The Role of Landscape Processes within the Climate System

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1 Introduction

Land-surface processes form a dynamic boundary interface within the Earth system (Fig. 1). The multiscale impacts of land-surface processes in modifying regional weather and climate is noted from both the analysis of observations, as well as systematic experiments involving nonlinear, coupled modeling systems. Landscape processes and their interactions with the atmosphere are critical at different micro, regional, and global scales for weather, hydrological and other broad range environmental modeling studies (Alpert et al. 2006).

The land-surface characteristics determine the surface energy partitioning by assigning the distribution of incoming solar radiative energy (insolation) into sensible, latent, and ground heat fluxes. The change in the surface radiative energy affects regional- and larger-scale moisture and temperature. Modifications in the surface fluxes and the thermodynamic parameters lead to changes in regional wind fields and localized circulation patterns. The changes in wind and regional thermodynamic variables alter convective potential and interact with large-scale processes to affect the amount and distribution of clouds and rainfall (Pielke et al. 2007). At a larger scale, the systematic transformation of the land surface can alter regional flow patterns associated with developing persistent zones of moisture convergence, and localized pockets that lead to long-term regional warming or cooling.

The role of landscape processes within the climate assessments however has been mostly ignored except in terms of how carbon assimilation is affected. As summarized in the National Research Council (2005) report, the role of vegetation and soils is much more than that and includes effects on water and heat storage and their fluxes, as well as effects on a variety of other gases and aerosols. The climate system is an integration of physical, biological, and chemical effects associated with land, atmosphere, ocean, and continental ice interactions. The current IPCC (2007) focus on radiative forcing of well-mixed greenhouse gases is too limiting; a broadening in its perspective is overdue. The current view, unfortunately, does not

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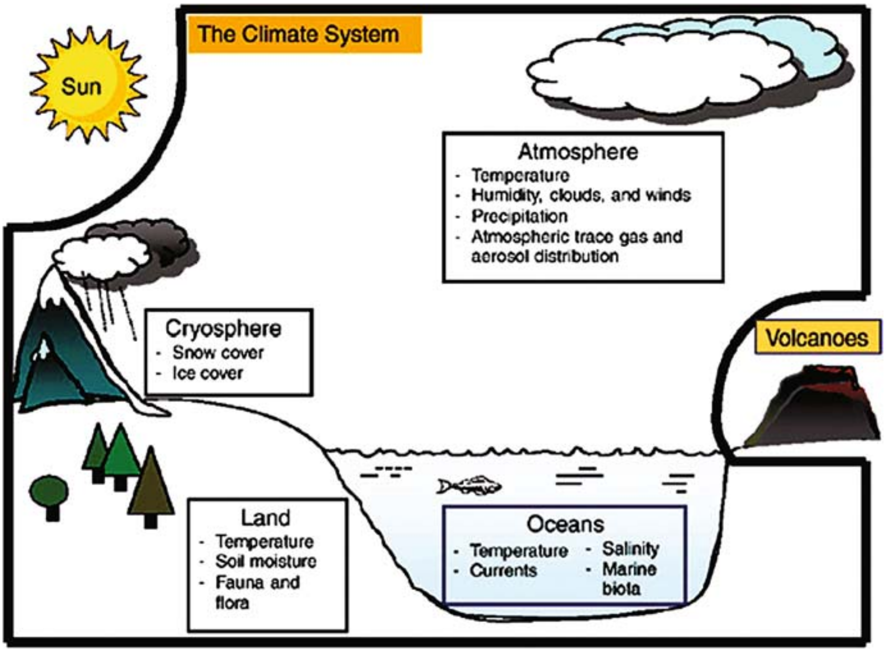

Fig. 1 The climate system, consisting of the atmosphere, oceans, land, and cryosphere. Important state variables for each sphere of the climate system are listed in the boxes. For the purposes of this paper, the Sun, volcanic emissions, and human-caused emissions of greenhouse gases and changes to the land surface are considered external to the climate system
[Source: National Research Council 2005]

properly address the diverse effect of the human disturbance of the climate system. The role of land-surface forcing and feedbacks within the climate system, as one important example of this need for broadening, provides a dynamical feedback that is required if regional-scale climate assessments are to become skillful.

The nonlinear interrelationship between the various surface, boundary layer, regional circulation, cloud and moisture, and biogeochemical factors hinders an accurate assessment of the role of land surface on regional and global climate. Hence, the need for integrated assessments is becoming more important in order to understand the uncertainty and variability of the climate system (Pielke et al. 2002, Marland et al. 2003). We show in this paper that land-surface processes, as part of the climate system, need to be considered not only for developing projections at regional and larger scales, but also for developing vulnerability assessments and mitigation strategies to satisfy the United National Framework Convention on Climate Change (UNFCCC 2007).

Recognizing the need to address the broader role of the land surface and to include nonradiative climate processes, the 2005 National Research Council report had the following priority recommendations:

- Test and improve the ability of climate models to reproduce the observed vertical structure of forcing for a variety of locations and forcing conditions.

