A Global Vegetation Modeling System for NEWS

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This is a Discovery-Driven NEWS Investigation that includes the NEWS strategic elements:

Observation, Understanding, Models, and Prediction

Abstract

We propose to develop, parameterize, and evaluate a global modeling system for simulating land-atmosphere exchanges of water, energy, and carbon that will be applied in both a prognostic climate model (Community Climate System Model, CCSM) and in a global operational diagnostic (data assimilation) model (Land Information System, LIS). The model will be based on improvements to the Community Land Model (CLM3) with extensions for prognostic phenology, ecosystem competition, subgrid-scale water redistribution, physiological stress, and canopy air space energy budget. The model will be parameterized using satellite products documenting fractional land coverage by plant functional types and the fraction of photosynthetically active radiation absorbed by plant canopies (FPAR). Model evaluation at multiple spatial scales will be performed using local measurements of micrometeorological fluxes and storage of water and carbon, stream discharge from instrumented catchments, and regional information about snow cover and water storage. The modeling system and related data sets will be delivered to both the CCSM and LIS groups through structured collaborations (see attached letters).

1. Introduction

Land-atmosphere interactions are now widely recognized to play important roles in the distribution and availability of water resources for society and also comprise a major component of climate feedback and climate change. Prognostic simulation of land-atmosphere interaction with respect to climate variability and change requires treatment of changing distributions of transpiring leaves in response to seasonal, interannual, and longer-term changes in weather and climate. On decadal and longer time scales, these variations include ecosystem disturbance (e.g., harvest, disease, and fire), growth, and succession: so-called Dynamic Global Vegetation Models (DGVMs) are now recognized to be crucial to simulation of past or future climates (e.g., Prentice et al, 1992; Woodward et al, 2000; Thonicke et al, 2001; Sitch et al, 2003). DGVMs simulate changes in the geographic distribution of vegetation that are driven by changing climate, and also contribute to changes in physical climate itself.

At shorter time scales, changes in the state of the vegetated land surface can impact physical climate and hydrology, even given a fixed distribution of major vegetation types. During transitional seasons (spring and fall), phenological changes (e.g., emergence and senescence of leaves) can have profound impacts on ecosystem-level transpiration and Bowen ratio (Hogg et al. 2000; Fitzjarrald et al. 2001; Schwartz and Crawford 2001), and therefore the temperature and circulation patterns of the overlying atmosphere (Tsvetsinskayaet al 2001; Lu et al , 2001; Lu and Shuttleworth, 2002). Springtime emergence of leaves in seasonally cold climates is not random, but rather tends to occur systematically during periods of unseasonably warm weather. Levis and Bonan (2004) found that simulation of temperature and circulation patterns was substantially improved by including an algorithm to predict the emergence of a transpiring canopy in the land-surface component of a climate model. Such *prognostic phenology* is a component of DGVMs, which typically simulate the dynamics among competing types of plants in an ecosystem to update their distributions. Successful simulation of seasonal transitions is therefore an important criterion for evaluation of DGVM logic.

The need to predict hydrologic change as a component of climate change has led to a proliferation of hydrologic submodels as climate model components, and these submodels are increasingly being used diagnostically in data assimilation ("nowcast" or "hindcast" mode, e.g., Mitchell et al, 2004; Rodell et al, 2004). This application is analogous to the important role of numerical weather forecasting and reanalysis, three decades of which has established the credibility of the physics and numerics used in climate models. Using many data streams (precipitation, surface temperature and humidity, radiation, vegetation and soils, etc), diagnostic hydrologic models characterize time-space variability in water and energy fluxes and storage. Hydrologic data assimilation provides important observationally-based information to land managers and the public. Being confronted with model error and bias on a daily basis allows hydrologists to gain crucial insight into model behavior and develop predictive skill which greatly enhances the prospects for prediction of future changes.

Most diagnostic analyses of land-atmosphere interaction still prescribe both the geographic distribution of plant types ("biomes") and seasonal changes in their transpiring leaf area index (LAI). This is done either according to "look-up tables" which relate LAI by biome to the time of year (e.g., Dai et al, 2003) or by using LAI derived from satellite imagery (e.g., Sellers et al, 1996b; Lu et al, 2001). An important advantage of the satellite approach is that it is intended to capture realistic spatial, seasonal, and interannual patterns in vegetation and therefore lead to more realistic analyses. An unfortunate consequence is that this approach fails to reveal biases in prognostic phenology or dynamic vegetation algorithms that must be used for simulations of longer-term climate change, and therefore an important linkage between diagnostic and predictive modeling is forsaken.

Another limitation of hydrologic data assimilation that uses prescribed phenology from satellite imagery is due to "contamination" of imagery by clouds. Even partial obscuration of the land surface by clouds reduces vegetation indices based on optical remote sensing. This has led to the widespread practice of various forms of "maximum-value compositing" of vegetation indices, in which a number of images are processed to obtain the greenest value of each pixel during the compositing time period to reduce the impact of cloud contamination (e.g., Holben, 1986; Los et al, 2000; Myneni et al, 2002).

