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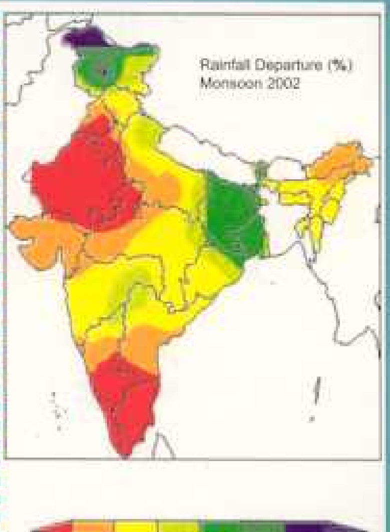

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Challenges of Representing Land-Surface Processes in Weather and Climate Models over the Tropics: Examples over the Indian Subcontinent

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ABSTRACT

Land-surface processes are an important driver for weather and climate systems over the tropics and particularly the Indian subcontinent. Realistic representation of land-surface processes over the Indian region will help accurate simulations of environmental processes at micro, meso, and regional climate scale. However, in order to achieve these potential benefits, it is necessary to develop a strategy through the Indo-US Forum on Science and Technology that will address and overcome the different challenges associated with the representation of the land-surface processes over the Indian region. In this review, seven focus areas are identified: (i) development of a high-resolution surface data set for soil and vegetation /biophysical characteristics; (ii) testing of different biophysical Parametrizations in the land-surface schemes including ecological/ photosynthesis based land surface models at different scales; (iii) developing techniques to assimilate surface meteorological and land surface data in to regional analyses; (iv) development of regional climate studies to identify the radiative and other biogeophysical forcings that are critical to this region so as to include them in GCM studies; (v) studying the recirculation of evaporation, transpiration, and precipitation as part of the Indian monsoon system as well as effects of land – atmosphere interactions on heavy precipitation and tropical storm track and intensity; (vi) assessing the effect of regional aerosols and soot on global climate through changes in land – atmosphere interactions, cloudiness, and water vapor recirculation; and (vii) initiation of studies related to the inclusion of population growth and corresponding energy usage and land use change as a forcing within regional climate models.

1. INTRODUCTION

Land-surface processes form a critical pathway of energy and mass transfer. The surface can be a source as well as a sink of energy and mass transfer. For instance, the surface is a sink for momentum transfer; and absorbs the incident radiation during the day. At night, the land surface releases this stored radiative energy in the form of longwave emission. In addition to the energy exchange, the land surface is also known to be a significant source–sink mechanism for the greenhouse gases. Similarly, it is well established that vegetated surfaces can also act as a source for trace gases and other pollutants, including pathogens. Various such examples can be cited which show the significance of land-surface processes in energy and mass exchanges for different environmental applications affecting the short–term weather as well as regional climate simulations.

The role of land-surface processes is particularly interesting in the tropics. Often this is because the lack of frontal and synoptic activities (particularly in the absence of the monsoons) make the local surface interactions a dominant forcing for the atmospheric boundary-layer processes. Further, our understanding of the interactions between tropical surface and atmosphere exchanges is still relatively limited compared to that in the midlatitudes. This may be due to the lack of detailed field studies, as well as the extreme nature of the hydrological cycle (drought and flooding) in the tropics. Additionally, tropics support a large global population, often with limited agricultural and water resources. This could lead to important societal implications when the regional weather and climate are altered, or if it could be better predicted.

In this review, we discuss the different aspects of these land-surface interactions, with specific reference to the Indian subcontinent. The Indian subcontinent is an important region meteorologically and an ideal study domain for several reasons. These include the availability of long observational data series; interactions between land–air–sea and topographical features (such as the Western Ghats); presence of a variety of landscapes and soil textures over different biogeographical regions; and intense landuse change in recent years due to agricultural and industrial advances and large population growth.

In the following section, we describe the basic components of the land-surface processes within a meteorological model. Section 3 presents discussion on some of the challenges in representing land-surface processes in weather and climate models over the Indian subcontinent. Concluding remarks are presented in Section 4.

2. COMPONENTS OF LAND-SURFACE PROCESSES AND LAND-ATMOSPHERE INTERACTIONS

Land-surface processes are interactive at all scales — micro, regional, and global. The impact land-surface processes have on weather and climate can be appreciated through the energy balance equation. The surface turbulent heat energy can be partitioned as:

$$Q_N + Q_H + Q_{LE} + Q_G = 0; \text{ and } Q_N = Q_S\,(1\text{-}A) + Q_{LWD} - Q_{LWU}$$

where Q_N is the net radiation, Q_H is the sensible turbulent heat flux, Q_{LE} is the turbulent latent heat flux, Q_G is the ground heat flux, Q_S is the solar irradiance, A is the surface albedo, and Q_{LWD} and Q_{LWU} are the downward and upward longwave component of the solar irradiance.