- Undertake research to characterize the dependence of climate response on the vertical structure of radiative forcing.
- Report global mean radiative forcing at *both* the surface and the top of the atmosphere in climate change assessments.
- Use climate records to investigate relationships between regional radiative forcing (e.g., land use or aerosol changes) and climate response in the same region, other regions, and globally.
- Quantify and compare climate responses from regional radiative forcings in different climate models and on different timescales (e.g., seasonal, interannual), and report results in climate change assessments.
- Improve understanding and parameterizations of aerosol-cloud thermodynamic interactions and land-atmosphere interactions in climate models in order to quantify the impacts of these nonradiative forcings on both regional and global scales.
- Develop improved land-use and land-cover classifications at high resolution for the past and present, as well as scenarios for the future.
- Encourage policy analysts and integrated assessment modelers to move beyond simple climate models based entirely on global mean top of the atmosphere radiative forcing and incorporate new global and regional radiative and nonradiative forcing metrics as they become available.

Unfortunately, the timeline adopted by the IPCC in initiating the assessments, compile the material available for analysis, and develop a consensus view on the reports did not generally allow for recently published papers and reports to be properly considered. Thus the recommendations from the NRC report received little representation in the 4th assessment. It is not known if this would be modified in the next assessment.

The following sections provide examples of why landscape processes and the human role in altering them, need to be explicitly accounted for in future climate change studies and IPCC assessments.

2 Land Surface Processes

The land-surface feedback leads to an often significant forcing of regional and global climate through changes in the physical properties of the land surface. Traditionally, these changes are attributed to temporal and spatial inhomogeneity in surface albedo and evaporative fraction. The importance of land cover can be extracted from the review of the surface energy budget equations.

$$Q_N = Q_H + Q_{LE} + Q_G, \tag{1}$$

and

$$Q_N = Q_S^{\downarrow} (1 - A) + (1 - \varepsilon) Q_{LW}^{\downarrow} - \varepsilon \sigma T_S^4 \tag{2}$$

Here, Q_N is the net radiative flux, Q_H is the turbulent sensible heat flux, Q_{LE} is the turbulent latent heat flux (physical evaporation and transpiration), Q_G is the heat flux into the Earth's surface, $Q_S^{\downarrow}$ is the shortwave global irradiance, A is the surface albedo, $Q_{LW}^{\downarrow}$ is the downward atmospheric longwave radiation, and $\varepsilon\sigma T_S^4$ is the upward surface longwave radiation. Surface albedo, A, (fraction of the incoming shortwave radiative flux to that is reflected by the surface), varies with the land surface ranging from 5% (e.g., wet soil) to 90% (e.g., fresh snow).

Equation (2) suggests that a decrease in surface albedo under constant net longwave radiation, $(1-\varepsilon)\,Q_{LW}^{\downarrow} - \varepsilon\sigma T_S^4$, increases net radiation, Q_N. Thereby, more energy is available for the sensible and latent radiative heat fluxes, $Q_{LE} + Q_G$.

Considering humidity and moisture processes, over a bare soil, the landscape fluxes are governed by bare soil evaporation and diffusion within the soil layers depleting surface moisture availability. The moisture loss from the land surface then becomes a source for atmospheric humidity. When vegetation is present, the complex role of vegetation canopy and associated processes, such as from transpiration, dominate the energy and water vapor (and carbon) exchange. Additionally, the canopy can also intercept precipitation and part of the water that is intercepted by the leaves can be evaporated back from the leaf surface without reaching the ground.

The hydrologic balance over the vegetated landscape can be described as

$$\mathrm{Pr} = \mathrm{E} + \mathrm{T} + \mathrm{Ro} + \mathrm{I} \tag{3}$$

where Pr is the precipitation, E is bare ground evaporation, T is transpiration, Ro is surface runoff, and I is the interception. Processes such as ground water seepages, runoff, and the changes in the root dynamics are still poorly represented in current landform models and are included in most weather and climate modeling systems.

When a landform becomes vegetated, or has a transformation in its surface characteristics, additional energy partitions need to be considered. These would be related to the energy balance of the different mosaics (patches) of land surface, as well as the energetics that are dictated by the albedo and emissivity of the vegetation canopy. The transmittance, absorption, and reflectance of the vegetation canopy, the air space just above and within the canopy, the heat flux in the surface layer of the land boundary, and the atmospheric turbulent boundary layer each become means of complex energy exchange and storage.

Soil moisture is an important interactive and integrative factor relating the different processes within the land-surface system. Soil moisture regulates the evolution of various surface hydrological and energy balance processes. Changes in soil moisture affect surface albedo (Idso et al. 1975), the evaporative fraction (Kabat et al. 2004), and at the regional scale, the potential for cloud formation and precipitation and evaporation/transpiration recirculation ratio (Brubaker et al. 1993). Elevated soil moisture leads to lower albedo, higher emissivity, and higher evaporative fraction.

For example, Post et al. (2000) shows wet soil changes from wilting to field capacity can decrease surface albedo by up to 15%. Using NDVI datasets and a seasonal simulation using a coupled modeling system, Matsui et al. (2003) showed that soil moisture and evaporative fraction appear to be directly correlated. Soil moisture can lower the surface upward longwave radiation. Small and Kurc (2003) found that a volumetric water content increase of ≈5% yields an increase of 50 W m^{-2} of net radiation due to the decreased $\varepsilon\sigma T_S^4$.

