Progress in Modeling the Impact of Land Cover Change on the Global Climate

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Abstract: The prediction of the impact of anthropogenic land use change on the climate system hinges on the ability to properly model the interaction between the heterogeneous land surface and the atmosphere in global climate models. This paper contains a review of techniques in general use for modeling this interaction in General Circulation Models (GCMs) that have been used to assess the impact of land use change on climate. The review includes a summary of GCM simulations of land cover change using these techniques, along with a description of the simulated physical mechanisms by which land cover change affects the climate. The vertical extent to which surface heterogeneities retain their individual character is an important consideration for the land-atmosphere coupling, and the description of a recently developed technique that improves this aspect of the coupling is presented. The differences in the simulated climate between this new technique and a technique in general use include the presence of a boundary layer feedback mechanism that is not present in simulations with the standard technique. We postulate that the new technique when implemented in a GCM has the potential to guide an improved understanding of the mechanisms by which anthropogenic land use change affects climate.

Key words: Modeling, land-atmosphere interactions, land cover change, climate change.

Introduction

Significant current research efforts are devoted to gaining an integrated understanding of the interactions among the Earth's climate, land use and land use change, and human activities in various areas of the world (e. g., Climate Land Interaction Project: http://clip.msu.edu/). Changes in land use are directly linked to many environmental problems at both global and regional scales, and are intrinsically related to the evolution of the regional and global climate due to the energy and material exchanges that occur at the land surface. The current climate trend, as measured by the record of observed global surface air temperature over the past century, indicates a clear warming for our planet, with the year 2001 being the second warmest on record (IPCC 2001).

Many studies are reported which evaluate the impact of the temperature trend and the changes in moisture that it brings on regional and local ecosystems and on the ability of the land to be used for agriculture, grazing and ecological evolution of species. These studies commonly use the IPCC simulations under the different scenarios to evaluate the impact of climate change on the local land use and ecology (for example, see Global Environmental Change Part A, 2004; Solecki and Olivieri, 2004). There are also many studies which evaluate the impact of land use practices on the regional and global climate. There is now evidence from these studies that the warming observed over the last 50 years is due in part to anthropogenic activities, including greenhouse gas emissions and land use change. This evidence is derived in large part from comparisons of observed and predicted global-mean temperatures (Hulme, 1999). The evidence that anthropogenic activity is contributing to the warming trend is supported by the fact that comparisons between observations and global model simulations of the evolution of the earth's climate over the period 1860-2000 show that the closest agreement between observed and simulated climate is obtained when the simulations include both natural and human factors. The simulations include the effects of the anthropogenic increase of greenhouse gases in the atmosphere as well as a rudimentary accounting for the effects of anthropogenic changes in land cover. Climate models are extensively used to assess the causal factors of observed climatic changes as well as to make long-term climate projections and to assess the risks associated with future anthropogenic forcing scenarios. For a report on the increasing importance of the role of General Circulation Models (GCMs) as essential tools to study regional and global impacts resulting from anthropogenic greenhouse gases and land use changes see Soon and Baliunas (2003).

Anthropogenic land use change, which causes changes in the land cover, includes urbanization, deforestation, desertification and agricultural practices, all of which have been shown to have an important effect on climate and climate change (Pielke *et al*., 2002). Many observational studies have shown the impact of land cover change (LCC) on regional climate. For example, an analysis of observations has shown that urbanization and the associated heat island contribute regionally to the warming trend of the last 50 years over the United States (Gallo *et al*., 1999), and that the contributions of urbanization and agricultural expansion combined account for as much as half of that trend (Kalnay and Cai, 2003). In addition, satellite observations show an increase in the seasonality of clouds and convection over the Amazon basin associated with deforestation (Durieux *et al*., 2003). Other observational studies show that the change in the Florida Everglades between 1900 and 1990 from wetlands and marsh to agricultural and urban terrain has been connected with a drier and warmer climate (Pielke *et al*., 1999), that the conversion of terrain in southwestern Australia has been associated with increased formation of cumulus clouds in that region (Ray *et al*., 2001), and that the deforestation of southern Spain since the middle ages is associated with a regional desertification and change in the regional hydrological regime (Millan *et al*, 2005).

It is now well recognized that the biosphere can contribute to changes in climate (Narisma and Pitman, 2004), and tropical deforestation experiments (Bounoua, 1999; Costa and Foley, 2000) demonstrate that the impact of LCC on climate can be as significant at the regional scale as increasing CO_2. Many simulations and studies of the effects of deforestation and overgrazing have been conducted using coarse resolution global models, and although they agree better with observations than simulations that do not include these effects, they still produce results that

differ from high-resolution models and observations. In addition, the results are highly dependent on the specific land surface model formulation (Koster *et al*., 2002). A critical component of the land surface model formulation is the technique used to account for the fact that the surface underlying a General Circulation Model (GCM) grid box is heterogeneous in vegetation and soil properties. Properly capturing (parameterizing) the effects of this heterogeneity on the grid scale is crucial to the prediction of climate and climate change, and to the prediction of the effect of LCC on the changing climate.

