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The Community Land Model Philosophy: model development and science applications

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The Community Land Model (CLM) is the dynamic land model component of the Community Earth System Model (CESM). As with many land models, it was originally developed primarily as a lower boundary condition for the atmosphere, principally the Community Atmosphere Model within the CESM (though CLM is also used in several regional climate models and the Norwegian Earth System Model). The focus, therefore, of early versions of CLM was on the simulation of water and energy budgets over land.

Since that time, CLM has evolved considerably. Its principal (but not exclusive) purpose continues to be as the terrestrial component within an Earth System Model (ESM) and as a tool to promote understanding of the complex land surface contributions and responses to climate variability and change. To this end, two central themes drive CLM development and use: 1) terrestrial ecosystems, through their cycling of energy, water, chemical elements, and trace gases, are important determinants of weather and climate, and 2) the land surface is a critical interface through which climate change influences humans and ecosystems and through which humans and ecosystems can affect global environmental change.

When viewed in this light, the utility of CLM is and can be vastly expanded beyond its original purpose and in fact there are multitudinous actual and possible applications of CLM. Importantly, it is increasingly used as a tool for assessing climate change impacts on ecosystems and ecosystem services, hydrological systems (including drought and flooding), agriculture, and urban environments.

Development philosophy and science priorities

The overarching development strategy for CLM rests on the notion that the land system is highly coupled and that improvements, for example in the representation of biogeochemical cycles, contribute to improved hydrologic and energy cycle simulation, and vice versa. The model thus benefits from a holistic perspective of the terrestrial system on a wide variety of time and spatial scales. Core biogeophysical and biogeochemical parameterisation development is complemented by efforts to expand model functionality. Priorities are broadly set to improve and enable the capacity of the model to be applied to address pressing terrestrial climate science questions. Examples of scientific topics that are driving current CLM model development include the following:

- To improve understanding of carbon and nitrogen cycle interactions and their influence on long-term trajectory of the terrestrial carbon sink;
- To assess the response and vulnerability of ecosystems to climate change and disturbances (human and natural) and the possibility for ecosystem management to mitigate climate change;
- To quantify the role of terrestrial processes in diurnal to interannual weather and climate variability including influence on droughts, floods, and extremes;
- To establish the vulnerability of water resources under climate change;
- To quantify land feedbacks to climate change: for instance, permafrost-carbon feedback, snow- and vegetation-albedo feedback;
- To prognose anthropogenic and natural land cover/land use change and trace gas emissions and their influence on climate;
- To examine the impact of urbanisation on local climate and the unique impact of climate change in urban areas;
- To assess how land surface heterogeneity affects land-atmosphere interactions and carbon cycling, including scale issues;
- To enable model – data fusion and increase exploitation of experimental ecosystem data;
- To quantify parameter uncertainty and investigate parameter optimisation techniques

