Enhancing the community Noah-MP land model capabilities for Earth sciences and applications

Cenlin He¹, Fei Chen¹, Michael Barlage², Zong-Liang Yang³, Jerry W. Wegiel⁴, Guo-Yue Niu⁵, David Gochis¹, David M. Mocko⁶, Ronnie Abolafia-Rosenzweig¹, Zhe Zhang⁴, Tzu-Shun Lin¹, Prasanth Valayamkunnath⁷, Michael Ek¹, Dev Niyogi³

¹ National Center for Atmospheric Research (NCAR), Boulder, Colorado, USA
² NOAA Environmental Modeling Center (EMC), College Park, Maryland, USA
³ Department of Earth and Planetary Sciences, University of Texas Austin, Austin, Texas, USA
⁴ Hydrological Sciences Laboratory, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
⁵ Department of Hydrology and Atmospheric Sciences, University of Arizona, Tucson, Arizona, USA
⁶ SAIC at NASA Goddard Space Flight Center, Greenbelt, Maryland, USA
⁷ Indian Institute of Science Education and Research, Thiruvananthapuram, India

Corresponding author: Cenlin He (cenlinhe@ucar.edu)

What, When, Where Box:

First International Noah-MP Annual Users’ Workshop

What: More than 200 registered workshop participants from 16 countries gathered in person and online to discuss scientific and modeling advances in using and developing the Noah-MP land surface model and explored current challenges, future priorities, and collaborative opportunities in enhancing the model capability, applicability, and interoperability in earth system applications.

When: May 23-24, 2023

Where: Boulder, Colorado, USA (in-person), and remote (virtual)

Early Online Release: This preliminary version has been accepted for publication in Bulletin of the American Meteorological Society, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-23-0249.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

© 2023 American Meteorological Society. This is an Author Accepted Manuscript distributed under the terms of the default AMS reuse license. For information regarding reuse and general copyright information, consult the AMS Copyright Policy (www.ametsoc.org/PUBSReuseLicenses).
Key words: land modeling, Noah-MP, model development and application, Earth sciences

Introduction

Land surface plays an important role in the Earth system, modulating global and regional energy and water balances through interacting with the atmosphere, biosphere, hydrosphere, lithosphere, ocean, and sea ice. Accordingly, land surface models (LSMs), which simulate the key biogeophysical and biogeochemical processes that interact with and feed back to weather, climate, and other earth environments, are an indispensable component of Earth system models (ESMs). LSMs have been broadly used in Earth science applications to tackle critical and big societal challenges, including wildfire, flooding, heatwave, drought, water availability, agriculture, food security, urbanization, weather forecast, and climate projection (Blyth et al., 2021).

The community Noah with Multi-Parameterizations (Noah-MP; Niu et al., 2011; Yang et al., 2011) is one of the most widely used state-of-the-science LSMs, which has been applied to a broad range of spatial and temporal scales for various purposes (He et al., 2023), such as numerical weather prediction, climate extremes (e.g., fire, drought, flood, and landslide), hydrology, agricultural management, urban heat island, food-water-energy nexus, and biogeochemical cycling. Noah-MP has also served as a land component of several important research and operational weather and hydrological modeling systems internationally, such as the NCAR High-Resolution Land Data Assimilation System (HRLDAS), the NASA Land Information System (LIS), the Weather Research and Forecasting model (WRF), the Model for Prediction Across Scales (MPAS), the NOAA operational National Water Model (NWM)/WRF-Hydro, the NOAA Unified Forecast System (UFS), the operational Korean Integrated Model (KIM), and the Chinese Global-to-Regional Integrated forecast SysTem (GRIST) model.

In light of the growing popularity of Noah-MP, this hybrid international Noah-MP workshop provided a platform for the international Noah-MP community to share Noah-MP research progress, exchange ideas for current model development and challenges, and discuss future priorities of model development and application. This workshop was held at the National Center
for Atmospheric Research (NCAR) in Boulder, Colorado, USA. More than 200 registered participants from 16 countries (Figure 1) attended the workshop, including graduate students, postdoctoral researchers, scientists from national laboratories, and university professors (Figure 2). Participants reported their recent studies for Noah-MP model development, improvement, and application in addressing various Earth and environmental science issues, as well as discussed the formation of model technical and steering committees and model challenges and future directions. The workshop presentations and recordings are available online at https://ral.ucar.edu/events/2023/noah-mp-annual-users-workshop.

The ultimate goal of this work is to answer the following three questions:

● Where will Noah-MP be in the next 5 to 10 years? What aspects and applications should future Noah-MP developments focus on?
● What are the current challenges to achieve the above vision and goal?
● What resources will we need in the future to achieve the above vision and goal?

