Climate risks in the water sector: Advancing the readiness of emerging technologies in climate downscaling and hydrologic modeling

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Grey Nearing (Co-I, Univ. of Alabama)

Personnel:
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Andrew Bennett (University of Washington)
Kristine Verdin, James Geiger, Scott Rheingrover (NASA/GSFC)

Earth Science Technology Forum 2019
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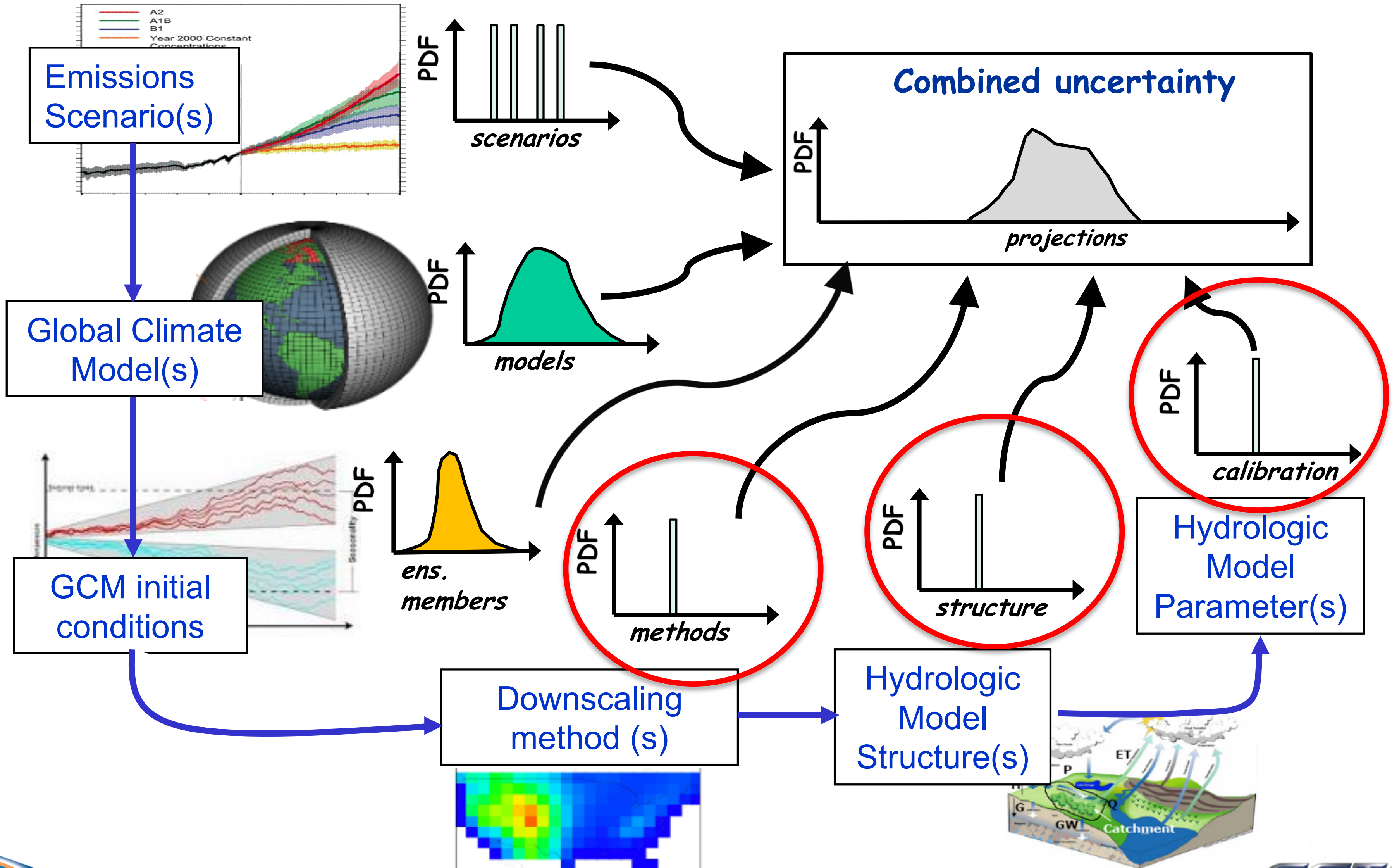
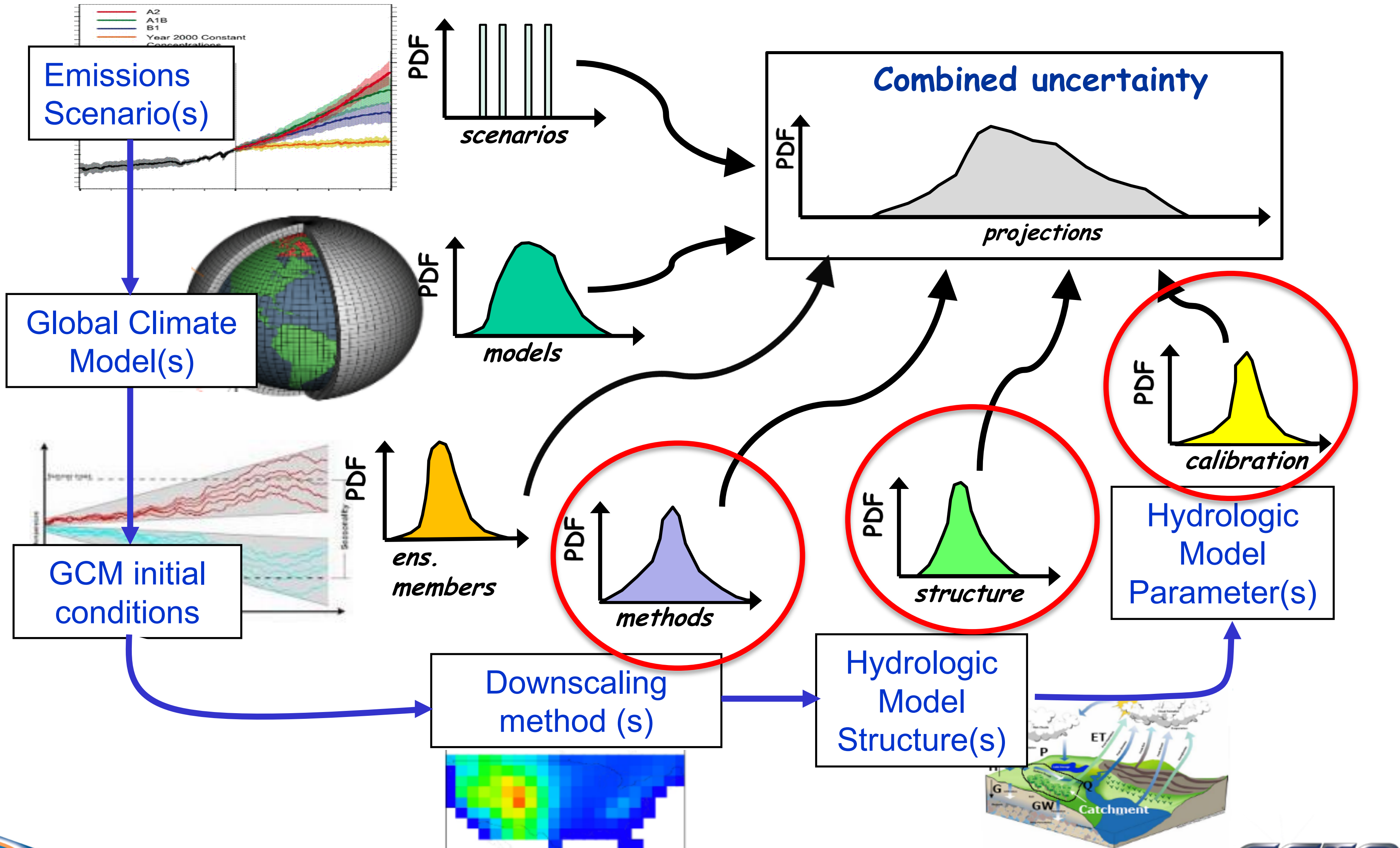
Water security

- The U.S. Army Corps of Engineers, the Bureau of Reclamation want to use the latest in climate & hydrology modeling to understand risks to water security.
- Scientific understanding of the weather-water-climate nexus is critical
- Advances enable water agencies to develop strategies to modernize and maintain their infrastructure

Project Context: Quantifying future hydroclimate uncertainty



Project Context: Quantifying future hydroclimate uncertainty

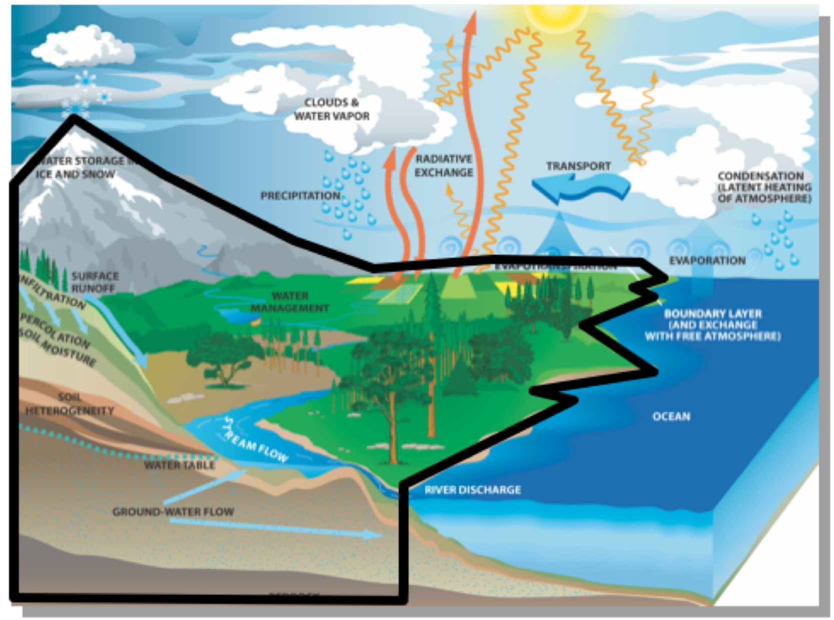


Project Objectives

- Increase the value of emerging science in climate downscaling and hydrologic modeling for water resources planning.
- Extend the NASA Land Information System (NASA-LIS) ecosystem to include new tools and models for evaluating climate-related risks in the water sector.
- Transition
  - new climate downscaling tools (ICAR/GARD)
  - a hydrologic model (SUMMA)
  - a streamflow routing model (mizuRoute)
  - a parameter estimation tool (MPR-Flex)
  - a tool for streamflow bias correction (bmorph).

