DYNAMIC LAND SURFACE/ATMOSPHERIC PARAMETERIZATION FOR THE SOUTH PLATTE RIVER DRAINAGE

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ABSTRACT: Understanding of two-way interactions between atmosphere and land surface processes is critical to understanding mesoscale climate and water basin hydrology. Terrestrial biospheric processes and terrain heterogeneity control fluxes of water, energy, and CO₂. These perform an important role in determining mesoscale climate development by modifying energy gradients, circulation patterns, and cloud formation. Climate affects land surface processes directly through radiation and moisture inputs and, indirectly, as changing climates from natural or human-caused influences affect longer-term terrestrial processes such as plant community development, rates of plant productivity and decomposition, and hydrologic processes such as snowpack accumulation and melt, soil water storage and rates of discharge. Increasing simplification, based on sound scientific understanding, of the representation of major processes that join the atmosphere, biosphere and hydrosphere allows us to explore these two-way interactions.

INTRODUCTION

The projected climate change from increasing atmospheric trace gases and alterations of the land surface will affect air temperatures and seasonal patterns, amount, and intensity of precipitation. Changes in these climatic parameters will directly affect hydrologic patterns in the mountains and plains, such as amount of snow, timing of snowmelt, and sources and seasonal distribution of atmospheric moisture. These, in turn, will affect hydro-biological processes, such as evapotranspiration, in mountain and downstream high plains environments. Altered snow timing and distribution may affect climate through altered albedos. Doubling of CO₂ will directly increase photosynthetic rates and water use efficiency of terrestrial vegetation, and this will, in turn, affect climate through latent heat fluxes. In this paper, we discuss one technique for addressing the interactions among climatic, hydrologic, and biological processes. This work is in its formative stages. Initial results of application of a simple climate simulator to the Front Range of the Colorado Rocky Mountains are presented.
Climate Effects on Land Surface Processes

The Colorado Rockies are the headwaters of the Colorado, Rio Grande, Platte, South Platte, and Arkansas River systems. The water yield from these rivers each year is directly proportional to amount of mountain snowpack. Long-term decreases in mountain snowpack could lead to loss of agricultural productivity, whereas increases may lead to seasonal flooding. Throughout the Rocky Mountains and the Southwest, where ecosystems are already stressed by limitations of temperature, moisture and nutrients, the effects of climate change will be dramatic.

The ramifications of hydrologic change to mountain ecosystems and downstream water users will be profound. With less snowpack, forests may experience increased drought stress if primary production increases in response to increased temperatures and CO₂ (Eamus and Jarvis 1989). Increased growing season, evaporation, and transpiration, and expansion of forests to higher elevations were predicted for northern Rocky Mountain watersheds under climate warming, leading to a 30% reduction in runoff (Running and Nemani 1991). Streams may become intermittent as a result of greater evapotranspiration and loss of the permanent snowfields. Permanent snowfields have been found to greatly enhance discharge late in the summer (Fountain and Tangborn 1985, Krimmel and Tangborn 1974).

Land Surface Process Effects on Climate

Recent work has demonstrated that atmospheric dynamics show a strong degree of sensitivity to land surface conditions, and in particular to terrain variability and biospheric controls on fluxes of H₂O, CO₂, and energy (Pielke et al. 1991, Avissar and Pielke 1989, Pielke and Avissar 1990, Segal et al. 1988, Pielke and Zeng 1989). Land surface heterogeneity (e.g. north- versus south-facing slopes or hillslope position) strongly affects energy and mass exchange between land and atmosphere, and land and hydrosphere through variability of the radiation environment, precipitation and temperature conditions, and soil water drainage (Band et al. 1991, Nemani et al. 1991). Biospheric processes exert an important role in determining reciprocal interactions between the atmosphere and the land surface (Schimel et al. 1991a, Dickinson and Henderson-Sellers 1988, Pielke and Avissar 1990, Avissar and Verstraete 1990). Over heterogeneous terrain, then, the patterns and variance of exchange processes can influence not only the areal average magnitudes of these processes, but also micro- and meso-scale atmospheric dynamics that may be below the resolution of many mesoscale and global atmospheric grid models (Pielke et al. 1991). Because the global climate consists of a spectrum of mesoscale climates, and because of dynamic feedbacks from mesoscale to larger scale climate, two-way interactions have global implications (Pielke et al. 1991, Pielke et al., this volume).

