Proc Indian Natn Sci Acad, **69**, **A**, No. 5, September 2003, pp. 585-602
© Printed in India.

A NEW PERSPECTIVE ON CLIMATE CHANGE AND VARIABILITY: A FOCUS ON INDIA

R A PIELKE Sr.*, D DUTTA S NIYOGI, T N CHASE AND J L EASTMAN

1371, Campus Delivery, Department of Atmospheric Science, Colorado State University,
Fort Collins, CO 80523-1371 (USA)

(Received 07 August 2002; Accepted 18 October 2002)

Our paper overviews the global context of climate change in terms of the Earth's heat budget. It is shown that the Earth's climate system, as the major store for heat, has warmed less than suggested by the IPCC reports. In terms of top of the atmosphere radiative heating, the globally-averaged radiative imbalance between 1955-1995 is about 0.3 W m^{-2}.

Then we focus on India and discuss the role of land-use change, vegetation dynamics, and aerosols in altering the regional climate on India. The current and natural landscape of the region is illustrated with 50 km horizontal grid scales and the effect on India's weather and climate is simulated using the NCAR CCM3 GCM.

Using NDVI satellite data, vegetation growth is shown to be closely correlated with precipitation that fell two months earlier. Aerosols are shown to significantly alter the direct and diffuse sunlight that reaches vegetation, which subsequently has an effect on carbon assimilation and transpiration. Population increases are presented as a primary driver of these regional climate changes in India.

Key Words: Regional Climate; Earth's Heat Budget; Climate Change; Indian Climate; Regional Aerosol Effects; Regional Land-use Change Effects; Regional Vegetation Dynamics

1 Introduction

This article begins with a discussion of climate in the context of Earth system heat storage changes. It builds on the discussion in Pielke[1], in which heat is shown to be an appropriate metric to assess the climate system. When the term "global warming" is used, for example, heat in units of Joules is the appropriate metric to use. Among the conclusions is that the Earth system has not warmed as much as implied by the IPCC[2]. Indeed it is spatial redistribution of heat by such effects of land-use change and anthropogenic aerosols which appear to exert a larger human influence on the Earth climate system than the radiative effect of doubling of carbon dioxide concentrations, as recently summarized in Pielke *et al.*[3]. This issue is illustrated in this article, with a particular emphasis on India.

2 Global Perspective

This section describes how an examination of the global heat budget allows a straightforward explanation for understanding one of the consequences of human changes in the composition of the Earth's atmosphere. Data and analysis provided in Levitus *et al.*[4,5] on increases in heat stored within the world's oceans provide a unique opportunity to explore this perspective. The use of a global heat budget to assess this consequence of human perturbations of the Earth system was also introduced by Pielke[1].

This section expresses the Levitus *et al.*[4,5] data in terms of long-term, globally-averaged values of heat flux (W m^{-2}), and relates the fluxes to the radiative forcing of the Earth's climate system. These fluxes provide a constraint on estimates of radiative forcing such as provided by the Intergovernmental Panel on Climate Change (IPCC). Such an assessment of the global heat budget was provided in Peixoto and Oort[6], based on the study of Ellis *et al.*[7], but this perspective is not appropriately utilized in the IPCC reports.

---

*Author for Correspondence. Email: tnk@io.met.fsu.edu

A few terms used in this article are worth highlighting at the onset. Radiative forcing is defined by the IPCC as

> "a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system, and is an index of the importance of the factor as a potential climate change mechanism. It is expressed in W m^{-2}."

We use the additional terms as follows. *Equilibrium radiative forcing* refers to the portion of an increase or decrease in radiative forcing that has resulted in a change in the Earth system such that the outgoing radiative fluxes have become equal in magnitude to the incoming fluxes. Non-equilibrium radiative forcing is the remaining portion of the radiative forcing which is still warming (or cooling) the Earth system. *Non-equilibrium radiative forcing* is also referred to as the radiative imbalance of the Earth's system. In the context of climate sensitivity, heat storage within the Earth system changes when there is a radiative imbalance. *Heat content* refers to the internal energy contained within the Earth system and is expressed in Joules. The *heat budget equation* for the Earth system expresses the change of heat content as a result of fluxes of heat into and out of the system, which is simply a statement of the conservation of energy. The *heating rate* refers to the introduction (or removal) of energy from the Earth system per unit of time. The *radiative flux divergence* is the term used to describe the differences in the radiative fluxes integrated across any time period.

The IPCC presents estimates of the change in radiative forcing of the climate system between 1750 and 2000 (presented in Fig. 3 of the Statement for Policymakers[2]). Uncertainty values are presented for each forcing. The global mean radiative forcing of the climate system for 2000, relative to 1750 associated with well-mixed anthropogenic greenhouse gases (primarily carbon dioxide and methane) is 2.43 W m^{-2}. The direct aerosol effect is –0.5 W m^{-2}, tropospheric and stratospheric ozone effects are +0.35 and –0.15 W m^{-2}, respectively, and a change in solar heating of 0.3 W m^{-2} was also estimated, with most of the increase in the early 20th Century. The total radiative forcing due to these effects is +2.43 W m^{-2}. The indirect effect of aerosols is estimated as –1 W m^{-2}, (but with an uncertainty from 0 to –2 W m^{-2}). Thus a continuous rate of 1.43 W m^{-2} of radiative forcing (i.e., 2.43 – 1 = 1.43 W m^{-2}) would correspond to a transfer of 2.30 × 10^{23} J of energy per decade into the climate system.

The Levitus *et al.* data provide an opportunity to assess the portion of this radiative forcing which is actually warming the Earth system. To do this, the Levitus *et al.* ocean data is reported in W m^{-2}. Expressing their data in this manner provides a constraint on the net radiative forcing that results from the terms listed in Fig. 3 of the Statement for Policymakers.

The heat budget for the Earth system can be expressed as

$$\iint_{t,A_{Earth}} R_N \, dAdt = \iint_{t,V_{atmos}} Q \, dVdt + \iint_{t,V_{ocean}} Q \, dVdt + \mathit{other\ heat\ reservoirs} \quad ...(1)$$

where R_N is the global mean non-equilibrium radiative forcing, A_{Earth} is the area of the Earth, Q is the heating rate, V_{atmos} is the volume of the atmosphere, and V_{ocean} is the volume of the ocean.

Since the troposphere encompasses about 80%, of the mass of the atmosphere, eq. (1) can also be integrated from the tropopause downward in order to relate more closely to the IPCC perspective of radiative forcing of the Earth system. It is important to note that R_N is not the quantity discussed in the IPCC Statement for Policymakers[2], but is the instantaneous radiative flux divergence. Temperatures regionally within the Earth system can change without a change in the left side of eq. (1). Cooling in one region can occur with warming elsewhere. However, unless the global mean non-equilibrium radiative forcing is non-zero, there will be no Earth system integrated heat change.

When the Earth system experiences a radiative forcing change, after some time the system responds by reaching a new thermal equilibrium state[8]. Thus, for any change in radiative forcing, there will be two components: the fractional portion of the equilibrium response, which has been achieved, and the remaining radiative imbalance. The equilibrium component is reflected in changes in the Earth system heat that have already occurred, and the imbalance component refers to heating or cooling of the Earth system which continues.

When considering the anthropogenic greenhouse gas radiative forcing felt by the Earth since 1750, and because some portion of that forcing has already resulted in warming the Earth, the non-equilibrium forcing, R_N, is the relevant term for calculating changes from the present to some point in the future. This quantity is approximately equal to the additional heat stored in the ocean. Following Levitus *et al.*[4], other heat reservoirs, such as sea ice and continental ice sheets, are assumed to be inconsequentially small. Thus, the radiative forcing of the system is a result of the left side of eq. (1). The first term on the right of eq. (1) is observed to be small (and essentially zero from 1979-2001; http://www.ghcc.msfc.nasa.gov/temperature).

The use of eq. (1) provides an alternative perspective to the concept of effective climate sensitivity, in which temperature is used as part of the analysis. As discussed in Raper *et al.*[9] following their eq. (1), for example, a global average surface air temperature along with a climate feedback parameter are used to evaluate the sensitivity of the Earth system to atmospheric radiative forcing. With eq. (1) of this commentary, however, the issue of feedback does not need to be estimated, since a closed heat budget is expressed by that equation.

The IPCC Statement for Policymakers[2] is missing important information because it fails to distinguish equilibrium from imbalance radiative forcing as most of the radiative forcing portrayed has already been realized in the climate system. The labelling of the left axis with the terms "warming" and "cooling" could be misinterpreted to mean that the entire listed radiative forcing is continuing to warm or cool. A figure is needed that portrays the actual current radiative forcing to the climate system that is felt at any particular time, in this instance in 2000. As this planetary energy imbalance is virtually the same as the energy stored in the top 3 km of the oceans, and other energy stores in the climate system are much smaller[5], we can examine either the global mean non-equilibrium radiative flux or the ocean storage to evaluate this quantity. Peixoto and Oort (see ref. [6], page 351) even concluded that such a relation exists between the radiative forcing and ocean heat storage over the annual time scale. They showed that the agreement between the annual variations of net radiation at the top of the atmosphere is in good agreement, both in phase and amplitude, with the ocean heat storage.

