NCAR Land Surface Model (NCAR LSM version 1)

Model Summary

The land surface model (NCAR LSM version 1) is a one-dimensional model of energy, momentum, water, and CO_2 exchange between the atmosphere and land, accounting for ecological differences among vegetation types, hydraulic and thermal differences among soil types, and allowing for multiple surface types including lakes and wetlands within a grid cell. Vegetation effects are included by allowing for twelve plant types that differ in leaf and stem areas, root profile, height, leaf dimension, optical properties, stomatal physiology, roughness length, displacement height, and biomass. These 12 plant types are combined to form 28 different vegetated surfaces, each comprised of multiple plant types and bare ground so that, for example, a mixed broadleaf deciduous and needleleaf evergreen forest consists of patches of broadleaf deciduous trees, needleleaf evergreen trees, and bare ground. Lakes and wetland, if present, form additional patches. Soil effects are included by allowing thermal properties (heat capacity, thermal conductivity) and hydraulic properties (porosity, saturated hydraulic conductivity, saturated matric potential, slope of retention curve) to vary as functions of percent sand and percent clay. Soils also differ in color, which affects soil albedos. Consequently, each grid cell in the domain of interest is assigned a surface type, a fraction covered by lakes, a fraction covered by wetlands, a soil texture (percent sand, percent silt, percent clay), and a soil color.

Major features of the model are:

- prescribed time-varying leaf and stem areas
- absorption, reflection, and transmittance of solar radiation, accounting for the different optical properties of vegetation, soil, water, snow, and ice
- absorption and emission of longwave radiation allowing for emissivities less than one
- sensible and latent heat fluxes, partitioning latent heat into canopy evaporation, soil evaporation, and transpiration
- turbulent transfer above and within plant canopies
- vegetation and ground temperatures that balance the surface energy budget (net radiation, sensible heat, latent heat, soil heat)
- stomatal physiology and CO_2 fluxes

- interception, throughfall, and stemflow
- snow hydrology
- infiltration and runoff
- temperatures for a six-layer soil column using a heat diffusion equation that accounts for phase change
- soil water for the same six-layer soil column using a one-dimensional conservation equation that accounts for infiltration input, gravitational drainage at the bottom of the column, evapotranspiration losses, and vertical water flow based on head gradients
- temperatures for six-layer deep and shallow lakes accounting for eddy diffusion and convective mixing

In coupling to the atmospheric model, the land surface model provides to the atmospheric model, at every time step, surface albedos (direct beam and diffuse for visible and near-infrared wavebands), upward longwave radiation, sensible heat flux, latent heat flux, water vapor flux, and surface stresses. The atmospheric model provides to the land model, at every time step, incident solar radiation (direct beam and diffuse for visible and near-infrared wavebands), incident longwave radiation, convective and large-scale precipitation, and lowest model level temperature, wind, specific humidity, pressure, and height.

A complete description of the model is provided in the documentation and user's guide.

Background

Land-atmosphere interactions have traditionally been described in terms of four sub-disciplines: biogeophysical fluxes, biogeochemical fluxes, hydrology, and ecosystem dynamics. However, many ecological, hydrological, and atmospheric processes are so intertwined that these cannot be considered separate disciplines. Successful modeling of net primary production, carbon storage, and trace gas emissions (e.g., methane, non-methane hydrocarbons, nitrous oxide) requires an accurate model of the micrometeorological and hydrological environments in addition to the traditional ecological emphasis on vegetation and biogeochemical controls. Successful modeling of latent and sensible heat fluxes requires an accurate description of the ecological state and biogeochemical controls in addition to the traditional emphasis on the physical environment.

More importantly, many ecological, hydrologic, biogeochemical, and atmospheric models parameterize the same processes though with vastly different time-scales and complexity. This introduces internal self-consistency problems when coupling component models into a comprehensive land-atmosphere model. See

- Bonan, G.B. 1993. Do biophysics and physiology matter in ecosystem models? Climatic Change 24:281-285.
- Bonan, G.B. 1995. Land-atmosphere interactions for climate system models: coupling biophysical, biogeochemical, and ecosystem dynamical processes. Remote Sensing of Environment 51:57-73.

for a discussion of some of the important issues.

