Final Report for DOE Grant No. DE-SC0002246

This project was initiated by the PI at Georgia Tech. The objective of the proposal was to develop a systematic subgrid scaling framework consisting of four elements: 1) a complex vegetation tiling representation; 2) an orographic tiling system; 3) a tiling system to describe the distribution of water table parameters that drives a realistic distribution of wetlands; and 4) a statistical estimation of scaling intensities based on the physics of the CAM convective parameterization with all 4 elements sharing the same set of computational components. The second of these two of these elements was largely completed at Georgia Tech and presented at CESM workshops. The work of this project was interupted by movement of the PI to a new institution, The University of Texas at Austin.

When it was renewed with a new team of researchers at the University of Texas Austin in 2008, it continued to address its objectives and focus on improvements to the land model through collaborations with Yong-Jiu Dai of Beijing Normal University (BNU), the lead in the development of the initial CLM, and other colleagues. His student, Hua Yuan, visited us for two years to complete a PhD dissertation by leading the completion of our treatment of complex vegetation with 3D canopy radiation, i.e., the second element of our proposal.

Our approach to treating canopy radiation in 3D was an outgrowth of the emphasis on stochastic approaches to tiling of multiple fields in our previous proposal. Two papers completed at Georgia Tech provided the theoretical framework needed (Dickinson et al., 2008, Dickinson, 2008). These papers provide analytic solutions for the idealized case of a spherical bush with leaves treated as homogeneous scatterers with an underlying black surface. At UT Austin we developed an approach to allow for radiative interaction between bushes and an underlying surface. Much of the structure of such a parameterization can be understood in terms of what fraction of the surface is covered by shadows. Bush overlap is accounted for with a statistical model that insures total shadow coverage is less than 100%. The student Yuan developed numerical codes to evaluate and improve our multiscattering treatment and to extend it to geometries that are not treatable with our current analytic approach. The finished version of the 3-D treatment broke canopies into 3 layers (cf. Fig. 1) and used matrix inversion as an efficient form of solution. The accuracy of all elements and final treatment were evaluated using Monte Carlo solutions of the assumed canopy structures (Yuan et al., 2014).

With the help of M. Shaikh, the 3D canopy theory was incorporated into the radiation code of the CLM and coupled to CAM4. For validation of the code, we used the same approach to solve the 2-stream model that is currently in the CLM, and were able to reproduce numerical results of the CLM 2-stream over the full range of parameters with errors mostly in the third decimal place, i.e., the modeled albedo, canopy absorption, and ground absorption agreed within 0.01 or so. Incorporation into a community usable version of CLM has been so far been deterred by the need to develop appropriate land data sets to support its logic, e.g. the coverage of the 3 canopy layers can be more than 100% since they overlap.

We also initiated new efforts in improving the biogeochemical aspects of the model. Haishan Chen, previously supported for two years at Georgia Tech, provided a detailed sensitivity studies of the CLM carbon assimilation model as published in Chen et al. (2011). The CLM implementation of the Farquhar scheme for leaf carbon assimilation uses the smallest of 3 limiting rates. Other implementations, e.g. in the SiB2 model, have used smooth interpolations between these rates. Chen found that using the "either or" logic of CLM versus the smoothed coupling of SiB2 with the same prescribed V_{cmax} rates can give very different rates of net carbon assimilation. This finding is especially relevant for CLM since, at least in earlier versions, it adopted its V_{cmax} values from SiB2.

The last two elements of the proposed work did not progress very far as they did not fit the interests of the two students and the research Associate two postdocs at UT Austin supported over the last two years of the grant. Rather, as students Ying Sun and Binyan Yan addressed various aspects of the carbon component of the land model, working collaboratively with scientists at ORNL. Drs. Kaicun Wang, Hua Su, and Bing Pu addressed issues of climate variability.

The PhD research of Dr. Sun under sponsorship of this grant addressed the role of mesophyll resistance in the assimilation of carbon. This resistance is as large as the more familiar stomatal resistance but was previously neglected in the carbon assimilation of climate models. Since model parameters had been adjusted to compensate for this omission, one of Dr. Sun's tasks was to obtain new parameters for the Farquhaar parameterizarion used in CLM. The inclusion of mesophyll resistance introduces a substantial change in the modeled sensitivity of the carbon assimilation to atmospheric carbon dioxide concentrations and so future climate (Sun et al., 2013, 2014a,b).