Background: NASA Land Information System (LIS)

- A system to study land surface processes and land-atmosphere interactions
  - Integrates satellite- and ground-based observational data products with land surface modeling techniques
  - Capable of modeling at different spatial scales



- A comprehensive, sequential data assimilation subsystem based on NASA GMAO infrastructure
- Coupled land-atmosphere systems that employ LIS as the land surface component (earlier Advanced Information Systems Technology (AIST) funded work)
- Comprehensive optimization and uncertainty estimation subsystems that employ remote sensing observations for parameter estimation (previous AIST project)

- NASA's 2005 software of the year award
- Used by the Air Force Weather Agency (AFWA) as the operational land surface modeling system
- An OSSE environment for hydrology mission studies was developed as part of an AIST-2011 project

NASA LIS and Land Surface Monitoring

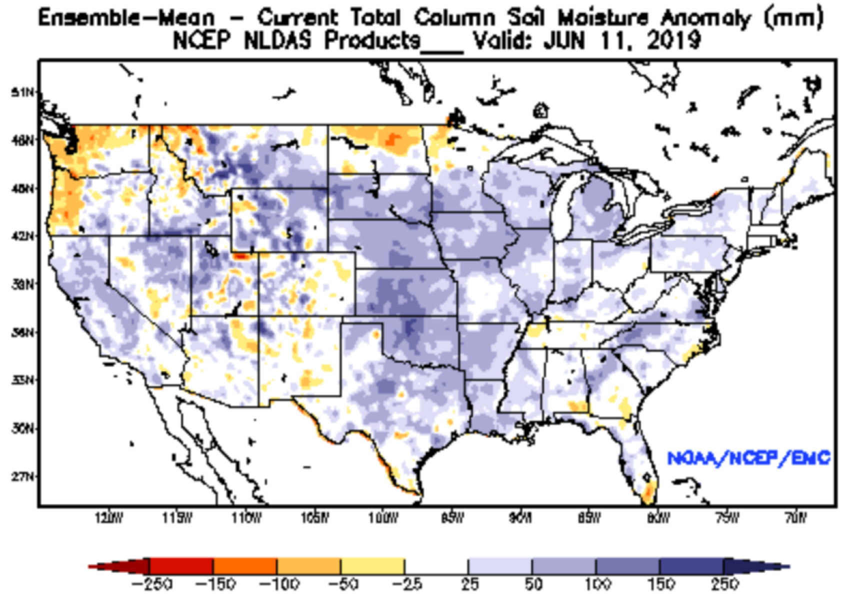
Soil Moisture

NOTE: This page is best viewed with a screen resolution of at least 1024x768

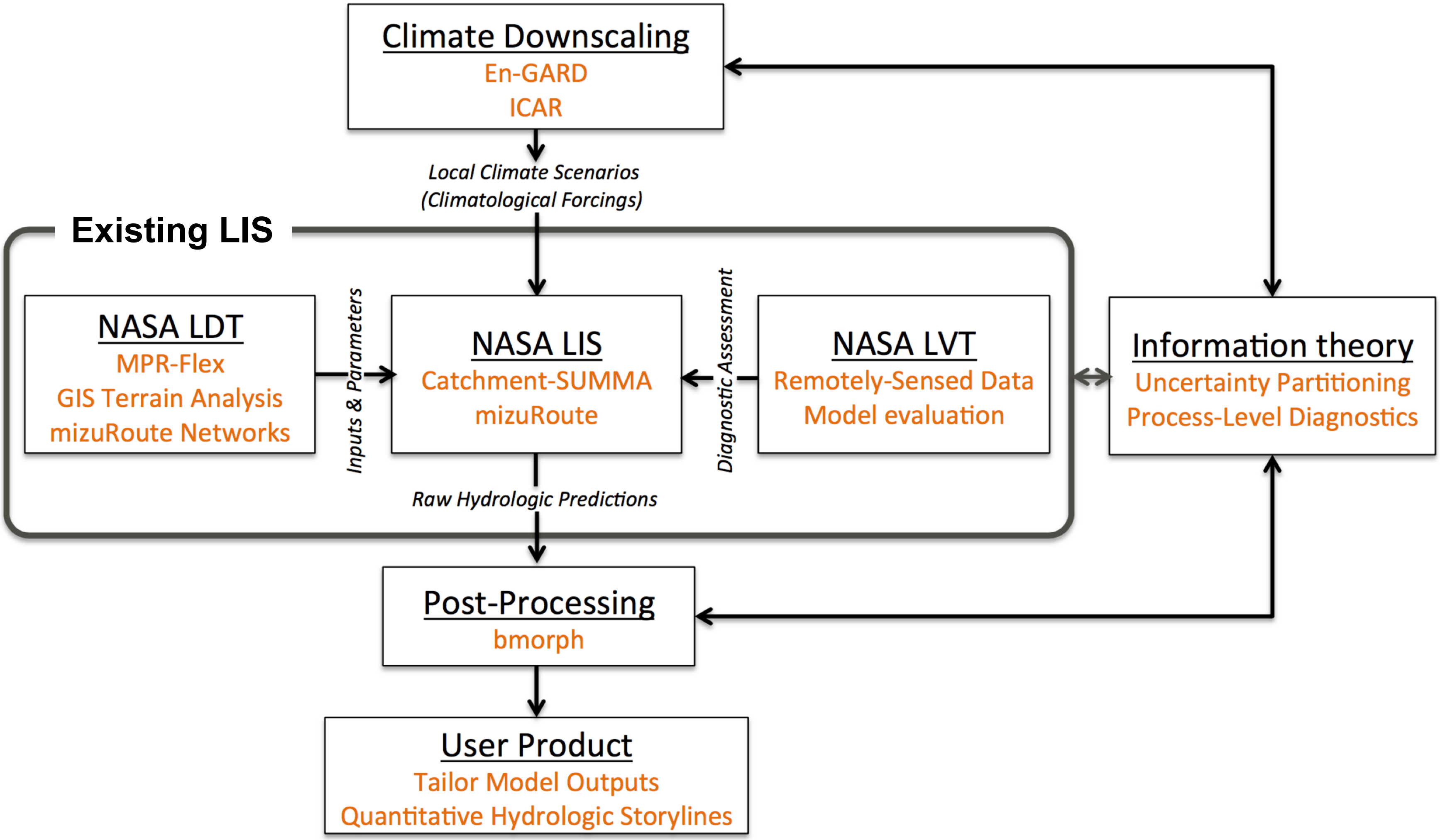
DISCLAIMER: Any data provided on this server should be used for research or educational purposes only. This data should NOT be relied on for any operational use as data gaps can occur due to hardware failure and/or model upgrading procedures.

Ensemble Mean LSM OUTPUT:

