



Cynthia Rosenzweig and Daniel Hillel

## Climate and Biosphere

### **Dynamic Partners**

*Some ancient societies believed that climatic phenomena — especially rainstorms — represented a primal mating of the sky with the earth. This intuitive depiction has long been supplanted by scientific inquiry. Yet the essential fact remains: climate and its short-term manifestations, called weather, are conditioned by interactions of the atmosphere with the earth's surface.*

**Although it covers only about 30 percent of the terrestrial realm, the land surface, with its various soil and vegetation zones, affects the global radiation balance, hydrological cycle, carbon and nutrient cycles, and momentum transfer (wind) of the entire earth and its near atmosphere.** Land-surface phenomena thus play a major role in determining climate, and are themselves likely to be affected reciprocally by its changes. Three interacting processes — the energy exchange, the hydrological cycle, and the carbon cycle — dominate land-surface/atmosphere dynamics. Different biomes — rainforests, boreal and deciduous forests, savannas, grasslands, and deserts — vary in the rates of these processes and create a variegated palette over the face of our planet (see Figure 1 on the next page).

### **THE ENERGY CYCLE**

**S**olar radiation received on the earth's surface is the major component of the energy

balance. The land surface plays an important role in reflecting, absorbing, and partitioning the received solar radiation. First, how much radiation does the surface reflect and how much does it absorb? The albedo, which is the percentage of light that a surface reflects back into the atmosphere, varies according to the color, roughness, and inclination of the surface. It is on the order of 5 to 10 percent for water, 10 to 30 percent for vegetation, 15 to 40 percent for a bare soil, and up to 90 percent for fresh snow. The smoother and drier the land surface (either vegetated or bare soil), and the brighter its color, the higher is its albedo and the smaller is the fraction of short-wave radiation (light) it absorbs.

The land surface also participates in the exchange of long-wave radiation (heat). The earth's surface, which converts incoming shortwave radiation to sensible heat, emits long-wave (thermal, infrared) radiation. At the same time, the atmosphere also absorbs shortwave and emits long-wave



Figure 1. Key ecosystems that affect the atmosphere.

radiation, part of which reaches the surface. The difference between these outgoing and incoming fluxes is called the net long-wave radiation. Calculating the net long-wave radiation at the earth's surface is not unlike calculating a household budget: "Income minus Outgo equals Net Change in Value." In our case, however, the currency involved is not money but radiant energy. Incoming sunlight is called "shortwave solar radiation," while heat outradiated from the earth's surface is called "long-wave radiation." During daytime, incoming solar radiation typically exceeds the emission of heat by the earth's surface, so often there is a net gain of energy and the surface tends to warm up. During the night, when no incoming solar radiation is present, there is a net loss of energy by long-wave radiation. Some of the emitted radiation is blocked by the atmosphere, espe-

cially if it is humid or cloudy. That is why we notice that cloudy nights tend to be warmer than clear nights.

The overall difference between total incoming and total outgoing radiation (including both the shortwave and the long-wave components) is termed net radiation, expressing the rate of radiant-energy absorption per unit area of land surface. The complete equation for the earth's net radiation can be stated very simply: Incoming Sunlight minus Reflected Sunlight, plus Incoming Heat minus Outgoing Heat, equals Net Energy Absorption.

The land surface affects the apportionment of the net radiation into different forms of energy. Green plants are able to convert a part of the received radiation into chemical energy. Thus, a small portion (generally less than 5 percent)

of the solar radiation is used in the vital process of photosynthesis, on which all life on earth ultimately depends. Part of the net radiation received by the land surface is transformed into heat, which warms the soil, plants, and the atmosphere near the ground. This is called "sensible heat." A major part is absorbed as latent heat in the twin processes of evaporation and transpiration (the latter denoting evaporation from plants). The allocation of the net radiation into these different forms of energy depends on the nature of the surface, especially on the availability of water for evaporation. In humid ecosystems, much of the energy goes into evapotranspiration. In arid regions, there is little moisture for evaporation so the major portion of net radiation goes into heating the surface. This is one reason why, for example, surface temperatures in Arizona are usually

higher than in Alabama, despite the fact that both locations are at the same latitude and, therefore, receive the same amount of sunlight.