The changes in the surface energy balance could be due to a number of factors primarily linked to land-surface characteristics. For example, the Bowen ratio of the surface will depend on the soil moisture availability, as well as on the evaporation–transpiration feedback as related to surface vegetation (coverage, density, as well as biophysical and soil textural properties). The surface albedo change is also a function of vegetation as well as soil moisture availability. Thus the hydrological and thermal effects associated with soil moisture–transpiration–evaporation cause coupled feedbacks.

The surface energy and mass transfer at leaf and canopy scale leads to differential surface heat fluxes as a function of landuse and the soil state. The spatial heterogeneities in the lateral surface fluxes often form a sufficient condition to trigger local (meso-) scale circulations and low-level convergence. Such circulations associated with moist air-dry air interfaces can lead to a preferential zone for cumulus formation and enhanced deep convection and inland thunderstorms. Even at larger scales (hundreds of kilometers in space, and years in time scale) changes in the vegetation and surface characteristics significantly correlate with the precipitation and temperature anomalies. Thus, through numerous nonlinear processes, leaf and canopy scale systems interact with mesoscale and regional-scale events at a time scale of a few hours to days and beyond. Figure 1 summarizes this coupled scale interaction and feedbacks from the leaf to the regional climate. Thus issues at the core of land-surface process studies include process representation, initialization of the surface base state, prognostic evolution of the surface state, analysis and validation of the different interactive features, impact on the weather and climate model performance, and predictability of the seasonal to regional climate.

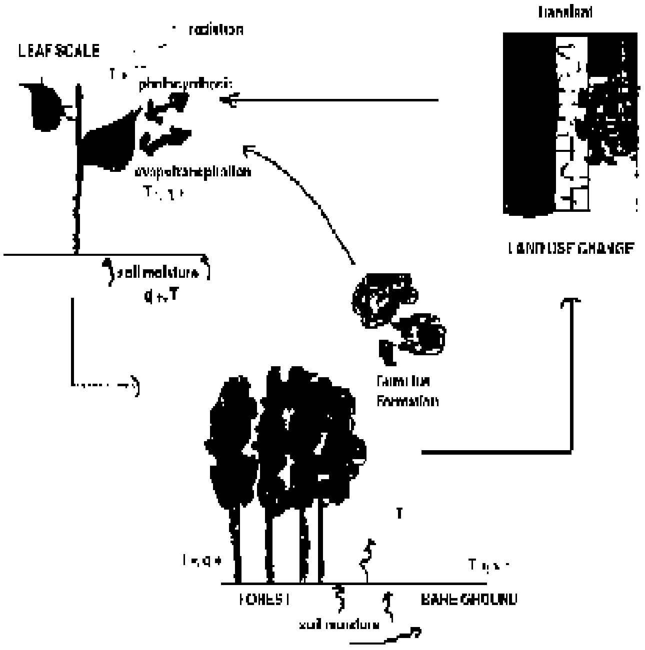

FIG. 1. Land-surface processes impact processes that can be characterized through the balance between energy and hydrological components at the earth's surface. Gradients in surface fluxes, circulation, convection and cumulus formation, precipitation and landuse change, and regional climate change are all factors assoicated with the surface energy and the hydrologic balance. In the figure, T and q represent temperature and humidity effects, while + and – sign indicate a potential increase or decrease in the temperature (T) or the humidity (q) effect.

3. CHALLENGES IN REPRESENTING LAND-ATMOSPHERE INTERACTIONS OVER THE INDIAN SUBCONTINENT

The multitude of interactions and the feedbacks associated with land-surface processes makes its accurate representation critical as well as challenging. In this section, we summarize some of the broad areas that need to be considered in developing a robust land-surface process representation for the tropical systems.

3.1 Resolution and Surface Data Representation

The earth's land surface is characterized by inhomogeneities due to variations in features such as vegetation types, soil types and moisture, canopy layers, urban effects, and topography. These inhomogeneities produce gradients in surface fluxes of momentum, heat, and moisture that drive three-dimensional circulations and significantly alter the low-level mesoscale thermodynamic and dynamic structure and aerosol distribution. For example, variations in soil moisture alone have been shown to enhance mesoscale features such as dryline formation, precipitation recycling, and convective initiation. To account for the effects of such land-surface heterogeneities, a numerical weather prediction model must be able to accurately represent the evolution and distribution of these inhomogeneities. Furthermore, a numerical model run at sufficient horizontal grid spacing that can resolve these inhomogeneities must have accurate databases that also resolve the relevant surface characteristics, such as soil texture, vegetation greenness, and landuse.

