. J. Vörösmarty, and U. C. Mohanty (2006), Changes in moisture and energy fluxes due to agricultural land use and irrigation in the Indian Monsoon Belt, *Geophys. Res. Lett.*, *33*, L14403, doi:10.1029/2006GL026550.

1. Introduction

[2] Globally, agricultural water use (in the form of crop irrigation) comprises 70% of all human water withdrawals. Irrigation water use can alter the hydrologic cycle in several ways: by reducing base flow to rivers, by increasing physical evaporation (from soils and standing water) and transpiration (from vegetation), by adding to the greenhouse effect (since water vapor is also a greenhouse gas), by changing cloud coverage and depth, through changes in vegetation distributions and surface albedo and roughness, and by subsequent feedbacks to precipitation, and runoff and contributions to the soil moisture and ground water storage. India leads the world in total irrigated land where irrigation withdrawals represent 80–90% of all water use in India. Approximately 60% of irrigated food production depends on irrigation from groundwater [*Shah et al.*, 2000]. Between 1950 and 1985, groundwater withdrawals increased 113-fold [*Sampat*, 2000], resulting in rapidly declining groundwater levels in as many as 15 states [*Bansil*, 2004]. An important question is whether such hydrologic alteration results in a collection of localized impacts or do they produce feedbacks that are significant at regional scales. Recent research [*National Research Council*, 2005; *Kabat et al.*, 2004; *Adegoke et al.*, 2003] has identified dramatic changes to local and regional hydrology and weather patterns due to agricultural conversion and expanded cropland irrigation. Traditionally, the effects of such changes have been investigated with regional to global general circulation models, a so-called "top down" approach that does not always sufficiently simulate the linkages and non-linear responses inherent in land-atmosphere interactions [*Niyogi et al.*, 2002a]. *Pielke and Bravo de Guenni* [2004] proposed a new vulnerability paradigm that has a "bottom-up" perspective, and focuses on the resource of interest (in our case, freshwater resources). Figure 1 (modified from *Pielke* [2004]) illustrates water resource vulnerability on human and natural systems in India. Changes in seasonal weather patterns, such as the Indian monsoon, could dramatically affect not only the water resources but also the economic and social factors that depend on these resources.

[3] Only a few studies have investigated the influence of intensive irrigation on terrestrial and atmospheric moisture fluxes and the consequences of groundwater mining on these processes. *Gordon et al.* [2005] note that increases in water vapor flows are correlated with intensive food production on the Indian subcontinent and suggest that expanding irrigation in this area will increase the risk for changes in the Asian monsoon system and possibly impact food production capacities in other regions (such as sub-Saharan Africa) as well. *Chase et al.* [2003] and *Pielke et al.* [2003] have documented changes of the global and Indian monsoon system. *de Rosnay et al.* [2003] reported a 9.5% increase in latent heat fluxes due to irrigated agriculture in India. In this paper we estimate changes in vapor fluxes due to conversion of the natural landscape to agricultural land use and then simulate representative feedbacks of these changes in the atmosphere. The purpose of this paper is to illustrate a "bottom up" approach to evaluating the impacts of land use change on land-atmosphere interactions in India and to highlight the effects of these changes on human vulnerability.

2. Methodology

[4] Vapor fluxes were estimated from the output of a terrestrial water balance model applied to India at a monthly

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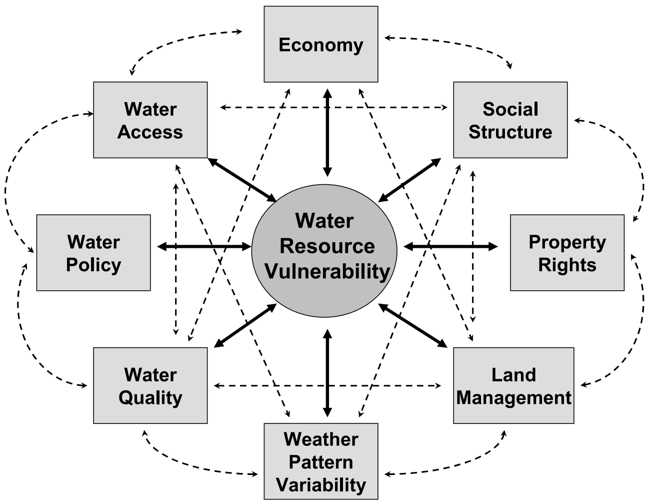