The present article focuses on the manner in which information is communicated between the heterogeneous land surface and the overlying atmosphere. In particular, we are concerned with the modeling techniques that are used to represent the aspects of the land-atmosphere exchange associated with small-scale heterogeneities in surface vegetation. The choice of modeling technique directly affects the ability of a GCM to assess and predict the contribution of changes in land cover to the observed climate state (temperature trends, for example) and therefore may aid (or limit) our understanding of the mechanisms involved in the impact of anthropogenic land use change on the climate system. Our primary objectives are to:

- present a review of techniques that are in general use in climate models for the coupling between the land surface and the atmosphere,
- discuss the GCM experiments conducted using these techniques to assess the climate impact of deforestation and desertification, the most extensively studied large-scale forms of LCC, in order to summarize our current understanding of the mechanisms involved in these processes,

- identify some limitations to the techniques generally used in GCMs to handle the land-atmosphere exchanges,

- review a new technique called 'Extended Mosaic' (EM), presently employed in only a few GCMs, that has the ability to overcome some of these limitations,

- review a GCM study that showed the impact of using EM on the simulations of the local boundary layer structure and on the strength of the land-atmosphere coupling, and thereby on the regional climate.

To conclude this paper, we discuss the implications of EM for modeling the impact of changes in land cover on regional and global climate and offer a perspective on how land surface processes might be more realistically and accurately calculated in the next generation of coupled models used for climate studies.

II. GCM Studies of the Effects of Land Cover Change

1 Parameterizations of Land-Atmosphere Coupling

The elements in a GCM that handle the land-atmosphere interface are the surface layer and boundary layer models, the land surface model, and the technique used to couple them. The surface and boundary layer models involve parameterizing near surface turbulence as a diffusive process (Randall, 2000), and the land surface model parameterizes the surface and sub-surface mass and energy transfers. A comprehensive review of the development of land surface models over the past forty years can be found in Pitman (2003). The focus of the present article is the techniques used in GCMs for the coupling between the land surface and the atmosphere.

The calculation of the land-atmosphere exchange in global climate models, as well as the prediction of the potential impact on climate of land cover change, is complicated by the fact that the character of the land surface is spacially variable. Vegetation cover, the types of terrain, soil texture and wetness, the amount of cloud cover and precipitation, and the extent of urban areas all contribute to land surface variability. The wide range of scales of variability in the land surface is apparent in the global vegetation maps that have been compiled from visible and other imagery. The scale of these heterogeneities may be smaller, and in some cases much more so, than the characteristic grid scale in most current GCMs used in climate studies (on the order of 200 km). Almost all the Soil-Vegetation-Atmosphere-Transfer (SVAT) models that are coupled to state of the art regional and global climate models employ some technique to attempt to account for the subgrid-scale heterogeneities. The most often used techniques are 'dominant', 'composite' and 'mosaic' and they are briefly discussed below. Figure 1 shows a schematic view of these different techniques. The top panel of the figure depicts a hypothetical grid square with four characteristic vegetation types and some known geographical distribution. Panels a), b) and c) depict the same grid square as 'seen' by the atmosphere in a GCM when three different techniques generally in use are implemented to describe the land surface. Figure 1.d shows the schematic of a recently developed technique called Extended Mosaic (see description in section 3.2) presently employed in only a few GCMs.

The earliest of the SVAT formulations for GCMs assumed that the land surface in a GCM grid square can be adequately described by the soil and vegetation characteristics of the region that occupies the majority of the area in a grid box (Dickinson *et al*., 1986). This 'dominant' technique cannot, however, account in any way for the influence of other vegetation and soil

types that may exist over significant areas of the grid box (see figure 1. a). Many of the GCMs

that are participating in the Atmospheric Model Intercomparison Project (AMIP) II (Gates, 1995)

account for the subgrid-scale variability by specifying soil and vegetation parameters that

represent a homogeneous 'composite' vegetated surface and its underlying soil for each GCM

grid square. Among these are the GCMs used at the ECMWF (Viterbo and Beljaars, 1995),

NCAR (Gates, 1995), NCEP (Pan and Mahrt, 1987), the Center for Ocean-Land Atmosphere

Studies (Xue *et al*., 1991), the Canadian Climate Centre (Verseghy *et al*., 1993), and Météo-

France (Mahfouf *et al*., 1995). Although the 'composite' technique accounts for the presence of

different vegetation types, the composited vegetated surface (depicted by the blended color in

figure 1.b) does not exist in nature.