Although compositing produces a "cleaner" (less noisy) LAI timeseries at the pixel level, it invariably leads to overestimation of the length and underestimation of the interannual variability of the growing (transpiration) season. Consider the case of monthly maximum-value compositing during the spring transition. If leaves emerge at a given location in late April, for example, an optical vegetation index (e.g., Normalized Difference Vegetation Index, NDVI, Los et al, 2000) will undergo an upward trend during the month. The algorithm will therefore always choose a value for the month that represents conditions on a clear day near the very end of the month, when LAI is highest, and assign that value as a mean for the whole month. An analogous effect in autumn will assign a systematically high value to the final period of greenness which will most likely be derived from a scene observed near the beginning of the compositing period. The problem is exacerbated if monthly composites are assigned to represent mid-month times and linear interpolation between monthly values is used (Sellers et al, 1996). In such an application, onset of greenness may occur during the last week of April, leading to a high LAI assigned to represent conditions on April 15, and interpolation to this high value would begin on March 16, nearly 1.5 months too early! In addition to systematic overestimation of growing-season length, this procedure obscures interannual variability because the compositing and averaging periods are longer than the typical variation in onset of greenness from year to year or due to secular trends (Myneni et al, 1997; Schaefer et al, 2002). It is important to note that LAI derived from the MODIS sensor (Myneni et al, 2002) is based on shorter (8-day) compositing periods, an so suffers less egregious time aliasing than monthly composited data described above. This is a matter of degree, however, and represents a "trade-off" in that more cloud contamination is tolerated (especially in the more-cloudy tropics), leading to more spurious high-frequency noise.

Prognostic phenology algorithms typically diagnose onset of greenness in seasonally cold ("summergreen") ecosystems using a thermal sum (growing degree days, e.g., Hunter and Lechowicz, 1992; Caprio, 1993) after fulfilling a chilling requirement (e.g., Kramer, 1994). Such models have long been evaluated by comparison to phenological datasets derived from field observations, but such data are of limited applicability at olarge scales because they usually represent conditions for single species (e.g., Defila and Clot, 2001), whereas global vegetation models run at coarser scales must inevitably rely on assemblages in biomes or plant functional types. White et al (1997) solved this problem by using individual pixel timeseries of daily NDVI (not maximum-value composites) to develop an empirical algorithm of this type for use in dynamic vegetation models. Stöckli and Vidale (2004) used the 20-year record of NDVI measured by the NOAA Advanced Very High Resolution Radiometer (AVHRR) to study phenological variability and trends in Europe, and found strong climate-related interannual variability and secular trends. Although more attention has been devoted to cold-deciduous ("summergreen") phenology in vegetation models, a related problem is the prediction of LAI in tropical and arid or semiarid ("raingreen") ecosystems that grow and lose leaves due to seasonal and interannual variations in precipitation. Prediction of phenological changes in these drought-deciduous ecosystems is more complicated than in summergreen systems because it is tied closely to soil moisture, vertical root distribution, and physiological stress. Finally, agricultural systems pose a unique challenge to prognostic phenology research and hydrologic modeling because seasonal changes in their leaf area is managed by people for profit.

Another approach to ecosystem phenology involves tracking carbon gain by photosynthesis; allocation of photosynthate to leaves, stems, and roots; and losses by growth and maintenance respiration. In this biogeochemical approach, leaves are grown when they provide ecological benefit by adding to the net capacity of the ecosystem to fix carbon, and are lost when maintenance costs in respiration exceed potential carbon gain (e.g., Kikuzawa, 1995). This approach is important because it can directly link phenology and canopy development with longer-term ecosystem dynamics that are necessary for simulation of land-atmosphere interactions during climate change.

We propose a three-year program of research that will lead to the development and evaluation of a Vegetation Modeling System (VMS) for improved diagnostic modeling of land-atmosphere exchanges of water and energy that includes global prediction of leaf-area index. The VMS will be developed from existing component models (section 2): the Community Land Model (CLM), Biome-BGC (Running and Hunt, 1993; Thornton 1998; White et al, 2000), and the Simple Biosphere Model (SiB, Sellers et al, 1996; Baker et al, 2003). The VMS will include options for fairly simple climate-based prognostic phenology and for more dynamic phenology based on biogeochemical cycling and allocation of nutrients and the fate of organic matter, and will be parameterized from remotely-sensed data (Section 3). The system will include improved representations of both vertical and (subgrid-scale) horizontal redistribution of soil moisture and its interaction with root distribution in modulating physiological stress and the temporal dynamics of drought-deciduous ecosystems. It will be evaluated against observations using eddy covariance records, instrumented catchments, and regional-scale water storage in snow, surface water, and soil (section 4). VMS components and input data sets will be developed to run within the Land Information System (LIS, Kumar et al, 2005; Tian et al, 2005; http://lis.gsfc.nasa.gov).

The proposed research directly addresses the "*NEWS Challenge*" outlined in the NRA: "documenting and enabling improved, observationally based, predictions of water and energy cycle consequences of Earth system variability and change, by developing, testing, and implementing approaches using innovative global environmental information from NASA's research programs that contribute to enhanced predictive capability for the water and energy cycles." We will work closely with our collaborators to transfer our results to the Land Information System (LIS) for high-resolution diagnostic modeling and assimilation of hydrologic data and to the Community Climate System Model (CCSM) for hydrologic prediction of climate change, thereby making decisive progress toward *assessments of natural variability in surface and subsurface moisture and energy* and in *improved water cycle forecasts for use in Decision Support Systems* on the Water and Energy Cycle Roadmap. Our phenology and vegetation dynamics research will use multiyear timeseries of optical imagery from space and multiple NASA data products to address a persistent bias in the timing of seasonal canopy development (LAI), and will combine ecophysiology and carbon and nitrogen biogeochemistry with soil and snow hydrology, spatial scaling, and data assimilation. These elements of the proposed research are specifically solicited under "NEWS Discovery Investigations" on pp 20-21 of the NRA.