We define land surface processes explicitly as combined hydrologic and ecosystem processes. While the addition of land surface characteristics improves the performance of mesoscale atmospheric models, these surface boundary conditions are usually fixed over time or have a prescribed annual cycle, preventing vegetation or hydrology from responding to changes in climate. Similar circumstances are often found in land surface process models, and climate is often prescribed and fixed in order for the model to focus instead on feedbacks and interactions between hydrologic and ecosystem processes. Changes in regional or global precipitation patterns or temperature will have dramatic long-term consequences on terrestrial ecosystems and regional scale hydrology (Rango and van Katwijk 1990,
Revelle and Waggoner 1983, Running and Nemani 1991) that, in turn, will influence mesoscale climate. Possible changes in ecosystem function that affect physical and chemical climate include alteration of flux rates and storage terms for water, nutrient and carbon cycles, and changing vegetation structure (Ojima et al. 1991, Schimel et al. 1991a).

Interactive Land Surface/Atmosphere Process Simulation

Many authors have commented on the complexity associated with attempting to couple land surface/atmosphere models (Pielke et al., this volume, Running and Nemani 1991, Uchijima and Seino 1988). Temporal and spatial heterogeneity of the land surface must be portrayed dynamically, often along different scales than those that portray mesoscale atmospheric patterns. Biological parameters, such as vegetation structure and physiology that influence atmospheric dynamics, are influenced not only by climate, but also by biotic biogeochemical processes (production, decomposition, nutrient cycling, succession), abiotic conditions (hillside position, soil drainage, exposure, microclimatic variability), human disturbance, and episodic natural events such as fire and grazing (Pielke et al. submitted, Schimel et al. 1991b, Pastor and Post 1986). One way of reducing complexity is by aggregating fine-scale components up to some optimum level where interaction between fine and coarse scale information can occur (Rastetter et al. 1992). Recent research in this area is encouraging in that it appears that complex spatial and temporal patterns in plant physiology and in hydrologic processes can be explained by simple models based on a few principles (Schimel et al. 1991a, Running and Nemani 1992, Band et al., accepted).

Scientists can take advantage of this simplification to increase understanding of how regional-scale land surface processes influence and in turn are influenced by regional climate. Are responses of components of climate, hydrologic, and ecologic systems significantly modified by interactions? What are the feedbacks of surface processes to mesoscale and larger scale atmospheric dynamics? How does the feedback of surface processes to the atmosphere vary as we alter the specificity and complexity of surface and atmospheric models? How much complexity do the models require in order to retain the important interactions and dynamics that can be observed? These are vital questions to address in order to approach the ability to predict effects of increasing concentrations of atmospheric greenhouse gases on hydrologic, climate, and ecosystem processes.

Simplification can also be used to extrapolate the capability of the coupled ecological/hydrologic/atmospheric models to interpret climate-ecosystem feedbacks from small to increasingly larger spatial scales (Costanza et al. 1990, Vörösmarty et al. 1989, Gildea et al. 1986). What are the responses of hydrological and ecological dynamics at watershed to region scale under current and changing climate? As we vary the spatial representation of surface terrain, vegetation and soil model parameters from a high resolution description of surface patterns and distributions to larger scale mean or representative conditions, how can the magnitude and patterns of these processes be properly represented? One promising approach is to reduce spatial complexity by aggregating similar responses of hydrological and ecologic processes across the landscape (Band 1989, Famiglietti and Wood 1990). Conceptually, then, land surface characteristics and physical processes are generalized to give an overall description of the dominant spatial patterns of surface properties and hydrologic pathways at the landscape level. Just how general one can get without losing the vital influence that terrain variability exerts over
both terrestrial and atmospheric processes is a topic that needs to be vigorously explored (Band et al. 1991, Pielke et al. 1991).

We are exploring the use of simplified model representations of land surface and atmospheric processes for the South Platte River basin in northeastern Colorado (Pielke et al. 1992). Our approach will be to link a mesoscale climate model, RAMS (Pielke et al. 1991), in which land surface processes are currently prescribed and non-reactive, with integrated land surface, hydrologic and ecosystem process models embedded in a geographic information system, RHESSys (Nemani et al. 1991, Band et al., accepted), where atmospheric processes are currently prescribed and non-reactive (Figure 1).

**REGIONAL HYDRO-ECOLOGICAL SIMULATION SYSTEM (RHESSys)**

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**Figure 1.** Flow diagram of information from raw image data through model parameter sets and simulation results for RHESSys. Surface parameter fields are computed from remote sensing imagery, digital elevation data, and aggregated to landform levels in the cartridge files. Within landform variability is represented in the distribution files. Information passed interactively down from RAMS to land surface models are distributed across the landscape using MT-CLIM and are represented with narrow arrows. Information passed interactively up to the atmosphere model is passed through LEAF to smooth and distribute land surface attributes, and is represented with broad, open arrows.
MT-CLIM Applications to the Colorado Front Range

We are in the initial stages of developing the dynamic links between atmospheric and land surface process simulations for the South Platte River drainage (Baron et al. 1991). We tested output from a very simple climate simulator, MT-CLIM, against actual climate for alpine and subalpine environments. MT-CLIM operates under the assumption that meteorologic observations from a low elevation base weather station can be extrapolated to higher elevations using meteorological principles including environmental lapse rate, local orographic controls, and radiation exposure. Output from the model includes high elevation daily precipitation, maximum and minimum air temperatures, dewpoint, and solar insolation (Running et al. 1987).

