CUAHSI-NCAR Working Group Meeting

On Improving Hydrologic Representations in Earth System Models

Report to NSF, October 2014

Participants

Jennifer Adam (Washington State University)
Jennifer Arrigo (CUAHSI)
Diogo Bolster (CUAHSI Board of Directors)
Martyn Clark (NCAR)
David Gochis (NCAR)
Rick Hooper (CUAHSI)
David Lawrence (NCAR)
Ruby Leung (Pacific Northeast National Laboratory)
Scott Mackay (University at Buffalo, *The State University of New York*)
Reed Maxwell (Colorado School of Mines)
Ben Mirus (University of North Carolina)
Ying Fan Reinfelder (Rutgers, *The State University of New Jersey*)
Chaopeng Shen (Pennsylvania State University)
Sean Swenson (NCAR)
Xubin Zeng (University of Arizona)

Summary

The first working group meeting was held at NCAR on Sept 2, 2014, with participation from members of the hydrology community, CUAHSI leadership on community modeling, and leadership on Community Land Model (CLM) development at NCAR. Martyn Clark led the discussion on opportunities to improve hydrologic process-representation in CLM, including various hydrologic stores/fluxes and their spatial variability and connectivity. Reed Maxwell led the discussion on model performance metrics and model inter-comparison strategies. Rick Hooper outlined the potential support from CUAHSI Water Data Center, and Dave Gochis discussed the community infrastructure needs and the potential role of the CUAHSI-NCAR postdoc to undertake the immediate tasks of building the infrastructure and dataset.

The meeting outlined a 5yr plan to develop/test a new version of CLM with the best hydrologic representation at multiple scales, for future CLM release and Coupled Model Inter-comparison Projects that inform IPCC. The main plan is to accelerate advances in hydrologic process-representation in CLM through development of Hydrology Process Teams (HPTs). The HPTs have two functions: (1) synthesis, where teams of leading scientists synthesize the state-of-science process-understanding and propose parameterization schemes, evaluation metrics and model experiments; and (2) implementation, where an agile team of postdocs/programmers implement immediate changes to CLM codes and test model performance. The proposed HPT builds upon the success of the Climate Process Teams (CPTs), whose concentrated efforts have transformed today's climate models.

Immediate actions are to (1) hold a second working group meeting in December at AGU to define model performance evaluation metrics, (2) position the currently funded CUAHSI postdoc to develop specific test cases and assemble the dataset needed to evaluate CLM hydrologic performance, and (3) seek support for the 5yr sustained HPT synthesis and implementation activities.

1. Background

Over the past six years CUAHSI held three community workshops exploring the development of a Community Hydrologic Modeling Platform (CHyMP: https://www.cuahsi.org/CHYMP). Among several recommendations, developing large-scale hydrologic models, focusing on water storages and fluxes in all terrestrial reservoirs at regional to continental scales, emerged as a direction where community efforts can potentially yield significant payoffs. Many of the scientific and societal challenges in understanding and preparing for global environmental change rest upon our ability to understand and predict the water cycle change at large river basin, continent, and global scales. However, current large-scale models, such as the land components of General Circulation Models (GCMs) or Earth System Models (ESMs), do not yet represent the terrestrial water cycle in a fully integrated manner or resolve the finer-scale processes meaningful and essential for most hydrologic applications, for the simple reason that they were not designed to be hydrologic models.

Over the past year the scope was further defined as improving hydrologic process representation in Earth System Models (ESMs) for two important reasons. First, ESMs are increasingly powerful and often the only tools for understanding global change and informing policy (e.g. IPCC assessments). The land portion of these models, although not designed to be hydrologic models, have tapped into the collective wisdom of the climate sciences community, garnered broad scientific and funding support, and advanced rapidly in the recent decade to include ecosystem processes such as dynamic vegetation and carbon/nutrient cycles. However, model advances in hydrologic process-representation has not kept pace, although it is widely understood that the land component of the water cycle is the most basic of biogeochemical cycles on Earth. One example of model deficiency in hydrology is the lack of explicit representation of groundwater storage and its flux exchange with soil, vegetation, rivers, floodplains and wetlands, and the multi-scale, three-dimensional nature of below-ground flowpaths. Field hydrologists and hydrologic process modelers know very well that groundwater has longer memories and buffers water availability for ecosystems and societies alike. In this regard, the active engagement of the hydrologic observational and modeling community in ESM development can expand ESM water cycle prediction capabilities, which will advance energy, carbon and nutrient cycle prediction capabilities through the fundamental role the water cycle plays in regulating these cycles.