The radiative, temperature, hydrological, and the biogeochemical processes over the land surface are inter-related. Analysis of the seasonal and annual values of CO_2 flux and water vapor exchange across global Fluxnet sites in forests, grasslands, crops, and tundra was pursued by Niyogi et al. (2004). They found that net carbon and net primary productivity uptake are greater under diffuse than under direct radiation conditions. The variability in seasonal plant phenological cycles modify total leaf area, canopy transmission/reflection, nutrient and carbon exchange rates, shading and canopy scaling, and root extent, all of which modify the capacity for the net photosynthesis, soil-moisture uptake and transpiration rate. Thus, changes in the biogeochemical cycles are also linked to the land-surface feedback and alterations of surface albedo and evaporative fraction.

Indeed, the presence of soil moisture feedback associated with landform changes has a strong impact on terrestrial ecosystem processes as well. Analysis by Niyogi and Xue (2006), using a coupled photosynthesis modeling system and resource allocation analogy, indicates that the soil moisture availability controls the participation of soil and vegetative processes as a unified system; and that under non-drought conditions, the transpiration and carbon assimilation responses are about 10–15% more than under moisture stress.

Figure 2 shows the partitioning of the sensible and latent heat flux under high and low vegetation, and for soil moisture availability. The results are based on a coupled land – atmospheric model (Alapaty et al. 1999, 2001) that was set up over the central United States for typical summertime environmental conditions. As shown in the figure, when the landform has high vegetation and abundant soil moisture, the incoming radiation is dominantly partitioned into the latent heat flux (combination of bare evaporation and canopy transpiration), and the residue is further partitioned into the sensible and ground heat flux in that order. Under low vegetation and low soil moisture conditions, the radiative energy is primarily partitioned into surface sensible heat flux and the residue is partitioned into ground heat flux and latent heat. Thus, the vegetated surface would have relatively lower air temperatures and higher specific humidity as compared to the low vegetation fraction and low soil moisture landform.

Figure 3 shows the surface air and specific humidity corresponding to the energy partitioning presented in Fig. 2. As shown in Fig. 3, there can be significant differences in the maximum daytime and minimum nighttime air temperatures and surface humidity as a response to the land atmosphere interactions. As shown in Pielke et al. (2009), changes in landform characteristics can significantly influence observations and can result in misinterpretations on the reasons for decadal surface temperature trends.

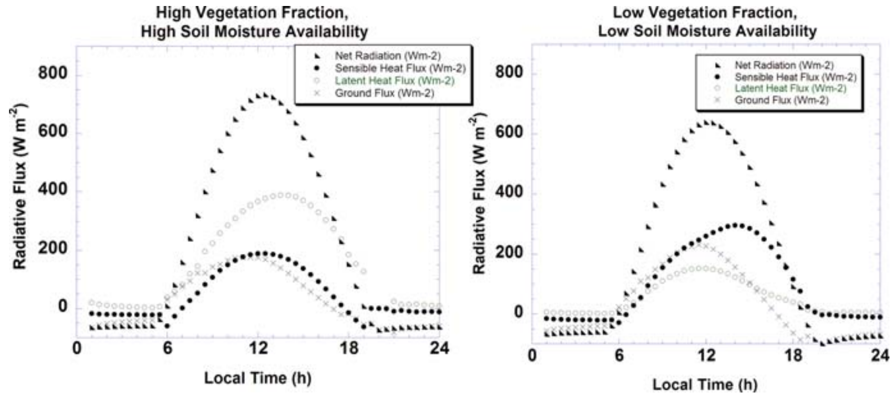

Fig. 2 Coupled land–atmosphere model-simulated diurnal surface radiative flux components representative of a vegetated high soil moisture landscape and a low vegetation fraction, low soil moisture landscape

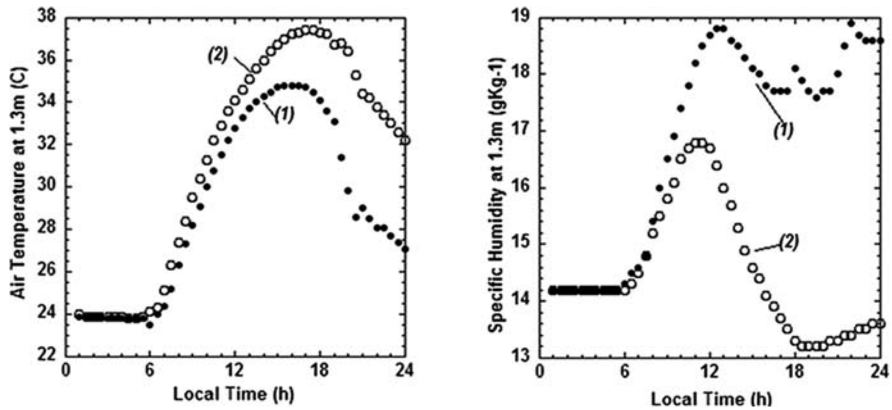

Fig. 3 Surface air temperature and specific humidity for (*1*): high vegetated/high soil moisture and (*2*): low vegetated/soil moisture landscape conditions and energy partitioning shown in Fig. 2

2.1 Boundary Layer Processes

The influence of land-surface characteristics is large on the atmospheric surface layer ($\approx$100 m during daytime). The entire atmospheric boundary layer, of course, is also influenced by the land-surface feedback and surface turbulent heat fluxes (Pielke 2001a). The surface fluxes, particularly during daytime, typically have a maxima at the surface. The height at which the turbulence ceases to exist (or is a very small fraction of the surface value) is designated as the boundary layer height.