A few of the AMIP II GCMs and some others account for the subgrid-scale heterogeneity using

the 'mosaic' approach (depicted in figure 1.c, termed 'mosaic'). In this approach, the

heterogeneous grid box is characterized by different vegetation and soil types ('tiles') and their

fractional area of coverage in the grid box (Koster and Suarez, 1992). This approach is depicted

in figure 1. c), termed 'mosaic'. The juxtaposition of different vegetation types is not included

here, the 'mosaic' approach only models the fractional area of any vegetation type in a GCM

grid box. Separate surface heat and moisture balance equations are solved for each vegetation

type contained within a GCM grid square, and the resulting heat and moisture fluxes, which

describe the coupling to the atmospheric boundary layer, are aggregated linearly. The turbulent

diffusion in the boundary layer and above is then computed based on the grid-averaged surface

flux of heat and moisture. The mosaic approach is employed, for example, in the GCMs used at

the Goddard Institute for Space Studies (Rosenzweig and Abramopoulos, 1997), Laboratoire

Météorologie Dynamique (Ducoudre *et al.*, 1993), the Australian Bureau of Meteorology

Research Centre (Desborough and Pitman, 1998), and the NASA/Goddard Seasonal to

Interannual Prediction Project (Koster and Suarez, 1992). Many researchers, using either *in situ*

data or high-resolution models as the basis for comparison, have carried out validations of the

mosaic approach for GCMs (see, for example, Bringfelt, 1999; van den Hurk and Beljaars, 1996;

Klink, 1995). The results of these evaluations generally show that the mosaic approach is an

improvement over a composite or dominant approach, and that mosaic provides a reasonable

approximation of the turbulent fluxes at the surface under many conditions.

2 Consensus of Results from GCM Studies of Land Cover Change

Using the land surface models described above, many GCM studies have been conducted to

simulate the impact of LCC on climate. The majority of these studies have focused on

deforestation. There have been several comprehensive reviews of GCM deforestation studies,

compiled by, for example, by Dickinson and Henderson-Sellers (1988), Shukla *et al.* (1990) and

Hahmann and Dickinson (1999). There is general agreement among these studies about the basic

processes which occur as a consequence of deforestation; however, the details and magnitudes

differ substantially from study to study. These simulations conceptualize deforestation in terms

of a conversion from forest into grassland. The interactions and feedback mechanisms involved

as deforestation takes place are described below, with the aid of the schematic in figure 2.

The analysis of the feedback mechanism begins with an examination of the implications of the

external forcing, and includes an examination of both energy and hydrological cycles. The two

parallel loops in the schematic represent the feedbacks associated with the energy and

hydrological cycles, and the box around the evaporation indicates the role of evapotranspiration in both cycles. As forested areas are converted to grassland, the albedo of the surface is increased, the surface roughness is decreased, and the ability of the underlying soil and vegetation canopy to hold water is also decreased. These are indicated in black ink by 'Bright', 'Smooth' and 'Dry Veg', respectively, in figure 2, depicted as the forcing in the simulations. In general, deforestation results in a reduction of evaporation and precipitation and an increase of surface skin temperature (red colored 'Evap' and 'Precip', and blue colored 'T surf', respectively). This is accomplished through several paths. In the energy cycle loop, the increased surface albedo of the pasture lands leads to a decrease in the net surface solar radiation (red colored 'Net Rad'), and so to a decrease in the energy available for evaporation and sensible heat flux. The decrease in surface roughness also contributes to the decrease in turbulent surface fluxes by reducing the mechanical sources of turbulence. In the hydrological cycle 'loop', the reduction in canopy and soil water capacity further serves to reduce the evapotranspiration, indicated as the inner loop of figure 2. As a result of the reduced evaporative cooling, the surface skin temperature increases, as shown in the outer loop in the figure. This temperature increase leads to an increased outgoing long wave radiation (blue colored 'LW up'), which further depletes the net energy available at the surface. The reduced evaporation also results in a reduction of precipitation and the continuation of the canopy and soil drying cycle. The warmer surface leads to an increase in buoyancy but the decrease in mechanical turbulence and evaporation compensate and overcome this increase, resulting in a net decrease in vertical motion, indicated by 'Rising Air' in red along the inner-most loop in figure 2, and, therefore, a decrease in the moisture convergence into the region (red colored 'Moist Conv'). This serves to further reduce the precipitation and accelerate the drying and warming feedback cycle.

GCM studies have investigated the relative role of different characteristics of a deforested region. Lean and Rowntree (1997) compared numerical experiments where deforestation alters only the albedo with experiments in which the albedo and surface roughness were altered. From these experiments they concluded that the albedo and roughness changes are comparable in their influence on the regional climate. In addition to the regional changes due to deforestation, GCM simulations also demonstrate its remote influence. Werth and Avissar (2002), in their study of the teleconnection patterns in European climate generated by Amazonian deforestation, suggest that planetary scale Rossby waves may indeed be excited due to processes that occur at the land surface, related to changes in landscape. Gedney and Valdes (2000) also found remote impacts of Amazon deforestation on the winter rainfall in the northeastern Atlantic and Western Europe, associated with the propagation of planetary waves. GCM simulations have also been performed to examine the combined effects of deforestation and doubling of carbon dioxide atmospheric concentrations (Costa and Foley, 2000). Both CO_2 increase and deforestation contribute to a warmer surface temperature. The competing effects on the hydrological cycle, however, were dominated by the deforestation, resulting in a decreased precipitation and evaporation.