The second reason to contribute to ESM advancement is that the hydrology community can apply these land models for large-scale hydrologic applications. Their large-scale emphasis, their integrative framework (coupled water, energy, biogeochemical cycling), their broad support from the scientific and application community ensuring that state-of-science ideas are incorporated, their ability to directly respond and feedback to climate simulations, and their computation efficiency, are extremely appealing to many hydrologists working on regional to continental-scale problems. However, a major barrier preventing hydrologic applications is that many of the basic hydrologic processes, such as groundwater-surface water exchange, are inadequately represented. Thus contributing to the improvement of basic hydrologic processes in ESMs will also directly benefit members of the hydrology community engaged in large-scale water and carbon cycle research.

The third reason is that our community can leverage the past experience of the ESM community on how to build our own community modeling system. Behind the ESMs are strong institutions and mature cultures that support a community governance process in model development, testing, improvement, versioning, and user support and training. Such a community modeling infrastructure does not yet exist in the hydrology community. Therefore, an initial focus on collaborating with the ESM community to improve large-scale hydrologic representation will also directly benefit the hydrology community; it will set an achievable and high-impact precedent for CUAHSI community modeling endeavors, and serve as a pilot project for other community modeling directions targeting smaller scales, such as a Community Watershed Model on par with the scales and processes targeted by the Critical Zone Observatories (CZOs). Through collaboration with ESM institutions, we will learn to build our own institution of community modeling, and nurture a culture of community level model development, testing, user support and training.

Understanding this mutual benefit, CUAHSI reached out to the leadership of the Community Land Model (CLM) at NCAR, and initial NSF funding was obtained to begin a joint CUAHSI-NCAR effort to explore ways to engage the hydrology community in advancing hydrologic process-representations in CLM. The funding includes support for two working group meetings and a postdoc to be jointly advised by CUAHSI and CLM working group members.

A community discussion was held on July 30th at the CUAHSI 2014 Biennial Science Meeting where CUAHSI leadership briefed the attendants on the rationale of the proposed CUAHSI-NCAR collaboration and the focus on CLM. This meeting was attended by NCAR's Martyn Clark who presented the hydrologic processes that need improvement in CLM, which helped to guide the discussions toward some of the tangible and achievable goals. The meeting sharpened the focus and helped to form an initial joint CUAHSI-NCAR working group, consisting of CUAHSI leadership on community modeling, NCAR leadership on CLM development, and members of the hydrology community who responded to a CUAHSI email invitation prior to the Biennial Science Meeting.

2. First Working Group Meeting at NCAR

The first working group meeting was held at NCAR on Sept 2, 2014, attended by members of the hydrology community (some remotely), CUAHSI leadership on community modeling, and NCAR leadership on CLM development (see list on front page).

Martyn Clark led the discussion on opportunities to improve hydrologic process-representations in CLM. Deficiencies or inconsistencies in CLM include canopy interception of rain and snow, sub-grid variability within large CLM model grids, surface runoff, plant water uptake, storage and flux in soils, water table dynamics, groundwater-surface water interaction, between-grid hydrologic connectivity, river-floodplain dynamics, and lakes-wetlands. The most pressing development priorities identified were better representations of spatial variability and hydrologic connectivity, within and between grids. This led to the suggestion by Xubin Zeng that Hydrologic Process Teams (HPTs) be formed, to conduct a synthesis of existing hydrologic process-understanding relevant to ESMs, along with selected, sharply focused tasks to incorporate current state-of-science schemes into the next generation ESM land models such as CLM. The HPTs are analogous to the Climate Process Teams (CPTs) which have accelerated the transfer of cutting-edge modeling concepts and parameterizations into ESMs, focusing on long-standing problematic climate modeling topics like cloud and ocean mixing parameterizations. Such HPTs, consisting of observationalists, theoreticians, process modelers, and ESM model developers, can recommend and comprehensively evaluate alternative schemes to represent a given process.