Current land-surface Parametrizations are based on several empirical relations and default characteristics associated with the surface as defined through different vegetation and soil texture look-up tables. The minimal input requirements for a typical land-surface model would include vegetation (or landuse) type, green vegetation fraction (temporally-varying, typically monthly or bi-weekly), and soil texture classes (at specified depths). Other parameters often provided by look-up tables include soil slope, background albedo (snow-free and snow-covered surface), and fractional and predominant vegetation types (if tiling techniques are used). From these basic parameters, a variety of other important land-surface parameters such as vegetative characteristics, and soil hydraulic and thermodynamic properties can be determined. The horizontal and temporal resolution of these basic parameters becomes more critical for accurate forecasts as the model grid spacing is reduced. Typically over the continental United States all of these parameters are currently available at both horizontal (~1 km or less) and temporal (~daily or weekly) grid increment commensurate with current weather prediction model resolutions. However, particularly outside the United States, the soil databases suffer from lack of sufficient horizontal resolution (~5-min to 1-degree). The impact of degradation in resolution outside the United States on model forecasts is not fully known.

Even with the existence of these high resolution databases, it is critically important in this regard to be able to validate the accuracy and representativeness of these parameters associated with the different landuse categories. Field studies and evidence from local experts have shown that soil texture (and even vegetation) classes used in land-surface models can be very different from ground truth observations, particularly in regions outside the continental United States, where observations are very limited.

With a heavy dependence on remotely-sensed observations, validation with ground truth exercises as well as remote-sensed data analysis and ingestion in the weather and regional climate models becomes even more crucial. This issue continues to be a significant challenge as models are being run with finer grid spacing, and the impact of heterogeneities and surface characteristics becomes more significant.

3.2 Biophysical Parametrizations in the Land-Surface Schemes

Improving the physics of the surface atmosphere exchange processes is another challenge in representing the tropical land-surface processes. Figure 2 shows the potential evolution of the land surface or evaporation and transpiration Parametrization schemes over the decades. As shown in the figure, initial models considered large-scale dynamical relations for assessing water vapor exchange between the different atmospheric layers. This was introduced in the climate models in early 1970s along with the so-called 'bucket' models. Parallel models used uncoupled Priestley–Taylor and Penman Monteith-type vegetation-based relations. This was generally followed by the advent of the coupled modeling studies involving an explicit feedback between the atmosphere onto the vegetation, followed by the change in the vegetation-induced environmental changes onto the model boundary conditions. One of the prominent features of this Parametrization continues to be the Jarvis–type approach. This involves modulating a predefined landuse/vegetation type based minimum stomatal resistance (Rsmin) value on the basis of environmental changes such as radiation, air temperature, humidity, and soil moisture. Some of the present-day models adopt the bucket and the Jarvis-type

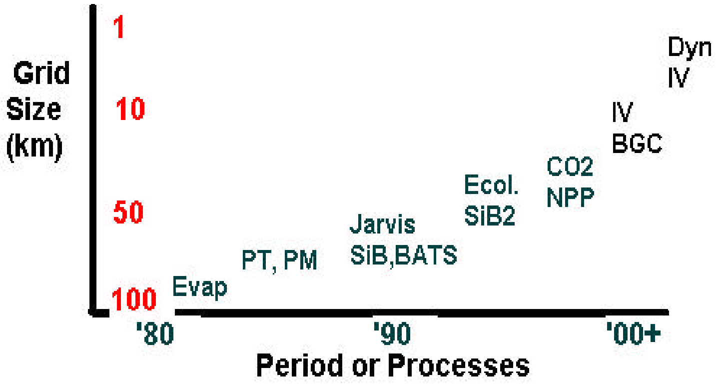

FIG. 2. Schematic representation of the development of vegetation schemes in land-surface models. Evap is large-scale evaporation schemes, PT, PM correspond to Priestley—Taylor alpha approach, and the Penman Monteith technique, Jarvis is the Rsmin-based Jarvis-approach, SiB and BATS are the Simple Biosphere model and the Biosphere Atmosphere Transfer Schemes. Ecol. is the ecological model such as in the SiB2, CO2 refers to the inclusion of explicit carbon effects using NPP or the net primary productivity consideration, IV EGC corresponds to interactive vegetation with biogeochemical models, and Dyn IV corresponds to the potential for dynamically-interactive vegetation models in which the vegetation state will change as a prognostic, coupled variable with the model meteorology. The period corresponds to the last 3 decades or so and is not precise. The grid size corresponds to the typical grid-scale spacing/model resolution adopted for model simulations. This is considered to provide the scale effect and is not accurate either. In general, the model grid spacing has decreased considerably and more detailed vegetation schemes are becoming increasingly popular.