During daytime, from Eqs. (1) and (2), the overall effect of elevated soil moisture and vegetation availability will often result in an increase in surface net available energy and evaporative fraction so as to induce an unstable vertical distribution in moisture and temperature in the lower atmosphere (Eltahir 1998). These fluxes can alter the surface temperature, provide more energy for evaporation from the bare soil, and transpiration from the vegetated surface. The moisture fluxes, in tandem with the winds and sensible heat can provide energy for convective clouds (e.g., Pielke 2001a). Transformation of increased surface albedo, (as a result of deforestation or desertification), leads to less availability of turbulent energy flux and thus a smaller likelihood of moist convection (e.g., Charney et al. 1977, Sud and Molod 1988, Xue and Shukla 1993). Similar to the surface albedo, the evaporative fraction: $Q_{LE}/(Q_H + Q_{LE})$, defined as a fraction of the latent turbulent heat flux over the available turbulent heat energy, varies with the landform.

Kabat et al. (2004) summarize, for example, that the evaporative fractions over a temperate forest is observed to be twice as large as that over a boreal forest. Consequently, the daytime boundary layer over the temperate forest is typically ≈1500 m, while it is closer to ≈3000 m for the boreal forest. Similarly the boundary layer heights over croplands and wooded forests are typically of the order of 1000 and 1500 m, respectively. A typical time evolution of the potential temperature sounding corresponding to the high and low vegetation and soil moisture conditions (corresponding to Figs. 2 and 3) is shown in Fig. 4. The boundary layer height (typically considered as the point of inversion on the temperature profile) is generally higher for low vegetation and low soil moisture conditions (which as shown in Fig. 2 are conditions of high surface sensible heating). Higher evaporative fraction (EF) lowers afternoon Planetary Boundary Layer (PBL) height and the Lifting Condensation Level (LCL) level, because of the suppressed sensible heat flux.

Alapaty et al. (1999) analyzed results from a 1D soil – vegetation – atmosphere – transfer model to assess the impact of different landform characteristics on the atmospheric boundary layer evolution. They concluded that soil texture changes have a

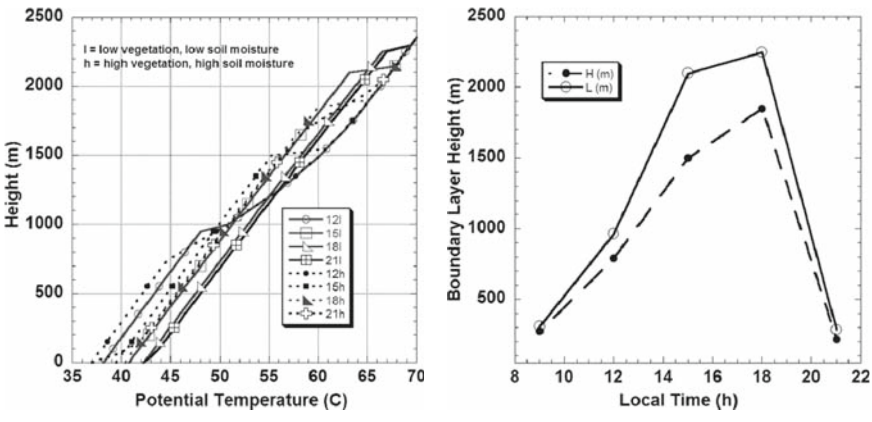

Fig. 4 (*left*) Potential temperature sounding and (*right*) the estimated atmospheric boundary layer height for high (h) and low (l) vegetation and soil moisture availability. The number in the legend for the plot on the *left* refers to the local time

dominant effect on surface fluxes, and boundary layer evolution because of its control of the hydraulic and thermal conductivity. A similar order of magnitude effect was noted when the vegetation characteristics such as transpiration/canopy resistance to water vapor exchange were modified. Depending on the land surface characteristics they found that the mid afternoon boundary layer height could vary from 1200 to 2400 m for otherwise similar initial atmospheric conditions.

Pielke (2001a) estimated the mean July convective available potential energy (CAPE) for North America using the 12 UTC rawinsonde observations. Typical values ranged between 300 and 600 J kg^{-1} over the Midwest and Great Plains and between 600 and 1000 for the southeast. If the dewpoints were increased by 1°C, an increase in the CAPE values by over 40% in some cases is obtained. The values tend to be increased by 200–400 J kg^{-1} for the Midwest and the Plains, and about 400–600 J kg^{-1} for the southeast. A 1°C warming of the surface layer temperature has a much smaller increase in the CAPE values ≈200 J kg^{-1} at most.

Changes in the boundary layer also affect the ventilation for atmospheric trace gases and aerosols. Shallower boundary layers generally have higher concentrations of aerosols and trace gases. The vertical gradients in the aerosols can cause further modification in diabatic heating rates within the boundary layer and thus alter the cloud and convective potential.

Thus, landscape processes and land use have a major effect on surface and vertical boundary layer fluxes of heat, water vapor, and other trace gases and aerosols.