Reed Maxwell led the discussion on model performance or benchmarking metrics and model inter-comparison strategies. The model performance metrics are defined as a set of essential hydrologic variables (stores and fluxes) at all scales that can be directly observed as well as computed by the model. These metrics will be used for gaging performance of competing schemes proposed by the HPTs. Inter-model comparisons of different grid resolutions are also suggested as useful exercises to understand model performance. A key challenge is that a comprehensive observation dataset for testing large-scale land hydrology model performance, merging point observations (e.g., flux towers, plant sap flow, soil moisture, water table depth) with remote sensing (e.g., GRACE, MODIS, snow cover, flooding, and surface brightness temperature), is yet to be assembled. This led to the discussion of the role of the CUAHSI data center and the tasks of the postdoc in current funding.

Rick Hooper outlined the potential infrastructure, data, and benchmarking support from CUAHSI Water Data Center (WDC: https://www.cuahsi.org/wdc). WDC currently catalogs observation time series from >100 water data sources including USGS, NWS and EPA, and provides data publication and product services to the hydrology and Critical Zone Science community. It is poised to play a key role by integrating the multi-scale data sources and creating gridded time series for testing model performance, and by providing future training and technical support for CLM applications to large-scale hydrologic investigations. This will also help define the future role of WDC in supporting other lines of community modeling efforts, such as the Community Watershed Model.

Dave Gochis guided the discussion on key infrastructure and data challenges in subjecting CLM to systematic scrutiny, and the potential role of the currently-funded CUAHSI-NCAR postdoc to undertake the immediate tasks of building the model evaluation infrastructure and compiling evaluation datasets. Among the tasks are (1) creating unified forcing/validation datasets for CLM that bring in multi-scale hydrologic observations not yet used for testing large-scale land hydrology models, including data from the CZOs and other observation networks and experimental watersheds, (2) adapt CLM to utilize novel datasets such as airborne Lidar data on terrain, snow and vegetation, (3) create capabilities to push/pull data from CUAHSI WDC, and (4) add capabilities in CLM to include tracers (online or offline) as a key diagnostic for hydrologic flow and transport paths and residence times.

The discussions converged onto a set of grand science challenges which can be significantly advanced through this joint CUAHSI-NCAR effort, including the following:

- How will the hydrologic stores (canopy, snowpack, soil moisture, groundwater, rivers and floodplains, lakes and reservoirs, and wetlands), and fluxes (canopy evaporation, snow, soil and water surface evaporation, plant transpiration, snowmelt, soil infiltration, surface runoff, groundwater recharge and discharge, lateral flow above and below-ground and regional water subsidy, and river discharge at all stream-orders) respond to global environmental change under natural (e.g., climate variability) and anthropogenic (e.g., land use change, irrigation) forcings? How will the water cycle response affect biological productivity and functioning in terrestrial and aquatic ecosystems? How will the hydrologic and ecosystem responses feedback to the climate system, and through what physical-biogeochemical pathways? What are the globally salient mechanisms of these responses and feedbacks?
- Given that groundwater is largely missing in ESMs, what is the role of the groundwater, with its large storage and slow response to climate forcing, in buffering water stress in terrestrial and aquatic

ecosystems and human societies? How will groundwater resource respond to climate change and increasing human pressure? How will the globally diminishing groundwater observed by GRACE affect dry-season streamflow, groundwater-supported ecosystem productivity, and water quality?