Parametrizations in some of the simpler land-surface schemes both for coupled as well as uncoupled studies for understanding land–atmosphere interactions and biosphere feedbacks on the environment.

Presently, a number of advances in the plant physiology and the crop modeling as well as remote-sensing algorithms for retrieving radiation biospheric feedbacks have been reported, as discussed earlier. This has resulted in the application of stomatal/ transpiration models of varying complexities, to be applied for simulating the land-atmosphere interactions. These models can be categorized as: a diagnostic radiation-based photosynthesis approach that utilizes a radiation-use efficiency approach and vapor pressure deficit feedback for providing the transpiration (latent heat flux) or water vapor exchange pathways; and an iterative/interactive photosynthesis approach which involves representing stomatal conductance-carbon assimilation/photosynthesis relations for water vapor and carbon exchanges. With the advent of high-resolution terrestrial remote-sensed data and techniques for assimilating this information into terrestrial models, there have been newer opportunities for adopting and developing such interactive and dynamically-evolving vegetation and land surfaces (as against a static entity of the weather and climate modeling system). Recent efforts in coupling ecological and photosynthesis-based models mark a definitive step towards such dynamical models, however, there are still very limited studies concerning the interactive, two-way coupled vegetation and atmosphere models (e.g., see Lu *et al.* 2001).

An outstanding question that remains to be addressed is: are there significant advantages in adopting more complex photosynthesis-like schemes over the tropical/ Indian subcontinent region?

Indeed, over the continental U.S. the representation of the stomatal resistance/ transpiration processes yield significant differences in the model outcome. As an example, Niyogi *et al.* (1998) tested the different stomatal resistance representations for their ability to represent the land-surface processes active for transpiration and water vapor exchange. They found each of the transpiration schemes converged on different scenarios, with the more detailed photosynthesis- based scheme showing the closest agreement with the observations. In a subsequent study, Alapaty *et al.* (2002) performed a series of summertime runs over the U.S. using a coupled mesoscale model with and without a photosynthesis–transpiration model. They found the model performance was comparable with no one model performing better than the other. Hence it is important to review the performance of the different land-surface modeling approaches over the Indian domain for different weather and climate regimes. Therefore, although a number of studies have been reported in the literature, and some were indeed pioneering in nature, they often resort to the use of limited field observations, or have been episodic in nature, or not focused over the Indian region. Further, the study objectives tend to be focused on comparing one scheme over other to show its ability to reproduce land-atmosphere interactions leaving a number of important questions related to land – atmosphere interactions unanswered. Thus a concerted effort to study and understand the limitations and advantages for adopting one approach over another is needed.

3.3 Coupling Observations with Modeled Analysis

The application of the different schemes needs to be evaluated with local field studies and observations. This is particularly important for land-surface processes since the variability in the land–atmosphere response over different geographical domains continues to be an important feature for climate models. As an example, Niyogi *et al.* (2001) showed that for similar meteorological forcing in the midlatitudes and the semi-arid tropics, there are similarities in the direct responses while the interactions or the indirect feedback pathways could be quite different. The arid tropical regimes are dominated through vegetative pathways (via variables such leaf area index, stomatal resistance, and vegetal cover), while the mid-latitudes show soil wetness (moisture) related feedback. Additionally, for the mid-latitudinal case, the vegetation and the soil surface acted in unison, leading to more interactive exchanges between the vegetation and the soil surface. On the other hand, the water-stressed semi–arid tropical surface showed response either directly between vegetation and the atmosphere or the soil and the atmosphere with very little interaction between the vegetation and the soil variables. Thus, the semi–arid tropics would require explicit bare ground and vegetation fluxes consideration, while the effective (combined vegetation and soil fluxes) surface representation used in various models may be more valid for the midlatitudinal case. This also implied that with higher resource (water) availability, the surface invested more in the surrounding environment. On the other hand, with poor resource availability (such as water stress in the tropical site), the surface components retain individual resources without sharing. The uncertainty associated with the input conditions and the memory of the errors with the subsurface initial conditions for the land-surface models also become important. The uncertainty is largest for extreme conditions (very wet or very dry) and during landscape transitions during the monsoons (Niyogi *et al.* 1999).