2. Model Description

The Community Land Model (CLM) has been developed from previous model components by a large number of researchers (Zeng et al, 2002; Dai et al, 2003), and is currently being run in the LIS (Kumar et al, 2005; Tian et al, 2005; http://lis.gsfc.nasa.gov). It has one vegetation layer, 10 unevenly spaced vertical soil layers, and up to 5 snow layers. In the LIS, seasonal phenology is derived from monthly mean (temporally smoothed) LAI obtained from MODIS imagery (C. Peters-Lidard, personal communication), which ties simulations to observed space/time variations, but leads unavoidably to aliasing in seasonal transitions as outlined above. The CLM has continued to evolve as the land component of the Community Climate System Model (Bonan et al, 2002a; Oleson et al, 2004), in which a large community of researchers develop and evaluate model improvements through a structured set of Working Groups (http://www.ccsm.ucar.edu). The most significant development in the CLM since its incorporation into the LIS is the reorganization of the grid structure into collocated patches of *plant functional types* (PFTs, replacing assemblages or biomes, Bonan et al, 2002b), and the subsequent introduction of competitive dynamics transforming CLM into a DGVM (Bonan et al, 2003; Levis et al, 2004; Levis and Bonan, 2004).

Horizontal land surface heterogeneity is represented by a nested subgrid hierarchy in which each atmospheric grid cell is composed of fixed geographic landunits (e.g., lakes, cities, and vegetated), soil columns, and co-existing plant functional types (PFTs) which compete for water and other resources (Fig 1). Biophysical processes are simulated for each subgrid unit landunit, column, and PFT) independently, and prognostic variables are maintained for each subgrid unit. Vertical heterogeneity is represented by a single vegetation layer, 10 layers for soil, and up to five layers for snow, depending on the snow depth.

The CLM3-DGVM simulates the distribution and structure of natural vegetation dynamically, using mechanistic parameterizations of large-scale vegetation processes (Foley et al. 1996; Brovkin et al. 1997; Friend et al. 1997; Cox et al. 1998; Potter and Klooster 1999; Woodward et al. 2000; Sitch et al. 2003). Each plant functional type (e.g., broadleaf deciduous trees, evergreen deciduous trees, C_3 grass) is represented by an individual plant with the average biomass, crown area, height, and stem diameter of its population, by the number of individuals in the population, and by the fractional cover in the grid cell (Bonan et al. 2003). With dynamic vegetation enabled, vegetation cover and leaf area index are predicted rather than obtained from prescribed surface datasets. Community composition and ecosystem structure are updated with an annual time step in response to establishment of new plants, resource competition, growth, mortality, and fire. An algorithm for leaf phenology (similar to Kucharik et al. 2000) updates leaf area index daily in response to air temperature for summergreen (cold deciduous) plants and soil water for raingreen (drought deciduous) plants.

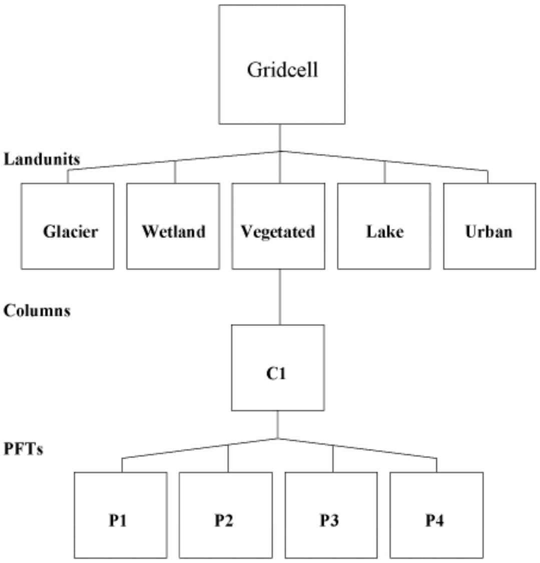

Figure 0: Conceptual organization of subgrid-cell heterogeneity in CLM

In the CLM3-DGVM phenology model, leaves emerge on summergreen trees when the accumulated growing-degree-days above 0°C exceed 100 days. Leaf emergence occurs over a period equal to 50 degree-days. Leaf senescence occurs at a rate of 1/15 day^{-1}. More specifically, leaf emergence and senescence for summergreen trees are represented by the fraction, ϕ, of the annual maximum leaf area index, LAI_{max}, present on a plant on a given day, where emergence:

$$\phi = (GDD_{0^\circ C} - 100)/50 \quad \text{when } T_{10d} \geq \max\,(T_f, T_c + 5), \tag{1}$$

and senescence:

$$\phi = \phi - 1/15 \qquad \text{when } T_{10d} \leq \max\,(T_f, T_c + 5), \text{ and} \tag{2}$$

$$LAI_{daily} = \phi \, LAI_{max} \tag{3}$$

where ϕ is constraint to be between zero and one, T_{10d} is the 10-day running mean of surface air temperature (K), T_f equals 273.16 K, and T_c is the 20–yr running mean of the minimum monthly temperature (K). Here $GDD_{0^\circ C}$ is the running accumulation of growing degree days above 0°C, smoothed out by using $T_{10d,}$ and reset to 0 when $T_{10d} < T_{f.}$

Photosynthetic carbon assimilation, *A*, is calculated using enzyme kinetics (Farquhar et al, 1980) and is linked to stomatal conductance, g_s, by the Ball-Berry-Collatz parameterization (Collatz et al, 1991; Sellers et al, 1996a; Bonan, 1996). The rate of photosynthesis depends on light, temperature, CO2 concentration, and soil water. In particular, photosynthesis is precluded with temperatures below freezing (-5 °C for needleleaf trees) and increases with warmer temperatures up to an optimal temperature of between 25°C and 30°C depending on the plant type. Use of 100 degree-day threshold above 0°C for leaf emergence in Eqn. (1) ensures that leaves emerge when conditions will also support photosynthesis.