Figure 1. Schematic of linkages (solid arrows) and interactions (dashed arrows) related to changes in the vulnerability of water resources in India due changes in the Indian Monsoon (modified from *Pielke* [2004]).

time step and a spatial resolution of 30 minutes (0.5 decimal degrees, latitude by longitude). The model was forced by a gridded climatology of observations [*New et al.*, 1998] and used two land cover data sets: a pre-agricultural land cover [*Melillo et al.*, 1993] and a contemporary land cover. The contemporary land cover was represented by overlaying estimated percentages of rain-fed, irrigated and fallow cropland onto the pre-agricultural land cover dataset. State-level, seasonal rain-fed, irrigated and fallow cropland area for 1999–2000 (Table 1) were developed to be as consistent as possible with state-wise datasets [*Chanda et al.*, 2003; *Frolking et al.*, 2006]. Irrigation intensity (gross divided by net irrigated areas) ranged from 1.03 (Arunachal Pradesh) to 1.87 (Punjab) and overall for India was 1.33. Total triple-cropped area in India is relatively small [*Frolking et al.*, 2006], hence, it was ignored. We consider two growing seasons: the wet season (Kharif), July through December, and the dry season (Rabi), January through May. We assumed that all cropland was fallow in June and that all cropland was cropped in Kharif. Seasonal rain-fed crop areas were equal to seasonal total crop areas minus seasonal irrigated crop areas. The gridded cropland areas from *Ramankutty and Foley* [1999] were then assigned fractional areas of seasonal cropping systems (irrigated, rain-fed, fallow) based on the appropriate state-level values.

[5] Vapor fluxes from irrigated cropland were set equal to ‘‘potential evapotranspiration’’ (PET), which represents crop water demand in the absence of water limitations [*Shuttleworth and Wallace*, 1985]. Vapor fluxes from rain-fed cropland were set equal to actual evapotranspiration (AET), which is constrained by available soil moisture. Mean monthly soil moisture, PET and AET were computed by the Water Balance Model (WBM) [*Vörösmarty et al.*, 1998]. Monthly PET and AET were then summed to estimate mean seasonal and annual PET and AET. Vapor fluxes from fallow land was set equal to 20% of cropland AET (J. Jacobs, personal communication, 2005), which

Table 1. Categories of Crop Area (Irrigated, Rain-Fed, and Fallow) Summarized by State

		Cultivated Area by Season, km^2						
		Kharif[b]			Rabi[c]			
State	Total Area[a]	Irrigated	Rainfed	Fallow	Irrigated	Rainfed	Fallow	Total Cropland[d]
Andhra Pradesh	272,684	43,840	62,260	0	13,620	10,510	81,970	106,100
Arunachal Pradesh	84,790	350	1,310	0	10	970	680	1,660
Assam	74,957	5,720	21,290	0	2,716	11,204	13,090	27,010
Bihar	166,041	27,605	46,765	0	20,475	4,945	48,950	74,370
Gujarat	185,662	30,820	65,850	0	7,580	0	89,090	96,670
Haryana	37,889	28,361	7,159	0	22,879	1,891	10,750	35,520
Himachal Pradesh	57,856	1,020	4,490	0	770	3,290	1,450	5,510
Jammu & Kashmir	105,673	3,030	4,300	0	1,350	2,100	3,880	7,330
Karnataka	197,502	25,480	77,110	0	6,140	12,240	84,210	102,590
Kerala	33,484	3,800	18,590	0	910	6,720	14,760	22,390
Madhya Pradesh	444,926	13,182	185,798	0	57,728	5,362	135,890	198,980
Maharashtra	317,965	7,970	168,940	0	29,720	16,880	130,310	176,910
Manipur	25,299	650	750	0	100	490	810	1,400
Meghalaya	22,344	530	1,870	0	28	232	2,140	2,400
Mizoram	22,742	80	830	0	30	0	880	910
Nagaland	13,910	644	1,966	0	86	254	2,270	2,610
Orissa	145,033	20,900	39,850	0	4,220	20,270	36,260	60,750
Punjab	53,253	34,830	7,550	0	40,020	0	2,360	42,380
Rajasthan	335,020	43,409	111,681	0	25,931	11,839	117,320	155,090
Sikkim	2,748	160	790	0	0	260	690	950
Tamil Nadu	130,572	29,720	24,920	0	6,130	4,420	44,090	54,640
Tripura	11,339	543	2,227	0	587	843	1,340	2,770
Uttar Pradesh	293,872	86,210	89,640	0	90,550	3,447	81,853	175,850
West Bengal	84,998	15,093	39,627	0	17,320	23,410	13,990	54,720
All India[e]	3,120,558	423,948	985,562	0	348,901	141,576	919,033	1,409,510