The construction of such a figure using R_N would require, for instance, knowledge of the net flux at the top of the atmosphere, averaged over the entire planet and averaged over a year, or instantaneously measured. In either case, direct observation of this quantity is difficult, given the required precision (0.1 W m^{-2}). An alternative approach is to use a model to calculate this quantity, however, the entire suite of climate forcings and feedbacks are not yet included in the models, as discussed by Pielke[1,10].

The Levitus *et al.*[4] data have large positive and negative amplitudes over the time period from the early 1950s to the mid 1990s. Satellite observations and models need to resolve this variability in order to improve our confidence in those tools.

One interesting consequence of displaying the data in terms of eq. (1) is that if a time period had zero heat storage change in the Earth system, there would be no "unrealized warming", such as discussed, for example, by Wetherald *et al.*[11]. The concept encapsulated by the term "unrealized heating" more appropriately refers to storage of heat in a non-atmospheric reservoir (i.e., primarily the ocean), with the "realization" of the warming only occurring when there are interfacial transfers of heat into the atmosphere.

Short-term radiative imbalances can also be assessed. The effect of the Pinatubo volcanic eruption of 1991, for instance, produced a radiative flux divergence of –4 W m^{-2} in August and September 1991, which gradually reduced to zero by March 1993[12]. This effect resulted in a reduction of 5.64 × 10^{22} Joules of heating within the Earth system [according to eq. (1)].

When presenting observations, it is important to assess the accuracy of the observational data. Levitus (2001, personal communication) has concluded that the "decadal" variation in the upper 300 meters is real. Below 300 meters the amount of data decreases with depth which is why the Levitus *et al.*[4] paper used 5-year running means. Thus their data should be interpreted as more of a challenge to modelers and observationalists than a confident diagnosis of the actual variations in heat content of the ocean on decadal time scales.

Over the period of observational record (1955-1995), the Levitus *et al.*[4] data produces an average heating rate of about 0.3 W m^{-2}. The model values of Barnett *et al.*[13] and Levitus *et al.*[5] are close to the long-term value. However, the large decadal variability in the observations should raise concerns as to whether the models' long-term agreement with observations on this time period occurs for the right reasons. Moreover, from this perspective, the IPCC should present the magnitudes of planetary energy imbalance simulated by all of the models used in the IPCC [1].

To be able to predict future climate change, in principle, it is necessary to be able to evaluate the actual current and future heating of the climate system from anthropogenic and natural sources as well as where this heat is accumulating. For example, if heat is stored in the ocean at depths greater than 3 km (where observations were not reported in the Levitus *et al.* studies), instead of lost to space, this could be accomplished through relatively small-scale areas of vertical turbulent mixing and three-dimensional circulations, which the coarse spatial resolution of the GCMs data might not be able to adequately simulate. Moreover, the latest assessment of tropospheric heat (July 2002) shows that the atmosphere has returned to near its 1979 value, after the warm recent ENSO event. This rapid cooling of the atmosphere, in conjunction with the Levitus *et al.*[4,5] studies, indicate that a scientific priority should be to precisely observe the global ocean heat content.

An assessment of the heat storage within the Earth's climate system offers a unique perspective on global change. If the heat actually remains within the Earth system in the deeper ocean, for example, while the heat content of the remainder of the heat reservoirs in the Earth system remains unchanged, sudden transfers of the heat between components of the system (from the ocean into the atmosphere) could produce rapid, unanticipated changes in global weather. Similarly, relatively large warming and cooling radiative forcings (e.g., well-mixed greenhouse gases and the indirect effect of aerosols) could be in near balance at present, suggesting that sudden climate changes could occur if one of these forcings becomes dominant. On the other hand, if a large portion of the increased radiative fluxes are lost to space, as the atmosphere adjusts, such as through a change in cloud cover (see ref. [14]), this would suggest that the climate system is relatively more resilient to continued anthropogenic heating effects than conventionally assumed.

The IPCC would present a more scientifically robust picture of the anthropogenic effect on the climate system by presenting a figure in terms of planetary energy imbalance in which observed changes in heat within the Earth system would be used to constrain the global mean radiative forcing. The relatively small accumulation of heat within the Earth's climate system to date also elevates the significance of anthropogenic land-use change as an influence on the global and regional climate as discussed later in this article[15-17], since this change appears to alter the long-term global atmospheric circulation even though the net average global changes in heat content may be small.

The assessment of the heat storage and its changes over time should be a focus of international climate monitoring programmes. This includes extending the Levitus *et al.* data up to the present and achieving annual time resolution. The reduction of the uncertainties in the global mean radiative forcing is also a clear priority. This requires improved monitoring of the agents of this forcing, including aerosols and their influences on cloud microphysical processes.

Thus, there are several major reasons that the assessment of the Earth system's heat budget is so valuable.

- Earth's heat budget observations, within the limits of their representativeness and accuracy, provide an observational constraint on the radiative forcing imposed in retrospective climate modelling.
- A snapshot at any time documents the accumulated heat storage and its change since the last assessment. Unlike temperature, in which there is a time lag after a heat change is imposed before the temperature would reach an equilibrium value, there are no time lags associated with heat changes.
- Since there is little heat storage associated with the surface temperature, its application as a monitor of Earth system climate change is not useful in evaluating the heat storage changes of the Earth system. The heat storage changes, rather than surface temperatures, should be used to determine what fraction of the radiative fluxes at the top of the atmosphere are in radiative equilibrium. Of course, since surface temperature has such an important impact on human activities, its accurate monitoring should remain a focus of climate research[18].

However, as discussed in Pielke *et al.*[3] and Pielke[16] it is not only the net energy imbalance globally which is an important climate indicator; it appears that the spatial redistribution of energy has a significant, perhaps dominant, effect on the Earth's climate. In the following section, we discuss this issue with respect to India.

3 Examples of Regional Climate Change and Energy Redistribution Mechanisms Affecting India

While the data shows a positive overall net planetary energy imbalance since the 1950s, the climate of India has undergone a much more complicated set of changes which could not be diagnosed by the globally-averaged heat budget. Here we discuss these complications and some of the processes that may affect regional energy distribution. In the Asian monsoon region, several very effective studies of regional climate have been performed, as summarized by Fu *et al.*[18]. Papers reported on include Xue[19], Wei *et al.*[20], Fu and Wen[21], Wei and Fu[22], Ojima *et al.*[23], Yasunari *et al.*[24], and Kanae *et al.*[25]. Among the conclusions are that land-surface conditions have been significantly modified by human activities, and, as a result, the Asian monsoon today is different in its geographic influences and temporal evolution from what would occur with a human undisturbed Asian landscape.

In the IPCC Special Report on The Regional Impacts of Climate Change: An Assessment of Vulnerability[26], several conflicting feedbacks can be found for the Indian region. These include possible scenarios where the region may show a positive feedback due to atmospheric changes, while considerations of additional model complexities tend to reverse the conclusions. As an example, a summary of the different GCM simulations considered over the Indian monsoon region provided an area-averaged increase in summer monsoon rainfall though its spatial distribution was highly variable among the different GCMs. Accordingly a consensus increase in monsoon rainfall over the monsoon region was obtained. Subsequent studies[27] which considered aerosol effects, in addition to the CO_2 effects used in the IPCC assessment, led to consistent simulations showing a marginal reduction in the monsoon precipitation. This highlights the variability of the tropical system and the difficulty associated with projecting regional climate effects over the Indian monsoon region. This is because of the numerous interactive features active over the highly diverse Indian subcontinent and the inability of the models to consider each of these interactions explicitly to skillfully represent regional climate change.

In this section, we will consider themes that need to be considered in future assessments for regional climate studies, particularly over the Indian region. The themes include the dynamic changes in regional land use and links between the regional radiative and hydrological features. Land-use change processes can be reviewed under two headings: the natural succession due to specie interaction and resource allocation, and the human–induced/population stress-based land-use change. The radiative and hydrological link will also be established by proposing a feedback between regional haze and aerosols as a driver for regional water vapour exchange and the hydrology.

3.1 Land-Cover Change

One often overlooked process affecting the regional redistribution of energy which changes in land cover. We performed model simulations using the National Center for Atmospheric Research Community Climate Model (NCAR CCM3) in order to investigate the effect of observed historical land-cover change on Indian Climate. Because the Indian subcontinent is strongly affected by large, hemispheric-scale circulations such as monsoons and Walker-Hadley cells, we explored the effect of regional land-cover change depicted in Fig. 1. Shaded cells in the figure represent deviations from natural (i.e., agricultural) vegetation. It has been shown in the past that global changes in historical vegetation can have large climatic effects both regionally and at far through atmospheric teleconnections and shifts in large-scale circulation features (e.g, refs. [15],[28]).

Fig. 2 shows the 12-year average difference in near-surface temperature between the current GCM simulation and the natural vegetation GCM simulation produced by the land-cover changes shown in Fig. 1. Statistically significant changes at the 10 and 5% levels are shaded in light and dark, respectively. Significance is assessed using a t-test and substantially more than 10% of the area is affected by significant changes in temperature. Most of the Maritime continent and southeast Asian peninsula shows significantly increased temperature during this month. The majority of India, however, shows cooling. The average temperature change in the area indicated by the dashed line box in Fig. 2 is 0.07°C.

