Global and Planetary Change 67 (2009) 117–128

Contents lists available at ScienceDirect

Global and Planetary Change

journal homepage: www.elsevier.com/locate/gloplacha

The impact of agricultural intensification and irrigation on land–atmosphere interactions and Indian monsoon precipitation — A mesoscale modeling perspective

E.M. Douglas [a,*], A. Beltrán-Przekurat [b], D. Niyogi [c], R.A. Pielke Sr. [b], C.J. Vörösmarty [d]

[a] University of Massachusetts, Boston, 100 Morrissey Blvd. Boston, MA 02125-3393, United States
[b] University of Colorado at Boulder, 1540 30th St, Boulder, CO 80309, United States
[c] Purdue University, 1088 Freehafer Hall, West Lafayette, IN 47907-108, United States
[d] University of New Hampshire, 39 College Rd. Durham, NH 03824, United States

ARTICLE INFO

Article history:
Accepted 8 February 2008
Available online 3 January 2009

Keywords:
irrigation
Indian monsoon
Regional Atmospheric Modeling System
agriculture
Land Use Land Cover Change

ABSTRACT

Using the Regional Atmospheric Modeling System (RAMS) we show that agricultural intensification and irrigation can modify the surface moisture and energy distribution, which alters the boundary layer and regional convergence, mesoscale convection, and precipitation patterns over the Indian monsoon region. Four experiments were conducted to simulate a rain event from 16 to 20 July 2002 over the Indian region: (i) a control with Global Land Cover land use and observed Normalized Difference Vegetation Index, (ii) an irrigated crop scenario, (iii) a non-irrigated crop scenario, and (iv) a scenario for potential (natural) vegetation. Results indicate that even under active monsoon conditions, the simulated surface energy and moisture flux over the Indian monsoon region are sensitive to the irrigation intensity and this effect is more pronounced than the impact of land use change from the potential vegetation to the agricultural landscape. When model outputs were averaged over the south Asia model domain, a statistically significant decrease in mean sensible heat flux between the potential vegetation and the irrigated agriculture scenarios of 11.7 Wm^{-2} was found. Changes in latent heat fluxes ranging from −20.6 to +37.2 Wm^{-2} (−26% to +24%) and sensible heat fluxes ranging −87.5 to +4.4 Wm^{-2} (−77% to +8%) fluxes were found when model outputs were averaged over Indian states. Decreases in sensible heat in the states of Punjab (87.5 Wm^{-2} or 77%) and Haryana (65.3 Wm^{-2} or 85%) were found to be statistically significant at the 95% confidence level. Irrigation increased the regional moisture flux which in turn modified the convective available potential energy. This caused a reduction in the surface temperature and led to a modified regional circulation pattern and changes in mesoscale precipitation. These agricultural changes, including irrigation modify the mesoscale convection and rain patterns in the Indian monsoon region. These regional changes in land use need to be considered in improved weather forecasting as well as multi-decadal climate variability and change assessments.

1. Introduction

Individuals and societies have always been vulnerable to weather extremes and rapid shifts in climate. But over the last few decades, evidence is growing that weather patterns and climate stability are vulnerable to humans as well. For instance, there is a growing consensus within the scientific community that human activities have played a key role in causing, or at least altering, the pace at which climate is changing. Although much of the current research focus has been on the direct effects of human activities on atmospheric composition, there is also mounting evidence that human-induced landscape changes can affect atmospheric processes from local to regional weather patterns (Cotton and Pielke, 2007; Pielke et al., 2002; Alpert et al., 2006) and climate variability (National Research Council, 2005; Kabat et al., 2004; Pielke et al., 2007a,b). Feddema et al. (2005) showed that the transient climate modeling based on the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) lead to different regional climates when the impact of land cover changes are considered in addition to the SRES forcing alone. Gordon et al. (2005) evaluated the effects of land cover change on water vapor flows globally. They report that irrigated agriculture has increased global vapor flows by about 2600 km^3 yr^{-1}, which is more than twice that of estimated global consumptive irrigation water losses (~1200 km^3 yr^{-1}; Vörösmarty et al., 2005). Irrigation has been shown to significantly affect local and regional climate in the United States (e.g. Barnston and Schickedanz, 1984; Adegoke et al., 2003; Pielke, 2001). In the U.S., land cover change over the last 290 years has lead to a weak warming along the Atlantic coast and a strong cooling of more than 1 K over the Midwest and Great Plains region (Roy et al., 2003). Some reduction in precipitation due to changes in large-scale moisture advection has also occurred over the

* Corresponding author. Environmental, Earth and Ocean Sciences, 100 Morrissey Blvd, University of Massachusetts, Boston, Boston, MA 02125, United States. Tel.: +1 617 287 7437; fax: +1 617 287 7474.
E-mail address: ellen.douglas@umb.edu (E.M. Douglas).

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doi:10.1016/j.gloplacha.2008.12.007

Midwest. Extensive agricultural conversion in southern Florida has resulted in reduced precipitation and redistributed latent heat flux and atmospheric water vapor (Marshall et al., 2004a,b). Such changes can result in increased vulnerability to human populations.