In the late-1980's, I became interested in combining the relevant biogeophysical, biogeochemical, hydrologic, and ecosystem processes into a comprehensive model of land-atmosphere interactions that was physically and biologically realistic and also internally self-consistent. The primary motivation for this work was to study land-atmosphere CO2 exchange in boreal forests. This early work directly lead to the development of a more generalized land surface model for coupling to atmospheric general circulation models.

Model Documentation

The land surface model has been thoroughly described in an NCAR technical note (150 pages with 31 figures and 17 tables). This Users Guide (ftp://daac.ornl.gov/data/model_archive/LSM/comp/NCAR_LSM_Users_Guide.pdf) is included as a companion file to the data model.

Model Applications

The model has been applied to study:

Land-Atmosphere CO_2 Exchange

Many ecological, hydrological, and atmospheric processes are so intertwined that these cannot be considered separate disciplines. Successful modeling of net primary production, carbon storage, and trace gas emissions (e.g., methane, non-methane hydrocarbons, nitrous oxide) requires an accurate model of the micrometeorological and hydrological environments in addition to the traditional ecological emphasis on vegetation and biogeochemical controls. Successful modeling of latent and sensible heat fluxes requires an accurate description of the ecological state and biogeochemical controls in addition to the traditional emphasis on the physical environment.

The following studies document my long-standing interest in combining the relevant biophysical, biogeochemical, hydrologic, and ecosystem processes into a comprehensive model of land-atmosphere CO_2 exchange that is physically and biologically realistic and also internally self-consistent.

Preliminary Work

The first model was a daily time step model of energy, water, and CO_2 exchange for aspen, birch, balsam poplar, white spruce, and black spruce forests near Fairbanks, Alaska. It combined photosynthesis and respiration with surface energy exchange and whole-tree carbon allocation. The model was quite successful simulating CO_2 uptake and loss during plant photosynthesis, plant respiration, and microbial respiration (as compared to annual net primary production and decomposition). The model also simulated the hydrologic and thermal (soil temperature) states of these forests fairly accurately.

- Bonan, G.B. 1991. Atmosphere-biosphere exchange of carbon dioxide in boreal forests. Journal of Geophysical Research 96:7301-7312.

- Bonan, G.B. 1991. A biophysical surface energy budget analysis of soil temperature in the boreal forests of interior Alaska. Water Resources Research 27:767-781.

Model applications:

- **Seasonal CO2 fluxes** . The increasing seasonal amplitude of atmospheric CO2 is thought to reflect increased photosynthetic uptake from higher CO2 concentrations or increased winter respiration loss due to warmer temperatures. Boreal forests have a large role in annual cycle of atmospheric CO2, and to test these hypotheses the model was driven with the observed annual atmospheric CO2 and observed daily air temperature and precipitation for the period 1974 to 1982. All other atmospheric variables were constant. During this period, the simulated seasonal amplitude in CO2 exchange for the boreal forests near Fairbanks increased by 0.52% per year. For comparison, the seasonal amplitude in atmospheric CO2 concentration increased by 0.4 to 0.8% per year. This shows that year-to-year differences in mean annual atmospheric CO2, daily air temperature, and daily precipitation can produce an increased seasonal amplitude in CO2 fluxes that is consistent with the observations. The increased amplitude was due to increased photosynthesis as atmospheric CO2 increased. However, the increase in annual aboveground tree biomass production was too small (3 g/m2/year/year) to be detectable given field sampling errors.

  Bonan, G.B. 1992. Comparison of atmospheric carbon dioxide concentration and metabolic activity in boreal forest ecosystems. Tellus 44B:173-185.