2.2 Heterogeneous Mesoscale and Regional Landscapes

The mosaic of heterogeneous landforms or land-surface discontinuities lead to lateral gradients in surface fluxes. Often, the available solar radiative flux received at the surface is relatively unchanged at a regional scale. The energy that the surface and boundary layer receive via increased latent heat flux is compensated by a loss in sensible heat flux. The gradients in mesoscale fluxes (that is, over areas that are typically tens of km) lead to atmospheric boundaries that can trigger and organize regional circulation and convergences. For example, higher evaporative fraction contributes to moisture convergence (e.g., Brubaker et al. 1993). As a result, entropy (moist static energy) is concentrated in the lower atmosphere, and is more likely to trigger moist convection (e.g., Houston and Niyogi 2007). Indeed, the horizontal variation in evaporative fraction (or sensible heat flux) can induce local solenoidal wind circulations (Simpson 1994). Subsequently, the likelihood of deep cumulus convection is increased in response to boundary wind convergence associated with local wind circulations (as is also seen for example in the case of sea breeze circulations, Pielke 1974). The deep cumulonimbus clouds export heat, moisture and kinetic energy to the upper troposphere, and these variables are diverged to form stratiform clouds (e.g., Houze 1993). Thus, changes in surface albedo and evaporative fraction due to the landform characteristics can affect the likelihood of thunderstorms (Pielke 2001a), which would result in further alteration in surface fluxes elsewhere through nonlinear feedbacks within the atmosphere's regional atmospheric circulations (Chase et al. 2000). We provide specific examples of such regional scale feedbacks here.

Pielke (1974) provided one of the first three dimensional modeling analyses of land-surface heterogeneities, using the southern Florida coastline as an example. The land – sea surface heterogeneity provides a classical case for the impact of landform heterogeneity and resulting impact on the regional convergence, mesoscale convection, rainfall occurrences, and the location of preferential zones for thunderstorms. Landform heterogeneities are ubiquitously present and can provide the setting for regional moisture convergences. Landscape heterogeneities tend to create similar mesoscale circulations as seen for land – sea breeze circulations (Segal et al. 1988).

Figure 5 shows an example of the impact of urban – rural land form heterogeneity and the land – sea heterogeneity on regional mesoscale circulation and convergence patterns. The domain covers central and eastern North Carolina, USA. As shown in Fig. 5 (left, top), the dark regions in the coastal periphery are indicative of vegetated landscape during late spring. The central North Carolina region is more urbanized and has different average landscape characteristics (for albedo and other vegetation/soil parameters). As a result of this landscape heterogeneity, the central region has relatively warmer surface temperatures as compared to the more vegetated regions (Fig. 5 right, top). The gradients in the surface temperature lead to sufficient gradients in the surface mesoscale boundaries so as to trigger an active mid to late afternoon sea breeze that penetrates about 50–70 km inland in the simulation (Fig. 5 left, bottom). Also interesting is the local circulation and convergence formed due to the urban – rural heterogeneity with the winds converging to central North Carolina. At night there are still remnants of some local circulations inland along with a significant land breeze in the coastal region (Fig. 5 right, bottom).

A traditional view related to the significance of the landform heterogeneity implied their significance only under calm weather conditions with weak synoptic forcing. Such conditions typically, for example, include summer afternoons without frontal passages. The landform heterogeneities are expected to provide significant surface forcing to cause modifications in mesoscale convergence and convective potential. Recent findings, however, provide consistent evidence that the landform heterogeneities and the land surface responses are generically important even under active synoptic conditions. As an example, Vidale et al. (1997) reviewed the fine/sub kilometer scale landscape heterogeneity during the Boreal forest experiment (BOREAS) and concluded that both the fine-scale turbulent and the mesoscale fluxes together contribute in generating realistic surface – atmosphere interactions under both the high and low synoptically active conditions. The landform heterogeneities exert an influence possibly because they tend to form coherent structures that have predictable features (Zeng and Pielke 1993).

Similarly, Pielke et al. (1997) used updated USGS land-use data to accurately simulate a dryline case over the Great Plains of the USA. With the correct (current) land surface representation, the model was able to reproduce an organized cumulonimbus system. With the natural land surface, only a disorganized line of towering cumulus were generated.