The student Yan expects to finish her disseration in fall of 2016. It addresses various issues involving the response of the Amazon forest in CLM to drought stress. Her first such effort is described in Yan and Dickinson (2014).

The effort of our project led by Chinese visitor, K. C. Wang) developed observational data sets to evaluate the performance of the land model (e.g. ET, Wang et al. f2010a,b). In particular, he has been able to show how Sunshine Duration (SunDu) data can be used to extend in time and space the current ground data sets on incident solar radiation. Furthermore, Wang et al. (2012) developed an empirical relationship for terrestrial ET in terms of this and other readily available surface meteorological data sets. With this relationship he developed a long-term global data set for ET. Global observations and modeling of ET were reviewed in Wang and Dickinson (2012).

Dr. Bing Pu addressed an issue of global climate change with CESM and regional climate variability over central US. The CESM study (Pu and Dickinson, 2014a) examined the land feedbacks on the hydrological cycle resulting the impacts on stomatal resistance of doubled carbon dioxide. Precipitation patterns changed in response to changed canopy temperatures. Her regional U.S. studies used vorticity analyses to examine diurnal precipitation variability over the Great Plains and inter-annual variability over the Gulf States. As a brief summary, Pu and Dickinson (2014b) showed that the nocturnal maximum in precipitation over the eastern Great Plains is at least in part a response to the vorticity tendency resulting from the late night slowing down of the Great Plains low level jet. Pu et al. (2016) related summer precipitation over the Gulf States to the strength of the Great Plains Low Level Jet and the Gulf of Mexico inflow. Precipitation is maximum with greatest Gulf inflow, perhaps not surprising, but less obvious, for weakest Great plains low level jet. The latter, when strong, generates vorticity from the frictional loss of its anti-cyclonic shear, which requires near surface sinking motion and divergence for the vorticity budget to be balanced.

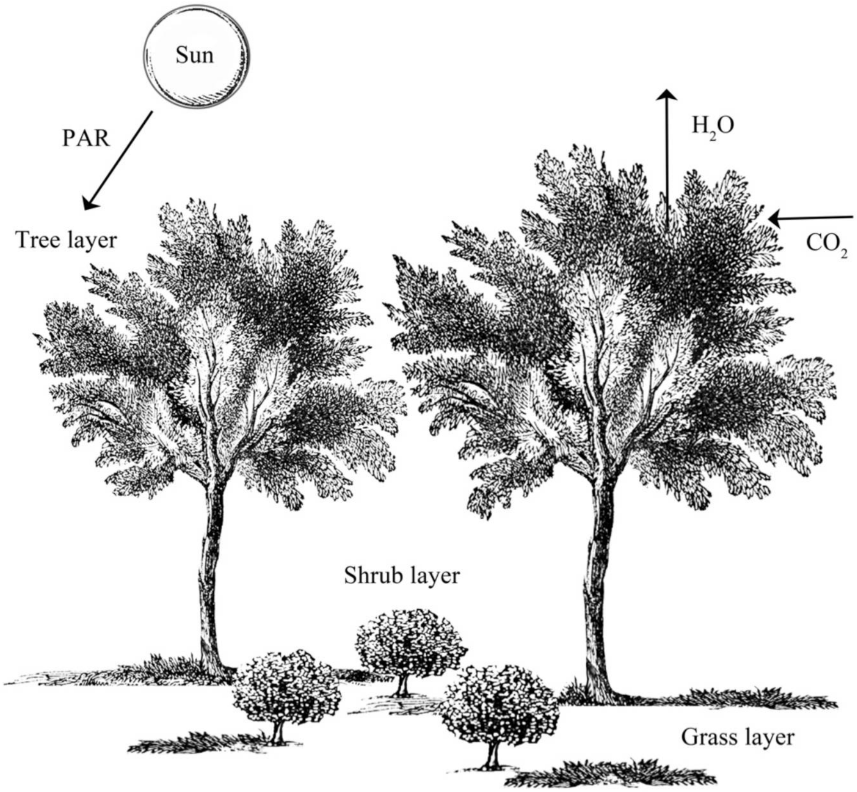

Figure 1 Sketch of the occurrence of a 3-level canopy as developed under DOE support. The upper story (high) canopy is comprised of trees, the middle of shrubs (i.e., bushes) and the low of grasses, forbs, or crops. One or more canopy levels may be missing. If there are no such levels, the surface is designated bare soil. Each level can cast a shadow fraction on each of the lower levels including underlying ground. A layer of moss-lichen or plant detritus can either be included as the lowest canopy layer or as the first layer of the underlying soil column

Supported Research Publications Referred to in Narrative

Dickinson, R. E., L. Zhou, Y. Tian, Q. Liu, T. Lavergne, B. Pinty, C. B. Schaaf, and Y. Knyazikhin (2008), A three-dimensional analytic model for the scattering of a spherical bush, *J. Geophys. Res.*, *113*, D20113, doi:10.1029/2007JD009564.