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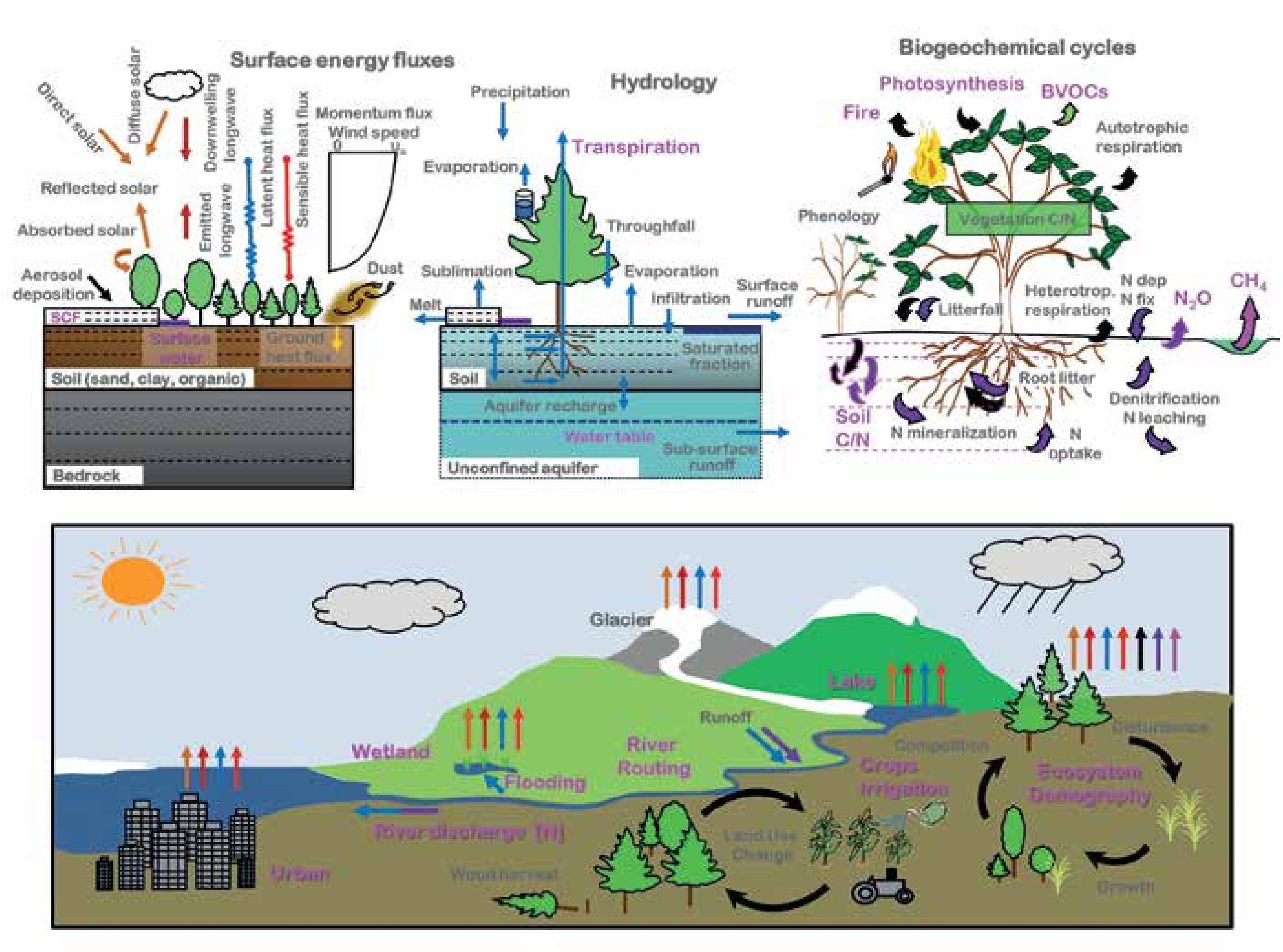
Current capabilities, use, and evaluation

The most recently released version of the model, CLM4 [1,2], represents a significant improvement in terms of model performance and functionality. In addition to its core functions of carbon, water and energy cycling, CLM4

Figure 1. Schematic diagram depicting processes represented in CLM. Items highlighted in pink are new or modified for CLM4.5. Note that not all processes are depicted.



also simulates a suite of more complex terrestrial processes. Such processes include dynamic vegetation changes that allow plant types to adapt to changing climate conditions, interactive nitrogen cycling that restricts the ability of the biosphere to sequester carbon beyond the limits of nutrient supply, crop behaviour, land-use change (including wood harvest) impacts on both carbon cycling and biogeophysics, urban environments, as well as permafrost dynamics, dust production, aerosol deposition onto snow, and, last but not least, biogenic volatile organic compound emissions.

With increased model complexity comes the need for new, better, and more comprehensive tools to evaluate the behaviour of the coupled land system. Though many of the fundamental questions that drive CLM development focus on longer timescales, long-term validation data is sparse. Consequently, model behaviour is routinely evaluated at diurnal, seasonal, and interannual time-scales, which is reasonable as these are the temporal resolutions at which the majority of simulated processes operate. Ideally, new developments to model structure should be evaluated systematically against a suite of validation data at multiple temporal and spatial scales. A comprehensive benchmarking system is not in place and therefore CLM validation remains overly subjective and case specific.

Improved model validation is the goal of the International Land Model Benchmarking project (ILAMB) and CLM researchers strongly support and maintain an active role in this project. There is also recognition that ILAMB will only be part of the model evaluation picture. We are increasingly exploiting experimental data from manipulation studies and process observations as powerful constraints on model behaviour and structure. Recent examples include model/experimental-data comparisons on the influence of nitrogen fertilisation on tree growth [3], litter-bag decomposition [4], ozone poisoning of vegetation [5], and snow-shrub-permafrost interactions [6].