The magnitude of the changes in climate due to deforestation differs substantially from model to model for comparable experiments. The reduction in precipitation ranges from 15 to 640 mm per year, the reduction in evaporation ranges from 25 to 500 mm per year and the range of increase in surface temperature is from 0.1 to 2.3°C (Lean and Rowntree, 1997). The studies showing the largest changes in precipitation do not correspond with those that report the largest changes in evaporation or surface temperature. The discrepancies among these GCM results are intimately

related to a large extent to the role that cloud radiative feedbacks play in the particular model. The reduced precipitation is associated with a decrease in cloud cover, which leads to an increase in downward solar radiation and a decrease in downward long wave radiation. It is the net effect of this radiative feedback on the surface energy balance that varies, both in magnitude and sign, from model to model. The discrepancies among the GCM results are also related to other details of the GCM parameterizations. The magnitude of precipitation recycling (the partition between local and remote moisture sources of precipitation) in the various models, tied in large part to the closure assumption in the cumulus parameterization, is related to the discrepancies in rainfall reduction in a deforested region.

Another important consequence of anthropogenic land use change is desertification. GCM studies have shown that this LCC induces changes in the regional climate in much the same manner as does deforestation. The most extensively studied area of desertification is the Sahel-Sahara region (see, for example, Nicholson *et al*., 1998). Charney's albedo feedback hypothesis (Charney, 1975) postulates that an increase in surface albedo would increase radiative losses over the Sahara and would enhance the negative net radiation balance of the desert and adjacent Sahel. GCM experiments on the roles of albedo, evapotranspiration, and roughness have generally concluded that a positive feedback exists, and includes a reduction in rainfall which further alters the vegetation and soil to promote desertification (see, for example, Sud and Molod, 1988 and Xue and Shukla, 1993). GCM studies have also shown that the Sahelian drought of the 1970s, although initiated by anomalous sea-surface temperatures was perpetuated by Charney-type local land-atmosphere interactions (Giannini *et al*., 2003). Similarly, precipitation anomalies associated with ocean temperatures, in conjunction with agricultural

practices, resulted in the initiation of local land-atmosphere feedbacks that led to the dust-bowl

event of the 1930s (Schubert *et al*., 2004). GCM studies have also demonstrated that large-scale

desertification in the northeast area of Brazil results in a weaker hydrological cycle (Sud and

Fennessy, 1982,1984), which, in addition, results in an increase in precipitation over the adjacent

ocean areas (Oyama and Nobre, 2004). As with GCM studies of deforestation, there are

discrepancies among GCM simulations of desertification in the northeast of Brazil. For example,

Dirmeyer and Shukla (1996) concluded that a change of the region's vegetation to a semi-desert

vegetation would not affect the regional hydrological cycle.

All of these modeling studies provide the means to understand the physical mechanisms and

feedbacks involved in the communication of the effects of anthropogenic activity to the regional

and global climate. The conclusions drawn from these studies rely on the details of the model

parameterizations and are sensitive to the choice of models. The lack of agreement among model

results is an indication of the inaccuracies in model parameterizations that still require close

inspection.

III. A Recent Development: 'Extended Mosaic'

1 Limitations of Previous Techniques

One of the assumptions made as part of the land-atmosphere coupling techniques is related to the

level at which the boundary layer is assumed to be homogeneous. Observational and modeling

studies (Claussen, 1995; Mahrt, 2000 and articles cited thereinhave shown that the individual

character of the surface elements extends vertically in the atmosphere up to a level that may be

above the surface layer (which is nominally 50 m above the ground) and within the planetary

boundary layer (on the order of 1 km above the ground). Early studies of the vertical influence of the land surface heterogeneities were conducted by Wieringa (1986), where he defined the 'blending height' as the level inside the planetary boundary layer above which the flow becomes horizontally homogeneous in the absence of other influences. For horizontal scales of heterogeneity of the order of 50 to 100 km or larger that characterize part of the globe, this would imply a blending height of 500 m to 1 km, which is of the order of the planetary boundary layer height. A comprehensive survey of blending height estimates under different atmospheric conditions was presented by Mahrt (1996), where he reported that the blending height can be as high as the height of the planetary boundary layer (PBL), or even higher for an unstable atmosphere under the influence of strong surface heating.

Additional observational evidence exists which supports the scaling arguments that suggest that the blending height may extend well into the PBL. Segal *et al*. (1989) show, using aircraft measurements of temperature and humidity at four levels in the atmosphere over the boundary between an irrigated and a dry crop area, that the contrast between the wet, cool air over the irrigated area and the dry, warm air over the dry area extends up to at least 440 m above the surface. These observations would suggest that the blending height is somewhere above 440 m. The presence of an "elevated large scale blending height" can also be inferred from lidar measurements of the mixed layer height taken in the vicinity of Nashville, Tennessee, spanning the interface between a forested and an agricultural area. The mixed layer heights over the different terrain with patch sizes of ~30 km were shown to differ by up to 400 m (Angevine *et al*., 2003).