Dickinson, R. E. (2008), Determination of the multi-scattered solar radiation from a leaf canopyfor use in climate models, *J. of Computational Physics*, *227*, 3667-3677.

Chen, H., R. E. Dickinson, Y. Dai, and L. Zhou (2011), Sensitivity of simulated terrestrial carbonassimilation and canopy transpiration to different stomatal conductance and carbon assimilation schemes, *Clim Dyn*, *36*, 1037-1054, doi:10.1007/s00382-010-0741-2.

Accurate simulations of terrestrial carbon assimilation and canopy transpiration are needed for both climate modeling and vegetation dynamics. Coupled stomatal conductance and carbon assimilation (A − g s) models have been widely used as part of land surface parameterizations in climate models to describe the biogeophysical and biogeochemical roles of terrestrial vegetation. Differences in various A − g s schemes produce substantial differences in the estimation of carbon assimilation and canopy transpiration, as well as in other land–atmosphere fluxes. The terrestrial carbon assimilation and canopy transpiration simulated by two different representative A – g s schemes, a simple A–g s scheme adopted from the treatments of the NCAR model (Scheme I) and a two-big-leaf A – g s scheme newly developed by Dai et al. (J Clim 17:2281–2299, 2004) (Scheme II), are compared via some sensitivity experiments to investigate impacts of different A − g s schemes on the simulations. Major differences are found in the estimate of canopy carbon assimilation rate, canopy conductance and canopy transpiration between the two schemes, primarily due to differences in (a) functional forms used to estimate parameters for carbon assimilation sub-models, (b) co-limitation methods used to estimate carbon assimilation rate from the three limiting rates, and (c) leaf-to-canopy scaling schemes. On the whole, the differences in the scaling approach are the largest contributor to the simulation discrepancies, but the different methods of co-limitation of assimilation rate also impact the results. Except for a few biomes, the residual effects caused by the different parameter estimations in assimilation sub-models are relatively small. It is also noted that the two-leaf temperature scheme produces distinctly different sunlit and shaded leaf temperatures but has negligible impacts on the simulation of the carbon assimilation.

Pu, B. and R.E. Dickinson (2014a), Hydrological changes in the climate system from leaf responses to increasing CO_2. *Clim. Dyn.* Issues 7-8, 1905-1923 doi:10.1007/s00382-013-1781-1.

Pu, B., and R.E. Dickinson (2014b): Diurnal spatial variability of Great Plains summer precipitation related to the dynamics of the low-level jet, Journal of Atmospheric Sciences. Issue 5, 1807-1818 doi:10.1175/JAS-D-13-0243.1

Su, H., R. E. Dickinson, K. L. Findell, and B. R. Lintner (2013), How Are Spring Snow Conditions in Central Canada Related to Early Warm-Season Precipitation?, *J Hydrometeorol*, *14*(3), 787-807,doi: 10.1175/JHM-D-12-029.1.

Sun, Y., R. E. Dickinson, L. Gu, S. G. Pallardy, J. Baker, Y. Cao, F. M. DaMatta, X. Dong, D. Ellsworth, D. V. Goethem, A. M. Jensen, B. E. Law, R. Loos, S. C. V Martins, R. J. Norby, J. Warren, D. Weston, K. Winter (2013), Asymmetric effects of mesophyll conductance on fundamental photosynthetic parameters and their relationships estimated from leaf gas exchange measurements., *Journal Plant cell and Environment*, doi: *10.1111/pce.12213*

Sun, Y., Gu, L., Dickinson, R. E., Pallardy, S. G., Baker, J., Cao, Y., Damatta, F. M., Dong,X., Ellsworth, D., Van Goethem, D., Jenses, A. M., Law, B. E., Loos, R., Martins, S. C.V., Norby, R. J., Warren, J., Weston, D. and Winter, K. (2014a), Asymmetrical effects of mesophyll conductance on fundamental photosynthetic parameters and their relationships estimated from leaf gas exchange measurements. Plant, Cell & Environment, 37: 978–994. doi: 10.1111/pce.12213