[a]Sum of 30-min cells within state boundaries.
[b]Wet season (summer) extending from July through December.
[c]Dry season (winter) extending from January through May.
[d]Total cropland for both seasons is identical.
[e]The following states and union territories are not represented in this analysis: Andaman an Nicobar Islands, Dadra and Nagar Haveli, Chandigarh, Daman and Diu, Delhi and Pondicherry.

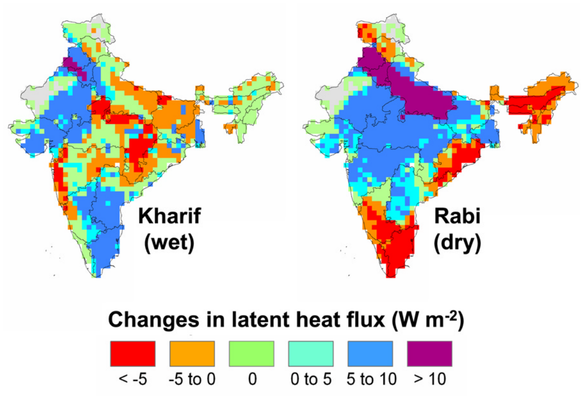

Figure 2. Geospatial changes in latent heat fluxes (in W m^{-2}) for Kharif (wet season) and Rabi (dry season) at resolution of 30-min (latitude by longitude). Negative changes denote decreases in vapor fluxes due to agricultural conversion of original forests; positive changes denote increases due to agricultural conversion of other land cover types and irrigation.

approximates the proportion of AET attributable to soil (physical) evaporation alone. The feedback of the surface moisture changes on the atmosphere were illustrated using a coupled land surface–atmosphere boundary layer model [*Niyogi*, 2000; *Alapaty et al.*, 2001].

3. Results and Discussion

3.1. Changes in Vapor and Energy Fluxes

[6] For the entire country, the mean annual increase in vapor fluxes between the contemporary and pre-agricultural scenarios was estimated at 340 km^3 (17% of pre-agricultural vapor fluxes). When converted to latent heat fluxes, this represents an areally-weighted average increase in latent heat flux of 9 W m^{-2}. Approximately 64% (5.7 W m^{-2}) of this increase can be attributed to contemporary irrigated cropland, which is nearly twice the mean annual increase of 3.2 W m^{-2} reported by *de Rosnay et al.* [2003]. Our higher result is likely due to: (1) the use of PET to represent irrigation vapor fluxes assumes that irrigation water is always sufficient and hence, may have overestimated irrigation fluxes somewhat; and, (2) we accounted for the updated, spatially-varying effect of double-cropping, which occurred on about 35% of the cultivated area overall (Table 1). Seasonally, vapor fluxes increased by 7% (117 km^3) in the summer (Kharif, wet season) and by 55% (223 km^3) in the winter (Rabi, dry season), which also may explain our higher over all total increase. By state, the highest variability in vapor fluxes also occurred in the summer, with a maximum increase of 85 km^3 (Uttar Pradesh, in north central India) and a maximum decrease of 15 km^3 (Tamil Nadu, in southern India). Decreases in vapor fluxes predominantly occurred where tropical forest was converted to agriculture, a land use change that is generally understood to reduce ET. The largest percentage change in vapor fluxes occurred in the states of Haryana and Punjab, where ET fluxes increased by 137% and 128%, respectively, over the pre-agricultural scenario. These states, although small in area, have the largest proportions of area devoted to cropland (88% and 97%) and irrigated area (69% and 71%). In addition, groundwater tables in these states are reportedly declining 1–2 m yr^{-1} [*Singh and Singh*, 2002], therefore, a large fraction of the vapor flux increases may be coming from groundwater mining. Seasonal and annual vapor fluxes (excluding June) by Indian state are presented in Table S1.[1] States and Union Territories with little cropland were excluded from the analysis.