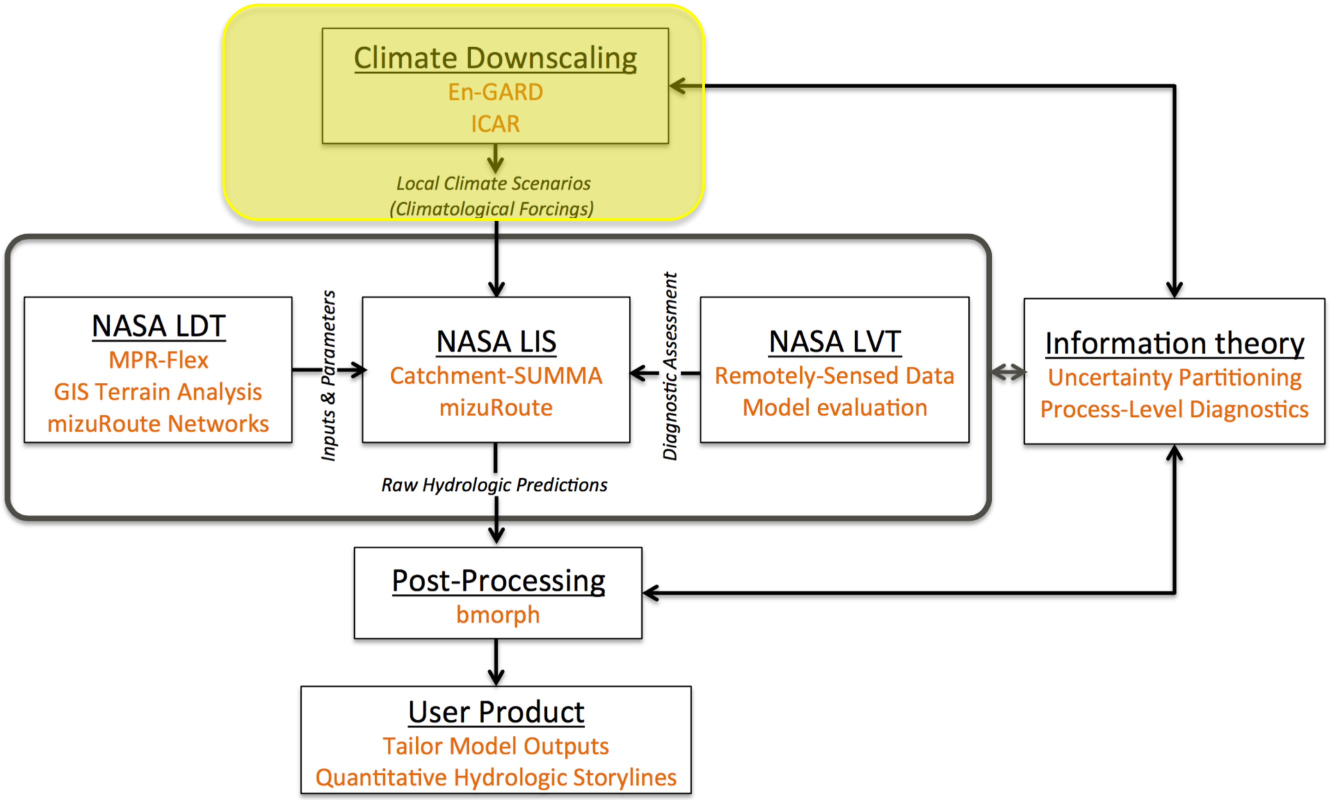
Current Total Column Soil Moisture Anomaly



Expanding the NASA-LIS Ecosystem



Climate Downscaling

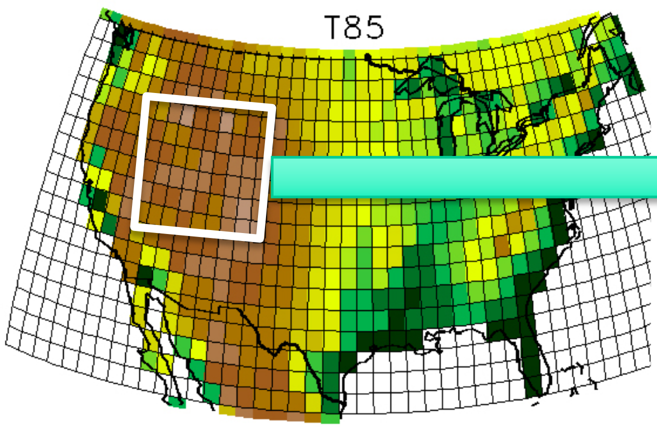


Tasks

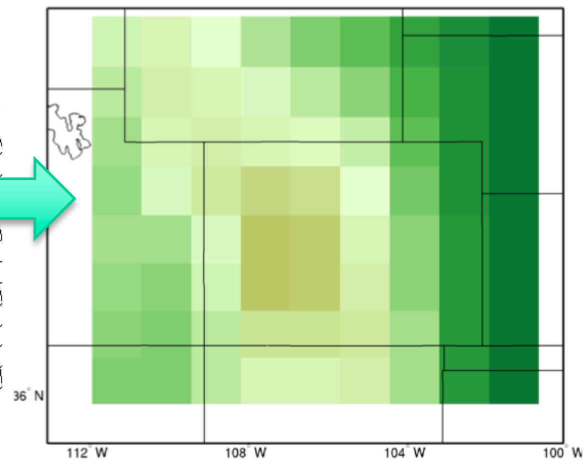
1. **Extend climate downscaling tools**
2. Customize hydrologic modeling capabilities in NASA LIS
3. Refine hydrologic modeling simulations from NASA LIS
4. Tailor model outputs
5. Use Information theory and machine learning

Background: Climate Model Native Resolution and Application Resolution

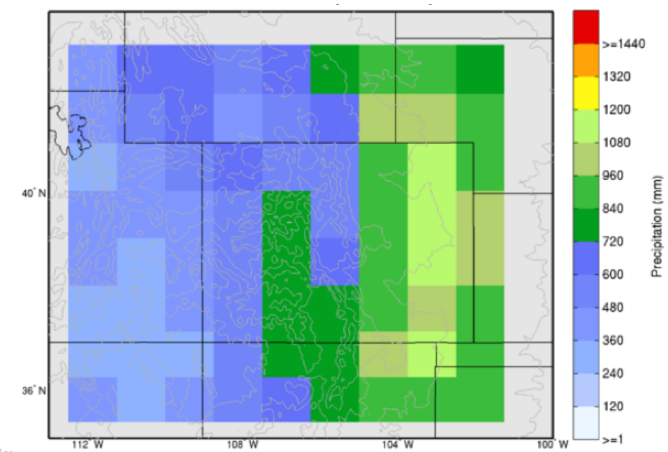
Climate Model Scale



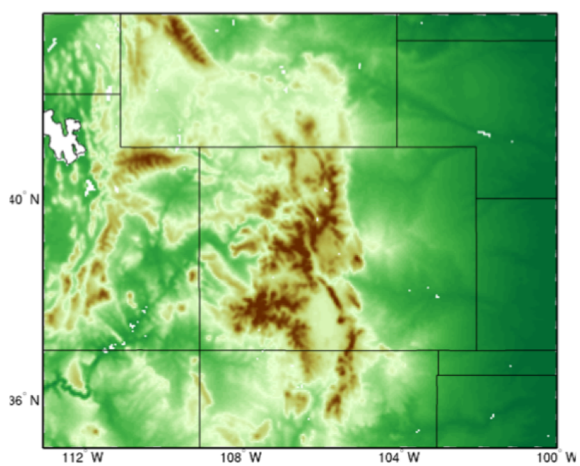
Topography



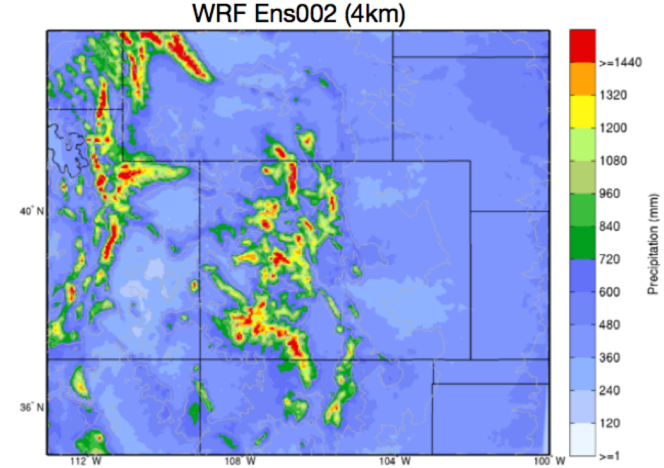
Precipitation



Application Scale



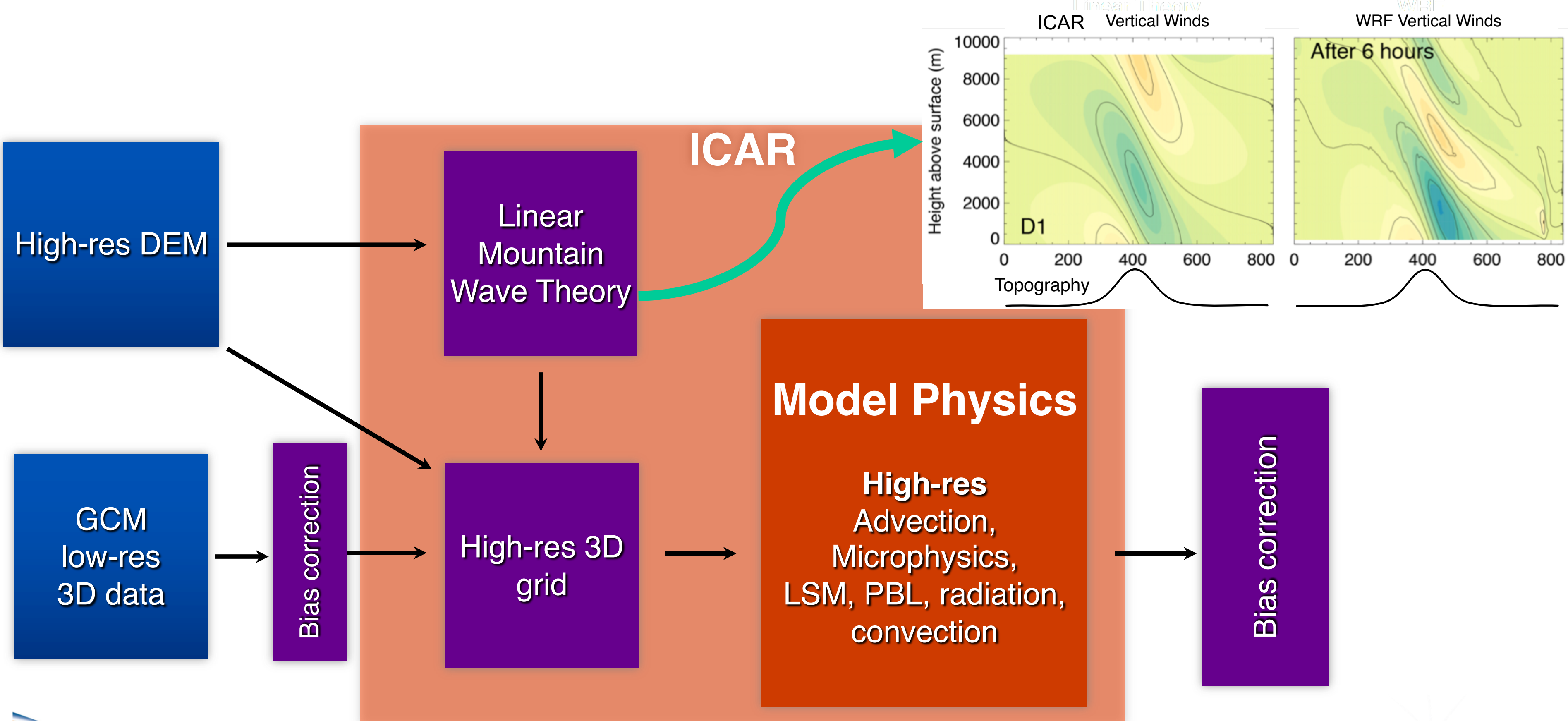
WRF Ens002 (4km)