- **Air temperature and tree growth**. The model, applied to a single-tree was used to derive the relationship between air temperature and tree growth for black spruce. Physiological properties of black spruce growing near treeline in subarctic Quebec were used for the simulations. This physiology allowed black spruce to grow over a wider range of air temperatures (annual growing degree days) than is reflected in its geographic distribution. In particular, the northern limit to black spruce was not caused by the direct effects of cold growing season temperatures on tree growth; growth was optimal, with respect to temperature, at the southern range limit.

Bonan, G.B, and Sirois, L. 1992. Air temperature, tree growth, and the northern and southern range limits to Picea mariana. Journal of Vegetation Science 3:495-506.

The model was substantially modified from this first version to study the environmental and physiological controls of forest production. The model was modified to include an updated photosynthesis parameterization and dynamic nitrogen limitation to tree growth. Photosynthesis was modeled using the Farquhar approach, with species-specific physiology. Decomposition and nitrogen mineralization were modeled using the Agren/Bosatta approach. The model was applied to aspen, birch, balsam poplar, white spruce, and black spruce forests near Fairbanks to examine the physiological controls of the carbon balance of boreal forests. Model analyses suggest that differences in the carbon balance of these forests can be explained by key physiological parameters that link photosynthesis, carbon allocation, nitrogen requirements, litter quality, and folige longevity. Simulations showed that coniferous and deciduous physiology maximizes annual tree production for coniferous and deciduous forests, respectively, giving a physiological basis for the evolution of their different life history characteristics.

- Bonan, G.B. 1993. Physiological controls of the carbon balance of boreal forest ecosystems. Canadian Journal of Forest Research 23:1453-1471.

Model applications:

- **Leaf area index, forest type, and photosynthesis**. The model was used to examine the relative importance of leaf area index and forest type, two key ecological variables that can be remotely-sensed, for land-atmosphere CO_2 exchange in the boreal forests near Fairbanks. Model sensitivity studies showed than net canopy CO_2 assimilation was as sensitivity to uncertainty in LAI as it was to uncertainty in species composition. The sensitivity to species composition was greater between needleleaf evergreen (black spruce, white spruce) and broadleaf deciduous (aspen, birch, balsam poplar) species than among species within a life form. These analyses highlight the importance of recognizing physiological differences among needleleaf evergreen and broadleaf deciduous forest types in addition to LAI when developing remotely-sensed based models of CO_2 fluxes in boreal forests.

Bonan, G.B. 1993. Importance of leaf area index and forest type when estimating photosynthesis in boreal forests. Remote Sensing of Environment 43:303-314.

- **Net primary production and mean annual air temperature**. The model was used to derive the observed relationship between NPP and MAAT. The model successfully reproduced this relationship and showed that it reflected, at least for boreal and temperate coniferous forests growing on moist soils, the length of the growing season, nitrogen limitation, and lower maintenance respiration rates in warm climates than cold climates. These analyses showed that simple physiological assumptions can result in reasonable predictions of NPP over a wide range of climates.

  Bonan, G.B. 1993. Physiological derivation of the observed relationship between net primary production and mean annual air temperature. Tellus 45B:397-408.

Current Work

These background studies were so successful (at least in my opinion) that I decided to abandon the boreal forest model and make a more general land-atmosphere model that would have a diurnal cycle and be applicable to all surface types. This would allow the model to be coupled to an atmospheric general circulation model. I call this new model the NCAR Land Surface Model.

- Preliminary simulations with version 0 of this model showed that simple physiological and ecological assumptions can result in reasonable simulation of land-atmosphere CO2 exchange, as compared to observed estimates of annual net primary production and annual microbial respiration.

  Bonan, G.B. 1995. Land-atmosphere CO2 exchange simulated by a land surface process model coupled to an atmospheric general circulation model. Journal of Geophysical Research 100:2817-2831.