Overall, there is a consensus from this workshop that Noah-MP development is a research priority for scientific and operational communities. This meeting summary provides a high-level overview of the workshop presentations and discussion outcomes.

![Figure 1. Spatial distribution of Noah-MP workshop participants.](image)
Model advances in Earth sciences and applications

Overview from main development groups. Several main Noah-MP development groups summarized the model advances and applications in the past few years. Specifically, the Noah-MP model history was reviewed, including milestones of major physics updates, substantially increased applications of Noah-MP in various research and operational systems, highlights of model enhancements in groundwater and climate-hydrology-agriculture processes, the advances in assimilating modern-era satellite data to improve land-atmosphere interactions, and the recent release of a modernized/refactored model version 5.0 that offers fresh avenues for developing novel physics options, strengthening model applicability and interoperability, and active participation within the Noah-MP community. Detailed improvements of model capabilities reported from different groups included enhanced key processes (e.g., soil hydraulics and hydrology, plant hydraulics, and carbon-nitrogen cycles); incorporating human dimension processes (e.g., urbanization, crop, and agricultural management) into Noah-MP; coupling capabilities with the NCAR Data Assimilation Research Testbed (DART); new development of a unified treatment of pressure driven water movement from the bedrock to the vegetation canopy; the advances of Noah-MP in operational transition in the NOAA UFS; coupling with WRF-Hydro
in real-time operational hydrological forecasting; implementation in the NASA LIS for land data assimilation (DA) applications; coupling with the Chinese GRIST model and the Korean Integrated Model; the development and application in the Global Hydro Intelligence (GHI) system.

**Hydrology.** The development and application of Noah-MP in addressing hydrological problems were discussed, including quantifying the meteorological drought propagation to hydrological drought; developing consistent soil and plant hydraulic schemes in Noah-MP to better capture different vegetation responses to droughts; enhancing process-level Noah-MP snowpack physics to better represent snow hydrology; assimilating snow water equivalent (SWE) observations into NWM/Noah-MP to improve hydrological simulations; coupling WRF-Hydro/Noah-MP with a new glacier model (CROCUS) to improve streamflow simulation from melting glaciers; quantifying irrigation water use and groundwater-fed irrigation impacts on terrestrial water storage.

**Soil moisture and land-atmosphere interaction.** Several efforts of evaluating and improving Noah-MP soil moisture modeling and feedback to the atmosphere were presented, including: (i) incorporating new dynamic root schemes to better simulate soil moisture conditions, surface fluxes (e.g., latent heat) to the atmosphere, and hence surface meteorology (e.g., 2-m temperature); (ii) assessing model accuracy of surface and root-zone soil moisture during droughts; and (iii) quantifying seasonal soil freeze/thaw variability via ensemble land surface modeling.

**Biogeochemistry and agriculture.** Noah-MP enhancements in several key biogeochemical and agricultural applications were reported, including: (i) incorporating atmospheric air pollution (ozone and aerosol) interactions with vegetation and soil to improve modeling of both air pollution and surface flux and meteorology; (ii) implementing a new carbon-nitrogen cycling scheme to assess impacts of nitrogen fertilization and improve simulations of soil nitrogen, vegetation/crop growth, net primary productivity, land surface flux and meteorology; (iii) coupling Noah-MP with a generic crop growth (GECROS) model to enhance simulations of crop and surface temperature; (iv) incorporating new irrigation and tile drainage schemes to realistically represent agricultural water management; (v) implementing new representations of spring wheat and a dynamic crop
planting/harvest scheme to assess climate impacts on food-water security; and (vi) applying Noah-MP to develop a high-resolution coupled climate-crop seasonal wheat yield prediction system.

Urbanization. The applications of Noah-MP in urban studies were presented, including developing a Noah-MP-Urban based downscaling approach for urban thermal environment to better quantify and predict urban heat island, and quantifying the impacts of urbanization on hurricane rainfall using the coupled WRF/NoahMP.

Land data assimilation. Several presentations discussed the enhancement and application of Noah-MP in various data assimilation systems, including: (i) improving Noah-MP simulated energy-water-carbon fluxes by hybridizing data assimilation and machine learning techniques; (ii) applying the LIS/Noah-MP data assimilation system to improve snow mass and soil moisture estimates; and (iii) implementing and assessing Noah-MP in the USAID’s Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS) to address global food-water security issues.

Weather/climate predictions. A number of studies on Noah-MP application in weather/climate predictions were reported, including: (i) enhancing Noah-MP in the NOAA UFS to improve forecast of near surface fields; (ii) applying Eta/Noah-MP coupled model to quantify impacts of land use change on hydroclimate predictions in South America; (iii) incorporating and assessing Noah/Noah-MP in medium-range hydrologic forecasts over Afghanistan; and (iv) optimizing Noah-MP parameters using Bayesian optimization to improve simulation and prediction of near-surface atmospheric states across the U.S. southern Great Plains.