The existence of a blending height on larger scales is also demonstrated by a study that uses radiosonde data from the 1994 field observations obtained during the Boreal Ecosystem Atmospheric Study (BOREAS) (Salmun *et al*., 2004). The data used in this analysis were from temporally concurrent measurements (daytime or afternoon), taken over a wide enough range of surface types and separated by distances comparable to a GCM grid size. Blending heights were observed in more than 80% of the vertical soundings from the seven locations that were analyzed, and on average over 50% of the estimated blending heights were found at altitudes above 1 km.

Evidence that the blending height may be of the same order as the planetary boundary layer height has implications for the different techniques used to capture subgrid scale heterogeneity in a GCM. The dominant and composite approaches place the blending height at the ground. The 'mosaic' technique places the blending height at or below the surface layer. The limits on the vertical extent to which surface elements retain their own character that isimposed by these techniques may well constitute an important limitation to capturing the effectiveness of the communication between the land surface heterogeneity and the atmosphere (Mahrt, 2000).

2 The Extended Mosaic Algorithm and its Impact on the Modeled Climate

The technique called 'Extended Mosaic' (EM) presented in Molod *et al*. (2003) is designed to allow the individual character of different sub-grid scale surface elements to extend vertically. This is depicted schematically in figure 1. d), where the lowest level is identical to the representation of a grid square using the mosaic approach depicted in figure 1. c). Figure 1. d) illustrates that in the EM technique the heterogeneity at each model level, LM, LM-1, etc., is

conceptualized in terms of the same tiles that characterize the surface. The subgrid-scale variability of the surface is modeled by computing energy and moisture transfers in the surface layer and soil separately for each 'tile' that makes up the mosaic, as with the standard mosaic technique. This idea is extended upwards in EM by computing energy and moisture transfers in the turbulent layer above the surface layer separately for each 'tile' as well. The net change in temperature and moisture (and passive tracers) is aggregated to compute a GCM grid average at *all levels* in the atmosphere. Implementation of this scheme in a GCM allows the level of the blending height to be *diagnosed as a result* of the behavior of the turbulent boundary layer over each different vegetation type, rather than be *chosen a priori*, as in previously existing techniques. Extended mosaic has been shown in Molod *et al*. (2004) to have an important impact on the simulated climate in global models. Two 10-year long simulations were performed with the GEOS GCM to evaluate the impact on the resulting climate of using the EM technique rather than a standard mosaic technique. The results of these side-by-side simulations showed statistically significant differences on local and global scales.

The impact on the local boundary layer structure was illustrated by elucidating a boundary layer eddy diffusion feedback mechanism present in several regions around the globe. This feedback is illustrated schematically in figure 3. The initiation of the feedback, indicated by 'More turb' in the figure, is the enhancement of the eddy diffusion in EM relative to M as a direct result of the change in technique. This enhanced eddy diffusion of heat and moisture generates higher temperatures and humidity aloft in the boundary layer (black colored 'higher T bl, q bl'). The behavior in the eastern U.S., is illustrated by the circular path on the left of figure 3. The higher boundary layer temperature ('T bl') resulted in a lower relative humidity at those levels, and the

suppression of the precipitation (red colored 'Rel Hum' and 'Precip', respectively). The lower precipitation resulted in drier soils and less evaporation (red colored 'Soil Wat' and 'Evap'), which acted to warm the canopy temperatures, denoted by 'T surf' in blue. The warmer skin temperatures, in turn, generated higher sensible heat flux and higher eddy diffusion (blue 'Turb' in the figure). This completed a positive feedback loop.

The enhanced eddy diffusion and subsequent increase of boundary layer temperature and humidity results in a pattern of opposite sign over a region in northern China and Mongolia, shown by the circular path on the right of figure 3. Over this region, the temperature aloft ('T bl'), canopy temperature ('T surf') and sensible heat fluxes (denoted as a decrease in 'Turb' for turbulent fluxes, in the figure) were all lower in EM, and the precipitation and evaporation were higher (blue colored 'Evap' and 'Precip'). The presence of a deciduous forest in this region, and the subsequently dominant role played by the moisture diffusion results in a higher relative humidity aloft (blue 'Rel Hum'), and enhances the precipitation in the EM simulation. This initiates a positive feedback in the opposite sense, with enhanced precipitation and wetter soils resulting in an increase in evaporation, and therefore a cooling of the surface (a further decrease in 'T surf').