## THE WATER CYCLE

The earth and the atmosphere are engaged in a reciprocal passing game whose main article of exchange is water. The forces that impel this exchange are the sun's radiant energy and the earth's gravitational pull. Precipitation in the form of rain and snow falls on the land surface. Some is intercepted by trees, such as conifers, while most strikes the ground, either to run off on the surface or to infiltrate to the store of soil moisture. Some of the infiltrated water joins aquifers and slowly winds its way to rivers and the sea. Another fraction of soil moisture evaporates from the soil surface or from the foliage of growing plants. In addition, water evaporates from lakes, reservoirs, and seas. The vapor carried in the air eventually recondenses as liquid and falls as rain, or freezes to form snow. The water thus returned feeds the rivers, which flow to the ocean. Evaporation from land and ocean sends water back to the atmosphere, and the exchange goes on continuously.

## THE CARBON CYCLE

The terrestrial carbon cycle interacts with the climate system at various time scales. On short time scales (minutes), plants regulate their stomates, the small openings in leaf surfaces through which CO<sub>2</sub> is absorbed and water is released. The stomatal aperture depends on the atmospheric demand for water and on the supply of soil water to the plant. On seasonal time scales (months), plants create vegetative canopies over which transpiration occurs. These canopies vary in structure

and density from season to season and from year to year, both responding to and affecting climate variability. On longer time scales (decades), the carbon cycle is affected by ecological succession and changes in the composition of the plant community, and thus may

climate, and that the interactions of soil and vegetation processes with the atmosphere must be incorporated in GCMs more realistically.

As GCMs have improved during the last two decades, the representation of land-surface processes

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have important feedback effects in a changing climate.

The three cycles — energy, water, and carbon — are inextricably linked because they involve identical or overlapping processes within the same environmental domain. The content of water in the soil affects the way the flux of energy streaming into the soil-plant complex is partitioned and used. Reciprocally, the energy flux affects the state and movement of water. Likewise, the carbon cycle is linked to the water and energy balances because plant photosynthesis both controls stomatal resistance, which determines transpiration rate, and governs the time evolution of vegetative canopies.

## LAND-SURFACE MODELS

When atmospheric scientists first created general circulation models, now known as global climate models (GCMs), the land surface was represented very simply as the "boundary condition" for the atmosphere. However, atmospheric modelers soon realized that the land surface plays an active role in weather and

has indeed become more realistic. The primary aim has been to improve the simulation of relevant fluxes to the atmosphere, especially the latent and sensible heat fluxes. A second aim has been to enhance the physical realism of the land-surface component of GCMs for earth-system global-change studies, such as the role of the carbon cycle in climate change, the effects of land degradation and deforestation on the hydrologic cycle, and the contribution of river discharge to ocean salinity.

Land-surface processes in GCMs include rainfall interception by vegetation and its throughfall, surface and subsurface runoff, infiltration, soil-water flow, transpiration, and direct evaporation from intercepted precipitation, dew, and bare soil. Latent and sensible heat fluxes between the land surface and an atmospheric reference layer are calculated.

One example of the inclusion of land-surface processes in an overall global climate model is the land-surface model developed at the NASA/Goddard Institute for Space Studies (Figure 2). In this model the major relevant processes are simulated in terms of mathe-