CLM also benefits from and contributes to many model intercomparison projects. CLM is employed as part of CCSM (Community Climate System Model) /CESM in the CMIP3 and CMIP5 coupled climate model intercomparison projects and a prior version of the model was used in the C4MIP carbon cycle feedback analysis. CLM simulations have also been submitted to the ongoing, biogeochemically focused TRENDY and Permafrost Carbon projects and several GEWEX-supported projects such as LUCID, the series of Global Land-Atmosphere Coupling Experiments (GLACE), which investigate the influence of soil moisture variability and trends on weekly to seasonal weather and climate, and the historic and forthcoming Global Soil Wetness Projects (GSWP). Feedback from participation in these projects informs CLM developers of deficiencies in the model that can be addressed in future versions of the model. For example, TRENDY analysis revealed that CLM underestimates the 20th century land carbon uptake (excluding carbon losses due to land cover change) and has led to an intensive effort to improve CLM carbon and nitrogen cycling.

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Future Directions

Knowledge of model limitations and strengths, determined in part through model intercomparisons and the increasingly numerous applications and science priorities of CLM and CESM, has spurred increasingly diverse and comprehensive model development activities. These development activities are within the scope and have benefited from the expertise of both the GEWEX and iLEAPS communities. Consequently, CLM researchers maintain a presence in both communities.

During the ongoing development cycle, the transformation of CLM4 to CLM4.5 (scheduled for release in 2013) has seen model improvement and expansion across many fronts (Fig. 1). Improved parameterisations are being incorporated throughout the model including for canopy physiology and photosynthesis [7], permafrost hydrology [8], snow, lake dynamics [9], river flow, runoff generation [10], and fire dynamics including anthropogenic triggers and suppression [11]. New features slated for inclusion in CLM4.5 include methane emissions [12], flooding and prognostic wetland distribution, ecosystem demography [13], vertically resolved soil biogeochemistry [14], multi-layer canopy radiation, crop fertilisation [15] and irrigation [16], and riverine transport of nutrients. The comprehensive development approach helps maintain scientific balance and is consistent with past CLM development experience that indicates that improvements in one facet of model behaviour often benefit other coupled processes.

On the longer term, developments that are being pursued for future model releases include data assimilation within the CESM Data Assimilation Research Testbed, enhanced two-way interactions with the socio-economic processes represented by Integrated Assessment Models, feedbacks between vegetation and canopy airspace properties, the influence of ozone on vegetation, and the capacity to simulate sub-grid soil moisture/snow distributions and lateral groundwater flow along with further parameterisation improvements to existing biogeochemical and biogeophysical processes.

Challenges

As is clear from the above discussion, CLM is being developed with the overarching goal of steady improvement in the process-oriented depiction of the global terrestrial system in an Earth System Model. Clearly, there are myriad directions in which the model can be developed with ever-increasing complexity and process fidelity. One major scientific and management challenge facing CLM is the maintenance of appropriate scientific balance across the processes represented: the overall model will suffer if excessive attention is paid to one set of processes at the expense of others. Ideally, process resolution should advance in parallel across the range of the model components in the context of emerging science priorities, which has roughly been the case (at least partly by design) for CLM4.5 development (model improvements spread across model, Fig. 1).

The existing CLM structure reflects a compromise between demands for increased process resolution both from ecological and hydrological perspectives. One way of ensuring a diversity of input is to engage with as wide a community of scientific developers, testers, and users of the model as possible, so that inappropriate model structures and parameterisations come to light quickly. Maintenance of such a complex and dynamic modelling environment requires broad trans-disciplinary participation, open-source coding practices, and sustained support for software development and maintenance as well as documentation.

Despite these challenges, the future of CLM and land modelling is bright. The number of problems to which these models can now be applied is impressive. CLM has advanced to the point that it is probably more appropriate to think of CLM (and comparable land models) as terrestrial systems models which are a result of synthesis and integration of existing knowledge manifest in land surface models but also drawing from hydrologic, ecosystem, and human dimensions models. Continued progression of these terrestrial systems models will require a sustained and cooperative effort involving the iLEAPS and GEWEX research communities and beyond. ■

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