- What parts of the world will likely experience water stress posing threats to ecosystem sustainability and water and food security for human populations? Can we quantify water resource vulnerability in the context of climate change and human development uncertainty?
- How will warming and sea-level rise affect the pan-arctic permafrost and peatlands? How will the projected large-scale thawing and draining affect hydrological conditions in the arctic regions and the carbon cycle by releasing to the atmosphere the long buried carbon since the early Holocene?
- Will riparian, hillslope, and upland zones respond to climate change and CO_2 fertilization differently? How will our model's ability to resolve these small-scale features of the landscape, explicitly or implicitly, change our understanding of ecosystem responses and resilience, and the water cycle – climate interactions?

Answers to these questions demand that our Earth System Models be capable of (1) representing the integrated water cycle as nature does it, and (2) resolving the fundamental and structural variability (e.g., ridges vs. valleys) within a large ESM model grid. The meeting ended with considerations for the following immediate tasks and a long-term vision.

3. Next Steps

3.1. Develop Model Performance Metrics

CUAHSI currently has funding for a second working group meeting and we propose to meet for 1-day in San Francisco during the Fall AGU meeting to develop model performance metrics. We will include more members of the community who could not participate in the Biennial discussions on July 29-31 and/or the working group meeting at NCAR on Sept 2. Several members of the community, particularly early-career scientists, have expressed strong interests in contributing to the effort.

The main agenda of the 1-day meeting is to (1) develop model performance metrics and an initial inventory of hydrologic observation datasets and data gaps, which will prepare the currently-funded postdoc for his/her tasks of creating gridded test datasets, and (2) strategize ways to support the HPT synthesis activities.

Regarding (1) above, the table below gives examples of the type of hydrologic data that need to be brought together and processed for testing model performance at a hierarchy of scales, from points (e.g., soil moisture and temperature at a probe, groundwater level and temperature in a well, snow water content at an USDA SNOTEL site), patches averaging multiple points (e.g., the footprint of an eddy-covariance tower, ~2km, instrumented hillslopes at CZOs), low-order catchments and watersheds integrating multiple patches (e.g., stream flow, temperature, geochemical constituents, sediment loads), successively larger river basins integrating multiple catchments, to continent and global observations from satellites (e.g., GRACE water storage change, snow cover and brightness, surface brightness temperature, and MODIS vegetation index), each with distinct footprints and frequency of overpasses. This initial table is organized by scale (point to global), but it could also be organized in terms of storage vs. flux, forcings (natural or anthropogenic) and physical characteristics (topography, permeability) etc.

Table-1. Examples of hydrologic observations in the US to be integrated for model benchmarking

Observation	Scale	Example Source	Challenges
Soil moisture / temperature	point	USDA SNOTEL, OK Mesonet; IL Water Survey, Nebraska SCAN, Individual investigators	varying depths, frequency, and record period
Groundwater level / temperature	point	USGS, state GS, Individual investigators	varying depths, frequency, and record period
Groundwater recharge	point	Individual investigators	one time estimate, various tracers and/or methods
Snow water equivalent	point	USDS SNOTEL snow-pillow	
Soil moisture from Gamma ray attenuation, electromagnetic imaging, and neutron backscatter (i.e. COSMOS)	Patch, cross-section	Individual investigators	sparse
Eddy-covariance flux tower measured sensible/latent heat, water vapor, CO_2 and CH_4 fluxes	patch, ~2km	AmeriFlux, North America Carbon Project, CZOs	sparse, varying periods
Hillslope response of water and geochem fluxes	hillslope, <1km	CZOs, research / experimental watersheds, Individual investigators	sparse, varying periods and scales
Catchment-watershed-river basin outflux of water, sed, and geochem	<all orders of streams	USGS, CZOs, research / experimental watersheds, Individual investigators	
Satellite observed topo elevation, snow cover/albedo, terrestrial water storage change, surface flooding, ET retrieval, surface temperature / soil moisture, vegetation index / productivity, fire	sensor footprint (1m-100km) to global	NASA/JPL retrieval product from GRACE, Landsat, MODIS, etc.	since the 80s, over individual satellite lifespan
Land-use land-cover change, reservoir operation, river diversion and groundwater pumping	Landscape, watershed, river basin, to regional	USGS water use, state water surveys, USDA census on crop acreage and irrigation	Incomplete documentation etc.