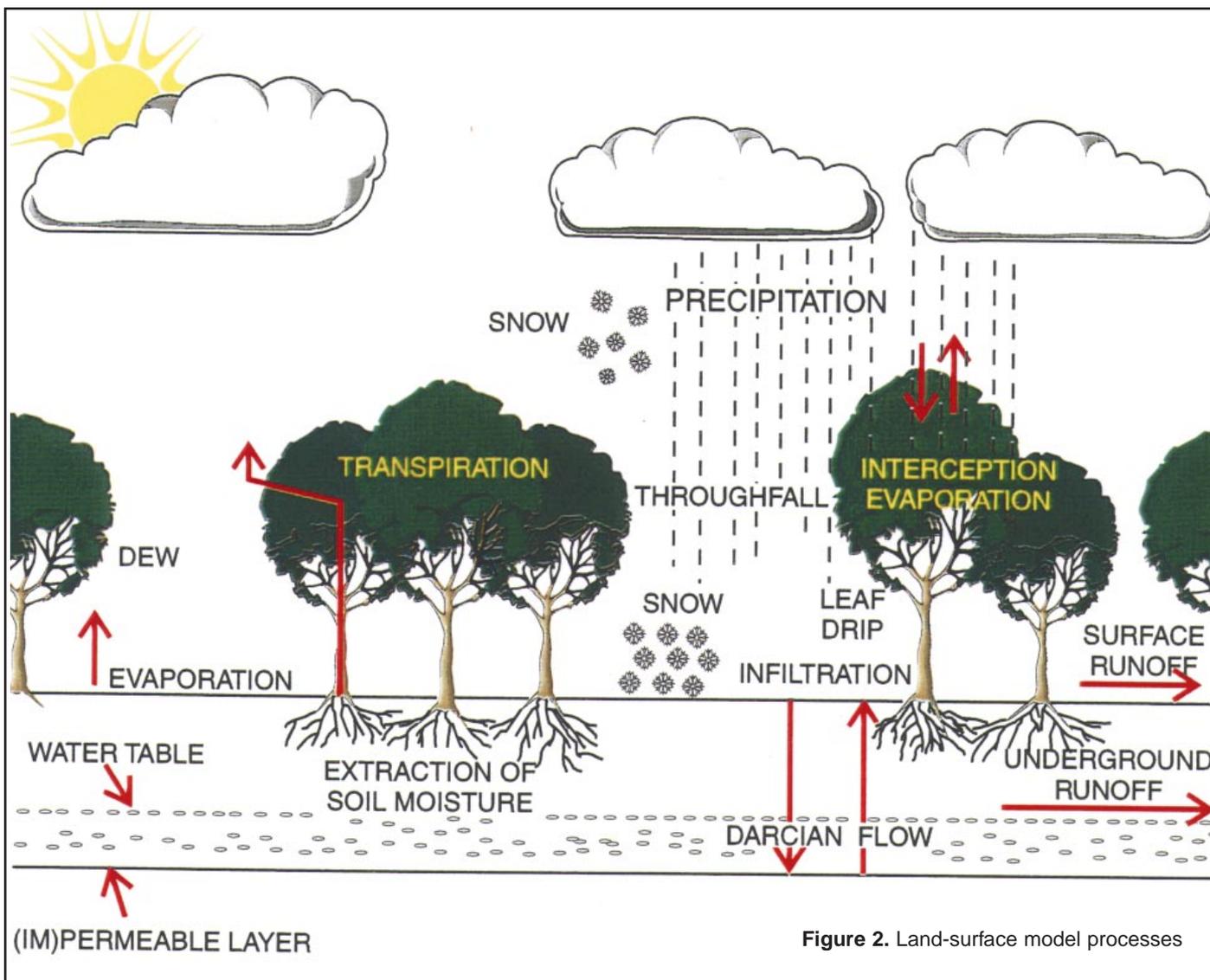


Figure 2. Land-surface model processes

mathematical equations. The variables interact in accordance with well-established physical and physiological relationships. An effort is made to validate the predictions of this mathematical model by comparison with observations made on the ground and by means of remote sensing (satellite imagery).

### ACTIVE RESEARCH

Current research is extending the land-surface models primarily in three ways. First, models are now including a more detailed and comprehensive representation of ecosystem process, especially the carbon cycle. Second, other modelers seek to

include the role of topography in soil-moisture heterogeneity, evapotranspiration and partitioning of surface fluxes, timing and partitioning of runoff, and baseflow on watershed scales. Third, the dynamic role of land-use change is now beginning to be represented in the models. All of these research areas are vital because GCMs are increasingly applied in earth-system studies that include land-surface changes such as shifts in natural as well as agricultural vegetation with global warming.

Some models now include the prediction of vegetation types on the basis of climatic, physiological, and ecological processes, recognizing the processes of long-term eco-