Simulated precipitation changes resulting from the land-cover changes in Fig. 1 are shown in Fig. 3. Again, significant regional shifts in precipitation occur over much of southeast Asia and the Maritime continent. Precipitation decreases over much of the Indian land area and increase significantly in the Bay of Bengal. The precipitation change over the entire dashed box in Fig. 3 is negligible as the positive anomalies over ocean areas and the negative anomalies over land very nearly cancel out. These precipitation changes on a seasonal scale can potentially cause significant changes in the vegetation greenness and natural landscapes, which in turn have a feedback on the regional climate. This issue is discussed in the following section.

3.2 Vegetation Dynamics and Land-Use Change

The changes in regional landscape are dynamic and continue affecting both the large-scale and the smaller mesoscale weather and climate regimes. Interactions on these space scales occurs between the land surface and the atmosphere as discussed in

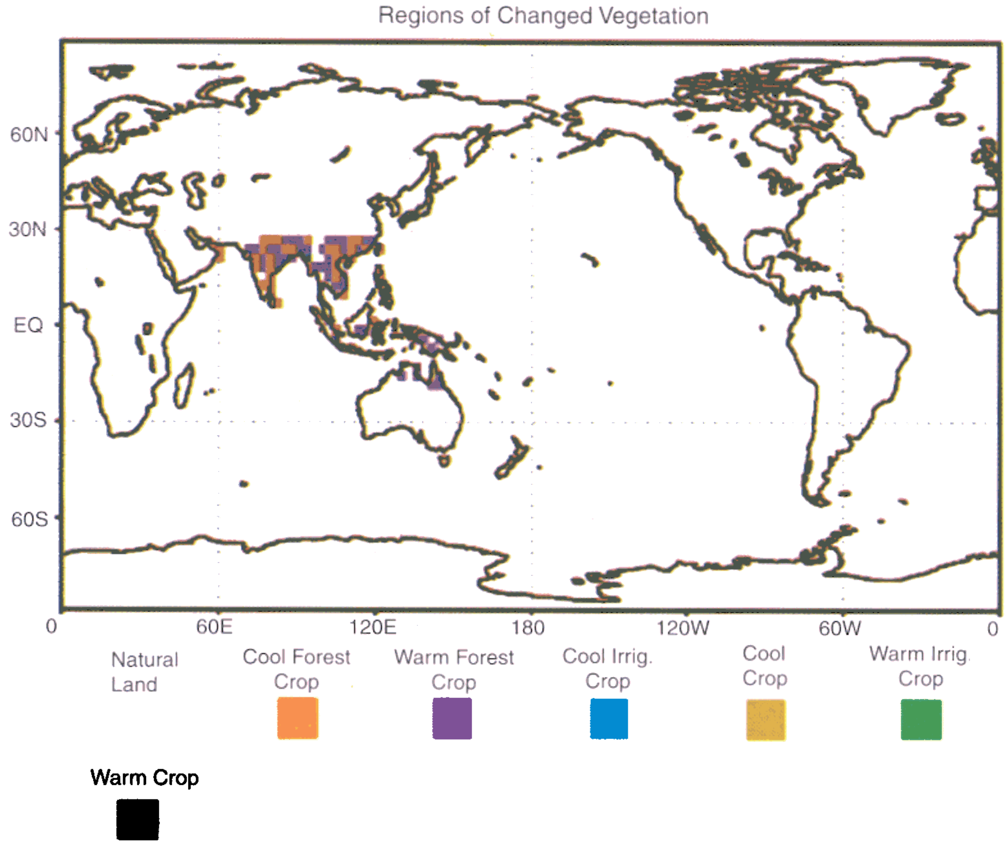


Fig. Regions of changed vegetation in the GCM simulation[15]

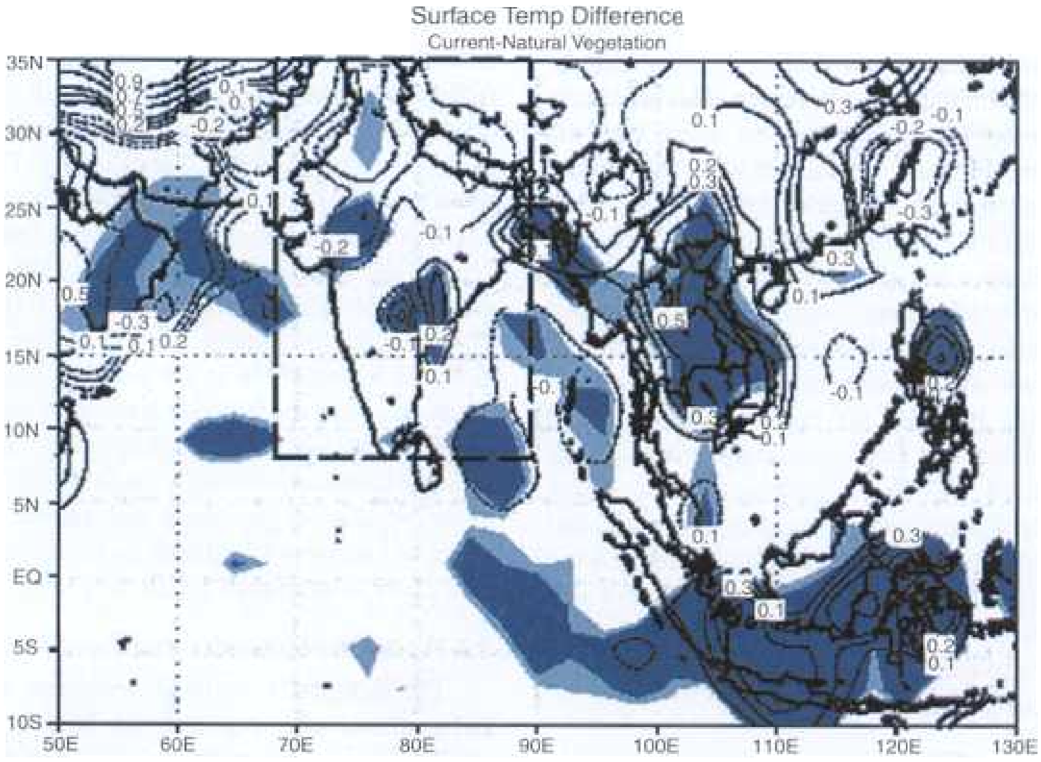
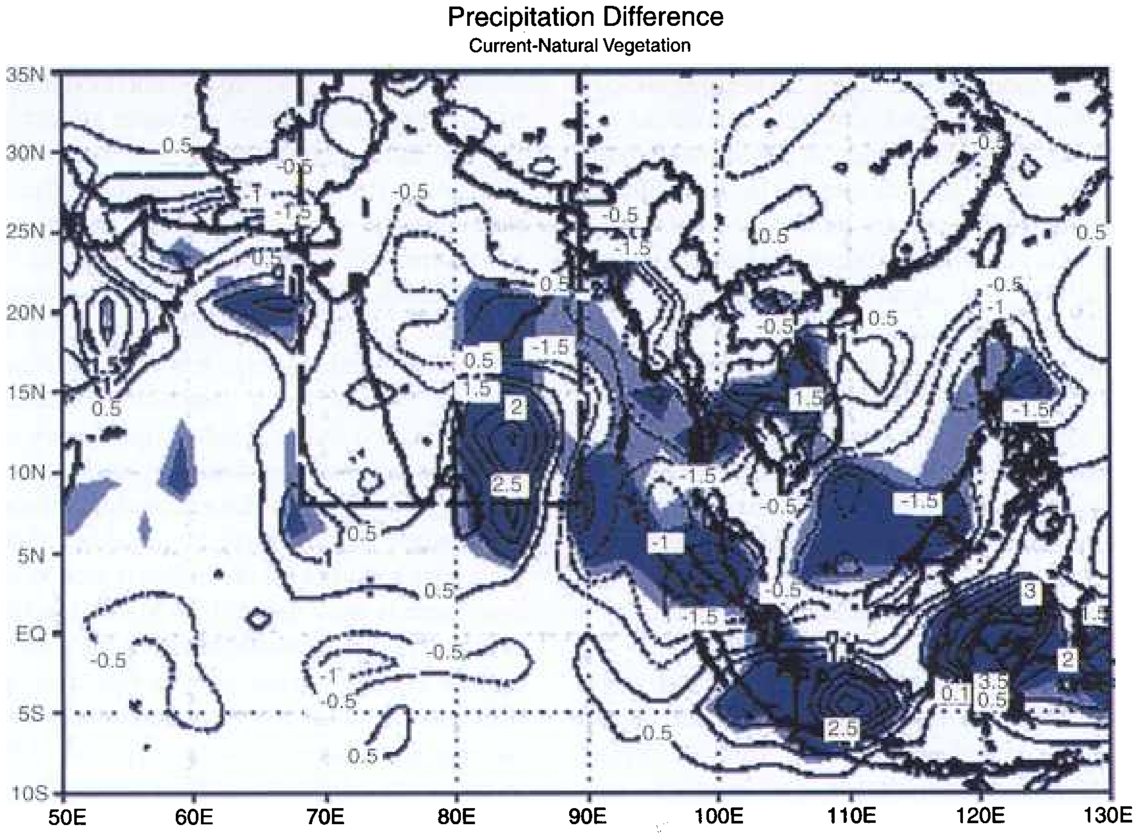


Fig. 2 Difference (degrees C) in near-surface air temperature (current-natural vegetation model simulation) for land-cover changes shown in Fig. 1



Precipitation Difference
Current-Natural Vegetation

Fig. 3 As in Fig. 2 but for precipitation rate difference (mm/day)

ref. [29]. Hence understanding the dynamics of land-use change over the Indian region is an important component of our ability to understand climate. The changes in the land-use patterns can be due to natural specie interaction and specie dominance because of changes in the regional climate or due to manmade policies. The issue of population change is also very pertinent over the Indian region. We will discuss these features from the perspective of including them inthe climate change and variability assessment over the Indian region.