The Indian subcontinent is a particularly interesting region for studying human–land–atmosphere interactions because it is home to one-sixth of the world's population, most of which rely very heavily on the summer monsoon rains for their survival. Gupta et al. (2006) document the rise and fall of agriculture and Indian societies in response to changes in the Indian monsoon. In general, humans prospered and agriculture flourished during wet phases of the summer monsoon while periods of weak summer monsoons led to famine and population migration (Davis, 2001). Irrigated agriculture in India has been a key component of economic development and poverty alleviation (Bansil, 2004). From 1951 to 1997, gross irrigated areas expanded four fold, from 23 million to 90 million hectares. While the benefits of this expansion in agricultural productivity have been immediate, the environmental and social costs over the long term are becoming increasingly apparent as well. For instance, most of the water used for irrigation in India is drawn from deep ground water bore wells. As a result, groundwater stores in India, estimated at 432 billion cubic meters (BCM; CWC, 1998) have been declining by 20 cm/yr^{-1} in as many as 15 Indian states (Bansil, 2004); groundwater stores in most of these states are predicted to dry up by 2025 or sooner (Jha, 2001). In addition to the impacts of intensive irrigation on local to regional hydrology, Gordon et al. (2005) suggest that expanding irrigation on the Indian subcontinent may increase the risk for changes in the Asian monsoon system and, thus, impact food production capacities in other regions (such as sub-Saharan Africa). Studies such as Boucher et al. (2004) concluded that the addition of water vapor in dry regions results in a nonlinear increase in precipitable water at the regional scale, which is compensated by a decrease in other regions through changes in convection.

Within India, there is also evidence that intensive irrigation has lead to changes in precipitation patterns. Lohar and Pal (1995) report that mean monthly rainfall from 1983–1992 in West Bengal, India, is less than half that observed from 1973–1982. The doubling of the area covered by summer paddy crops (mostly along the coast) over this time frame is a possible cause. Two-dimensional numerical simulations indicate that wetter soils along the coast reduce the temperature gradient between the land and the sea, hence weakening the sea-breeze circulation and reducing convective rainfall, which is a significant source of localized heavy precipitation rainfall in the coastal area.

Besides the obvious environmental and socioeconomic impacts that could result from changes in the Indian monsoon, Zickfeld et al. (2005) show that any perturbation in the radiative budget over the sub-continent can weaken the driving pressure gradient and

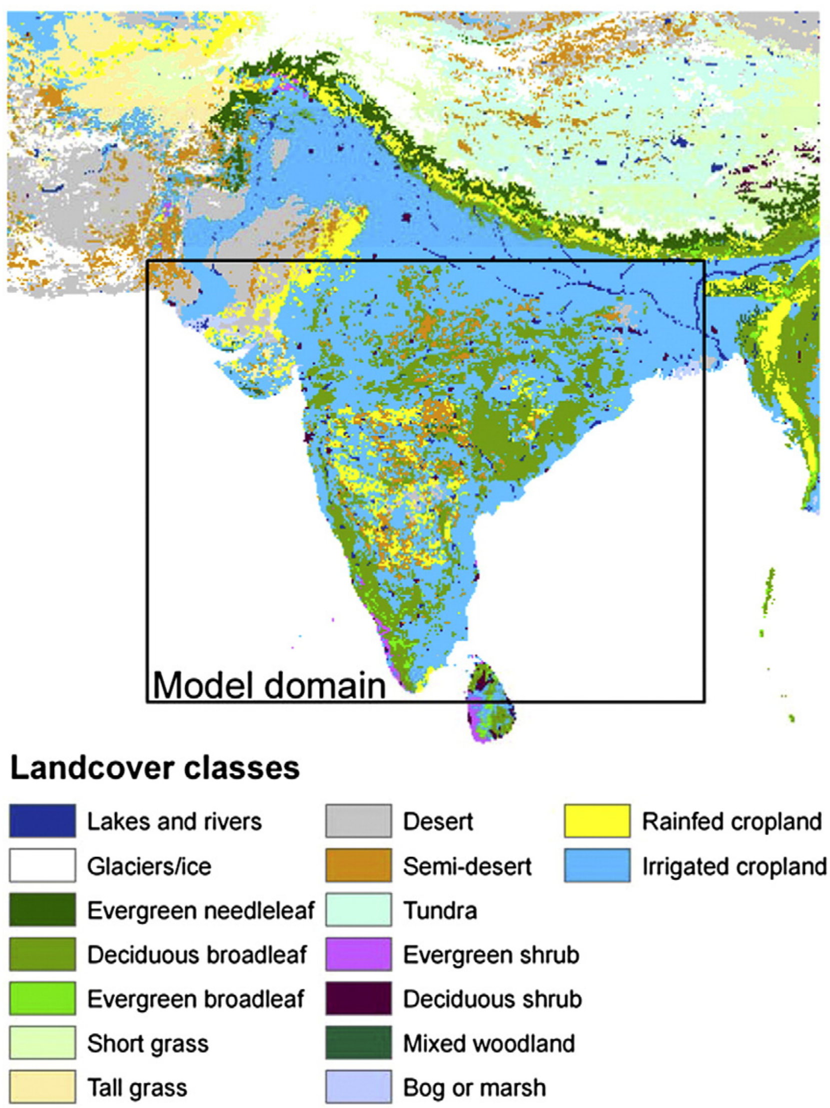

Fig. 1. Current state of land cover in India as represented by the GLC2000 land cover dataset. The model domain was constrained to peninsular India in order to reduce boundary effects due to the Himalayan Mountains.