Simulations with the EM technique were also shown by Salmun *et al*. (2003) to exhibit a stronger land-atmosphere coupling than simulations with the Mosaic technique, using a measure of the strength of the land-atmosphere coupling defined in Koster *et al*. (2002). Most of the regions for which the coupling is strengthened in EM coincided with regions identified as 'hot spots' in a study reported by Koster *et al*. 2004. We understand from this result that EM would

simulate an increased response to a change in the character of the land surface in relation to the techniques in general use.

IV. Concluding Remarks

In this article we have addressed some of the issues involved in understanding and predicting the impact of anthropogenic land use change and the resulting land cover change (LCC) on regional and global climate and climate change. To a large extent, our understanding of these issues comes from studies conducted with General Circulation Models (GCMs). We presented a description of the physical mechanisms involved in how deforestation and desertification impact climate from a consensus of GCM studies. A newly developed technique to model the land-atmosphere coupling in a GCM was discussed, which addresses some existing limitations in the models and may affect the results of LCC studies. We reviewed a study conducted using the new technique which revealed the presence of a boundary layer eddy diffusion feedback mechanism that was not present in simulations with the standard technique. In addition, a measure of the relative strength of the land-atmosphere showed that the land-atmosphere coupling was strengthened over a region in the U.S Central Plains when the new technique was used. This region coincides roughly with one of the 'hot spots' identified by the study of Koster *et al*. 2004, defined as regions where the atmosphere is strongly influenced by the land surface.

In our discussion, we stressed that the understanding of the physical mechanisms involved in the impact of anthropogenic land cover change on the climate system is tied to the particulars of the land-atmosphere coupling in GCMs. Our focus was the manner in which interactions at the land boundary are communicated higher up into the atmosphere, an issue which is specifically

addressed by the extended mosaic (EM) technique discussed here. We argue that this technique can provide new insight into understanding how LCC impacts climate. We illustrate this point by examining the mechanisms for the LCC impact laid out in the schematic of figure 2, which is based on a consensus of models using techniques other than EM. The particular causal link in the feedback loop that we focus on is the decrease of evaporation due to the decreased roughness during deforestation. An element of the boundary layer feedback mechanism found in the study comparing EM to a standard mosaic (figure 3) is the possibility that intensifying the turbulence can lead to *either* an increase *or* a decrease in the intensity of the hydrological cycle, depending on the character of the underlying surface. This suggests that in a deforestation simulation using EM the impact of the change in the intensity of the boundary layer turbulence due to the lowered surface roughness *may* result in an *increase* in evaporation if the surface is wet enough. If, for example, at the early stages of deforestation the surface is moist, is it possible to enhance the evaporation process despite the removal of the trees. As deforestation increases and the other stresses on the moisture become more important, the drying of the surface may result in a reversal of the causality, whereby a decreased roughness will result in a decreased evapotranspiration. The use of EM allows for the possibility of this alternative response, which may be relevant for investigating the impact of LCC such as deforestation.

Acknowledgments

version of the manuscript. We also want to acknowledge the unwavering support of Ann

Henderson of Hunter College.