3.2.1 Background

Precipitation processes have a direct link with the vegetation evolution in a majority of the Indian subcontinent. With the advent of the monsoons, the immediate greening of the landscape is a ubiquitous feature of the monsoon region. Indeed in satellite observations, there is a strong co-linearity between precipitation amounts and the greenness fraction over India. Changes in the landscape as a dynamic and interactive response to rainfall amounts and patterns have been identified as one of the missing components of land-surface process modelling over the tropics and Indian subcontinent in particular[29]. Though the effects are visible over the short-term observations, the relation between precipitation and regional landscape can be extended to a longer time scale. In that, with the potential for a regional weather change involving precipitation and temperature changes, there can be direct feedbacks on the natural landscape in the region. Landscape changes in turn can cause interactive alterations in the regional climate as discussed earlier in this paper and more extensively in studies such as Pielke[28]. Whether the landscape and the regional atmosphere seek to obtain equilibrium in the Gaian sense, or whether the coupled changes in the landscape and the regional atmosphere make the survival of the fittest specie in the Darwinian context over India remains to be investigated. This balance (or imbalance) can cause land-use resilience (or alteration) and has a feedback on the atmospheric systems' heat balance/ imbalance potential.

In either case, a scenario where a combination of the two i.e., some species dominating with their resilience and some biome species interacting with the habitat leading to a more synergistic environment through resource allocation is plausible. Indeed, as discussed in Niyogi *et al.*[31], one of the environmental modulators controlling the shift from the Gaian to the Darwinian response could be the regional hydrology. That is, when the hydrological conditions are non-limiting, the system tends to invest the resource (water vapour or soil moisture) in the different components leading to an interactive and unified response. This unified response makes the system more resilient and significantly less prone to a single specie dominance or aridness.

On the other hand, with lesser resource availability (such as during a drought), the Earth system tends to be more conservative and the individual components have a lesser propensity in investing the resources they have access to, in other system components. This leads to a system which is less interactive, and the individual components more responsive to perturbations and hence more vulnerable to specie dominance or extinction depending on the environmental signal.

In understanding the newer challenges towards developing an integrated regional climate assessment, particularly over the tropical regions such as the Indian subcontinent, there is hence a need to study the interactive role of vegetation dynamics in a changing climate.

3.2.2 Modelling Land-Use/Land-Cover Feedback

Several potential techniques exist for linking the regional weather and the land-use/land cover. These range from simple regression models[32,33] that relate past weather observations to landscape characteristics changes, and resulting equations/ classification schemes are used for potential vegetation changes for probable changes in the regional weather (surface temperature and precipitation, e.g., Holdridge Classification System). These functional models tend to provide a good fit for the direct effects but often tend to ignore the more pervasive indirect effects because of the nonlinear complexity and the limitations in using observations for developing such relations. Hence, a relatively complex form of regression models involving the resource allocation schemes[34] can be applied. Covariance and co-limitations to the regression models for changes in the surface weather and the corresponding change to the surface landscape are introduced. For example, the vegetation growth is typically a function of growing degree days and drought days in the growing season. There are different regional perturbations that can be made depending on the function form (such as linear or parabolic), stress due genetic adaptation (one specie winning over the other), and soil and management practices.

Though there are limited studies evaluating the use of such regression and/or resource allocation models for the Indian region, their use for linking socio-economic stresses, environmental effects due to pollution and regional land-use change appears to be promising. A class of the resource allocation model deals with the so-called crop growth models. Lu *et al.*[35] report the use of such a crop model for interactive feedback between the landscape and the regional weather for a seasonal simulation over the central United States. Such couplings are potentially ideal for regional and seasonal studies over certain Indian regions where a concentrated agricultural activity is practiced. Further, there are a number of studies that have been reported for the Indian region validating the crop models such as CERES-MAIZE, which appear to have a good agreement between the weather factors and the vegetation/crop growth. However, linking the different models in a heterogeneous land use, or mixed farming environment, which is typical of the Indian, is necessary before they can be applied for regional climate modelling studies.

A third set of models that can be applied for studying the coupling between the vegetation dynamics/ land-use and the regional atmosphere are the ecological models. These models tend to apply mechanistic relations based on leaf- and canopy-scale responses to environmental changes for transpiration, photosynthesis and energy and water balance. Though applying these models can produce a relatively more realistic outcome from the coupled studies, scaling the leaf- and canopy-scale relations to a region remains one of the ongoing challenges for these models. Lu *et al.*[35] and Eastman *et al.*[36,37] applied different ecological models (CENTURY, GEMTM) coupled to an atmospheric model (RAMS) and have found that vegetation dynamics significantly feedback to influence the seasonal weather patterns. Eastman *et al.*[36] found that the biogeochemical effect of doubled CO_2 in the Great Plains had a more immediate and more significant effect in seasonal weather than the radiative effect of doubling CO_2.

Incorporating the important perturbations such as from landfalling tropical storms, and prolonged droughts and the resulting changes in soil and plant nutrient strategies remains one of the biggest challenges in developing these couplings. The interactive feedbacks have been studied over the midlatitude regions, but the strategies will be significantly different in the semiarid regions of India. Further, most of the ecological models generally fail to reproduce the extreme environment (e.g., very dry or very wet soil and atmosphere) satisfactorily, and therefore model simulations over the Indian region are prone to a higher level of uncertainty when assessing the sensitivity of the different environmental forcings on regional climate.

Further, the ability to provide more realistic vegetation changes as boundary conditions significantly improves the model performance. So it may not be as much a choice of model, but the representation of the correct regional drivers that could be the critical aspect. It is important to realize that no single model can completely simulate the local, regional, and continental vegetation dynamics, and efforts are needed to compare the different modelling approaches with the observed vegetation dynamics over the monsoon region.

Similarly, the ecological models appear to be a better choice for the land-use land-cover change analyses since the regression or resource allocation estimates based on the preindustrial level CO_2 changes cannot be interpreted with the same certainty as the effects due to CO_2 changes from the present-day values to projected doubling.

As an example given in ref. [38], the response in plant–CO_2 interactions is known to be different and will have significant interactions with the soil moisture[39]. Specifically corresponding to the land-use over the Indian region, results from Niyogi *et al.*[40] suggest each biome has a different strategy to account for CO_2 changes with regard to soil moisture availability. Considering only the biogeochemical feedback of increased CO_2 levels, regions in the north that generally have winter wheat and other C3 crops will tend to show a positive response to CO_2 changes if the monsoon precipitation is not affected (or reduced). On the other hand, if the CO_2 increase indeed causes a decrease in the monsoonal rains over the Indian region, then the central and the southern belt with maize and other C4 predominance will tend to show a preferential dominance in the landscape.

However, these broad conclusions do not consider any management practices or additional financial investment as an input to crop response. However, events such as drought or high soil moisture availability need to be explicitly considered in carbon stock and regional weather variability assessments. This is because the hydrological feedback can enhance, or completely balance, or even reverse the biogeochemical effects associated with CO_2 changes, and needs to be considered in any comprehensive future assessment. It should be noted that often, despite dramatic leaf-level impacts due to weather changes, the natural ecosystem tends to be resilent and does not show a dramatic response. This feature is generally true for most ecological communities, but the changes introduced via manmade/population demands will have a potential for a more permanent and significant impact, and is discussed in the following sections.

3.2.3 Considerations for Human Population in Land-use Models

The role of population on the evolution and the projection of land-use change in understanding climate variability over India is an important and missing component of climate change studies. This feature is not presently considered in ecological models, which are generally based on results in Europe and other western countries, where population is not a critical driver. As an example, the United States has typically seen a growth in the population in the last 50 years from about 150 million to about 275 million, while for the same period, India's population has changed from approximately 375 million to over 1 billion. Translating this information into population density provides estimates of 30 persons per square kilometer for the U.S. and about 350 persons per square kilometer for India. The changes in the population density have a direct effect on resource allocation and land-use change. Population information also needs to include the significantly less resource use per capita in India than in the western countries. Interestingly, these dramatic increases in the population density do not show any significant change in the statewide statistics for land-use change in India.