Intermediate Complexity Atmospheric Research model (ICAR)

Understand tradeoffs in physical complexity and develop a streamlined model

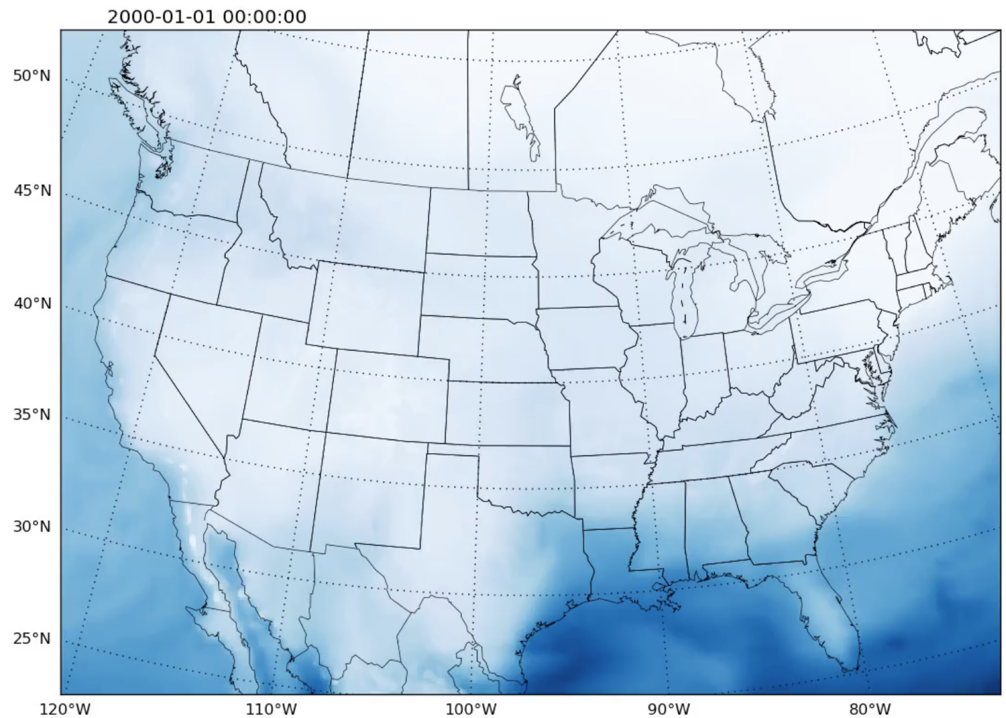
GOAL: >90% of the information for <1% of the cost



Intermediate Complexity Atmospheric Research model

1. Extend climate downscaling tools ICAR and GARD to provide climate change scenarios for input to NASA-LIS hydrology modeling
   a. Simplify pre-processing (eg for WRF output, Metgrid, ERAi, MERRA)
   b. Simplify configuration and testing
   c. Improve robustness and extensibility
   d. Document user options
   e. Add parallelization (scales at least to 20k cores)

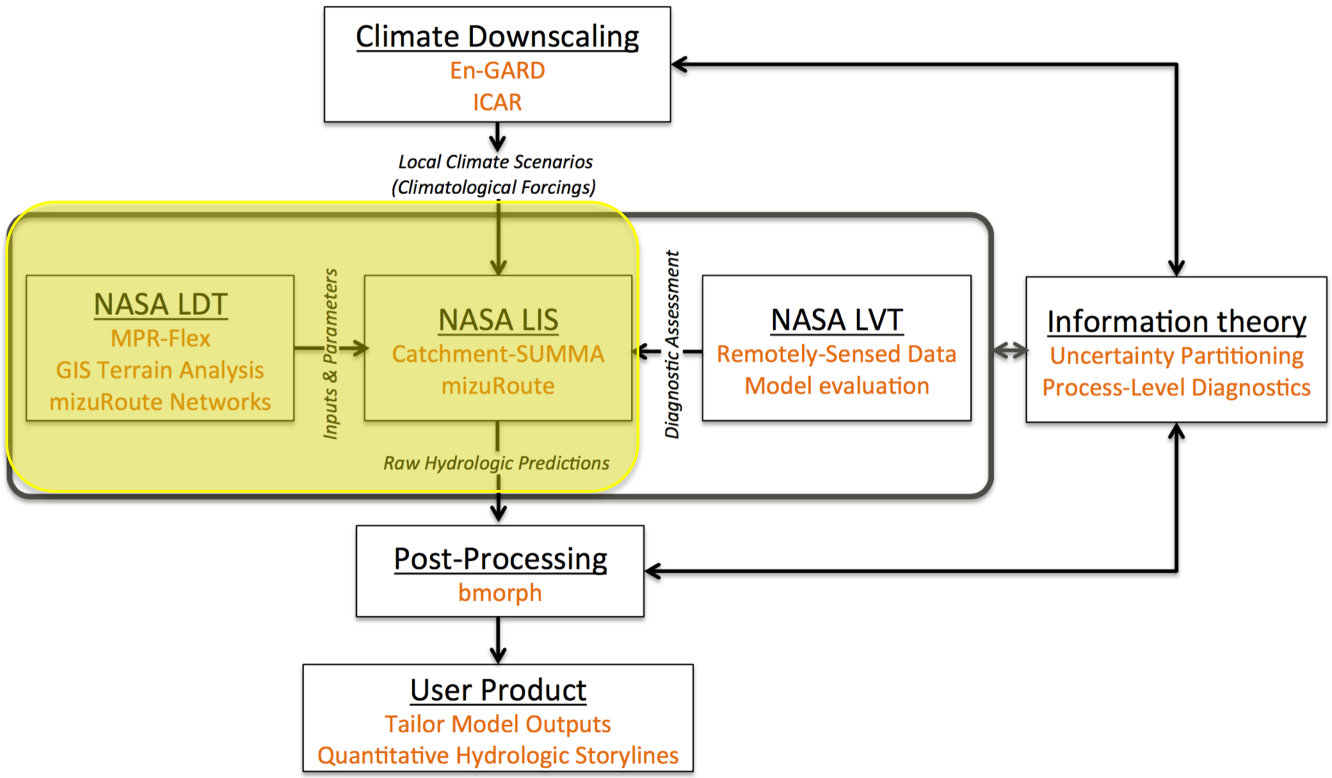
10-day CONUS 2km simulation



Pre-AIST sequential: 24 hours
Now: 2.5 minutes with parallelization

Results presented at SuperComputing 2018.

Land / hydrology modeling



Tasks

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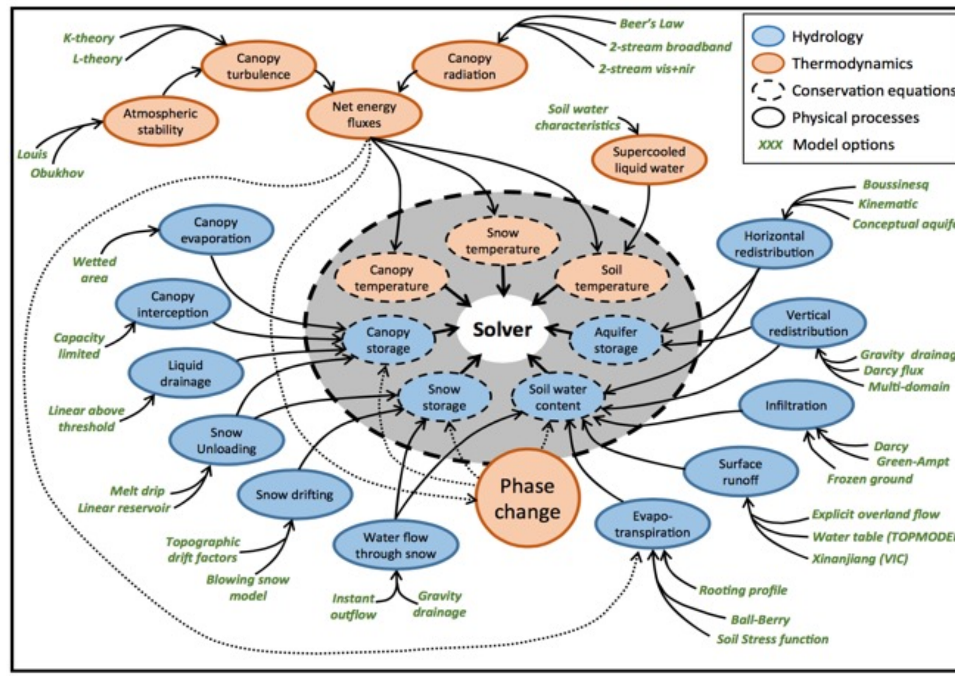
2. Customize hydrologic NASA-LIS extensions to define climate change impacts on hydrologic processes