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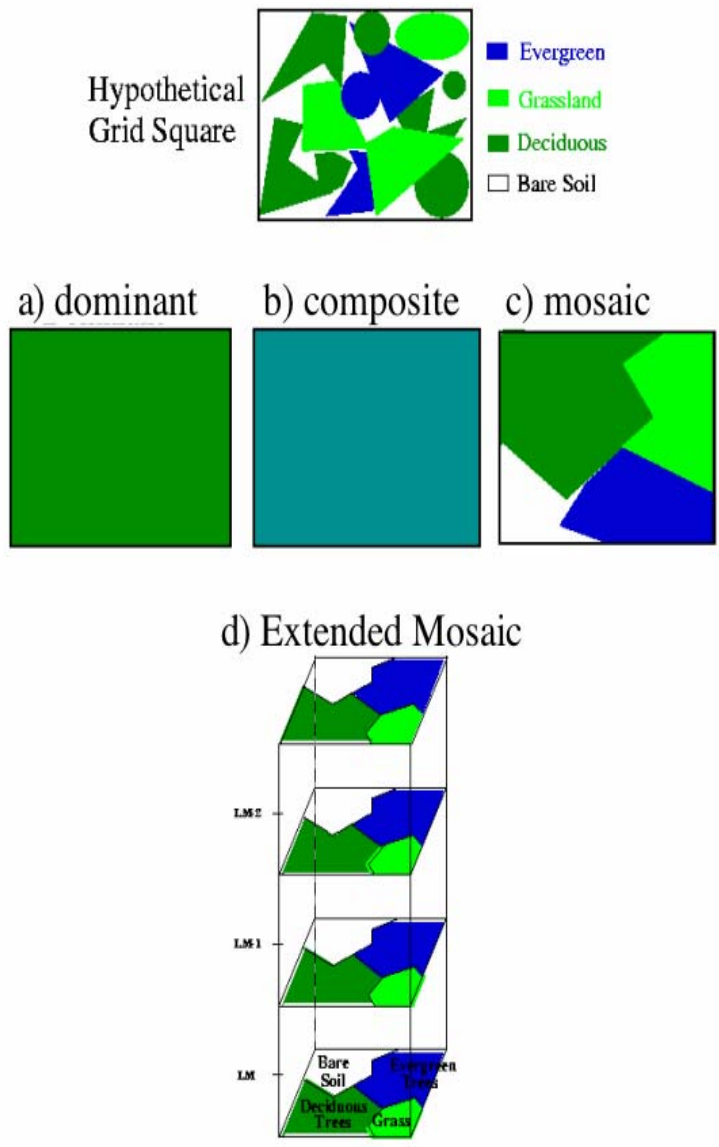
Figure 1 Schematic of the a) dominant, b) composite, c) mosaic techniques and d) extended mosaic techniques. The jagged shape of the tiles in the mosaic panel signifies an arbitrary shape, and the juxtaposition of tiles is not relevant. The vertical axis in panel d) indicates the GCM model levels, where LM is the lowest level and the level number decreases as we ascend in the column.
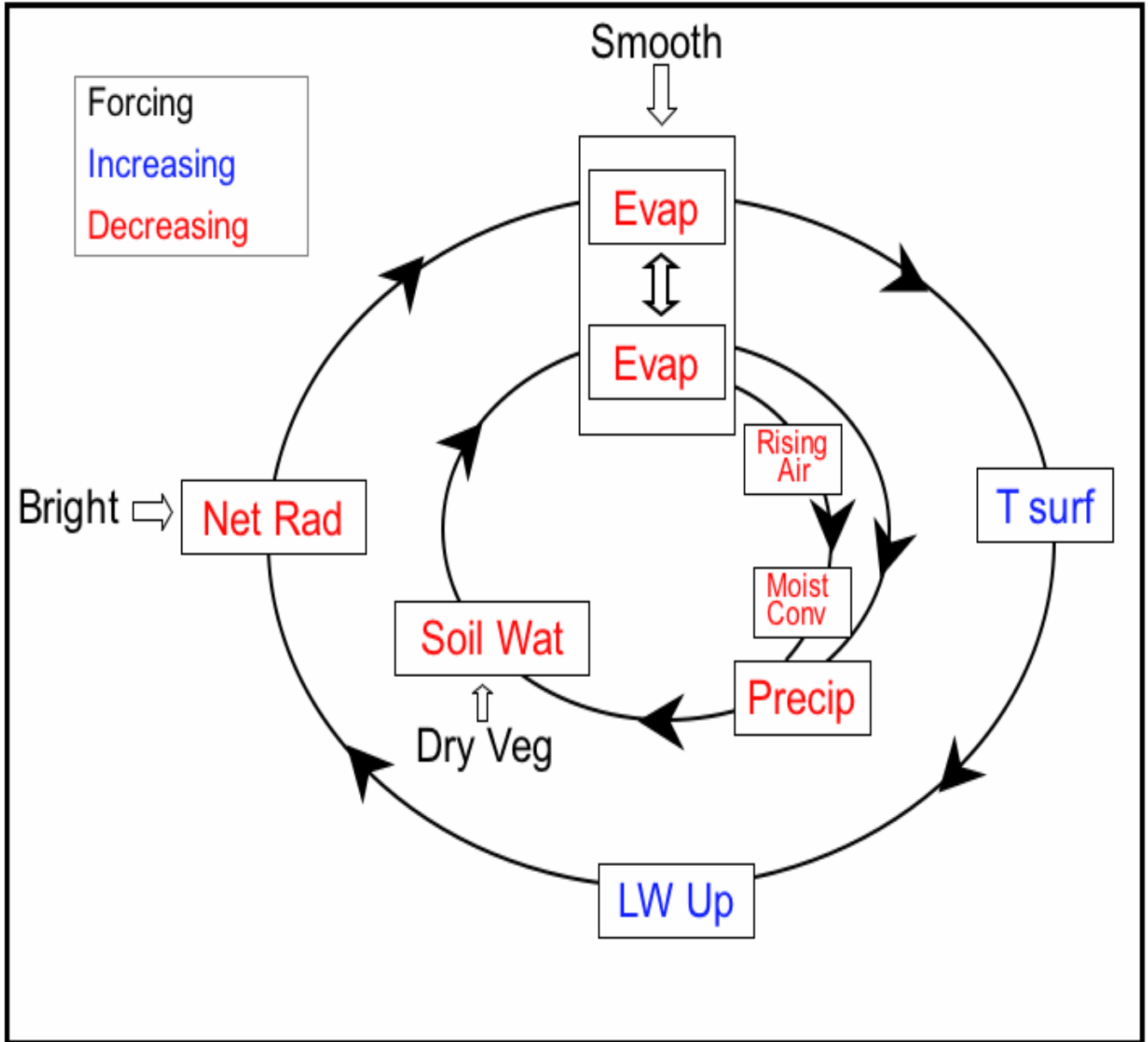
Figure 2 Schematic of the feedback mechanisms involved in deforestation, as described by GCM simulations. The symbols in the schematic are defined as follows: Soil Wat and T surf are the soil moisture and the surface temperature, respectively; Net Rad and LW Up are net surface solar radiation and the outgoing long wave radiation, respectively; Evap