[7] Figure 2 shows the distribution of seasonal changes in latent heat fluxes (in Wm^{-2}) across India at a spatial resolution of 30 minutes (0.5 degree). During Kharif, the largest flux increases occur in the northwest and the southeast portions of the country where both cropland and irrigated areas are high. During Rabi, a large portion of northern India is subject to high flux increases indicating that intensive irrigation is the dominant component of change, while fluxes have decreased in the southern and eastern extremes of the country indicating that land cover conversion (tropical forest to agriculture) is the dominant component of change. We estimated the fraction of seasonal vapor flux change attributable to non-crop land cover types and to irrigated, rain-fed and fallow cropland (Figure 3). Although there was not much seasonal difference in non-crop areas, irrigated croplands showed a nearly 250% increase in vapor fluxes between Kharif and Rabi. Based on tabulated irrigation sources [*Central Water Commission (CWC)*, 1998], groundwater-based irrigation contributed 14% of the vapor fluxes in Kharif and 35% in Rabi, indicating that groundwater withdrawals may have a large influence on contemporary atmospheric moisture fluxes [*Niyogi et al.*, 2002b].

3.2. Simulation of Land-Atmosphere Interactions

[8] The response of the surface moisture on the atmospheric boundary layer and the regional humidity over a representative column over India (Anand, Gujarat, 22.32 N, 73.00 E) was analyzed using observed and simulated changes in the land surface conditions. Surface meteorological measurements were compiled and included direct observations of net radiation, sensible heat flux, and observations of winds and thermodynamic variables such as air temperature and specific humidity at 1, 2, 4, and 9 m levels.

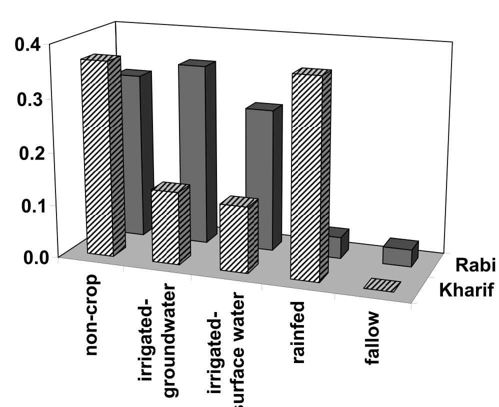

Figure 3. Fraction of ET flux difference attributable to non-crop, irrigated, rain-fed and fallow land covers. Over India as a whole, approximately 52% of irrigation water comes from groundwater [*CWC*, 1998].

[1] Auxiliary material data sets are available at ftp://ftp.agu.org/apend/gl/2006gl026550. Other auxiliary materials are in the HTML.

Soil temperatures were also recorded at various depths (0.1, 0.2, 0.3, 0.5, and 1m). Based on these measurements, values of latent heat flux were estimated using aerodynamic approaches (and also modeled using a detailed land surface model). A 24-h period starting from 0830 LT February 14, 1998 was selected to represent typical winter (Rabi) time conditions over the tropical Indian subcontinent. Observed and simulated peaks in sensible and latent heat fluxes corresponded to about 100 W m^{-2} and 275 W m^{-2}, respectively (see Figures S1a and S1b in the auxiliary material). The ET (latent heat) values are significantly higher than sensible heat flux, because of the higher soil moisture and the presence of vegetation. Corresponding impacts on the boundary layer depth indicate the early morning and late night planetary boundary layer (PBL) heights to be around 200 m, while the daytime values vary from about 1000 m around noon to about 1500 m in the later part of the afternoon. For the summer (Kharif) case, the model was initialized on May 13, 1998 at 0830 LT and integrated for a 24-h period. The notable difference in the two cases is the higher sensible heat flux values for the summer case (~300 W m^{-2}) and relatively lower ET values. The resulting summertime PBL is also significantly deeper (~3000 m). These results suggest that the irrigation impacts on land-atmosphere interactions could be quite substantial for both seasons though the feedback pathways could be different. For instance, winter increases, though smaller, can still lead to substantial moisture impacts in the shallower boundary layer, while during the summer, ET from irrigation could result in modifying the Bowen ratio and alter the land–atmosphere coupling with a higher convectively available potential energy. The validity of these findings are currently being evaluated in a follow up study using a coupled 3D modeling system.