Land modeling (SUMMA)

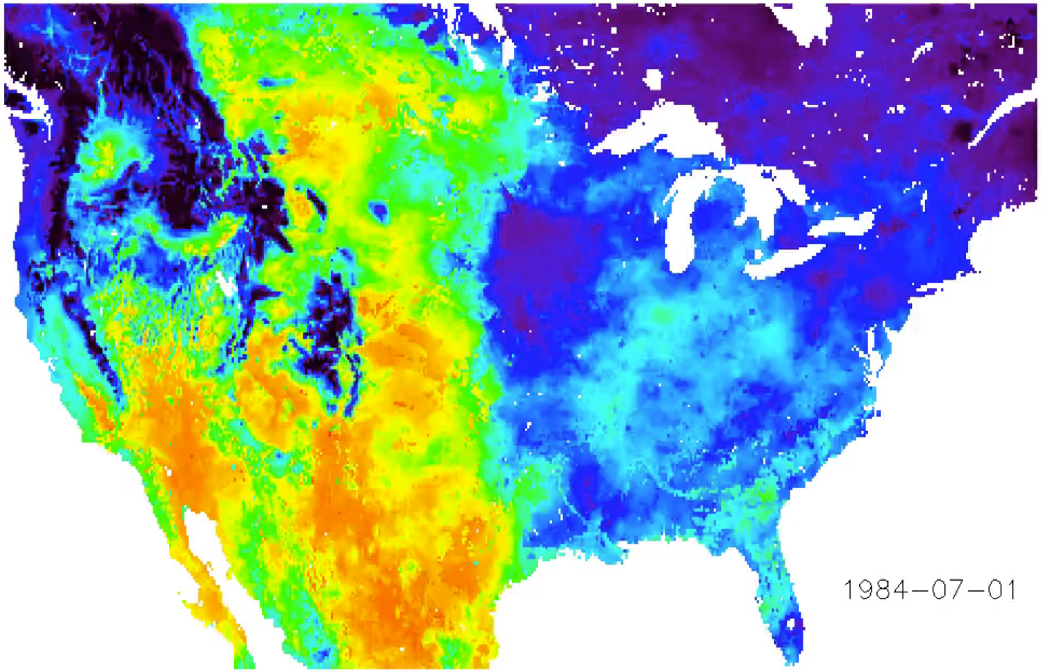
a. Develop terrain analysis procedure
b. Incorporate and evaluate alterative spatial configurations in SUMMA
c. Integrate into NASA-LIS Land Data Toolkit (refactor SUMMA)



Milestone B. NASA-LIS simulations using watershed-based land model configurations for the contiguous USA.

Adding a new land/hydrology model to the LIS ecosystem

Task 2a: Terrain analysis. *Develop terrain analysis tools to delineate landscape features and define hillslope characteristics*



SUMMA simulations of soil moisture

- SUMMA/mizuRoute configured for NHD++ (2.7M basins)
- Evaluating hydrologic prediction across scales through area-based aggregation of high-res network
- Explicitly incorporate riparian corridors and hydrologically similar hillslopes

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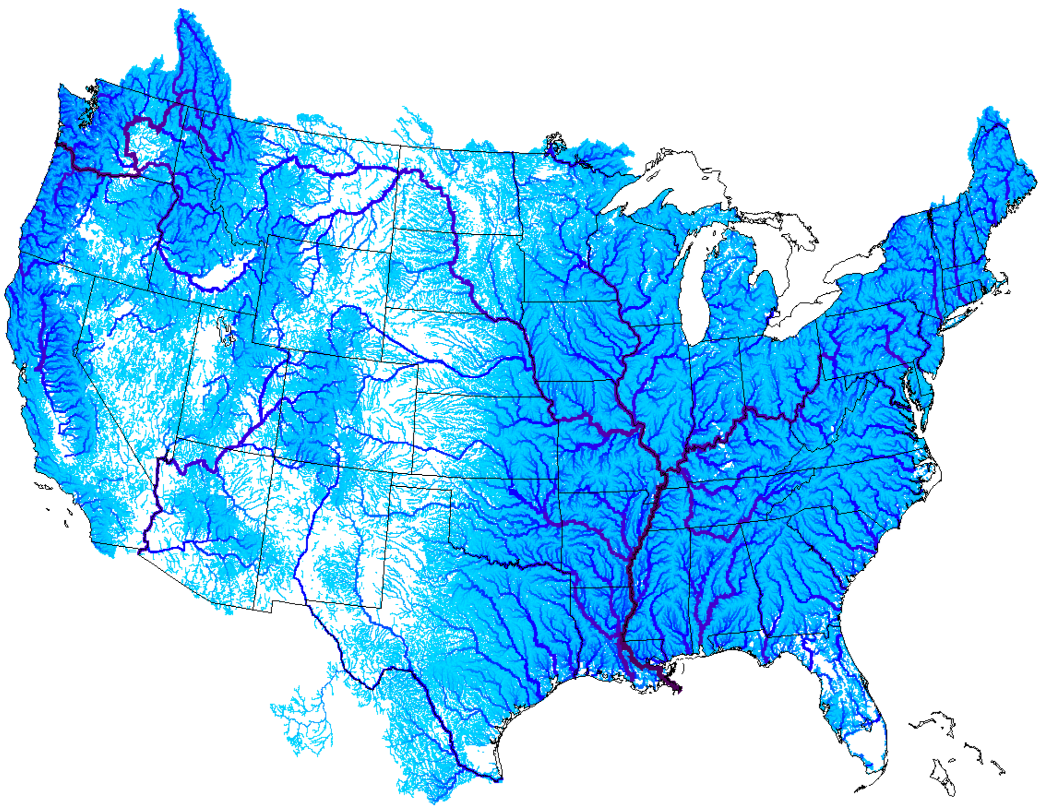
Adding a new land/hydrology model to the LIS ecosystem

Task 2d: Generalize the production of digital river networks to accommodate multiple routing models



SUMMA/mizuRoute simulations of mean annual runoff for the NHD++ network

- SUMMA/mizuRoute configured for the NHD++ network (2.7M streams)
- Major overhaul of mizuRoute to navigate the NHD++ network and generate information on reach characteristics to support multiple routing models
- Implemented a topological numbering scheme (Pfafstetter coding system) to simplify filtering of the river network and enable efficient network-based domain decomposition procedures
- Code parallelization with openMP and MPI
- Mizuroute now runs on Discover

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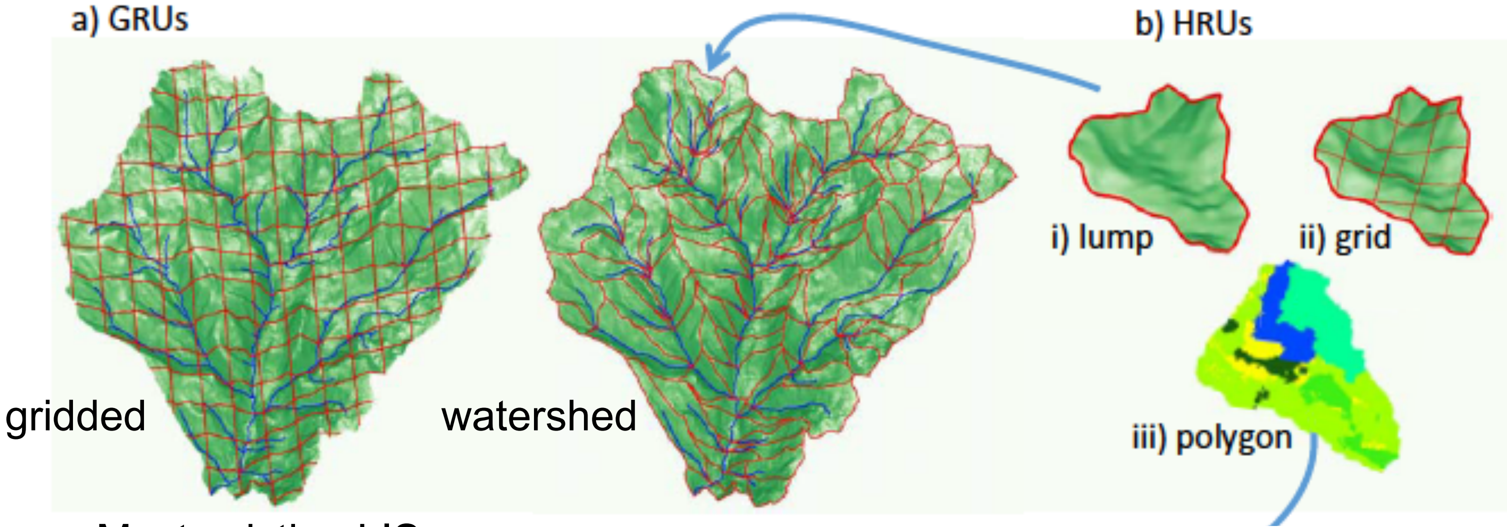
Flexible hydrologic model configurations

Task 2b: Incorporate alternative spatial configurations in SUMMA, and develop a workflow to experiment with alternative spatial configurations.