Working with our collaborators at NCAR, we will also develop and test new phenological algorithms based on the biogeochemical benefit and loss approach in CLM3. This will entail specification of allocation of new photosynthate to leaves, stems (wood), and roots based on plant functional type and ecosystem conditions (limitations to growth by availability of light, water, and nutrients). Research currently underway at NCAR (Peter Thornton, personal communication) includes the development of algorithms for tracking carbon and nitrogen in soils, plants, and litter, and both N-limitation and C & N allocation within the ecosystem. This work is coordinated through the CCSM Land and Biogeochemistry Working Groups, of which the P.I. is a member, and is based on similar logic in Biome-BGC (Running and Hunt 1993; Thornton, 1998; White et al, 2000). This version of the model is referred to as CLM3-CN. Phenology in CLM-CN is parameterized according to photosynthetic allocation to leaves and the associated carbon cost in maintenance respiration, which in turn depends on leaf nitrogen. The new modeling system will link exchanges of water and energy with those of carbon and nitrogen in a biophysically and biogeochemically realistic way, and will allow a new set of observational constraints (e.g., biomass surveys, soil carbon, atmospheric trace gas inversions of CO_2) to be brought to bear on hydrologic problems.

Working with our collaborators at NCAR and in the CCSM Working Groups, we will also modify the energy balance closure logic of CLM3-CN to include prognostic solution for canopy-air-space temperature, water vapor mixing ratio, and CO_2. This approach introduces a finite mass of atmosphere in contact with the vegattion canopy, leading to more stable numerical solution and much better behavior during transitions from turbulent to stable aerodynamics and vice versa. It also provides a framework for later addition of model functionality such as multilayer canopies and radiative transfer. We have already implemented this approach in SiB2.5, with excellent results (Baker et al, 2003; Stockli and Vidale, 2005).

CLM tracks changes in soil moisture in 10 layers in the vertical in each soil column, drawing a fraction of the water required for transpiration from the roots in each layer. The distribution of transpiration loss in the vertical, and the overall effect of vertical distribution of soil moisture, is crucial to the simulation of physiological ecosystem stress due to drought. The current version of CLM3 is overly sensitive to dry soils (P. Thornton, personal communication). We will experiment with new treatments of rooting distribution, transpiration, physiological stress, and hydraulic lift in the multilayer soil. The model already includes a simplified version of the subgrid-scale hydrologic redistribution algorithm TOPMODEL, which is based on topographic statistics. We will experiment with the TOPMODEL implementation to develop a new treatment of subgrid-scale variations in ecosystem physiological stress, possibly linked to the presence of patches of plant functional types within each soil column. A similar approach was used with SiB2.5 by Stockli et al (2005) and compared very favorably with catchment-scale stream discharge.

3. Parameterization of phenological submodel by assimilation of AVHRR and MODIS observations

The prognostic phenology logic in CLM-DGVM-CN contains many parameters. Some are generic to even simple phenology codes (e.g., the chilling requirement and degree-day thresholds for emergence of cold deciduous canopies, conditions for abcission of leaves, the dependence of these on vegetation type). The biogeochemical and ecosystem competition logic embodied in the new model provides flexibility for simulation of future climates and linkages to other parts of the Earth system, but introduces even more parameters associated with nutrient cycling, resource limitation, carbon allocation, and turnover times. Some of these parameters have been optimized in earlier models that use similar algorithms (e.g., CASA, Potter et al, 1993; CENTURY, Parton, 1996; Biome-BGC, White et al, 2000), and we will start with these parameterizations in VMS. In addition, we will conduct an ambitious research effort on parameter estimation in the phenological submodel by optimizing some of the most sensitive yet poorly known parameters for each plant functional type using satellite observations. In addition to the development of new phenology logic for land surface models and data assimilation systems, this work is expected to lead to new LAI data that can be used even if a modeler chooses not to implement the more complex biogeochemical logic of CLM-CN.

A particular strength of the VMS is the flexibility inherent in “continuous” mixtures of plant functional types, rather than predefined “discrete” biomes. This feature also poses a challenge for parameterizing phenology. We will develop high-resolution model parameter sets for subdomains in “end-member” regions of interest (boreal forest, temperate forest, C3 and C4 temperate grasslands, subtropical grasslands, tropical forests, croplands of various kinds, and pastures), in which we will map topography, soils, and all model parameters from available geographic data. We will work closely with our colleagues at NASA Goddard (see attached letter of collaboration) to parameterizse each subdomain in such a way that the VMS could be run in the LIS environment, and will obtain 1-km meteorological driver data for each subdomain. Initial distributions of plant functional type within each 1-km pixel will be specified from the MODIS *continuous vegetation fields* product, which has a one-to-one correspondence with the functional types simulated in CLM3-DGVM (Hansen et al, 2000, 2003).

We will then perform ensembles of multiyear simulations on the high-resolution subdomains, and use a radiative transfer calculation to calculate 1-km FPAR for each pixel each day, as was done by Tian et al (2004). Computed FPAR will be compared to MODIS FPAR pixel-by-pixel, for clearsky measurements made on real dates (not on 8-day composites). These runs will be performed in an ensemble framework, and parameters for each plant functional type will be optimized following the method of Zupanski et al (2005a,b). Finally, we will aggregate to coarser resolution (e.g., 50 km) and run the model at global scale using downscaled weather drivers (ECMWF reanalysis), and compare simulated FPAR and NDVI to the AVHRR record obtained since 1981.