This table will serve as an initial drawing board for agenda (1) community discussions. Given the challenges of bringing together this vast array of data, a meaningful first step might be to test the model's ability to simulate the observed streamflow at ALL scales, from headwater catchments (to the extent resolved by CLM) to continental river systems such as the Mississippi, as suggested by David Gochis at the working group meeting at NCAR. The US Geological Survey has gaged the nation's streams at tens of thousands of sites for over a century, and the resulting wealth of data, encompassing drainage areas from less than 1km^2 to over 6million km^2, is yet to be brought together to truly test our ability to get the land hydrology right, without parameter tuning, at ALL scales across which our river systems integrate. This is not a trivial task, for to get the streamflow right at all scales, one must correctly capture the fully 3-dimensional nature of groundwater convergence including short-shallow, and long-deep flowpaths, and those in between, and the evapotranspiration fluxes. This exercise, to test the new CLM's ability to simulate multi-scale stream flow without parameter tuning, will likely become the first systematic effort of the anticipated hydrologic benchmarking.

3.2. Commission the funded CUAHSI Postdoc

CUAHSI has funding for a postdoc for calendar year 2015. At the Sept 2 working group meeting at NCAR, it was agreed that an immediate task the postdoc can begin is to (1) enhance the CLM infrastructure to enable meaningful evaluation of existing model representation of hydrologic processes, and (2) prepare the large forcing and hydrologic test datasets (see table above) to evaluate CLM hydrologic performance. It was also agreed that this postdoc may be better positioned at NCAR, under the supervision of Dave Gochis and Martyn Clark who have been bridges between the CUAHSI and NCAR communities. The postdoc will also work closely with the CUAHSI Water Data Center staff to prepare the benchmarking datasets. Lastly, it was agreed that it would be difficult to attract a highly qualified postdoc with only 1-year of secured funding, and it was suggested that the fund may be better used to support an existing NCAR staff member already familiar with CLM and with expertise in hydrology. If this path is taken, then thoughts need to be given to ensure a strong continuity of CUAHSI presence and active engagement, particularly through the Water Data Center.

4. Long-term Vision

We propose to follow the lead of the successful Climate Process Teams (CPTs) in the past decade which brought together field observers, theoreticians, process modelers and the large modeling centers to concentrate on the most critical and difficult scientific problems facing climate models. CPTs were established and supported by multi-agencies to accelerate the research-to-operation (implementation) transition on crucial processes in the atmosphere and the ocean. Such concentrated efforts have transformed today's Earth System Models. However, no CPTs on hydrological processes have been supported. Here we propose to form Hydrology Process Teams (HPTs) with two sets of activities: synthesis and implementation.

4.1 HPT Synthesis

The synthesis activities will be led and coordinated by CUAHSI, through focused working group meetings and resulting in a set of synthesis papers to be published in peer-reviewed journals. CUAHSI may issue a call to the community to form synthesis teams through open competition, with the goal of supporting 2-3 groups. Individual PIs from the community can form groups and write a proposal for a synthesis team, including field observers to scientists from large modeling centers such as but not limited to NCAR. CUAHSI will provide support for workshop meetings of the winning synthesis teams, as well as early-career scientists who wish to contribute, but all members of the community are welcome to participate if providing own travel support.