As an example, Haryana in northern India has about 2.5% forest and 81% agriculture and these figures have not shown any systematic change at a statewide regional scale in the last 30 years. However, there are significant microscale land-use alterations evident in several parts of the state. Consequently, the scale of the population land-use model will be a critical factor in considering these feedbacks for regional climate studies. This then poses additional questions about using national averages (or even statewide statistics) for developing climate assessments for regions such as India. These land-use change drivers can be considered as microscale changes, yet they may have significant feedbacks within the regional climate system, and this needs to be investigated further.

3.3 Analysis of Land-use/Land Cover and Precipitation Changes over India

In order to quantify the year-to-year variability we obtained the Advanced Very High Resolution Radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) dataset from the Goddard Space Flight Center's Distributed Active Archive Center (DAAC) for 1989 through 2000, excluding 1994, which was an incomplete record. This dataset is used to derive the Leaf Area Index (LAI) for the coupled GEMTM/RAMS modelling system. The data have a pixel size of 8 km that were scaled up to the grid. The vegetation classes are based on Olson's Global Ecosystem (OGE) dataset. The dataset employs 1 km pixel sizes, which were used to determine the most dominant vegetation class in each 50 km grid cell (Fig. 4).

The dataset was derived using 1993 AVHRR data and ground truthing. For this analysis, the NDVI values were masked with a land-water mask and according to three broader vegetation classes: urban, semi-desert, and desert, and any remaining classes for ease of interpretation. Shown in Fig. 5 is a breakdown of vegetation predominance for the indicated vegetation type. Water was intentionally left off the figure and amounted to nearly 36% of the grid cells. The figure indicates that nearly 5% of the domain area is covered with the urban class, while desert and semi-desert combine to over 18%.

We first examined the monthly domain-averaged NDVI for each of the three broadly defined classes. The results are shown in Fig. 5. The seasonal cycle is readily apparent for each class. The figure also displays the active and break monsoon periods for winter and summer monsoons and their local minima and maxima. In addition, there appears to