4. Model Evaluation

We will use an integrated approach including satellite remote sensing products, flux tower observations and catchment-scale observations, as proposed by Running et al. (1999) and Turner et al. (2004), to learn more about the land surface processes simulated by the proposed VMS. Simulations and observations will be compared at selected field sites (e.g., flux towers, instrumented catchments) for each of the plant functional types defined by CLM. We will test the model over a wide range of spatial scales, from individual sites to regional scale. Testing areas will be chosen to include the most complete vegetation-related datasets available with regards to both site and spatially distributed data, and cover as many diversified climate-ecosystem zones as possible, and perform un-tuned model comparisons to observartions, which guarantees that the evaluation results can be generalized for global coupled or off-line simulations (as in Stockli and Vidale, 2004). These are the observational datasets we will use:

The evaluation of the proposed VMS will be performed in several steps, focusing first on process scales and aggregating to increasingly large areas:

1. testing the predictions of vegetation phenology against local observations:
   - IPG: observed phenology in phenological gardens (20 sites, 47 year long dataset, Europe only, http://www.agrar.hu-berlin.de/pflanzenbau/agrarmet/ipg_2.html)
2. understanding the sensitivity of modeled land surface heat, water and carbon fluxes to prognostic vegetation phenology at local scales;
   - FLUXNET: a global array of over 200 flux towers, providing multi-year time-series (1995-present) of eddy covariance water, energy, momentum, and carbon fluxes, soil temperature and moisture profiles, micrometeorological measurements (Baldocchi et al., 2001).
   - To evaluate our improved treatment of physiological stress, we will focus on a variety of sites that have been shown to make well-observed transitions from unstressed to stressed conditions and back (seasonal drought in Oregon and Oklahoma; interannual changes in dry-season duration and severity at the Tapajos sites in Brazil (Humberto Rocha, LBA, personal communication), and severe seasonal drought in southern Africa (Niall Hanan, personal communication).
3. evaluation of biogeochemical cycling against local measurements of biogeochemical fluxes and pool sizes in well-studied ecosystems;
   - LTER: gound observed vegetation states (26 sites, 20 year long dataset, USA only, http://www.lternet.edu/)
4. Comparison of aggregated spatially-explicit predictions of soil moisture and runoff against soil moisture data and stream discharge measured from gauged catchments;
   - Oklahoma mesonet (Illston et al, 2003)

    - SMEX campaigns in Oklahoma, Alabama, Georgia and Brazil). More detailed information regarding the SMEX03, including AMSR images, photos, and experiment plans, can be found at: http://hydrolab.arsusda.gov/smex03/
    - GRDC: Global river runoff time-series of catchments and sub-catchments, worldwide availability and long-term coverage. (http://grdc.bafg.de)

5. Comparison of regionally-aggregated prediction of snowpack distribution and total water storage against global satellite observations
    - snow depth and cover data NASA Cold Land Processes Experiment (CLPX) (http://www.nohrsc.nws.gov/~cline/), and NOAA National Operational Hydrologic Remote Sensing Center (NOHRSC) (http://www.nohrsc.nws.gov/), MODIS (NASA's TERRA and AQUA satellites) snow cover (1km, global)
    - GRACE (NASA's Gravity Recovery And Climate Experiment): monitoring capability of the large-scale water cycle, especially of changes in the terrestrial water storage, including deep groundwater and snow depth (global coverage, 2002-present).

The successful application of the above procedures guarantees that the new model framework provides an improved parameterization of phenology in operational land surface model computations (e.g. LIS, GLDAS, NLDAS). We will next conduct land surface model evaluations to understand whether an improved representation of spatial, seasonal and interannual variability of vegetation phenology allows to better model land surface heat, water and carbon fluxes. The prediction of these fluxes is of central interest for agricultural production, water resource management, and flood, weather, and climate predictions (Kumar et al., 2004).

5. Products & technology transfer

The parameterization and high-resolution evaluation of a major component of a the Community Climate System Model will allow this work to have wide applicability to a

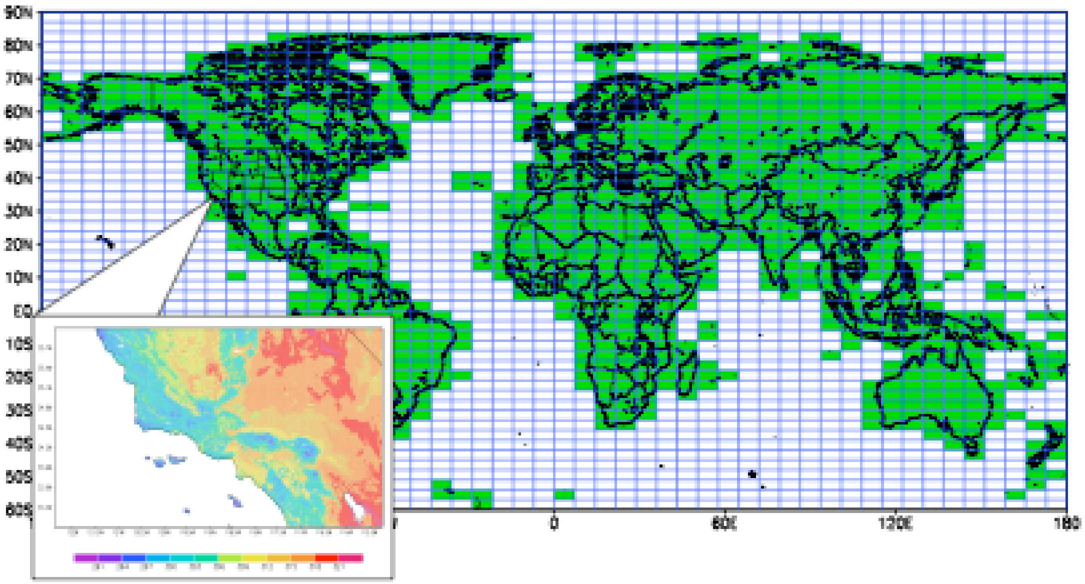

Figure 2: Computational architecture of 1-km simulations in LIS. Tian et al (2005)

large group of climate researchers. The PI already participates in a well-organized effort to improve this model through the CCSM Working Group structure (see attached letter of collaboration).