3.3. Potential Effects on Local- to Regional-Scale Circulation and Weather

[9] As discussed by *Pielke* [2001], surface net radiation is partitioned between sensible and latent heat fluxes. A greater fraction that is associated with latent heat fluxes (physical evaporation and transpiration) can result in a greater convective available potential energy (CAPE), as well as added water vapor to fuel deep convection, if it develops. A 1°C increase in dew point at temperature in summer and tropical conditions has a much greater effect on CAPE than does a 1°C increase in dry bulb temperature [*Pielke*, 2001]. During the dry season in India, physical evaporation is generally small in the non-irrigated areas such that deep convection that develops in these regions has transpiration as its primary land source to add to the CAPE and to the atmospheric water vapor. In non-irrigated regions, net radiation will primarily be associated with sensible heat fluxes; vapor fluxes into the atmosphere from water stressed vegetation will be almost zero. However, irrigation in these dry regions will introduce significant latent heat fluxes resulting from the transpiration (and associated physical evaporation from the adjacent bare soils) of water vapor. If the irrigated areas are large enough (10s of km on a side or larger), mesoscale circulations can develop associated with boundary layer wind convergence between the dry and wet areas, similar to what occurs with sea breeze convergence zones [*Pielke*, 1974] and deforested areas [*Avissar and Liu*, 1996]. *Lohar and Pal* [1995] suggested that irrigation in the South West Bengal region reduces the intensity of sea breeze activity, resulting in decreased thunderstorm activity, and hence rainfall, during the pre-Monsoon season.

4. Summary and Conclusions

[10] In this paper, we investigated the changes across India in vapor and energy fluxes between a potential (pre-agricultural) and a contemporary agricultural land cover. We found that mean annual vapor fluxes have increased by 17% (340 km^3) with a 7% increase (117 km^3) in the summer (Kharif) and a 55% increase (223 km^3) in winter (Rabi), indicating a dramatic influence of dry-season agriculture on atmospheric moisture and energy fluxes. Two-thirds of the annual increase was attributed to irrigation; groundwater-based irrigation contributed 14% of the vapor fluxes in Kharif and 35% in Rabi. The area-averaged change in latent heat flux across India was estimated to be 9 Wm^{-2}, nearly three times the increase estimated by *de Rosnay et al.* [2003]. However, conversion to irrigated agriculture did not universally increase latent heat flux. In more humid southern India, latent heat flux from pre-conversion tropical forests was greater than from contemporary agriculture, even though roughly half the cropland in Tamil Nadu is irrigated, thus the region had an overall reduction in latent heat flux. In the drier north and north central India conversion to predominantly irrigated agriculture lead to significant increases in vapor and latent heat fluxes.

[11] The potential implications of flux changes reported in this study are consistent with the interpretation from similar work in other regions of the world [e.g., *Marshall et al.*, 2004; *Adegoke et al.*, 2003]. In addition to alterations in the surface heat and moisture fluxes due to regional landscape change, the spatial heterogeneity of such a change also influences rainfall patterns [e.g., *Segal et al.*, 1989; *Lohar and Pal*, 1995; *Pielke*, 2001]. These flux and rainfall alterations, when they cover a large enough area, can result in teleconnection effects which influence monsoon and global circulations [e.g., *Fu et al.*, 2004; *Chase et al.*, 2003]. Following the vulnerability paradigm used to assess risks associated with environmental/societal resources [*Kabat et al.*, 2004; *Pielke et al.*, 2006], we identified linkages and interactions with economic, societal and water resource factors that need to be investigated in more detail in future work. With this "bottom up" approach, the threats to a resource are identified such that procedures can be developed to reduce the risk to both natural and human systems that depend on them.

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