We envision the HPTs to consist of 10-15 scientists with expertise from observations to theories, and from process-scale modelers to global model developers at large modeling centers including NCAR. The team composition is intended to bridge scales (from the atmosphere-canopy-soil-groundwater column to global) and across disciplines (hydrologists, ecologists, geochemists, and climate scientists), to bring in observation networks to contribute data for testing model performance, and to open a 2-way communication channel between CZO/watershed observers and global Earth System modelers. The synthesis teams will engage in the following activities:

(1) Develop state-of-science hydrologic process syntheses, focusing on a theoretical framework to address multi-scale process interactions, and with the specific goal of recommending the best ways to represent them in ESMs. An example question to be explored by the HPT is: How do we represent both sub-grid variability and between-grid connection, both above and below the land surface capturing the 3D nature of groundwater flowpaths? No matter how fine model grids may become in the future, there will always be important processes that cannot be explicitly resolved. For runoff generation, a fundamental scale in land hydrology is arguably that of a hillslope, from the ridge top to the valley bottom, forming the strongest gravitational gradient driving the strongest lateral convergence of water above or below the surface. However, the role of macro-pores (the relatively few but high conductivity preferential flow paths in dominating subsurface hydrologic flow rate, residence times, stream response and geochemical signature) has challenged the hillslope view. What are the theoretical frameworks for addressing scale interactions, and how do we systematically assess the importance of one scale to the other? At what scale (time/space) do certain processes become important? In atmospheric models, resolving convective scales (~1-2 km) fundamentally enhanced models' ability to simulate boundary layer dynamics/thermal dynamics, and high-intensity precipitation events that are critical for hydrologic forecasting. Are there similarly fundamental scales in land hydrology that are best resolved explicitly? In the Earth System Modeling context, what matters to land hydrology may not influence land-atmosphere coupling. At what scales and under what atmospheric conditions do land surface flux behaviors become first-order drivers of atmospheric response? What are the processes that are better explicitly represented, and what are those that can be parameterized, and how?

(2) Based on the science synthesis above, propose alternative process-representations, each of which may perform better in certain climatic-hydrologic-ecologic regimes and for particular applications. These alternative schemes will form the basis for multiple parameterization options in CLM hydrology. Alternative schemes can also be proposed for a hierarchy of scales, enabling future capabilities that would allow the model to be used more broadly by the hydrology community and to test/assess the importance of unresolved processes on larger scale simulations.

(3) Develop model performance evaluation metrics, test cases and methodologies to evaluate the alternative schemes, participate in model evaluation, and if necessary, return to the drawing board and revisit the syntheses and the schemes.

Thus the HPT synthesis group will participate in the entire process of science synthesis, model conceptualization, model development, and model evaluation. The final deliveries of the HPT activities are a set of peer-reviewed publications articulating the state-of-science across scales, a new generation of parameterization schemes, their implementation in ESM, their evaluation against all available observations, and the impact of these new schemes on improving ESM's ability to simulate terrestrial water cycle and ecosystem dynamics, and their further impact on the simulated Earth System interactions. The outcome of the HPT will far exceed a series of community workshop reports, but will mark a milestone in developing the next generation of the land component in Earth System Models.

4.2. HPT Implementation

Proceeding in parallel with the HPT synthesis activities, we will form an implementation team of 3-5 postdocs and software engineers, to work closely with the HPT synthesis team by participating in all HPT meetings and calls, and to immediately code and test the recommended parameterization schemes and provide feedbacks to the HPT synthesis teams. This will allow us to make rapid initial progress, such as preparing the CLM architecture for the anticipated changes, assembling the essential datasets for testing models, and coding the changes that are considered "low-hanging fruits" already known to need immediate attention, such as sub-grid variability and lateral connectivity though river and groundwater convergence. As the project develops the implementation team will systematically compare alternative (competing) schemes, present results to the synthesis teams, and implement preferred schemes for subsequent CLM releases. This will accelerate the model development by dedicating a work force to the more technical aspects of the project. In addition, such a collaborative, problem-driven work experience on cutting-edge science and technology can bring long-lasting positive impact to the careers of the postdocs and programmers involved.