Most existing LIS-based simulations

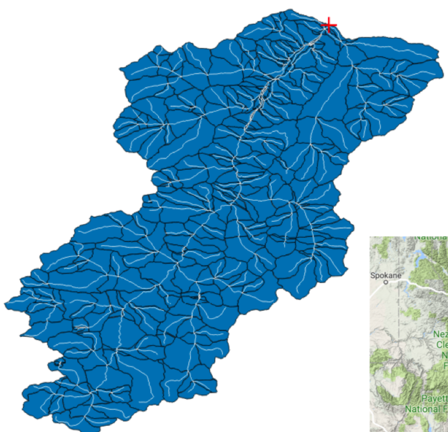
AIST enhancments

The motivation is to provide a flexibility to run models in LIS that more closely resemble those used operationally in water management than the gridded LSMs that are common in Earth Science applications.

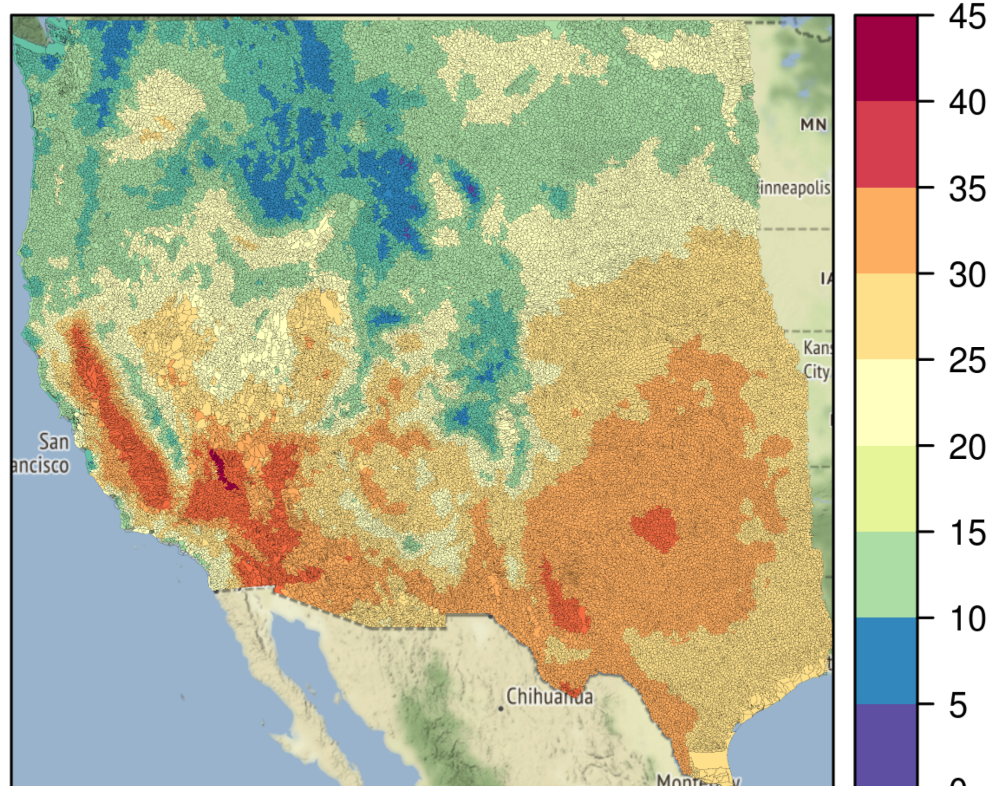
Flexible hydrologic model configurations

Task 2b: Incorporate alternative spatial configurations in SUMMA, and develop a workflow to experiment with alternative spatial configurations.

USGS HUC12 SUMMA +
NHD+ Mizuroute routing



USGS 06280300 South Fork Shoshone near Valley

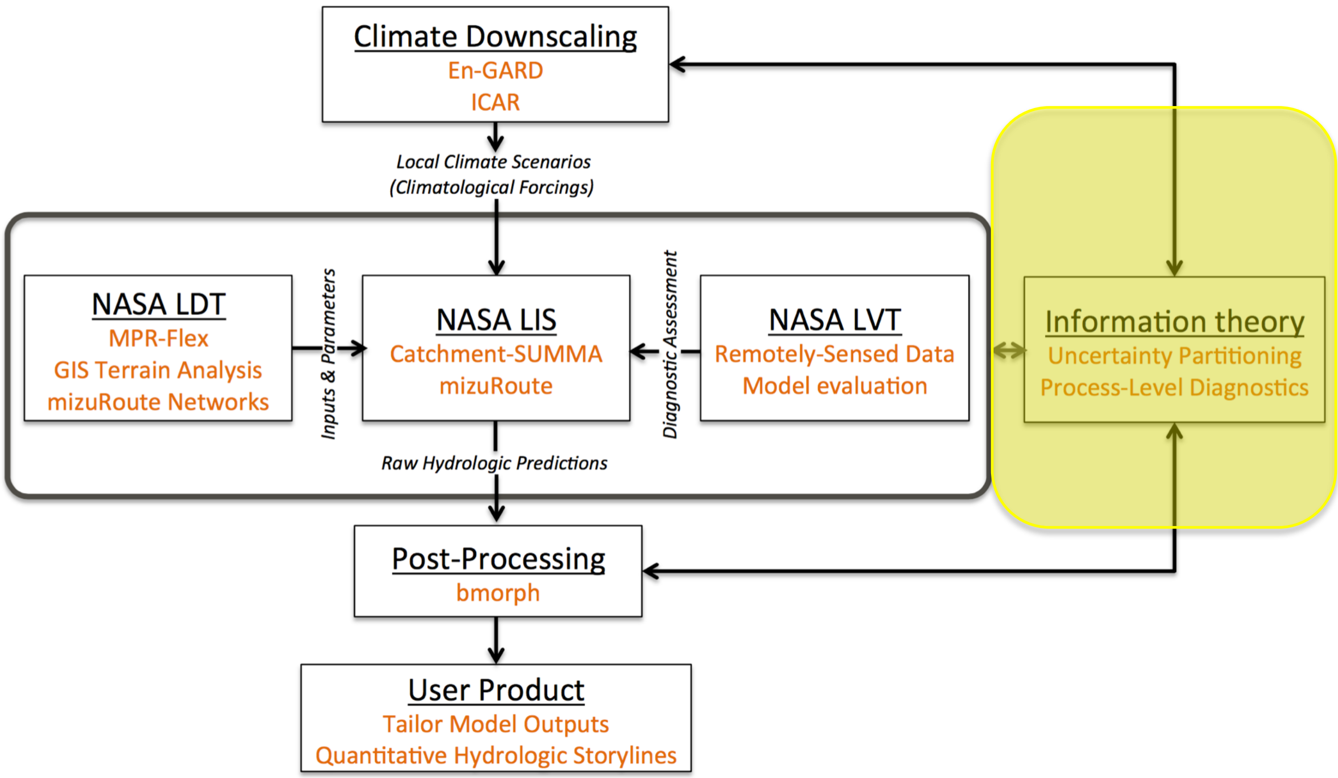


USGS HUC12 western domain

Tair (deg C)

Developed, implemented, and started calibrating watershed-based large-domain modeling with SUMMA. Application to NLDAS region is in progress, pending extension of watershed fabric outside of CONUS.

Applications of Information Theory in Hydrology



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5. **Use Information theory and machine learning**

Applications of Information Theory in Hydrology

5. Use information theory and machine learning to identify process-level tradeoffs between modeling options, and guide future research investment priorities

a. Identify watersheds and evaluation data for process-level analysis
b. Train benchmarking neural networks and perform uncertainty decomposition in representative watersheds
c. Identify process-level tradeoffs using network analysis
d. new tool: Hydrologic Entropy Estimators based on Nearest Neighbor Approximations (HYEENNA)