Effects of Lakes and Wetlands on Climate

Lakes and wetlands can comprise a large fraction of the land surface. In regions of high inland water, they have a significant impact on climate because of differences in albedo, heat capacity, roughness length, and energy exchange compared to vegetated surfaces. I used version 0 of the NCAR Land Surface Model, coupled to a modified version of the NCAR Community Climate Model version 2, to examine the effects of inland water bodies on climate. The land surface model allows for multiple surface types within a grid cell. A lake/swamp model is used to calculate surface fluxes and temperatures for the fractions of the grid cell covered by lakes and wetlands.

In July, the presence of water bodies results in a spatially consistent signal in which high inland water regions are 2 to 3C cooler, have increased latent heat flux (10 to 45 W/m2), and decreased sensible heat flux (5 to 30 W/m2) compared to a simulation without inland water. These changes are statistically significant (based on 5-year simulations) in the lake region of NW Canada, the Great Lakes region of North America, the swamp and marsh region of the Siberian lowlands, and the lake region of East Africa. January effects were difficult to interpret due to large interannual model variability. In East Africa, the January (wet season) signal was less than the July (dry season) signal.

References

Bonan, G.B. 1995. Sensitivity of a GCM simulation to inclusion of inland water surfaces. Journal of Climate 8:2691-2704.

Infiltration and Surface Runoff

I used preliminary versions of the NCAR Land Surface Model in two studies to examine the importance of infiltration and surface runoff parameterizations for climate studies.

- In Bonan (1994), I used prescribed atmospheric forcings to compare NCAR LSM (version 0) and the LSX (version 1.02) land surface model. These models have different parameterizations of energy exchange, turbulent transfer, and hydrology. Although the two models have quite different canopy energy exchange parameterizations, especially turbulent transfer, most differences in sensible and latent heat fluxes are related to the parameterization of infiltration capacity. NCAR LSM has greater infiltration and less runoff than LSX. When NCAR LSM uses the infiltration capacity of LSX, the NCAR LSM simulations are similar to the LSX simulations. Stomatal resistance is also important, and when given the same stomatal resistances both models have similar transpiration rates.

- In Bonan (1996), I used version 0 of the NCAR LSM land surface model, coupled to a modified version of the NCAR Community Climate Model version 2, to examine the importance of infiltration in a coupled land-atmosphere model. A sub-grid scale parameterization of infiltration and surface runoff was compared to a grid-average parameterization. Averaged over 5-year simulations, the sub-grid parameterization resulted in significantly less infiltration compared to the grid-average parameterization. As a result, the soils were drier, latent heat flux decreased, and surface air temperature increased. These results are consistent with other sub-grid hydrology studies, which also resulted in drier soils, decreased latent heat flux, and warmer surface temperatures.

References

Bonan, G.B. 1994. Comparison of two land surface process models using prescribed forcings. Journal of Geophysical Research 99:25803-25818.

Bonan, G.B. 1996. Sensitivity of a GCM simulation to subgrid infiltration and surface runoff. Climate Dynamics 12:279-285.

Land Surface Climatology of NCAR LSM coupled to CCM3

The NCAR Land Surface Model (NCAR LSM version 1.0) replaces prescribed surface wetness, prescribed snow cover, surface albedo, and surface flux parameterizations previously used in the NCAR Community Climate Model version 2 (CCM2), thereby fully accounting for the land surface processes for CCM3. The model's land surface climate was documented using a 15 year fully coupled atmosphere (CCM3) and land (NCAR LSM 1.0) simulation for the study period of December 1978 to September 1993. Analyzing surface air temperatures, precipitation and soil water, the model successfully simulates geographic and seasonal patterns. However, Spring and Autumn were better simulated than Winter and Summer, and precipitation was better simulated than runoff. Due primarily to the inclusion of net land-atmosphere CO_2 exchange, the model is well suited for studies of the global carbon cycle. The model simulates (1) a well defined growing season based on temperature and soil water, and (2) annual net primary production consistent with other estimates.

Bonan, G.B. 1998. The Land Surface Climatology of the NCAR Land Surface Model Coupled to the NCAR Community Climate Model. Journal of Climate 11:1307-1326.