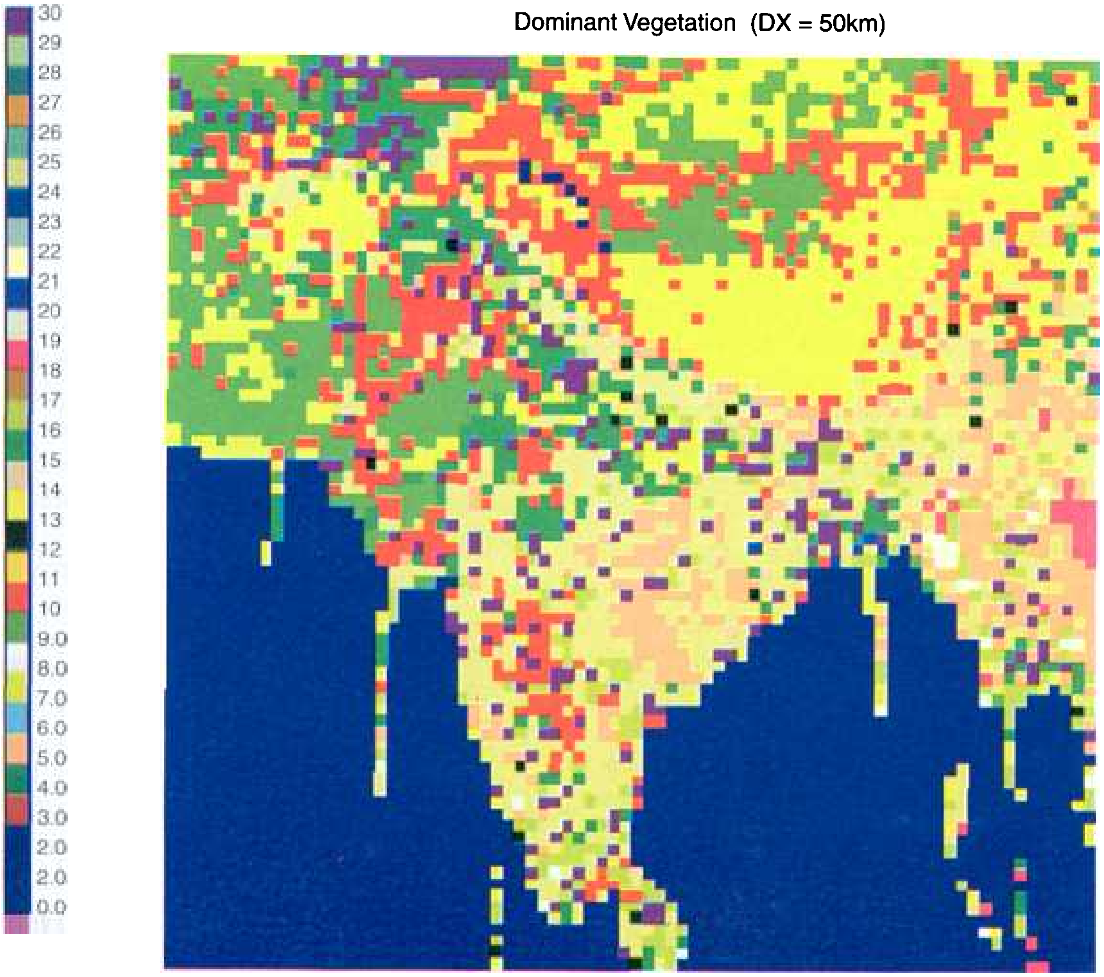


Fig. 4 Dominant vegetation classes over the Indian region

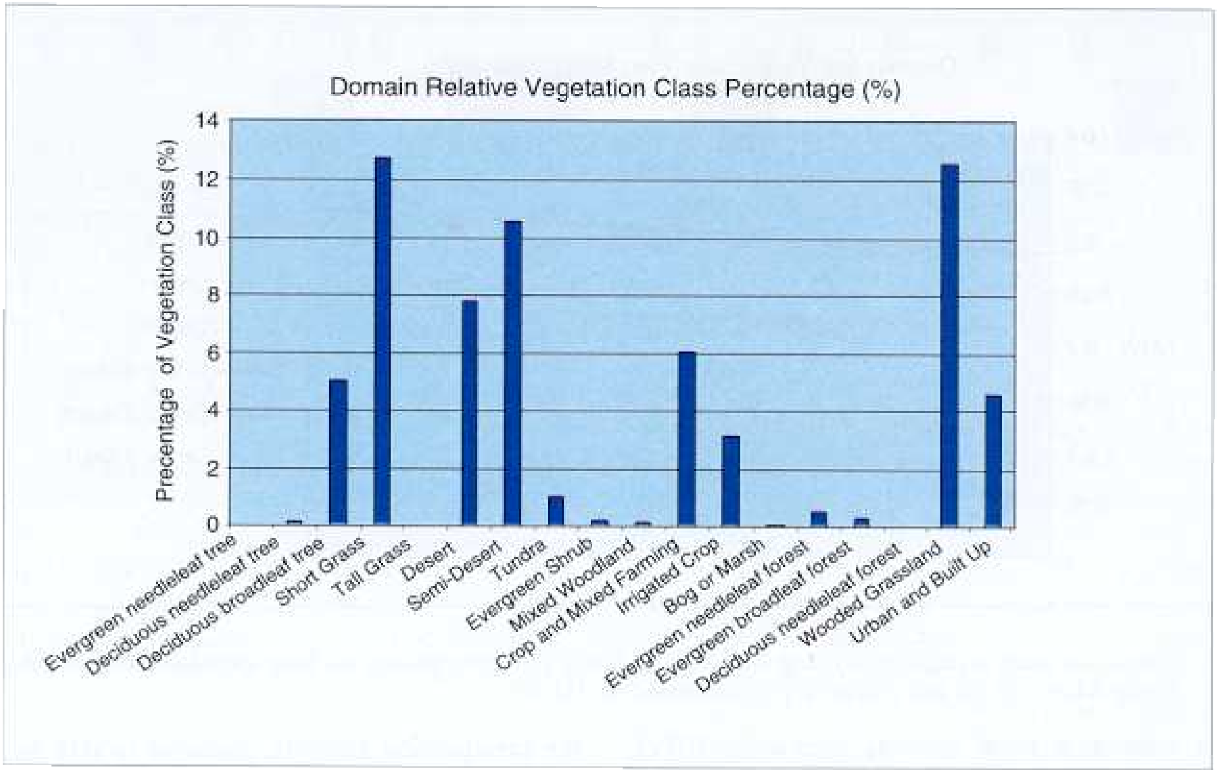


Fig. 5 Domain relative vegetation class percentages

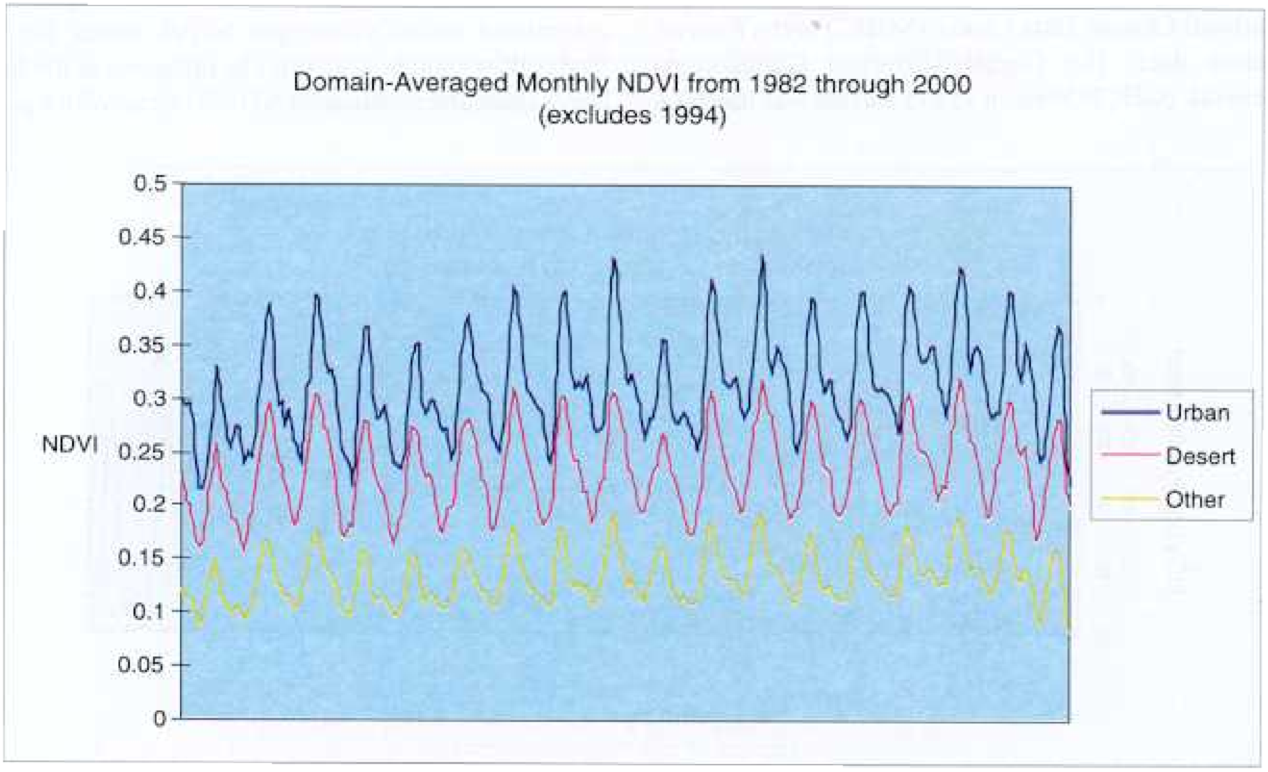


Fig. 6 Domain-averaged monthly NDVI from 1982-2000 excluding 1994

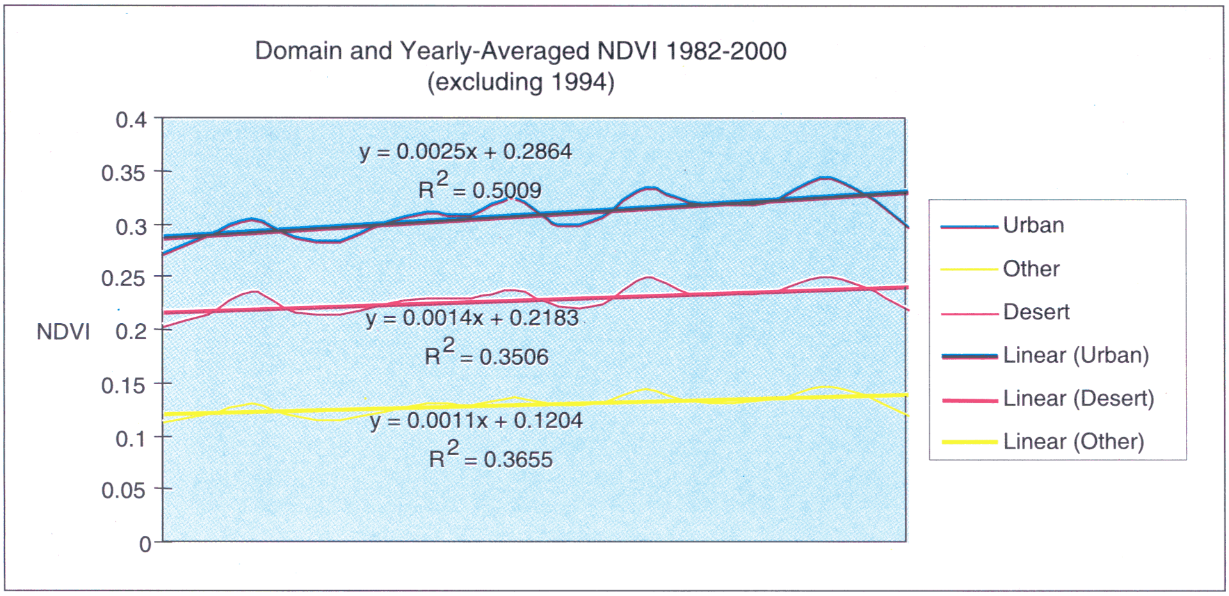


Fig. 7 Domain and yearly-averaged NDVI from 1982-2000 excluding 1994. Precipitation has been normalized where a value of 1 corresponds to 178 cm and a value of zero corresponds to 111 cm

be a noticeable trend towards increasing NDVI, notably in the urban classification and to a lesser degree for the desert cells.

Precipitation data were acquired for the same temporal period as the NDVI analysis from the National Climate Data Center (NCDC) in the form of station data. The Global Historical Climatology Network (GHCN Version 2; 41) dataset was used for the precipitation analysis. Included in this analysis were the monthly totals for stations in India. We excluded 1994, in order to be consistent with the NDVI data. Fig. 8 shows the normalized monthly totals for all stations in India, as well as the corresponding normalized monthly-averaged NDVI values for all land cells within the domain. The influence of the July and August precipitation on NDVI is clear, with a peak

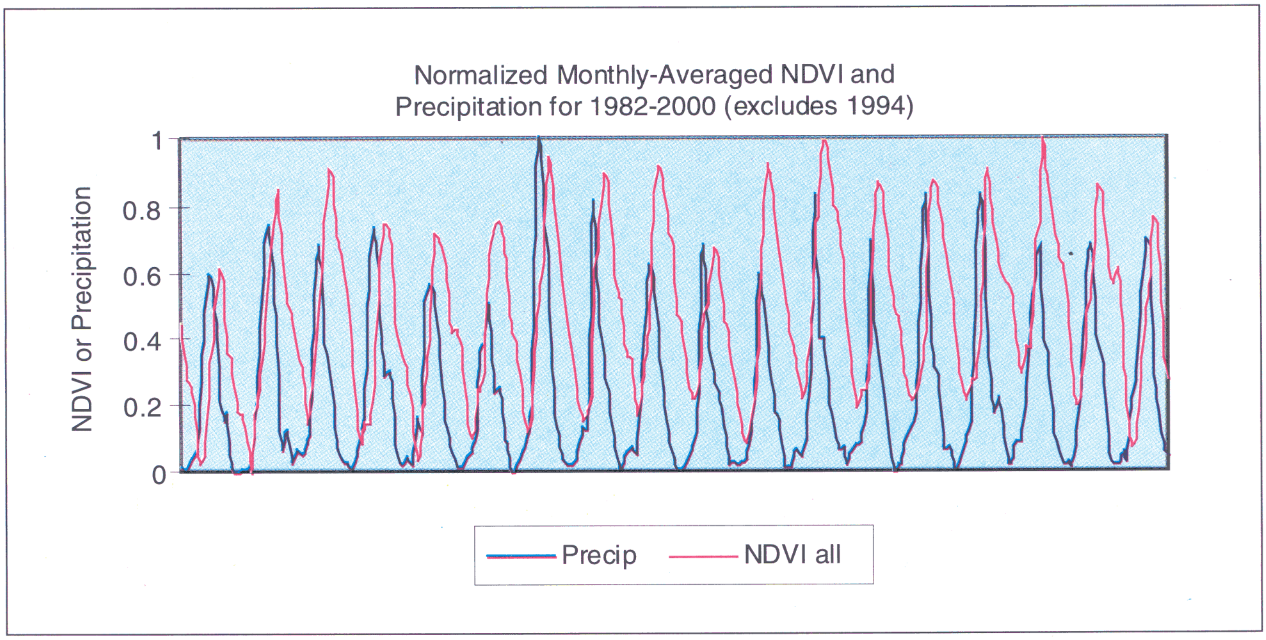


Fig. 8 Normalized monthly-averaged NDVI and precipitation for 1982-2000 excluding 1994. Precipitation has been normalized where a value of 1 corresponds to 47.8 cm and a value of zero to 0.4 cm

in precipitation (usually in July) showing as a peak in NDVI in September. A simple canonical regression was performed on the raw data values. The R^2 was 0.071, thus the precipitation explains only 7.1% of the variance. We next shifted the precipitation ahead 2 months, corresponding to the apparent lag in NDVI peaks relative to precipitation peaks. The regression found a correlation coefficient of 0.845 corresponding to an R^2 of 0.714. The magnitude of this result indicates that two-month forecasts may be possible based on the intensity of the monsoon. Still, nearly 30% of the variance is likely related to nonlinear feedbacks between the soil/vegetation/atmosphere continuums. This work will aid in the evaluation of the coupled modelling system, to see if a dynamic soil/vegetation/atmospheric interface will also lead to further simulation skill. This can be accomplished through multiple and nonlinear regression techniques.