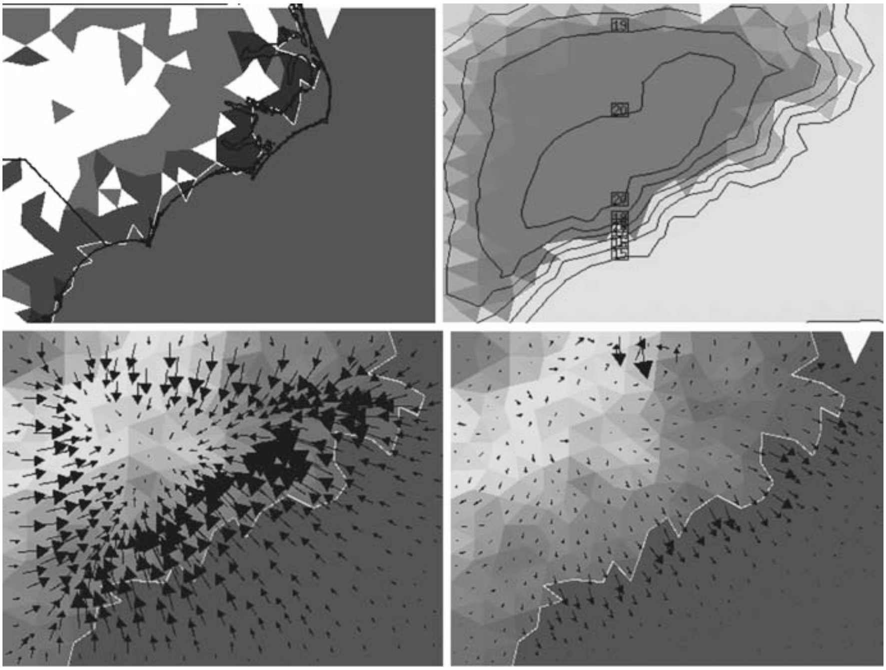

Fig. 5 Example of the impact of landform heterogeneity manifesting in regional temperature, and convergence/circulation patterns. The domain is for coastal and central North Carolina, USA. The panel shows, (*top left*) dark areas of high vegetation, and the white (light) areas of higher urban center; (*top right*) simulated midday surface temperature gradients for a typical early spring; (*bottom left*) simulated afternoon sea breeze and urban convergence due to heterogeneity; and (*bottom right*) nighttime land breeze and zones of local inland convergences

In another recent analysis, Holt et al. (2006) studied the impact of the representation of land surface heterogeneity on a synoptically active summer storm event over the Southern Great Plains that was observed during the International H2O Project (IHOP 2002). Based on the synthesis of different model configurations, the study concluded that only when an accurate representation of the landform characteristics is made, is the coupled atmospheric model able to simulate the storm characteristics of the synoptically forced convection event. Thus the land-surface feedback and heterogeneity significantly affect the timing, location, and intensity of storms and associated rainfall.

The Holt et al. study was extended further to study the case of urban – rural heterogeneity by Niyogi et al. (2006). Taking a thunderstorm case from the Joint Urban Experiment over Oklahoma City, Niyogi et al. showed that the urban landforms act in modifying the storm direction and intensity by creating changes in convergence zones. The feedback was diagnosed using a statistical – dynamical approach in which the “pure” effect of the urban area, the rural landscape, and the urban – rural heterogeneity interacted to affect the convection. The results indicate that the rural areas can provide the moisture feedback to make the storms more convective, while the urban regions with their roughness and sensible heat flux gradients can induce zones of enhanced convection at the boundaries that can cause more intense storms. The interaction between the mesoscale boundaries due to the land gradients appears to cause the tilting of the storms that leads them into an enhanced convection region after splitting around the urban landscape (Shepherd 2005).

The majority of the studies that report on the impact of land-surface processes on the weather and climate patterns are often process based and rely on few select cases. However, the findings are generic enough so as to be applied to regional climate studies. For example, Marshall et al. (2004a) extended the sea breeze – land surface heterogeneity analysis of Pielke (1974) to assess the impact of agriculture -based land transformation on the regional climate over Florida. They concluded that the decreasing mean July–August rainfall and the increasing surface temperature from 1924 to 2000 over peninsular Florida can be explained by the massive land transformation that has occurred at the regional scale. The changes in the land cover have led to the modification of convection potential and hence the associated rainfall. The land cover transformation has also led to large changes in the surface energy balance, often resulting in warmer temperature trends. Interestingly, the land transformation could also explain the increasing freeze damage incidences for cold winter nights.

This role of land transformation affecting regional climate was also reported over the Indian monsoon region (Roy et al. 2007). The Indian monsoon region has undergone widespread agricultural intensification since its "green revolution" in the 1960s. Analyzing the temperature data in northwest and north central India, Roy et al. conclude that the agriculture and irrigation have caused a reduction in the daily temperature range over India primarily from the March to May period over the 20th century. The processes are similar to those elucidated via cases studies in Douglas et al. (2006, 2009) and are associated with the energy budget changes and associated boundary layer feedbacks (Niyogi et al. 2007).

Studies such as Gero et al. (2006) and Pyle et al. (2009) have conducted multi-year storm analyses around urban centers. These studies use high resolution radar datasets with mesoscale models in analyzing the changes in the temperature and rainfall characteristics. While the role of urbanization and the localized warming because of urban-heat island is well known, the impact on rainfall climatology is still evolving (Shepherd 2005). An analysis reported in Pyle et al. (2007) for the Indianapolis, Indiana urban region indicates that nearly 60% of storms changed composition as influenced by urban regions compared to only 38% over the rural regions. As a response to the urban – rural heterogeneity and the associated surface fluxes, daytime convection appeared to be the most likely to change with 70% changing composition and only 30% during nighttime hours. Coupled modeling -results confirm that the urban region causes distinct differences in the regional convection via the modification of the mesoscale boundaries.

Thus, land-surface processes and the land–atmosphere feedbacks that have been delineated from the mesoscale case studies for short-term weather can be extrapolated to explain broader climatic changes. Further, there is sustained evidence now that heterogeneous landscapes and land management have a major effect on the weather and climate at the mesoscale and regional scale.

2.3 Global Climate Effects

There are a number of papers that document that landscape effects alter the climate on the global scale. These include Werth and Avissar (2005), Feddema et al. (2006), Chase et al. (2001), Marland et al. (2003), Pielke (2005), and Voldoire (2006). Figure 6 produced from the model output in Chase et al. (2000), illustrates that the hydrologic cycle is altered when human-caused land-use change occurs. Feddema et al. (2005) shows that a significant human disturbance of the climate system on the global scale is a robust conclusion (e.g., see Fig. 7 from Feddema et al. 2005).