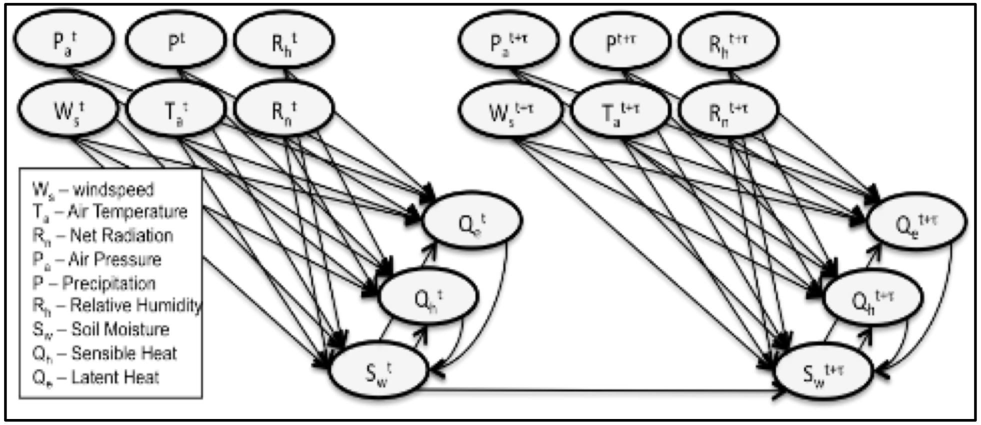
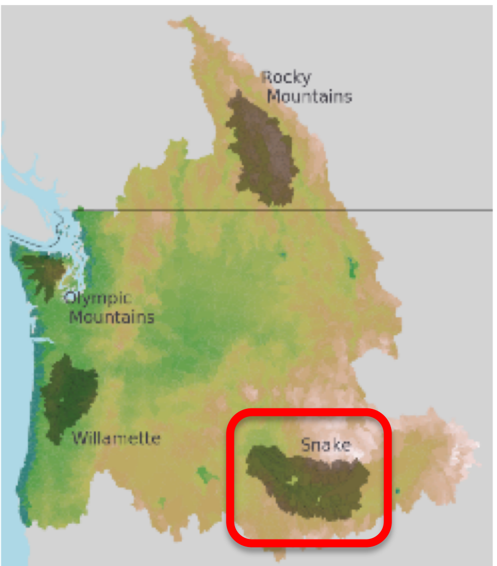
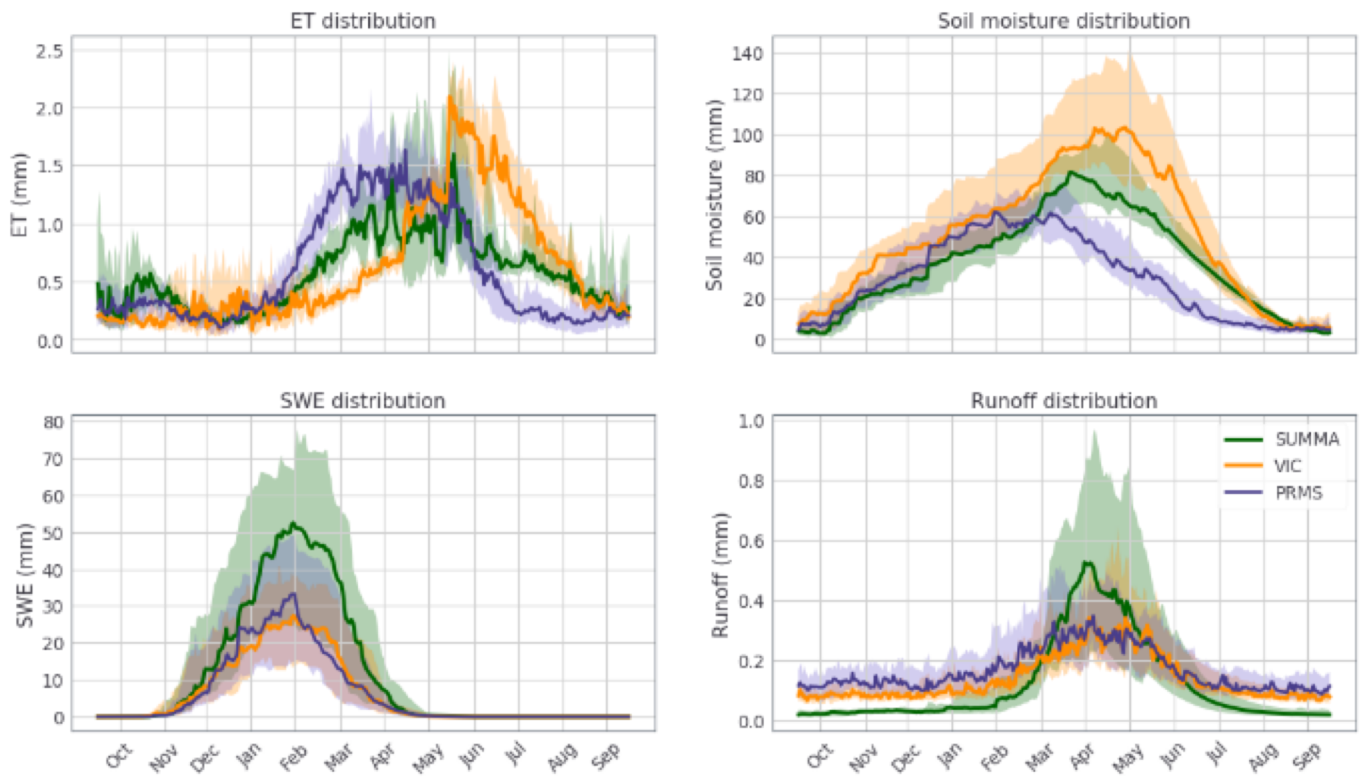


Figure: A dynamical process network representing variables measured at FluxNet sites