Sun, Y., L. Gu,, R. E. Dickinson, R J. Norby, S. G. Pallardy, and Forrest M. Hoffman (2014b), Impact of mesophyll diffusion on estimated global land CO2 fertilization, PNAS 11 (44) 15774-15779;

Yan, Binyan, Dickinson, R.E.(2014) Modeling hydraulic redistribution and ecosystem response to droughts over the Amazon basin using Community Land Model 4.0 (CLM4) *J. Geophysical Research* Volume: 119 Issue: 11 Pages: 2130-2143

Yuan, H., R. E. Dickinson, Y. Dai, M. J. Shaikh, L. Zhou, W. F. Shangguan, and D. Ji (2014), A 3-D canopy radiative transfer model for global climate modeling: description, validation and application, *J Climate*, 27, 1168-1192. doi:.org/10.1175/JCLI-D-13-00155.1.

Wang, K., R. E. Dickinson, M. Wild, and S. Liang, 2010: Evidence for decadal variation in global terrestrial evapotranspiration between 1982 and 2002 Part I: method development, J. Geophys. Res., 115, D20112, doi:10.1029/2009JD013671

> Estimating interannual to decadal variability of terrestrial evapotranspiration (ET) requires use of standard meteorological data complemented with some high-resolution satellite data. A semiempirical expression for this purpose is developed and validated with data from 2000 to 2007. These data were collected at 64 globally distributed sites, including the continuous measurements collected by the Atmospheric Radiation Measurement (ARM) and FLUXNET projects, and are the longest available, with continuous worldwide multisite measurements of ET, and a total of 274 site years. The sites are mainly located in North America and Asia, with the exception of three sites in Australia, two in Europe, and one in Africa. The climates of the sites vary from tropical to subarctic and from arid to humid. The land

> cover types of the sites vary from desert, croplands, grasslands, and shrub land to forests. On average, the 16 day average daily ET can be estimated with an error (standard deviation) of 17 W m−2 (25% in relative value), and with an average correlation coefficient of 0.94. The standard deviation of the comparison between measured and predicted site-averaged daily ET is 9 W m−2 (14%), with a correlation coefficient of 0.93. The model is also satisfactory in reproducing the interannual variability at sites with 5 years of data in both humid and arid regions. The correlation coefficient between measured and predicted annual ET anomalies is 0.85. This simple but accurate method permits us to investigate decadal variation in global ET over the land as will be demonstrated in part two of this paper series.

Wang, K., R. E. Dickinson, M. Wild, and S. Liang, October 2010: Evidence for decadal variation in global terrestrial evapotranspiration between 1982 and 2002 Part II: Global application, J. of Geophysical Research, 115, D20113, doi:10.1029/2010JD013847

> Terrestrial evapotranspiration (ET) cools the surface and moistens the atmosphere near the Earth's surface. Variations in this important climate factor have major environmental and socioeconomic impacts. How terrestrial ET has varied in the past and what caused the variations, however, have remained quite uncertain. These issues are addressed by calculating monthly global ET from 1982 to 2002 at 1120 globally distributed stations, using a modified Penman-Monteith method that was developed in the first part of the two-part paper. Our analyses show that ET has a significant decadal variation (~10%) regionally and globally. Over the period analyzed ET for global land increased by 0.6 W m−2 per decade equal to 1.2 W m−2 (about 2.2% in relative value) or 15 mm yr−1 in water flux during the study period. We show that long-term variations of ET in humid areas such as the tropics, Europe, and humid areas of Asia are primarily controlled by variations in incident solar radiation R s connected to changes in cloudiness and aerosols. However, soil water supply, estimated here by RH, and connected to precipitation, is the dominant factor in controlling long-term variations of ET in arid areas. A correlation analysis demonstrates that the dependence of ET on R s switches to negative in dry regions. Furthermore, its dependence on relative humidity switches from negative in moist regions to positive in dry regions. Its dependence on normalized difference vegetation index is uniformly positive.

Wang, K.C. and R.E. Dickinson, 2012: A review of global terrestrial evapotranspiration: Observation, modeling, climatology, and climatic variability, *Rev. Geophys.*, **50**, RG2005, 54pp, doi:10.1029/2011RG000373

Wang, K.C., R.E. Dickinson, and S. Liang, 2012: Global atmospheric evaporative demand over land from 1973 to 2008, *J. Climate*, **25**, 8353-8361, doi: 10.1175/JCLI-D-11-00492.1