To better understand the land–atmosphere interactions over the Indian subcontinent, a number of field experiments have been recently undertaken. The measurements, by their very nature are point representations and need to be interfaced with models for developing three–dimensional analyses over the study region. One such challenge in developing the land-surface process representation in the tropical perspective is to develop and test different surface assimilation techniques coupled with a land-surface model. One such approach was developed by Alapaty *et al.* (2002) for the MM5 modeling system. In this study, the errors in the model-simulated scalar or flux variables were converted into equivalent soil moisture and soil temperature corrections following an inverse technique, which are then used in a sequential assimilation approach for model integration. Figure 3 shows a typical time series with and without the nudging of the surface variables with the land-surface scheme. The ability of the model to simulate the observations better increases considerably due to such inversion/correction techniques. Such approaches can be easily adopted for developing realistic surface–atmosphere interaction assessments over the Indian region, where mesoscale monitoring is not available, and synoptic/frontal activity is often minimal.

3.4 Modeling the Regional Climate over the Indian Subcontinent

Regional climate models provide a powerful tool to study several of the outstanding questions related to the biophysical representation over the Indian subcontinent. Figure 4 shows the typical land use over the Indian subcontinent. The socioeconomic outlook in the Indian subcontinent is weather sensitive. With newer trade and agricultural opportunities, there is an increased need for regional climate information.

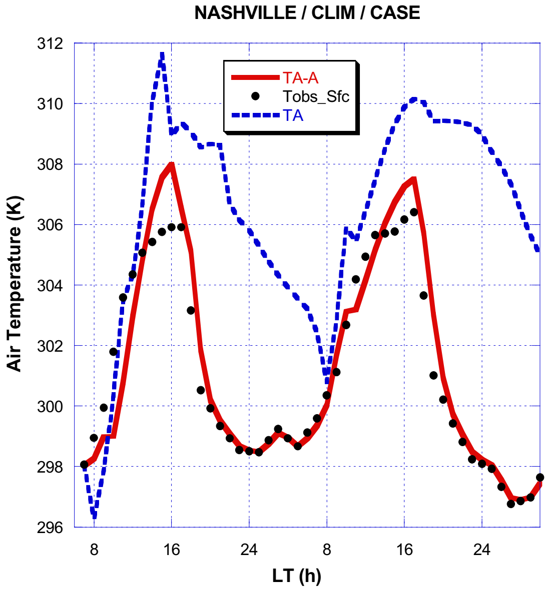

FIG. 3. Typical time series of model-simulated surface temperature using the climatological bucket scheme within MM5. The model was integrated over Nashville. TN using tower observations. The FASDAS/nudging approach of Alapaty *et al.* (2002) as a applied for connecting the initial estimates of soil moisture and/soil temperature using a nudging correction.

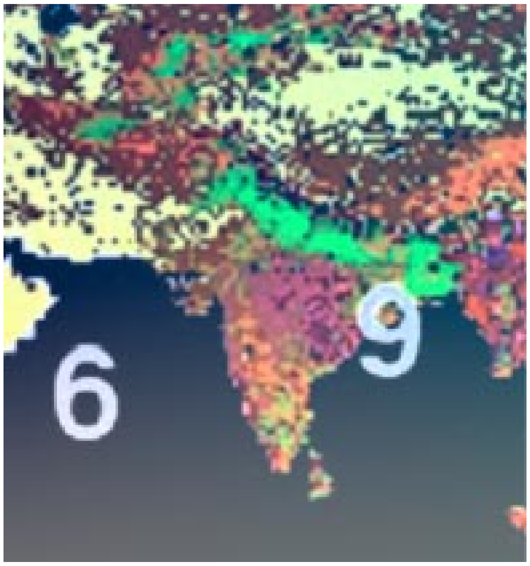

FIG. 4. Typical landuse over the Indian subcontinent. Using the global vegetation classification database, the agricultural landuse (Simple Biosphere Model ver-2-SiB2, vegetation type 9) and the tropical grassland and fallow (SiB2 vegetation type 6) appear to be the most predominant landuse category. Note that this will change for a given region, with seasonality, and there will be significant heterogeneity which can local scale weather and variability in the outcome.

This will require detailed, realistic regional climate models to be integrated over the study regions. As an example, the application of coupled regional atmospheric-ecological models is a new tool which has been applied successfully in the U.S. to assess the sensitivity of seasonal climate to landuse change and biogeochemical feedbacks associated with elevated carbon dioxide (e.g., Eastman *et al.* 2001; see also references in Pielke 2001). These are ideal tools to apply to the Indian subcontinent where vegetation processes are expected to exert a major role on the region's climate system, as discussed in Pielke *et al.* (2002a). Development and application of locally- representative regional climate models should be one of the priorities of weather and climate programs over the tropics. The nature of the forcing will be different than in the midlatitudes and the ability of the surface to regenerate and to respond to the environmental forcing needs to be assessed with regionally-representative observations.