Current challenges

Model limitations. Important Noah-MP model limitations were highlighted, including: (i) uncertainties in processes such as snowpack physics, vegetation dynamics, soil/plant hydraulics, infiltration of ponded water, preferential flow, and groundwater, coupled carbon-nitrogen cycle, turbulence treatment across canopy column, coupling with boundary layer physics, and glacier
representations; (ii) missing land surface processes such as blowing snow, wetland, environmental disturbances (e.g., fire and beetle damages, deforestation/ reforestation), vegetation recovery and replacement, and groundwater pumping; (iii) lack of flexible coupling interfaces with external data assimilation frameworks; (iv) insufficient representation of subgrid heterogeneity; (v) lack of code debugging capabilities as well as documentation and constraints for model parameters in the look-up table; (vi) pool treatment of ecosystem-air pollution interactions; and (vii) lack of connection with human dimensions (e.g., socio-economic impacts and Earth system-society interactions).

**Data and tool limitations.** Several limitations about model-relevant data and tools were also identified, including: (i) lack of high-resolution spatial and/or temporal varying input datasets for vegetation and soil properties as well as those required by certain model physics (e.g., water table, irrigation maps, and tile drainage maps); (ii) lack of scripts and datasets for model benchmarking, testing, post-processing, and diagnostics; (iii) lack of automated model parameter calibration/optimization packages; lack of “simple” toy models for each major Noah-MP component to diagnose and isolate biases hierarchically; and (iv) insufficient model platforms (e.g., container or cloud-based) and tutorial materials for educational purposes.

**Community limitations.** There is insufficient communication about model updates and code sharing within the Noah-MP community. As a result, many important model physics updates are only available in the private platforms maintained by each individual research group worldwide (see He et al. 2023 for a summary of those updates), which are not yet in the community Noah-MP version (https://github.com/NCAR/noahmp). In addition, there is a lack of efficient mechanisms and coordination for universities and national laboratories to work together to transfer users’ code updates to the community version and operational systems.

**Resource limitations.** There is a lack of funding and human resources to facilitate the transfer of users’ model development to the community version and operational systems as well as to maintain and organize the community code contributions and updates. Almost all the model developments in the past few years have been project-based and project-targeted, however, a set of funding resources set aside specifically for facilitating, coordinating, and maintaining the Noah-MP
community model development and updates in various research and operational systems are urgently needed.

Future priorities

The Noah-MP community has recommended several key priorities for future model developments and applications in actionable Earth sciences in the next 5 to 10 years:

1) Advancing toward the leading land DA modeling framework by providing flexible interfaces to accommodate observations (including new/upcoming satellite retrievals), more tightly coupling model physics with observations, allowing simultaneous optimizations of state and parameter variables, and increasing compatibility with different coupled weather, climate, and hydrological models;

2) Improving land physics in subseasonal-to-seasonal predictions in coupled models toward the leading weather modeling system, particularly for hydroclimate extremes that are societally relevant (e.g., drought, fire, flood, and heat wave), and applications in informing resource management decisions to mitigate the impacts of hydroclimate extremes;

3) Strengthening capabilities and applications in modeling anthropogenic processes, including agricultural practices (e.g., irrigation, crop management, groundwater pumping, etc.) and human-managed land use land cover change (e.g., deforestation and urbanization), particularly under climate change;

4) Establishing a Noah-MP Academia Collaboratory consisting of universities and national laboratories to support the coordination and management of community collaborations, to secure continuous funding and human resources to facilitate model applications and developments, and to interact with stakeholders to enhance research-to-operation activities.

Acknowledgements

We acknowledge the support by the NCAR Water System Program, NOAA WPO S2S grant NA22OAR4590503, and NOAA CPO MAPP grant NA20OAR4310421. The workshop organizers thank the kind help from the NCAR IT technical support team and NCAR/RAL
administrative support team. We also acknowledge the strong support and enthusiasm from the international Noah-MP community.

**Data availability statement**

There is no data associated with this meeting summary.

---

**Box 1:**

**Main Takeaways:**

1. Community efforts aiming to advance Noah-MP toward the leading weather and land data assimilation (DA) modeling framework are diverse and substantial.
2. Future Noah-MP priorities in actionable Earth sciences include enhancing capabilities in land DA and modeling hydroclimate extremes and anthropogenic processes.
3. There is a need to establish Noah-MP community governance and more community coordination and funding resources, including establishment of an Academia–National Laboratory Noah-MP model development collaboratory.

**References**

