Representing the Integrated Water Cycle in Community Earth System Model

Hong-Yi Li, L. Ruby Leung, Maoyi Huang, Nathalie Voisin, Teklu Tesfa, Mohamad Hejazi, and Lu Liu

Pacific Northwest National Laboratory
Water in the human-Earth system

- Water underlies and influences many important climate processes and feedbacks – a leading cause of uncertainty in projecting future climate

- Water is essential for energy systems, ecosystem services, and a wide range of life sustaining and other critical human activities

- Global and regional water cycles are influenced by natural processes as well as the human systems – how will they co-evolve in the future?
Processes in the integrated water cycle

Challenge: How to represent the multi-scale, dynamic interactions among the atmosphere, terrestrial, and human systems.
Modeling the integrated water cycle

Objectives

- Represent the dynamic interactions between the human and earth systems and their influence on the water cycle
- Use the models to investigate the nexus of climate, energy, water, and land under climatic and societal changes for sustainable energy and water in the future

Approach

- Improve model scalability to address the multi-scale atmospheric and terrestrial water cycle processes
- Add human components (water management, water use, water demand) of water cycle processes in CESM
Model Structure

- CESM
  - CAM
    - Atmospheric forcing
    - Flux Coupler
      - Surface fluxes
  - POP
    - Atmosphere and ocean boundary conditions

- RESM
  - WRF
    - Atmospheric forcing
  - Flux Coupler
    - Surface fluxes
  - CLM
  - ROMS

- GCAM
- R-GCAM

- River Routing/ Water Management
- Electric Infrastructure/ Electricity Operations
- Land Use

Pacific Northwest
NATIONAL LABORATORY

© 2023 Pacific Northwest National Laboratory operated by Battelle

5
CLM coupled with river routing and water management

Improve and add new capabilities in Community Land Model (CLM) to represent hydrology and human – water cycle interactions at multiple time and space scales.
Runoff parameterizations in LSMs

CLM4

• Based on TOPMODEL

• Assumptions:
  ▪ High-resolution topographic data are available;
  ▪ Subsurface flow is topographic driven.
  ▪ A quasi-steady state to approximate saturated zone dynamics;
  ▪ Recharge to ground water is spatially uniform;

These assumptions are invalid, e.g., over flat terrain or arid regions.

VIC

• Conceptual

• Limited assumptions:
  – land surface, and therefore surface runoff generation, is heterogeneous;
  – Subsurface flow is a nonlinear function of deep-layer water availability

• Calibration of parameters are recommended
VIC as an hydrologic option in CLM
To be released in Summer 2013

Li et al., 2011
Comparison of observed and simulated annual LH over MOPEX basins: CLM, CLMVIC, and other NLDAS models
Runoff schemes affect C cycle modeling through interactions among water, energy, and C cycles

Both structural and parameter uncertainties in the runoff generation schemes can lead to large uncertainty in carbon modeling, highlighting the significant interactions among the water, energy, and carbon cycles and the need for improving hydrologic parameterizations in land surface models.

MODIS: 112 Pg C/year
CLMVIC: 114 Pg C/year
CLM4.0: 143 Pg C/year
Enhancing the CLM spatial structure

- Subbasins vs lat/lon grids as computational units
- Subgrid structure: PFT/elevation, permanent channel/floodplain
- Subgrid atmospheric forcing
- 3D radiative transfer in mountains
Comparison of grid vs subbasin representations

- Land surface heterogeneity such as topography has a dominant influence on hydrological processes.
- Using subbasins as the computational units eliminates the need to represent the redistribution of soil moisture between units and improve the accuracy for estimating the topographic index used in the TOPMODEL parameterizations of surface and subsurface runoff.

Grid-based representation (CLM)  Subbasin-based representation (DCLM)
The subbasin representation improves scalability

Model skills (MAE) at different resolutions are more strongly correlated and model skill increases systematically with resolution in the subbasin representation but not the grid representation.
Hillslope routing to account for event dynamics and impacts of overland flow on soil erosion, nutrient loading etc.;

Sub-network routing: scale adaptive across different resolutions to reduce scale dependence;

Main channel routing: explicit estimation of in-stream status (velocity, water depth etc).

(Li et al., JHM, 2013, in press)
Case Study: Columbia River Basin

- Daily runoff generation from Variable Infiltration Capacity model (VIC) at 1/16 degree resolution
- Off-line evaluation against monthly naturalized streamflow data at selected major stations
MOSART is more skillful in simulating streamflow compared to RTM

NS coeff. for monthly mean streamflow – grid based representation

NS coeff. for monthly mean streamflow -- subbasin based representation
MOSART reproduces monthly variation of channel velocity with minimum calibration.
Model for Scale Adaptive River Transport (MOSART)

Coupling MOSART to CLM4

- Grid-based representation: replacing RTM with MOSART, keeping remapping and parallel algorithms
- Subbasin-based representation: one-one mapping between CLM and MOSART grids

Supporting global multi-resolution database

- Hydrography parameters (flow direction, channel length and slope etc.) directly derived from high resolution DEM (1km) at 1/16, 1/8, ¼, ½, 1 and 2 degree resolutions
- Other parameters (channel geometry and Manning’s coefficients) derived based on landcover and empirical Hydraulic Geometry relationships

Global testing using NCAR benchmarking case (I-2000 )

- Global run done for 1948-2004 period (spatial resolution of CLM4 0.9*1.25 degree, MOSART 0.5 degree)
1129 GRDC stations were geo-referenced to the new river network (drainage area error no more than 10%)

NSC > 0 for 470 out of 1129 GRDC stations for monthly streamflow
Couple riverine biogeochemistry into MOSART

- CLM
- Water column
  - Active layer
  - River bank
- Water column
  - Active layer
  - River bank
- Inundated area

Flow paths:
- Water
- Sediment
- Nutrient

Routing:
- Hillslope routing
- Sub-network routing
- Main channel routing
Water management model (Voisin et al. 2013, HESS, submitted)

- Designed for full coupling in an earth system models
  - Assume no knowledge of future inflow
  - Use generic operating rules
Water management model

Irrigation demand → CLM → Irrigation supply

WRM → Natural flow in each units → Routing model → Regulated flow

Total water demand

Reservoir dependency
Combining flood control and irrigation objectives in operating rules best capture the observed regulated flow in the Columbia river basin.
Reservoir storage and supply deficit

- Reservoir storage is only reproduced using operating rules that combine flood control and irrigation priorities.
- At the American Falls, supply deficit is related to groundwater use.
Integrating with IAM: Water market and water demand

Water demand for various sectors driven by energy demand, GDP, and agricultural land demand is simulated by IAM (GCAM).

GCAM also solves the energy market, land market, and water market simultaneously to establish prices and shares by source.

Water demand from sectors other than agriculture.
Summary

On hydrologic modeling and model scalability:
- Subbasin representation offers some advantage in scalability
- The new river routing model (MOSART) represents hillslope, tributary, and channel routing and works well across scales
- A new CLM subgrid structure is being developed to account for subgrid PFT, elevation, and inundation

On representing the dynamic interactions between human and earth systems:
- Developed a coupled system including CLM, river routing, and water management to represent irrigation water use and water management
- Ongoing research to represent water demand, water use, and water market using the coupled CESM - GCAM

Global implementation and evaluation underway