As a final example of the linkage between the precipitation and the regional vegetation coverage, we computed the same quantities as Fig. 9 on a yearly time scale. Fig.10 shows the curves for NDVI and precipitation along with simple linear regression lines. The R^2 for NDVI was 0.351, while precipitation had a value of 0.125. The results indicate that there was indeed an increase in precipitation and NDVI over the period from 1989 through 2000.

One of the salient features of the model study is the use of actual NDVI forcing over the study area. The performance would be deteriorated without such observed/analyzed NDVI fields over the monsoon region. Hence techniques assimilating the satellite biophysical data form an important next step in regional climate studies over the monsoon region.

3.4 Hydrological–Aerosol Dynamics

Globally, aerosols are abundant in the environment both as natural dust particles as well as anthropogenic residues of combustion or other energy production-related activities (see a commentary by Broecer[42], highlighting dust as the single most important aspect of past and future climate change). The direct effect of aerosol loading in the environment is on atmospheric radiation. Unlike the long-lived greenhouse gases, which are distributed uniformly over the globe, aerosol lifetimes are only a week or less resulting in substantial spatial and temporal variations with peak concentrations near the source.

Analyses from the Indian Ocean Experiment (INDOEX), suggests that the aerosols and haze over the Indian subcontinent is one of the most visible impacts of the human activities[43]. In the recent IPCC assessments, there are examples of AGCMs that are already considering the thermodynamic feedback of aerosols on regional climate.

As an example, aerosol feedbacks may have caused reduced warming potential for several of the Indo-Chinese regions in climate change simulations.

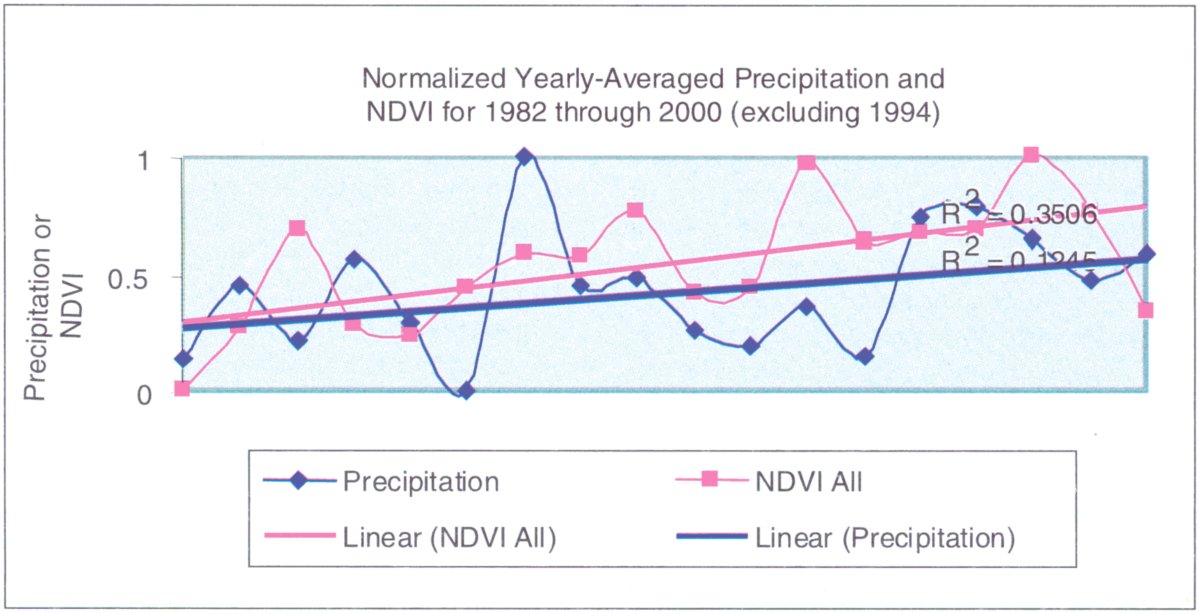


Fig. 9 Normalized yearly-averaged precipitation and NDVI for 1982-2000 excluding 1994. Precipitation has been normalized where a value of 1 corresponds to 178 cm and a value of zero to 111 cm

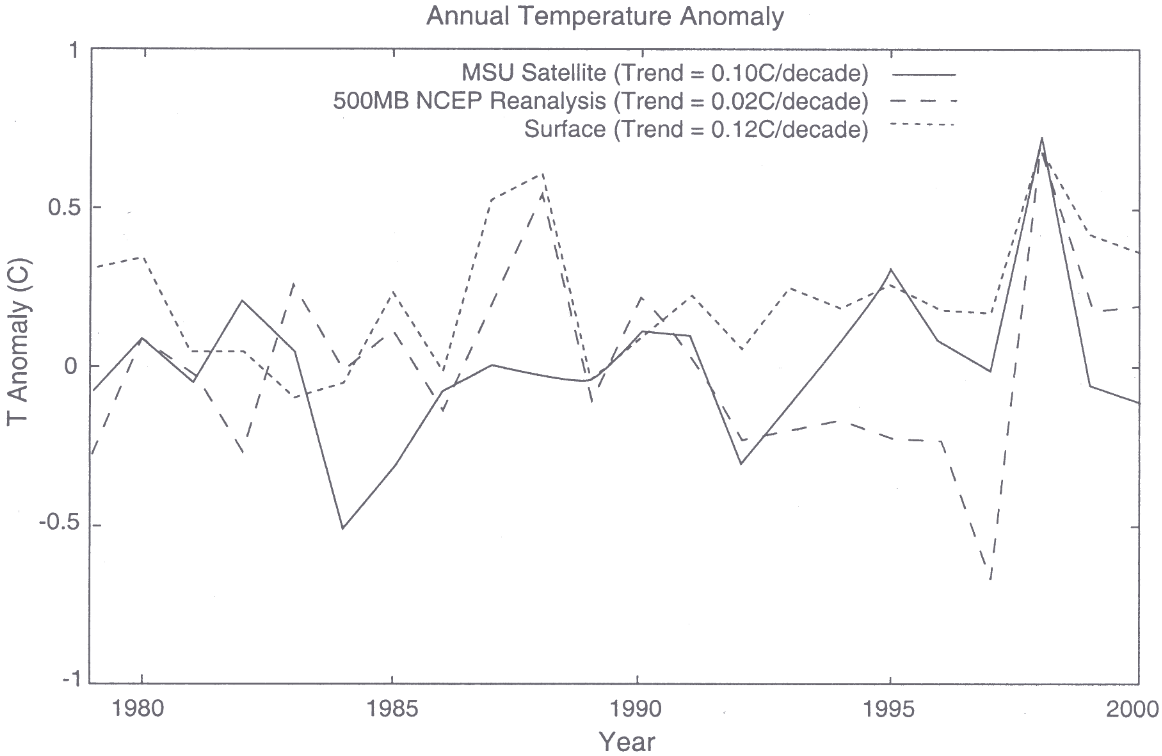


Fig. 10 Canadian Centre for Modelling and Analysis projections of surface and 500 mb temperatures averaged over the area 8-35 degrees N and 68-89 degrees E for the years 1979-2000

As discussed in Ramanathan *et al.*[43], bringing the GHGs and aerosols to the preindustrial values, the outgoing long-wave radiation would increase to 237.4 W m^{-2}, and the absorbed solar radiation would increase to 238.5 to 240.5 W m^{-2}.

Anthropogenic aerosols are typically in the submicrometer to micrometer-size range and are composed of numerous inorganic and organic species falling under four broad categories: sulphates, carbonaceous aerosols [black carbon (BC) and organic carbon (OC)], dust, and sea salt. The natural and the anthropogenic aerosols also absorb solar radiation, and this solar absorption within the atmosphere, together with the reflection of solar radiation to space, leads to a large reduction in the solar radiation absorbed by the Earth's surface. Further, there is growing evidence that the aerosol and haze concentrations are increasing globally[44]. The broad features of the aerosol interactions are now being considered in a majority of modelling studies, however the direct and indirect feedback on the terrestrial hydrological cycle is still missing. Presently, the direct effect of aerosols leading to the reduction in the atmospheric radiative warming has been the focus of the climate feedback cycle. This is an important feature for the Indian region, since the growing aerosol pollution has local, regional, and global implications, including a reduction of the oxidizing power of the atmosphere[45].

Additionally, there is now evidence that aerosols can have another feedback via the terrestrial hydrological and carbon cycle for regional climate change[31,46,47] We will discuss this aspect relating to the potential hydrological feedback over the Indian region. The changes in the radiative properties associated with the aerosol and soot loading can change the evaporation/transpiration over the landmass, which in turn can cause significant changes in the humidity fluxes over this region. The changes in the moisture flux can potentially affect the local precipitation patterns and regional hydrology. Since there is evidence[48] that the changes in the surface energy balance over the Indian subcontinent have a direct feedback on the monsoon and even the Somali Jet interaction during the summer monsoon, it is therefore possible that the aerosol effects can have a direct control over the monsoonal cycle as well.