We will also work closely with our collaborators at NASA to port our new modeling system for use in the land information system (lis.gsfc.nasa.gov, see attached letter of collaboration). It may well be that the full dynamic vegetation logic is too computationally expensive to be run online in the operational LIS runtime environment. We will cooperate with LIS personnel to develop code that is sufficiently compact and efficient to use operationally at 1-km resolution (Fig 2). In addition, we will port all necessary data sets to work in LIS, including an offline phenology "product" that can be used offline of the VMS within the LIS.

Finally, we note the opportunities for transfer of VMS functionality to carbon cycle models and observing systems being developed for the North American Carbon Program (NACP). The PI currently serves as the Chair of the Science Steering Group for NACP, and is developing Mesoscale data assimilation (under separate funding), which would be a natural vehicle for future application of the VMS.

6. References

Baker, I.T., A.S. Denning, N. Hanan, L. Prihodko, P.-L. Vidale, K. Davis and P. Bakwin, 2003: Simulated and observed fluxes of sensible and latent heat and CO_2 at the WLEF-TV Tower using SiB2.5. *Global Change Biology*, **9**, 1262-1277.

Bonan, G.B., Oleson, K.W., Vertenstein, M., Levis, S., Zeng, X., Dai, Y., Dickinson, R.E., and Yang, Z.-L. 2002a. The land surface climatology of the Community Land Model coupled to the NCAR Community Climate Model. *J. Climate* **15**, 3123-3149.

Bonan, G.B., Levis, S., Kergoat, L., and Oleson, K.W. 2002b. Landscapes as patches of plant functional types: An integrating concept for climate and ecosystem models. *Global Biogeochem. Cycles* **16**, 5.1-5.23.

Bonan, G. B., S. Levis, S. Sitch, M. Vertenstein, and K. W. Oleson, 2003: A dynamic global vegetation model for use with climate models: concepts and description of simulated vegetation dynamics. *Global Change Biol.,* **9**, 1543-1566.

Bounoua, L., G. J. Collatz, S. O. Los, P. J. Sellers, D. A. Dazlich, C. J. Tucker, and D. A. Randall, 2000: Sensitivity of climate to changes in NDVI. J. Clim., 13, 2277–2292.

Brovkin, V., A. Ganopolski, and Y. Svirezhev, 1997: A continuous climate-vegetation classification for use in climate-biosphere studies. *Ecol. Model.,* **101**, 251-261.

Caprio, J. M., 1993. Flowering dates, potential evapotranspiration, and water use efficiency of *Syringia vulgaris* L. at different elevations in the western United States of America. *Agric. Forest Meteor.*, **63**, 55-71.

Cox, P. M., C. Huntingford, and R. J. Harding, 1998: A canopy conductance and photosynthesis model for use in a GCM land surface scheme. *J. Hydrol ,* **213**, 79-94.

Dai, Y., X. Zeng, R.E. Dickinson, I. Baker, G.B. Bonan, M.G. Bosilovich, A.S. Denning, P.A. Dirmeyer, P.R. Houser, G.-Y. Niu, K.W. Oleson, C.A. Schlosser and Z.-L. Yang, 2003: The common Land Model (CLM), *Bull. Amer. Meteorol. Soc.*, **84**, 1013-1023.

FAO, 1995: A Digital Soil Map of the World. Published on CD-ROM. 67.

Farquhar, G. D., von Caemmerer, S. and Berry, J. A., 1980. A biochemical model of photosynthetic CO_2 assimilation in C_3 plants. *Planta*, **149**, 78-90.

Fitzjarrald, D. R., O. C. Acevedo, and K. E. Moore, 2001: Climatic consequences of leaf presence in the eastern United States. *J. Climate*, **14**, 598–614.

Foley, J. A., I. C. Prentice, N. Ramankutty, S. Levis, D. Pollard, S. Sitch, and A. Haxeltine, 1996:

An integrated biosphere model of land surface processes, terrestrial carbon balance, and vegetation dynamics. *Global Biogeochem. Cycles,* **10**, 603-628.

Friend, A. D., A. K. Stevens, R. G. Knox, and Cannell, M. G. R., 1997: A process-based, terrestrial biosphere model of ecosystem dynamics (Hybrid v3.0). *Ecol. Model.,* **95**, 249-287. 47.

Hansen, M. C., R. Defries, J. R. G. Townshend, and R.Sohlberg, 2000: Global land cover classification at 1km spatial resolution using a classification tree approach. *Int. J. Remote Sensing*, **21**, 1331–1364.

Hansen, M.; DeFries, R.; Townshend, J.R.; Carroll, M.; Dimiceli, C.; Sohlberg, R.. 2003. 500m MODIS Vegetation Continuous Fields. College Park, Maryland: The Global Land Cover Facility.

Hogg, E. H., D. T. Price, and T. A. Black, 2000: Postulated feedbacks of deciduous forest phenology on seasonal climate patterns in the western Canadian interior. *J. Climate*, **13**, 4229–4243.

Holben, B. N., 1986: Characteristics of maximum-value composite images from temporal AVHRR data. *Int. J. Remote Sens*., **7**, 1417–1434.

Houser, P.R., M. Rodell, U. Jambor, J. Gottschalck, B. Cosgrove, J. Radakovich, K. Arsenault, M. Bosilovich, J. K. Entin, J. P. Walker, K. Mitchell, H. L. Pan, and C.-J. Meng, 2001. The Global Land Data Assimilation System, *BAHC News* (9) - *GEWEX News*, **11.**

Hunter, A. H. and M. J. Lechowicz, 1992. Predicting the timing of budburst in temperate trees. *J. Appl. Ecol.*, **29**, 597-604.