However, there are still several challenges that need to be addressed to make the regional climate models representative over the tropical and Indian subcontinental region.

As an example, the General Energy and Mass Transfer Model (GEMTM, Chen and Coughenour 1994) has been linked to the Regional Atmospheric Modeling System (RAMS). This coupled modeling system was developed to study regional climate for the Great Plains of the United States (Eastman *et al.* 2001). Consequently, the biome types used in the model are biased to this region's vegetation. Subsequent to this initial development phase, the coupled modeling system has been adapted to accommodate other regions around the globe. There are ongoing applications directed towards Australia, South America, and the Caribbean. Presently, the coupled system is being applied to study the regional climate over the Indian subcontinent (Pielke *et al.* 2002a). In each of these studies it has been found that new vegetation classes, and vegetation and land characteristics which define the regional features, need to be added to the RAMS and GEMTM model parameters lists. As an example, over the Caribbean region, it was found that seasonal tropical forest, dry tropical forest, closed and open tropical rainforest, coniferous and broadleaf rainforest, and mangrove vegetation classes needed additional treatment in the models. An immediate solution to this problem is to develop a detailed wide literature survey in order to determine gross biophysical parameters specific to these vegetation types. Similar research was required in the other regional applications. In order to address global applications of the coupled modeling system, a team of collaborating researchers need to create a database specific to the Indian region similar to the Olson's Global Ecosystem classification system (Olson 1994), for example. Presently, there are 94 classes described in this classification system, and once the database is completed, it will enable more reliable application of the coupled modeling system to the Indian subcontinent. Thus, the Parametrization tests need to explicitly consider development of biophysical constants and land-surface parameters that are needed for adopting the different models over the Indian region.

3.5 Indian Monsoonal Circulation and Hydrological Recirculation

The regional climate models provide an efficient means of evaluating land-atmosphere interactions. However, the importance of land-atmosphere interactions is not limited to long-term regional climate simulations alone. Raman *et al.* (1998) investigated the influence of soil moisture and vegetation variation on the simulation of monsoon circulation and rainfall using a coupled land–atmosphere model. For this purpose, a simple land-surface Parametrization scheme was incorporated in a three-dimensional regional high resolution nested grid atmospheric model. Monsoon features such as the Somali jet, monsoon trough, and tropical easterly jet were found to be sensitive to land-surface process representation. Inclusion of realistic land surface resulted in not only a realistic short-range weather numerical prediction but also an enhanced short-range prediction of the hydrological cycle including precipitation over the Indian subcontinent. The gradients in the surface latent heat fluxes over land increased the low-level convergence in their study. The increased heat flux gradients, especially latent heat flux, further enhanced the convection and precipitation providing realistic diabatic forcings in the model. This further intensified the large-scale circulation as the strengths of both the low-level Somali jet and the upper-level tropical easterly jet increased because of the realistic land-surface conditions. Stronger meridional circulation caused by large-scale divergent flow and stronger vertical motion further enhanced evaporation. This provided better simulation of the monsoon circulation and its associated precipitation for summer monsoon circulation features and rainfall over India as a direct feedback of better land-surface representation.

Similarly, a general circulation model-based sensitivity study by Ferranti *et al.* (1999) indicates that though the ITCZ propagation is a dynamical feature, the temporal characteristics of the fluctuations between the two TCZ regimes, are influenced by the land-surface processes. Indeed, the low-frequency intraseasonal monsoon variability was also found to be enhanced by hydrological surface feedbacks. When the land-surface processes are not considered, the active and break regimes are significantly altered and the changes appear to depend on the land-surface conditions prior to the monsoon onset. Interestingly, the time-mean monsoon circulation, and the statistics of the intraseasonal oscillations (such as frequency of occurrence and mean amplitude), is also modified by the surface feedbacks, highlighting the importance of land-surface processes in the interannual predictability of the time-mean monsoon simulations.