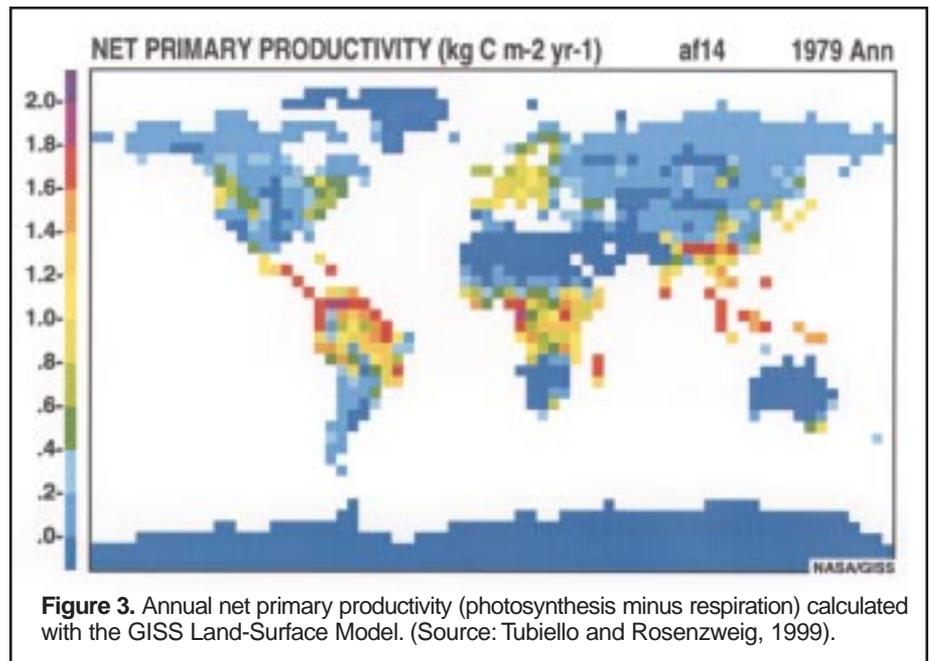
logical succession. Models also include short-term carbon and nitrogen dynamics in vegetative biomass, litter, and soil organic matter. Figure 3 shows the projection of annual net primary production (photosynthesis minus respiration) of global vegetation simulated with a new version of the GISS land-surface model.

Modelers are also actively seeking to improve the simulation of the water cycle by including the role of topography. Topography plays a strong role in routing both above- and below-ground runoff, and in creating areas of enhanced soil moisture. The latter, in turn, affects evapotranspiration and partitioning of latent and sensible heat fluxes.

Finally, because humans are rapidly and radically altering the land surface, modes of land use and management are also being taken into consideration. An example is the transformation of the vast savannas known as the Cerrados in Brazil into commercial soybean and maize production. Simulations are now designed to predict crop suitability, agricultural zones, and crop production on global scales, based on climate, soil resources, and management. The aim of the work is two-fold: 1) To provide more realistic characterization of land-cover types within global climate models, thus improving the calculation of water and carbon fluxes at grid-box scales; and 2) To implement a new generation of global land-use/land-cover models with the capability of simulating the effects of climate change on agricultural production in a self-contained manner.

## LAND PROCESSES AND GLOBAL CLIMATE CHANGE

Global climate change, arguably the most profound environmental issue of our time, makes it imperative for us to understand climate-biosphere interactions in quantitative terms. The land surface is an active participant in, not merely a passive recipient of, global climate change. Deforestation through burning releases carbon dioxide (CO<sub>2</sub>) and methane (CH<sub>4</sub>) from existing biomass, while cultivation of “new” land speeds the decomposition of the initially present soil organic matter. These processes contribute to the accumulation of greenhouse gases in the atmosphere. As global warming occurs, ecosystems will respond by alteration of species composition and shifts in location. However, these changes are likely to be thwarted by the fragmentation and island-like isolation of the once-



extensive ecological domains resulting from the human usurpation of the greater fraction of the planet's terrestrial surface. Some species, perhaps even entire biotic communities, may not survive changes in climate if they are prevented from migration. Consequently, the role played by natural ecosystems in environmental processes (O<sub>2</sub>-CO<sub>2</sub> exchange, runoff, evaporation, groundwater recharge, nutrient recycling, and more) may be jeopardized.

These and other threats to the integrity of the biosphere require us not merely to continue but indeed to intensify the effort to understand land surface-climate interactions in terms of quantitative dynamic processes. That is the aim and challenge of current modeling efforts, accompanied by continuous monitoring and data collection. In ancient times, our forebears attempted to affect climate by appeal (in prayer and sacrifice) to the gods whom they believed to control both storms and droughts. Today we are no less affected by the same forces of nature. Those forces are in part conditioned by our actions, and are in part beyond our control. It is our task to prevent or mitigate those deleterious

changes that are subject to our action, while understanding and adjusting to those processes (such as the El Niño phenomenon) that are beyond our control.

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**Rosenzweig and Hillel are the co-authors of *Climate Change and the Global Harvest: Potential Impacts of the Greenhouse Effect on Agriculture* (Oxford University Press, 1998).**