Illston, B.G., J.B. Basara, and K.C. Crawford, 2003: Soil Moisture Observations from the Oklahoma Mesonet. GEWEX News, Vol 13, No. 3, p. 13-14.

Kikuzawa, K., 1995. Leaf phenology as an optimal strategy for carbon gain in plants. *Can. J. Bot.*, **73**, 158-163.

Kramer, K. 1994. Selecting a model to predict the onset of growth of *Fagus sylvatica*. *J. Appl. Ecol.*, **31**, 172-181.

Kucharik, C. J., and Coauthors, 2000: Testing the performance of a Dynamic Global Eco-system Model: Water balance, carbon balance, and vegetation structure. *Global Bio-geochem. Cycles,* **14**, 795-825.

Kumar, S. V., C. D. Peters-Lidard, Y. Tian, P. R. Houser, J. Geiger, S. Olden, L. Lighty, J. L. Eastman, B. Doty, P. Dirmeyer , J. Adams , K. Mitchell, E. F. Wood, J. Sheffield, 2004: Land Information System - An Interoperable Framework for High Resolution Land Surface Modeling. Submitted to *Environmental Modelling & Software*. (http://lis.gsfc.nasa.gov/Papers/index.shtml).

Levis, S., G.B. Bonan, M. Vertenstein, and K.W. Oleson, The Community Land Model's Dynamic Global Vegetation Model (CLM-DGVM): Technical description and user's guide. NCAR Technical Note NCAR/TN-459+IA, 50 pp, 2004.

Levis, S., C. Wiedinmyer, G.B. Bonan, A. Guenther, Simulating biogenic volitale organic compound emissions in the Community Climate System Model. *J. Geophys. Res*., **108**(D21), 4659, doi:10.1029/2002JD003203, 2003.

Levis, S., and G. B. Bonan, 2004. Simulating springtime temperature patterns in the Community Atmosphere Model coupled to the Community Land Model using prognostic leaf area. *J. Climate*, **17**, 4531–4540.

Los, S. O., G. J. Collatz, P. J. Sellers, C. M. Malmstrom, N. H. Pollack, R. S. DeFries, L. Bounoua, M. T. Parris, C. J. Tucker, and D. A. Dazlich, 2000: A global 9-yr biophysical land surface dataset from NOAA AVHRR data. *J. Hydrometeorol.*, **1**, 183–199.

Loveland, T. R., B. C. Reed, J. F. Brown, D. O. Ohlen, Z. Zhu, L. Yang, and J. W. Merchants, 2000: Development of a global land cover characteristics database and IGBP DISCover from 1km AVHRR data. *Int. J. Remote Sensing*, **21**, 1303–1330.

Lu, L., and W. J. Shuttleworth, 2002: Incorporating NDVI-derived LAI into the climate version of RAMS and its impact on regional climate. *Journal of Hydrometeorology,* **3**, 347-362.

Lu, L., R.A.Pielke, Sr., G.E. Liston, W. Parton, D. Ojima, and M. Hartman, 2001: The implementation of a two-way interactive atmospheric and ecological model and its application to the central United States. *Journal of Climate,* **14**, 900-919.

Miller, D. A., and R. A. White, 1998: A conterminous United States multi-layer soil characteristics data set for regional climate and hydrology modeling. *Earth Interactions.*

Mitchell, K. E., et al, 2004. The multi-institution North American Land Data Assimilation System (NLDAS): Utilizing multiple GCIP products and partners in a continental distributed hydrological modeling system, *Journal of Geophysical Research*, **109**, D07S90, doi:10.1029/2003JD003823.

Myneni RB, et al.2002. Global products ofvegetation leaf area and fraction absorbed PAR from year one of MODIS data. *Remote Sensing of Environment* **83**, 214–231.

Oleson, K.W., Y. Dai et al., 2004: Technical description of the Community Land Model (CLM), NCAR Technical Note NCAR/TN-461+STR, 173 pp.

Parton, W. J. 1996. The CENTURY model. In: D. S. Powlson, P. Smith, and J. U. Smith, (Eds.), *Evaluation Of Soil Organic Matter Models Using Existing Long-Term Datasets*, Springer-Verlag, Berlin, Germany, pp. 283-293.

Potter, C. S., and S. A. Klooster, 1999: Dynamic global vegetation modeling (DGVM) for prediction of plant functional types and biogenic trace gas fluxes. *Global Ecol. Biogeogr. Lett.,* **8**, 473-488.

Potter, C. S., J. T. Randerson, C. B. Field, P. A. Matson, P. M. Vitousek, H. A. Mooney, and S. A. Klooster. 1993. Terrestrial ecosystem production: A process model based on global satellite and surface data. *Global Biogeochemical Cycles*. **7(4)**:811-841.

Randerson, J.T., M.V. Thompson, T.J. Conway, I.Y. Fung, and C.B. Field 1997. The contribution of terrestrial sources and sinks to trends in the seasonal cycle of atmospheric carbon dioxide. *Global Biogeochem. Cycles* **11**, 535-560.

Rodell, M., P. R. Houser, U. Jambor, J. Gottschalck, K. Mitchell, C.-J. Meng, K. Arsenault, B. Cosgrove, J. Radakovich, M. Bosilovich, J. K. Entin, J. P. Walker, D. Lohmann, and D. Toll, The Global Land Data Assimilation System, *Bull. Amer. Meteor. Soc*., **85 (3),** 381-394, 2004.