The reason for this is straightforward as discussed in Pielke (2001a, b) and summarized as follows. As with ENSO events (Glantz 2001), land-use change is of a *large magnitude* with respect to its alteration of the energy fluxes, *persists for a long time*, and is *spatially coherent.* Since ENSO events, which involve alterations in the spatial pattern of energy fluxes in the tropical Pacific Ocean, cause significant global climate effects, land-use change should also have global scale consequences.

The role of heterogeneous climate forcings such as landscape change was further demonstrated by Matsui and Pielke (2006) with respect to the role of the atmospheric heating by aerosols, who found that the much larger spatial variations of the direct aerosol heating of the atmosphere, has a larger effect the pressure field (and thus circulation features) in the atmosphere than do the well-mixed greenhouse gases.

Feddema et al. (2005) found, as summarized in their abstract, that considering the effects of changes in land cover to the A2 and B1 transient climate simulations described in the Special Report on Emissions Scenarios (SRES) by the Intergovernmental Panel on Climate Change lead to significantly different regional climates in

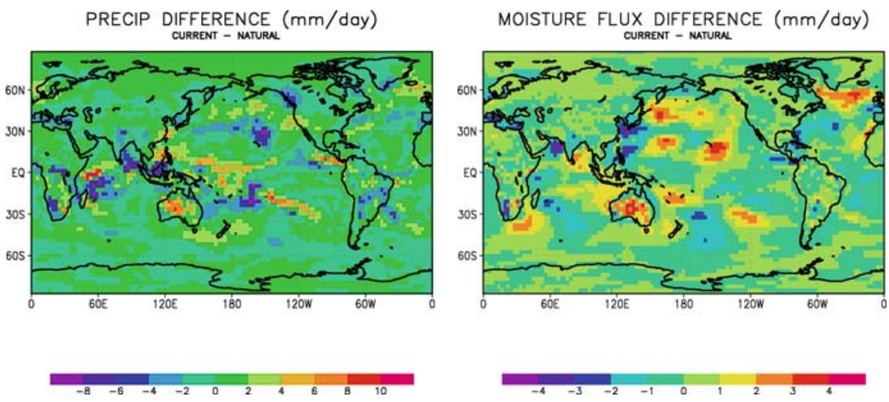

Fig. 6 Changes in the (*left*) precipitation (mm/day) and (*right*) flux changes (mm/day) for changes in the landscape. Absolute value of the global average change in the precipitation is 1.2 mm/day and the moisture flux is 0.6 mm/day. From Chase et al. 2001

2100 as compared with climates resulting from atmospheric SRES forcings alone. Agricultural expansion in the A2 scenario, for example, results in significant additional warming over the Amazon and cooling of the upper air column and nearby oceans. These and other influences on the Hadley and monsoon circulations affect extratropical climates. Agricultural expansion in the mid-latitudes produces cooling and decreases in the mean daily temperature range over many areas (e.g., see Fig. 2 in their paper).

2.4 The Need to Focus on Vulnerability

Within the climate system, the need to consider the broader role of land-surface feedback becomes important not only for assessing the impacts but also for developing regional vulnerability and mitigation strategies.

The IPCC fourth assessment second and third working groups deal with a range of issues targeted to these topics (Schneider et al. 2007). The IPCC identifies seven criteria for "key" vulnerabilities. They are: magnitude of impacts, timing of impacts, persistence and reversibility of impacts, likelihood (estimates of uncertainty) of impacts and vulnerabilities and confidence in those estimates, potential for adaptation, distributional aspects of impacts and vulnerabilities, and the importance of the system(s) at risk. While a number of potential vulnerabilities and uncertainties are considered (such as irreversible change in urbanization), the resulting feedback on the atmospheric processes due to such changes is still poorly understood or unaccounted for in these assessments. Indeed the UNFCCC Article 1 states: "'Adverse effects of climate change' means changes in the physical environment or biota resulting from climate change which have significant deleterious effects on the composition, resilience or productivity of natural and managed ecosystems or on the operation of socio-economic systems or on human health and welfare." Thus, while the role of landscape is inherent within the UNFCCC framework, the corresponding translation for the assessments still remains largely greenhouse gas driven.

Further, while the climate change projections have largely been at coarser resolution, the impacts and potential mitigation policies are often at local to regional scales. For example, climate models often project increasing drought at a regional scale. The resilience to such increased occurrence as well as changes in the intensity of droughts is, however, dependent on the local scale environmental conditions (such as moisture storage, and convective rainfall), and farming approaches (access to irrigation, timing of rain or stress, etc). As summarized in Adger (1996), an important issue for IPCC-like global assessments is to assess if the top-down approach can incorporate the "aggregation of individual decision-making in a realistic way, so that results of the modelling are applicable and policy relevant".

Therefore, as the community braces to develop resilience strategies it will becoming increasingly important to consider a bidirectional impact, i.e., not just the role of atmospheric changes (such as temperature and rainfall) on the physical environmental or biota, but also a feedback of the biota and other land-surface processes on further changes in the atmospheric processes – such as reviewed in this chapter.