and Precip are the evaporation and the precipitation, respectively; and Moist Conv is the moisture convergence into the region.
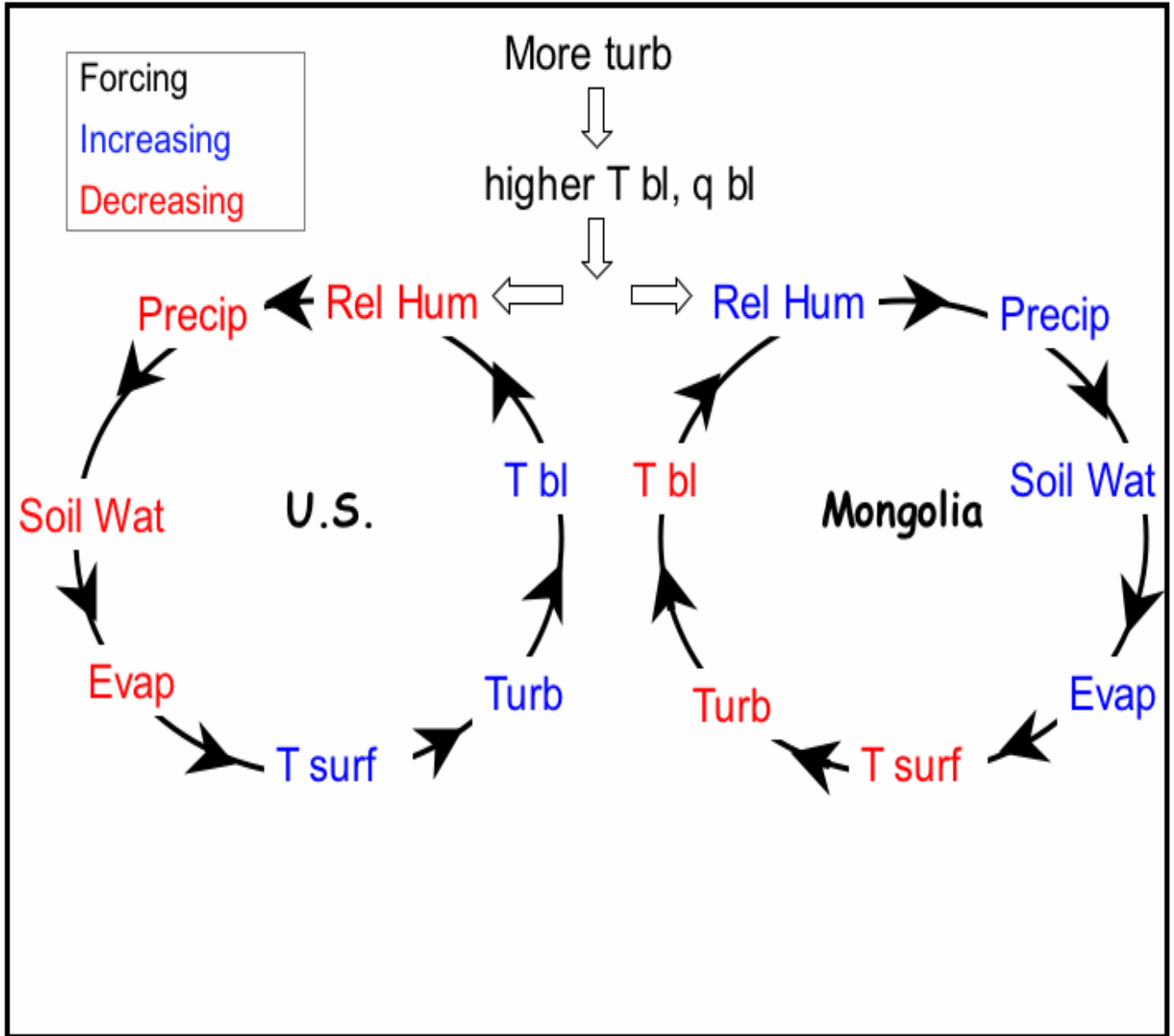
Figure 3 Schematic of the boundary layer eddy diffusion feedback mechanism due to using EM in GCM simulations performed by Molod *et al*. 2004. The manifestation of this feedback in the summertime over the eastern U.S. is shown on the right of the figure and its manifestation over an area of northern Mongolia on the left. Both loops indicate the positive feedback, but have opposite sense depending on local characteristics, that results from the enhancement of diffusion of heat and moisture when using EM. In the schematic, Soil Wat, T surf, T bl and Turb are used to denote soil moisture, surface (or canopy) temperature and boundary layer temperature aloft and eddy diffusion, respectively.