Thus, improvements in the representation of land-surface processes will have a significant impact on the short- to medium-range forecasting as well as regional climate studies over India. The impact of changes in the surface landuse and hydrology on the subsequent precipitation patterns still needs to be addressed as a dynamic landuse change problem. The interactive vegetation growth and seasonal landuse change aspects need to be developed and tested with reference data over the Indian subcontinent. Specifically, there are several crop growth and ecosystem-based models that have been developed for different agricultural practices. Lu *et al.* (2001) developed one such model successfully over the central U.S. to study regional-scale two-way interactions between the atmosphere and biosphere. The atmospheric and ecosystem models exchanged information on a weekly time step, while the ecosystem model produced vegetation characteristics, which are an essential input for the land-surface schemes. Their results show that seasonal vegetation phenological variation strongly influences regional climate patterns through its control over land-surface water and energy exchange. The coupled model captures the key aspects of weekly, seasonal, and annual feedbacks between the atmospheric and ecological systems. In addition, it has demonstrated its usefulness as a research tool for studying complex interactions between the atmosphere, biosphere, and hydrosphere. The rapid greening and the modulation of the vegetation as a function of precipitation and monsoon activity over India is a complex land–

atmosphere issue, which requires such dynamic vegetation models to be explicitly developed and tested over the Indian region.

There are still unresolved issues pertaining to the use of such models for mixed farming and agricultural practices that are predominant over the Indian region. So there is a need to develop simple techniques for assimilating remote-sensed information over land in the weather and climate models, and for precipitation and temperature-based plant growth relations in the model. However, development of such relations will require detailed studies involving surface and remote-sensed observations, development of assimilation techniques, and ensemble analysis of the model meteorological fields, and plant growth algorithms to provide regionally- representative feedbacks due to short-term landuse land-cover changes (such as during the monsoon onset).

3.6 Regional Climate Feedbacks on Global Climate

Another factor that is pertinent over the Indian region, and is not represented well in the mesoscale and regional climate models, is the radiative feedbacks affecting the terrestrial water vapor exchange. The environmental conditions in the Indian subcontinent are conducive to particulate and aerosol transport. Using the Indian Ocean Experiment (INDOEX) observations, Raman *et al.* (2003) developed a dynamical scenario explaining the aerosol transport as a feedback between land–air–sea interactions of the land plume originating over the Indian subcontinent. These aerosol plumes can interact with the direct radiative forcing on the surface that can affect the Bowen ratio of the surface vegetation. This has implications for hydrological feedback as well as the carbon source/sink potential for the region and hence the plant growth, resulting landuse change and the regional climate. This effect of aerosol–induced radiative feedback of the terrestrial landscape is an important energy exchange pathway, which is currently poorly represented in the weather and climate models. The land-based aerosol plumes also significantly influence the microphysical processes associated with the cloud and precipitation, and this feature needs to be investigated further at micrometeorological to monsoonal scales.

In addition to the meteorological aspects of the weather and climate scenario developments, the Indian subcontinent has an important role for the global carbon cycle studies. This effect of the land-surface feedback will be addressed separately in studies such as Pielke *et al.* (2002a) and is not discussed here. Overall, one of the important aspects of the carbon management is to understand the ability of the terrestrial landscape to be a carbon sink. Studies are needed which will identify the conditions for carbon source/sink pathways over the Indian subcontinent. The interaction of the monsoonal cycle with the carbon cycle and the feedback on the regional productivity is still one of the unresolved issues in the global carbon cycle. Issues relating to the scaling and integration of ecological land-surface models in weather and climate models are also poorly represented and the magnitude of the impact of such errors is also not understood. This coupled representation of the water, energy, carbon and other trace gases and aerosol processes needs to be achieved in weather and climate models and tested over the Indian subcontinent.

3.7 Population Change as a Driver for Landuse Land-Cover Change in the Indian Subcontinent

An important component of the land-surface models in regional climate studies is to understand landuse change and factors affecting regional landuse changes. Present investigation of the impact of the landuse change is more in a post-analysis mode with little ability to predict such changes. One of the important stresses for the Indian subcontinent is the population increase and its impact on regional landuse.

The Indian population was about 350 million in 1947, and has since tripled to 1027 million per the 2001 census. The growth of population in the country peaked during 1961-71. Even though the average annual growth rate has registered a significant deadline, the rate in the recent decade was 1.9 percent. Population density of 77 km^2 in 1901 increased to 117 km^2 in 1951 and to 324 km^2 in 2001. These changes in the population densities and the migration patterns from rural to urban centers have caused significant changes in the regional landscapes.

Thus, a pertinent question to ask is what will be the size of Indian population in the foreseeable future, and what could be the resulting impact on the landscape modification. The recent national population policy contemplates that the country would achieve the replacement level fertility (an approximate level of total fertility rate of 2.1) by 2010. According to demographers, however, this seems overtly optimistic, and a more realistic assumption is that the replacement level fertility would be achieved by the year 2026. Irrespective of whether the goal is reached in 2010 or 2026, the population of the country is estimated to reach a level of 1.4 billion in 2026. In other words, the country will add about 400 million persons to its present population in another 25 years.