The MT-CLIM model has worked well in variable terrain where precipitation is orographically-controlled (Band et al. accepted, Running et al. 1987). The Front Range of Colorado, however, is climatically complex (Barry 1973). Major sources of precipitation west of the mountain crest are synoptic scale frontal disturbances bearing Pacific moisture. These storms are most prevalent during the winter months, and mountain locations just east of the mountain crest are influenced by these winter storms. Springtime moisture originates commonly from the southwest to the southeast, and is associated with cyclonic flow of moisture from the Gulf of Mexico and California. These types of storms lose their moisture along the high plains and eastern foothills, with decreasing amounts at higher elevations. Although synoptic scale flow is still responsible for the flow of moisture into the region during the summer, precipitation events most commonly result from local convective activity, as opposed to larger patterns (Toth and Johnson 1983). These precipitation complexities, coupled with strong winds along the east slopes of the Front Range, caused us to hypothesize that MT-CLIM would not perform as well in Colorado as in more orographically-controlled mountain environments.

Our study sites were Niwot Ridge, and Loch Vale Watershed (Figure 2). Both sites are located on the eastern slopes of the Colorado Front Range northwest of Denver and are the locations of long-term ecological research supported by the National Science Foundation (Niwot Ridge), and by the National Park Service and the U.S. Geological Survey (Loch Vale Watershed). Niwot Ridge is an east-west trending alpine ridge ranging from 4,150 m to 3,530 m. Loch Vale Watershed in Rocky Mountain National Park is a deeply-incised alpine and subalpine glacial valley ranging from 4,010 m to 3,100 m. Base station weather data were taken from Nederland, CO, (2,512 m) to parameterize MT-CLIM for Niwot Ridge, and from Estes Park, CO (2,295 m) to parameterize MT-CLIM.

Simulated maximum and minimum temperatures were close to actual temperatures ($r^2=0.80$ for maximum and minimum temperatures) recorded for Niwot Ridge in 1984 (Figure 3a). The Loch Vale Watershed comparison (with 1985 data) was not quite as good, but 51% and 47% ($r^2=0.51$ and 0.47) of the variance in maximum and minimum temperatures, respectively, can be characterized by variation in Estes Park temperatures (Figure 4a). Cold air drainage into valley bottoms is not handled well yet by MT-CLIM, and this may explain some of the poor model fit to minimum temperatures for Loch Vale Watershed. The simulated annual total precipitation for Niwot Ridge of 105 cm was much greater than recorded precipitation (65 cm). MT-CLIM predicted 133 cm precipitation in 1985 for Loch Vale Watershed, compared with 108 cm recorded. Simulated precipitation from the Nederland and Estes Park base stations were compared with smoothed running median
precipitation values from the higher elevation areas (Figures 3b and 4b). The $r^2$ suggested 18% of Niwot Ridge precipitation can be explained by precipitation patterns and amount at Nederland, but only 7% of Loch Vale precipitation can be explained by Estes Park precipitation.

The failure of MT-CLIM to predict high elevation precipitation can be explained by the meteorological complexity of the Front Range discussed above. Upslope storms that cause precipitation at low elevations may cause reduced or no precipitation at higher elevations. Pacific moisture may fall at high elevations, but not at lower elevations to the east. This re-emphasizes the need for incorporating more realistic climate representations into any future work on interactive climate/ecological/hydrologic/biogeochemical processes that will be affected by climate change.
Figure 3. Simulated (MT-CLIM) versus actual climatic data for (a) maximum and minimum daily temperature, and (b) daily precipitation for Niwot Ridge, Colorado, using 1984 data. Base weather station data used to parameterize MT-CLIM are from Nederland, Colorado.
ACKNOWLEDGEMENTS

Sincere appreciation is given to Brian Newkirk for executing the MT-CLIM runs, and to Tim Seastedt and Rick Ingersoll, NWT LTER, for access to Niwot Ridge data. This research was supported by the National Park Service Global Change Research Program.

Figure 4. Simulated (MT-CLIM) versus actual climatic data for (a) maximum and minimum daily temperature, and (b) daily precipitation for Loch Vale Watershed, Rocky Mountain National Park, Colorado, using 1985 data. Base weather station data used to parameterize MT-CLIM are from Estes Park, Colorado.
REFERENCES