Further in GCM studies[27] the presence of the effects of aerosols and other atmospheric particles are often considered in the models only through weather forcings such as rainfall, evaporation, and temperature;

however, the direct effect on the radiative component (direct and diffuse irradiance) of the vegetation–atmosphere interaction has not been explicitly considered[49].

Considering that the global solar irradiance comprises the direct beam and the diffuse radiation, the increase in the atmospheric particles lead to more diffuse radiation in the atmosphere[50]. The changes in the diffuse to direct ratio of the atmospheric radiation (DDR) due to aerosol loading have been established through several surface and remote-sensed observing studies. The radiative effects of aerosol loading and its impact on DDR are well known, and relatively well understood. The question then is, what will be the potential effect of aerosols on regional radiation and the terrestrial hydrology?

For the Indian region, Reddy and Venkataraman[50,51] present a 0.25 degree grid increment aerosol emission database. They report $PM_{2.5}$ emitted was 0.5 and 2.0 Tg yr^{-1} for the 100% and the 50% control scenario, respectively, applied to coal burning in the power and industrial sectors. Coal combustion was the major source of $PM_{2.5}$ (92%) primarily consisting of fly ash and accounted for 98% of the "inorganic fraction" emissions (difference between $PM_{2.5}$ and black carbon+organic matter) of 1.6 Tg yr^{-1}. Black carbon emissions were estimated at 0.1 Tg yr^{-1}, with 58% from diesel transport, and organic matter emissions at 0.3 Tg yr^{-1}, with 48% from brick-kilns. Fossil fuel consumption and emissions peaked at large point industrial sources and in 22 cities with elevated area fluxes in northern and western India.

Therefore, a synthesis involving aerosol interaction over India is feasible. Additionally, analysis from INDOEX has led to increased understanding between the aerosol–terrestrial radiation interactions. As an example, George[53] reports changes in surface radiation of about 25 W m^{-2} with and without dust and aerosol loading in this region.

Studies such as Ansmann[54], Mohanty *et al.*[55], and Raman *et al.*[56] describe two distinct zones over the Indian subcontinent with and without aerosol fronts. These regions evolved dynamically depending on the source area. The aerosol optical depths are nearly 50% lower for the region without aerosol air mass. Further, there are significant diurnal and seasonal changes in the aerosol concentrations as revealed from surface observations over different regions in India. As an example, for the southern tip of India (Trivandrum), Parameswaran *et al.*[57] indicate aerosol mass loading to change from about 30 micrograms per metre cube during the day to about 90 during the nocturnal conditions. At a monthly scale, assuming a dry environment, the concentrations in the aerosol loading was found to be approximately 100 mmg/m^3 in the winter months, to about 250 mmg/m^3 during the summer. Without normalizing for constant humidity considerations, these values range from about 100 in the winter month to about 600 in the summer.

Aerosol feedbacks are a dominant feature of the Indian environment and therefore have a potential to have a dramatic feedback on the regional climate. However, the aerosol composition over the Indian region appears to show large latitudinal variability (from the Himalayan region to the southern Indian tip).

For example, measurements by Sarkar *et al.*[58] indicate total and black carbon concentrations in urban Delhi to be 14 and 2 mmg/m^3 respectively, while values off the Indian Ocean correspond to be about 2 and 0.2 mmg/m^3. Therefore, the feedback will be different depending on whether it is a northeast monsoon or a southwest monsoon. Further, the aerosol transport is largely due to the monsoonal winds over the region. The aerosol source regions can be quite variable ranging from Arabia to the Himalayas. In addition to the source region, the aerosol patterns are governed by at least two factors: the regional topography and the rainfall occurrence. As shown in Roswintiarti *et al.*[59] the aerosol plume can be trapped and recirculated over the western coast due the Western Ghats. However, once it escapes the Western Ghats, it has a potential to transport itself hundreds of km both inland as well as offshore. Within this perspective, there is a need to develop a synthesis for possible modulation in the hydrological cycle component of the regional climate system over India.

4 Comparison of the Observational Record over India with Global Model Simulations

General circulation models of the effects of rising atmospheric CO_2 are designed to simulate the broad features of climate change, particularly the net energy imbalance at the top of the atmosphere discussed in Section 2. In this section, we compare the regional predictions of these simulations with observations over India. The regional influences on climate discussed in

Section 3 are not included in these simulations. Model simulations of the effects of rising CO_2 and increased sulphate aerosols indicate a warming surface to an extent observable by the present day. These simulations also indicate that mid- and upper tropospheric temperatures should warm at a rate significantly faster than the surface, particularly in the tropics. For example, Fig. 10 shows temperature anomalies from an ensemble average of three simulations from the Canadian Centre for Climate Modelling and Analysis (CCCma) coupled ocean-atmosphere model CGCM2 averaged over the area 8-35 degrees north and 68-89 degrees east. A highly significant warming is simulated both at the surface ($p = 0.004$) and in the mid-troposphere at 500 mb ($p < 0.0001$). The warming trend aloft is approximately 50% faster than at the surface consistent with overall greenhouse warming scenarios.

Observed trends are shown in Fig. 11 for the period 1979-2000. A surface warming trend has been measured ($p = 0.11$). Weaker, statistically insignificant warming is also observed above the surface in both satellite observations ($p = 0.22$) and in the NCEP Reanalysis at 500 mb ($p = 0.88$). The upper levels do not support a strongly enhanced warming aloft and are in disagreement with each other as to the magnitude of the trend. As discussed in Section 3, the neglected physical and biological processes (land-use change, vegetation dynamics, and aerosol dynamics) may explain the reason for the failure of the GCMs to replicate the temperature observations. The precipitation record is more ambiguous.

For annual precipitation over the same region, both model and observed trends are slightly upward but insignificant. The Canadian Climate Model ensemble simulates a trend of 0.74 mm/year ($p = 0.73$) while satellite observations from the Global Precipitation Climatology Project measure an increase of 2.07 mm/year ($p = 0.41$).

During the Indian monsoon season (JJAS), rainfall trends are also indistinguishable from zero in both the satellite observations (trend = 2.05mm/year; $p = 0.76$) and the CCCma ensemble (trend = -4.34mm/year; $p = 0.42$).

5 Conclusions

This article overviews several aspects of climate variability and change which have not been adequately addressed by international assessments such as in the IPCC reports. This failure renders model projections of future climate in the Indian region (and elsewhere) as being of very limited value. A report by the International Geosphere-Biosphere

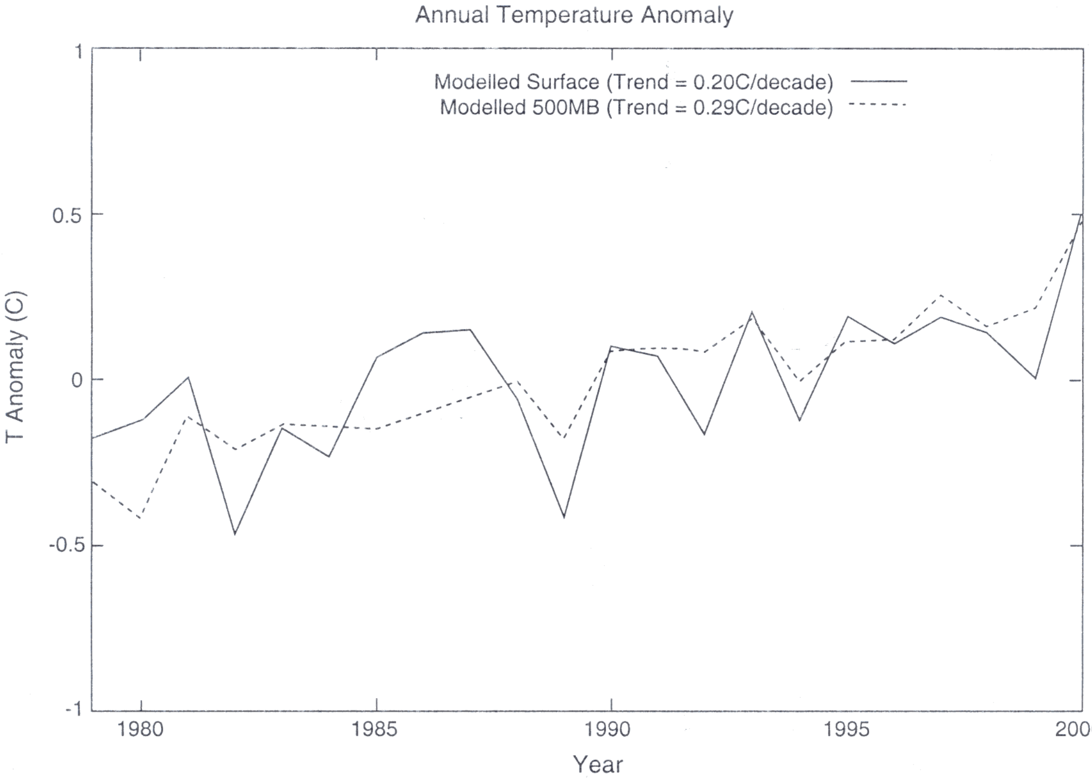


Fig. 11 Same as Fig. 10 except for observations