Because this CUAHSI-NCAR collaboration is intended to benefit both the hydrology and the ESM community, an open interface with clearly defined exchange variables and program hooks will be developed, to (1) allow compatible hydrologic science subroutines to execute, interoperate with CLM variables and maintain mass balance; bypassing some CLM functions if needed; (2) permit flexible spatial discretization allowing lateral and subgrid fluxes to be computable; and (3) allow definitions or redefinitions of input datasets, e.g., subsurface porosity, conductivity and water retention parameters, channels, surface roughness. Scale issue, representation of spatial heterogeneity and lateral connectivity are central topics of discussion in designing this interface. Enabling such an interface will allow the broader hydrologic community, with diverse interests at various spatiotemporal scales, to easily adapt and play with their own hydrologic processes, parameterizations, and customized datasets, while taking advantage of the integrative environment and the modeling platform of CLM. The project will then truly attract and benefit from contributions from diverse players in the community. However, as community models are necessarily constrained by various infrastructural considerations, the scope, possibilities and level of flexibility of such an interface need to be carefully discussed and debated.

5. Time Lines and Milestones

We propose a 5-year plan to develop a new version of CLM with state-of-science hydrologic process representations, with initial advances included in interim releases of CLM and a comprehensive overhaul of hydrologic process representation targeted for the release of CLM6.0 in the year of 2020, and its application in the subsequent Coupled Model Inter-comparison Projects that inform the IPCC Assessments. A tentative time line is proposed below:

2015 - Publish the first synthesis paper in WRR 50yr Anniversary Special Issue, articulating the need for systematic evaluation and improvement of hydrologic process representations in ESMs, the need for active engagement by the hydrologic sciences and the Critical Zone science community, as well as the immediate advances that can be made

- Develop hydrologic benchmarking metrics, datasets and test cases, using initial CUAHSI funding; the effort will begin at the AGU meeting in December (agenda item-1)
- Position the currently funded postdoc at NCAR to prepare CLM infrastructure and the benchmarking dataset in coordination with the CUAHSI Water Data Center

<u>2016</u>
- Form the HPT synthesis teams and conduct synthesis workshops
- Seek support to implement initial advances (i.e., the 'low hanging fruits') in multi-scale hydrologic process representation in CLM, focusing on the initial development priorities identified in the first synthesis paper in the WRR 50yr Anniversary special issue
- Provide detailed evaluation and documentation of hydrologic process advances, focusing on the model's ability to simulate streamflow at all scales (discussed above), and improve code to meet standards for a CLM interim release
- Develop CLM interface with other models employed by the hydrology community, and hold CLM tutorial workshop for the CUAHSI community at the 5th Biennial Science Meeting

<u>2017</u>
- Publish a series of synthesis papers with HPT recommendations for model development

<u>2017-18</u>
- Comprehensively evaluate competing model representations of hydrologic processes
- Implement advances in hydrologic representation in CLM, guided by the development priorities identified in the synthesis papers and results from the comprehensive evaluation

<u>2017-19</u>
- Provide detailed evaluation and documentation of hydrologic process advances, and improve code to meet standards for the CLM 6.0 release

<u>2019</u>
- Release of beta version for community testing
- Community workshop and training
- CLM 6.0 release, application in CMIP for IPCC Assessments

6. Concluding Remarks

Over the past year CUAHSI and the CLM land model working group at NCAR began a collaboration to challenge and improve the way hydrologic processes are represented in Earth System Models. This pilot project, with a focus on large-scale Earth System Models, will allow us to explore and establish a community process and culture to foster other lines of community models, such as watershed-scale hydrology or biogeochemistry models.

Our first working group meeting at NCAR outlined the vision and strategies to move this joint effort forward. This collaboration will benefit the hydrologic sciences by establishing a mechanism to link what we observe and conceptualize in the field to what we must predict at the continental and global scales, and vice versa, by knowing what to observe and how it may or may not scale up to large-scale and long-term processes and patterns. The proposed interface with other hydrology models, within the integrative framework of CLM, will open new channels of dialogues between the two communities. Contributing our community's collective hydrologic wisdom to Earth System Modeling will also benefit ESM development, because the cycling of water mediates, to a large extent, the cycling of energy and biogeochemical elements on land. After all, what makes our planet unique is the presence of liquid water; its incessant movement and phase change link the many spheres that sustain life on Earth.