Running,S.W., and E.R. Hunt Jr. (1993) Generalization of a forest ecosystem process model for other biomes, BIOME-BGC, and an application for global-scale models. pp. 141-158, In: *Scaling Processes Between Leaf and Landscape Levels*. J.R.Ehleringer, C.Field eds. Academic Press

Running, S. W., D. D. Baldocchi, D. P. Turner, S. T. Gower, P. S. Bakwin, and K. A. Hibbard, 1999: A Global Terrestrial Monitoring Network Integrating Tower Fluxes, Flask Sampling, Ecosystem Modeling and EOS Satellite Data. *Remote Sensing of Environment*, **70**, 108–127.

Schaefer, K., A.S. Denning, N. Suits, Jorg Kaduc, I. Baker, S. Los, and L. Prihodko, 2002: The effect of climate on inter-annual variability of terrestrial CO2 fluxes. Global Biogeochemical Cycles, 16, 1102, doi:10.1029/2002GB001928.

Schwartz, M. D. and T. M. Crawford, 2001: Detecting energy-balance modifications at the onset of spring. *Phys. Geogr*., **22**, 394–409.

Sellers, P.J. et al,, 1996a: A Revised Land-Surface Parameterization (SiB2) for Atmospheric GCMs. Part 1: Model formulation. J. Clim., 9, 676-705.

Sellers, P. J. et al,, 1996b: A Revised Land-Surface Parameterization (SiB2) for Atmospheric GCMs. Part 2: The generation of global fields of terrestrial biophysical parameters from satellite data. J. Clim., 9, 706-737.

Sitch, S., B. Smith, I.C. Prentice, A. Arneth, A. Bondeau, W. Cramer, J.O. Kaplan, S. Levis, W. Lucht, M.T. Sykes, K. Thonicke, and S. Venevsky, Evaluation of ecosystem dynamics, plant geography and terrestrial carbon cycling in the LPJ dynamic global vegetation model. *Global Change Biol*., **9**, 101-185, 2003.

Stöckli, R., and P. L. Vidale, 2004: European plant phenology and climate as seen in a 20-year

AVHRR land-surface parameter dataset. International Journal of Remote Sensing, 25, 3303–3330. 8, 47, 67, 102

Stöckli, R. and P.-L. Vidale, 2005. Modeling diurnal to seasonal water and heat exchanges at European Fluxnet sites. *Theor. Appl. Climatol.* in press.

Stöckli, R., P. L. Vidale, A. Boone, M. Hirschi, and C. Schär, 2005. Sensitivity of the diurnal and seasonal course of modeled runoff to three different land surface model soil moisture parameterizations. *J. Hydrometeorol.* , submitted.

Thonicke, K., S. Venevsky, S. Sitch, and W. Cramer, 2001: The role of fire disturbance for global vegetation dynamics: coupling fire into a Dynamic Global Vegetation Model. *Global Ecol. Biogeogr.*, **10**, 661-677.

Thornton, P. E., 1998: Description of a numerical simulation model for predicting the dynamics of energy, water, carbon, and nitrogen in a terrestrial ecosystem. Ph.D. dissertation, University of Montana, Missoula, MT, 280 pp.

Tian, Y., R. E. Dickinson, L. Zhou, X. Zeng, Y. Dai, R.B. Myneni, Y. Knyazikhin, X. Zhang, M. Friedl, H. Yu, W. Wu, and M. Shaikh, 2004. Comparison of seasonal and spatial variations of leaf area index and fraction of absorbed photosynthetically active radiation from Moderate Resolution Imaging Spectroradiometer (MODIS) and Common Land Model. *J. Geophysical Research*, **109**, D01103, doi:10.1029/2003JD003777.

Tian, Y., C. D. Peters-Lidard, S. V. Kumar, J. Geiger, P. R. Houser, J. L. Eastman, P. Dirmeyer, B. Doty, and J. Adams, 2005. High-performance land surface modeling with a Beowulf cluster. Submitted to Computing in Science & Engineering. (http://lis.gsfc.nasa.gov/Papers/index.shtml).

Tsvetsinskaya, E. A., L. O. Mearns, and W. E. Easterling, 2001. Investigating the effect of seasonal plant growth and development in three-dimensional atmospheric simulations. Part II: Atmospheric response to crop growth and development. *J. Climate*, **14**, 711–729.

Turner, D. P., S. V. Ollinger, and J. S. Kimball, 2004: Integrating remote sensing and ecosystem process models for landscape- to regional-scale analysis of the carbon cycle. *Bioscience*, **54**, 573–584.

White, M. A., P. E. Thornton, and S. W. Running, 1997: A continental phenology model for monitoring vegetation responses to interannual climatic variability. *Global Biochemical Cycles*, **11**, 217-234

White, Woodward, F. I., M. R. Lomas, and S. E. Lee, 2000: Predicting the future production and distribution of global terrestrial vegetation. In: J. Roy, B. Saugier and H.A. Moonie (eds) *Terrestrial Global Productivity,* Academic Press, 573 pp.

Zeng, X., M. Shaikh, Y. Dai, R. E. Dickinson, and R. B. Myneni, 2002. Coupling of the Common Land Model to the NCAR Community Climate Model, *J. Clim*., **14**, 1832–1854.

Zupanski D. and M. Zupanski, 2005: Model error estimation employing ensemble data assimilation approach. Submitted to *Mon. Wea. Rev*. (available at ftp://ftp.cira.colostate.edu/Zupanski/manuscripts/MLEF_model_err.revised.pdf).

Zupanski, D., M. Zupanski, T. Vukicevic, T. Vonder Haar, D. S. Ojima, W.-S. Wu and D. Zupanski, M., 2005: Maximum likelihood ensemble filter: Theoretical aspects. Submitted to *Mon. Wea. Rev.* (available at ftp://ftp.cira.colostate.edu/Zupanski/manuscripts/MLEF_MWR.pdf).