The impact of this population increase along with increasing consumption levels can be easily seen on our natural and man-made resources. For instance, availability of water per capita has shrunk from 5236 m^3 at the time of independence to 2227 m^3 by 1990-91. Water requirement is estimated to increase from 552 km^3 in 1990 to 750 km^3 in 2000 and further to 1050 km^3 by 2025. Utilization of ground water is estimated to increase from 190 km^3 in 1990 to 350 km^3 by 2025.

Deforestation, in particular, is one of the major adverse consequences of this rapid population growth and development. With the enormous increase in human population and development works like roads, dams, mines, industries etc., massive biotic pressure is brought about on the country's forest resources. Encroachment is generally on marginal land, often on hill slopes, unsuitable for cultivation. Denudation of the slopes leads to erosion and siltation of rivers and reservoirs, resulting in inadequate recharge of ground water. The processes to meet the increasing demand for energy (both due to population growth and increasing standard of living) have serious environmental implications. The demand for total primary commercial energy increased from 25.5 metric tons of energy (MTOE) in 1953-54 to 212.9 MTOE in 1994-95 representing an increase of more than 8 times over a period of 40 years. It is likely to increase to 770 MTOE by 2011-2012. In particular demand for electricity is likely to increase by about 3.5 times by 2011-2012. The coal demand is estimated to increase 2.6 times by 2011-2012 (776 million tons) as compared to 1996-97 (296 million tons).

Thus population change can cause a stress on the socioeconomic growth and result in land use change, as well as anthropogenic particulates and greenhouse gas consumption. Therefore, incorporating the effects of population change in regional climate models stands out as an important challenge facing the regional climate community today. Studies are needed to link population models with the regional models as a biophysical feedback, and this remains a unique problem particularly for the Indian subcontinent.

4. CONCLUSIONS

Pielke *et al.* (2002b) propose a regional climate change potential as an intrinsic component of the climate system in which the surface processes provide the driving mechanism. The modulation of the Asian monsoons and the processes over the Indian subcontinent are largely surface driven, and hence models and policies which include the critical land–atmosphere interaction processes as well as socioeconomic couplings are needed. Towards this development, studies are initially needed to investigate the importance of different land–atmosphere components, the role of dynamic vegetation changes coupled with hydrology, aerosols, and other natural as well as anthropogenic modulations on the interannual variability of the Indian monsoon.

Specifically, this Indian region shows significant heterogeneity in the landuse land cover, which will directly affect simulation of weather and climate features such as convection initiation, localized heavy rainfall and variability in the precipitation patterns, precipitation and effects associated with the landfalling tropical systems, and even the monsoonal flow simulation. Hence a wide variety of weather processes will be directly affected depending on the land-surface model considered in the meteorological model. Further, landuse/land-cover changes and dynamical evolution need to be simulated along with soil and surface variables initial conditions.

Finally, studies involving validation and evaluation of the different land-surface schemes are necessary using observations available over Indian regions (such as the land-surface experiments in Anand-LSPX and Bangalore-VEBEX). These studies are needed using both site-specific field validations, as well as tests with episodic case studies for convection and storm events and from regional climate studies.

Questions such as what level of complexity is required (in the LSM) for simulating the tropical weather processes and what is their impact on model performance, are other immediate research priorities for land-surface models.

Another pertinent research area for the Indian and tropical regions is the effect of LSMs on landfalling tropical systems track, structure, and intensity. Thus, studies are needed which test different initialization techniques for the land surface particularly for summer conditions.

The feedback processes need to be explicitly coupled with the gradual but obvious changes in the population and regional landscape, which will form an important component of the regional climate studies.

Land-surface processes are an important driver for weather and climate systems over the tropics and particularly the Indian subcontinent. Realistic representation of land-surface processes over the Indian region will help accurate simulations of environmental processes at micro, meso, and regional climate scale. However, in order to achieve these potential benefits, it is necessary to develop a strategy which will address and overcome the different challenges associated with the representation of the land-surface processes over the Indian region. Some of the key challenges related to the issue of model database development, Parametrizations and biophysical scheme evaluations, model validations, and development of newer modeling approaches were identified and discussed in this brief review. A framework will be needed through the Indo-U.S. Forum on Science and Technology to develop a comprehensive, long-term priority to support research activities directly contributing to the challenges identified for the issue of land-surface models. Such a concerted, long-term effort will provide immense benefits in the form of improved simulations for better forecasting of natural disasters such as tropical cyclones, monsoon structure and their dynamics, and the regional climate. This in turn will provide synergistic feedback to the socioeconomic well-being and geopolitical stability of this region.

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