Klein et al. (1999) sought to assess whether the IPCC guidelines for assessing climate change impacts as well as adapative strategies can be applied to one example of coastal adaptation. They recommend that a broader approach is needed which has more local-scale information and input for assessing as well as monitoring the options. Again the missing link between local-scale features with global scale projections become apparent. The expanded eight-step approach of Schroter et al. (2005), designed to assess vulnerability to climate change, states the need for considering multiple interacting stresses. They recognize that climate change can be a result of greenhouse gas changes which are coupled to socioeconomic developments, which in turn are coupled to land-use changes – and that all of these drivers are expected to interactively affect the human – environmental system (such as crop yields).

To extract the significance of the individual versus multiple stressors on crop yields, Mera et al. (2006) developed a crop modeling study with over 25 different climatic scenarios of temperature, rainfall, and radiation changes at a farm scale for both C3 and C4 types of crops (e.g., soybean and maize). As seen in many crop yield studies, the results suggested that yields were most sensitive to the amount of effective precipitation (estimated as rainfall minus physical evaporation/transpiration loss from the land surface). Changes in radiation had a nonlinear response with crops showing an increased productivity for some reduction in the radiation as a result of cloudiness and increased diffuse radiation and a decline in yield with further reduction in radiation amounts. The impact of temperature changes, which has been at the heart of many climate projections, however, was quite limited particularly if the soils did not have moisture stress. The analysis from the multiple climate change settings do not agree with those from individual changes, making a case for multivariable, ensemble approaches to identify the vulnerability and feedbacks in estimating climate-related impacts (cf. Turner et al. 2003).

Another issue is the coupled vulnerability of the land surface to socioeconomic and climate change processes. This question was addressed by Metzger et al. (2006). They concluded that most assessment studies cannot provide needed information on regions or on ecosystem goods that are vulnerable. To address this question, we can hypothesize that the vulnerability of landscape (V) change is a product of the probability of the landscape change (Lc) and the service (S) provided by the landscape:

$$V = \text{prob}\,(Lc)\ ^{*}\ S \tag{4}$$

The service provided is a broad term and could mean societal benefits (such as recreation), or economic benefits (such as timber and food), or physical feedbacks as in terms of the modulating impact a landscape may have on regional temperatures or precipitation. While a variety of studies on vulnerability have sought to look at the economic and societal feedbacks, the physical feedback of the fine-scale land heterogeneities have been critically missing in the literature. It is however important that land heterogeneity and transformation potential be considered at a finer scale because the landscape changes will in turn affect the regional and local vulnerability.

Current economical assessment studies (Stern 2007) conclude that controlling land-use change such as from deforestation provides an opportunity cost in excess of $5 billion per annum. This estimate however appears to only consider the land transformation impact of deforestation and the resulting greenhouse emissions. As summarized in this chapter, the dynamical effects such as changes in rainfall, evaporation, convection, and temperature patterns due to landform changes can cause additional vulnerability (or resilience in some cases) and needs to be considered in such assessments (Marland et al. 2003). Similarly, the UNFCCC Article 3 also seeks afforestation (reforestation minus deforestation) since 1990 as a country's commitment towards the greenhouse gas emission controls. Not considering the dynamical feedbacks due to such forest land transformation can lead to additional vulnerabilities as described in Pielke et al. (2001a, 2002).

3 Conclusions

Humans are significantly altering the global climate, but in a variety of diverse ways beyond the radiative effect of carbon dioxide (Cotton and Pielke 2007, Kabat et al. 2004, National Research Council 2005). The IPCC assessments have been too conservative in recognizing the importance of these human climate forcings as they alter regional and global climate. These assessments have also not communicated the inability of the models to accurately forecast the spread of possibilities of future climate. The forecasts, therefore, provide limited skill in quantifying the impact of different mitigation strategies on the actual climate response that would occur. In this paper, we discuss one of these issues, namely the role of land-surface processes within the climate system, including how these processes are altered by human activities.

The needed focus for the study of climate change and variability is, therefore, on the regional and local scales. Global and zonally-averaged climate metrics would only be important to the extent that they provide useful information on these space scales. Global and zonally-averaged surface temperature trend assessments, besides having major difficulties in terms of how this metric is diagnosed and analyzed, do not provide significant information on climate change and variability on the regional and local scales.

Global warming is also not equivalent to climate change. Significant, societally important climate change, due to both natural- and human – climate forcings, can occur without any global warming or cooling. Landscape management is one example of such a forcing. Thus attempts to significantly influence regional and local-scale climate based on controlling CO_2 emissions alone is an inadequate policy for this purpose.

We, therefore, propose that the assessment of vulnerability, focused on regional and local societal and environmental resources of importance, is a more inclusive, useful, and scientifically robust framework to interact with policymakers, than is the focus on global multi-decadal climate predictions which are downscaled to the regional and local scales (see also Pielke Jr. et al. 2007). The vulnerability paradigm permits the evaluation of the entire spectrum of risks associated with different social and environmental threats, including climate variability and change.

Finally, unless there is a broadening of the current IPCC focus it will only lead to promote energy policy changes, and not provide an effective climate policy, which necessarily needs to include how humans are altering the climate system through land surface processes. Policymakers need to be informed of this very important distinction where a separation of climate policy from energy policy is essential.

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