Intercomparing model states and fluxes

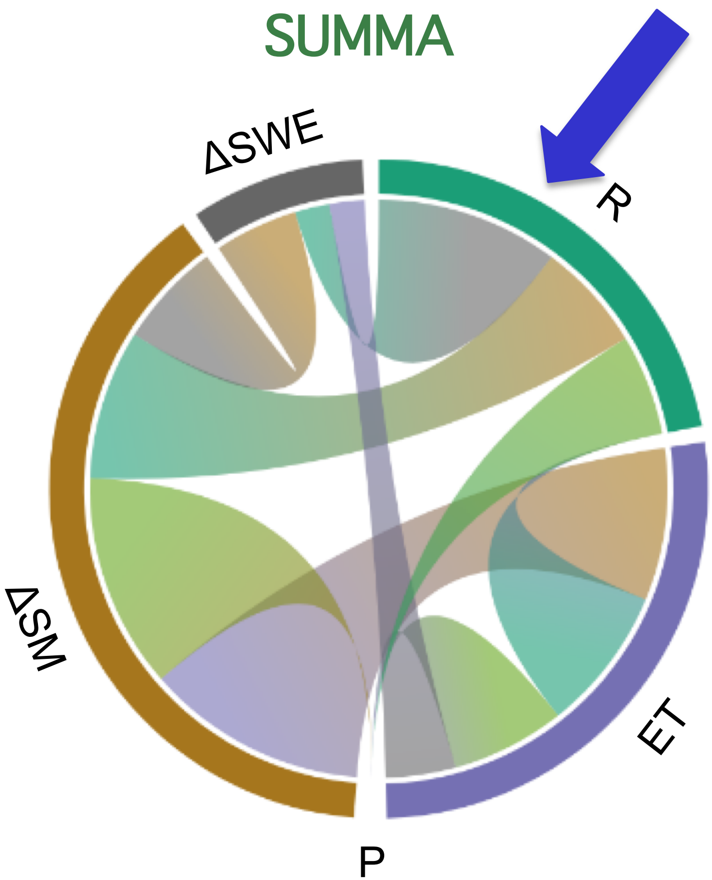


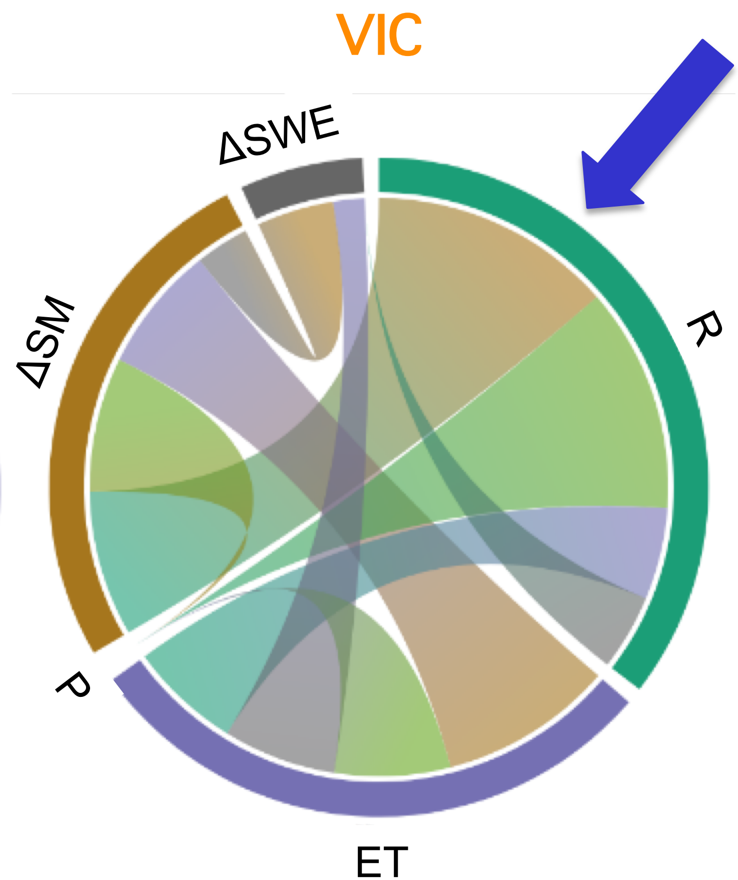


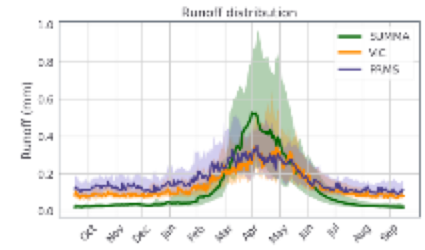
SUMMA VIC PRMS

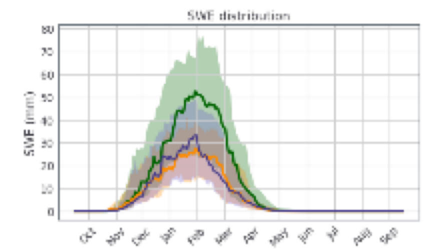
Intercomparing model process linkages

SWE drives runoff relatively less in VIC than SUMMA

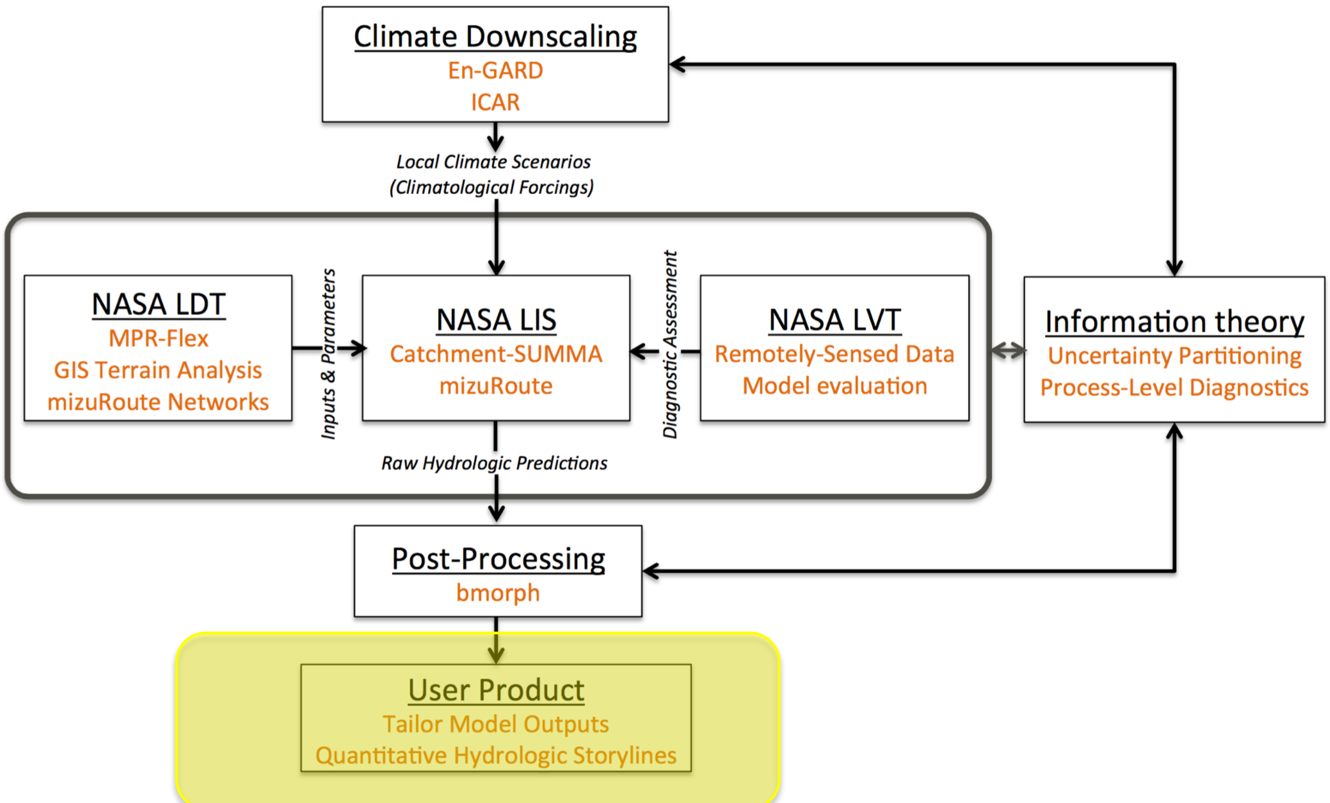








User Community Outreach



Tasks

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4. **Tailor model outputs**
5. Use Information theory and machine learning

Connecting with stakeholders in water management communities

Reclamation

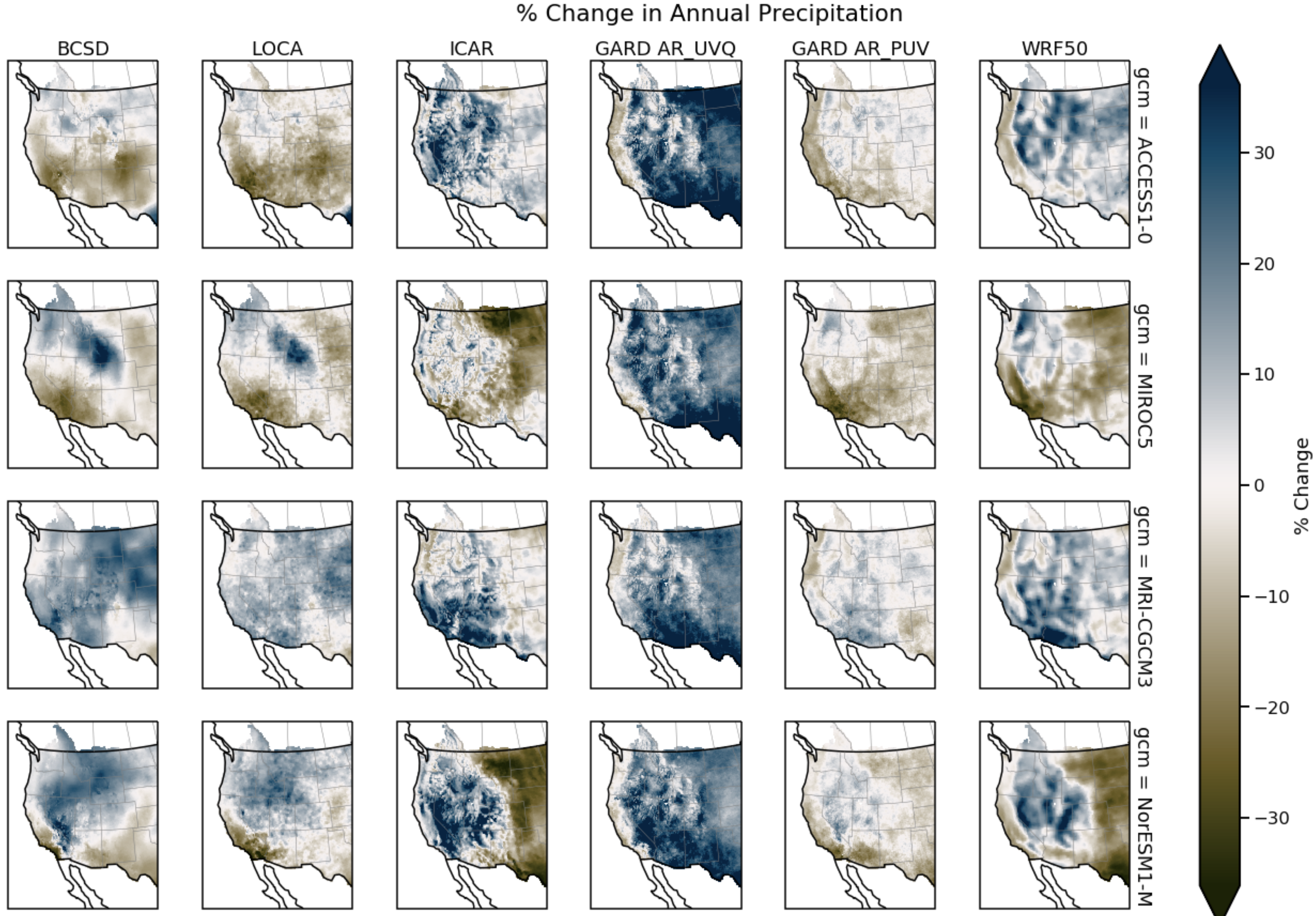
Connecting with stakeholders in water management communities

- Presented at WUCA's technical training course, Boulder, CO, Los Angeles CA, Portland, Tampa Bay (this May), Austin, TX (this December)
- Presented keynote at American Water Resources Association Winter Mixer, ASCE lunch seminar, AWRA dinner meeting keynote (in end of April)
- Meetings with six utilities in Puget Sound region related to Water Suppliers Forum climate modeling workshop, featured in WSF Resiliency Study
- Meetings with water managers at Seattle District Office USACE
- Workshop with Colorado River Basin Stakeholder
- Presented at Climate Prediction Applications Science Workshop (CPASW), at National Adaptation Forum (in April)
- Webinars for Mt. Climate Services (starting in May)
- Science to Action at AGU community of practice

Accomplishment: Well-connected with stakeholders *and* other organizations engaged in bringing climate information to water managers.

Multi-model & Multi-method datasets for hydroclimate analysis

Milestone: A large suite of downscaled projections using ICAR and the GARD (Generalized Analog Regression Downscaling) tool



Summary of Outcomes

This work has strengthened modeling and analytical capabilities required for assessing climate variability and change impacts on hydrology and water resources, through 5 key efforts:

- Task 1: Advance large-domain climate downscaling tools
- Task 2: Extend hydrologic modeling capabilities in LIS
- Task 3: Refine the hydrologic modeling simulations from LIS
- Task 4: Tailor model outputs
- Task 5: Information theory and machine learning

Outcomes include improved LIS-compatible modeling as well as datasets targeting water management and planning needs.

https://ncar.github.io/hydrology/projects/AIST

Contact: andywood@ucar.edu

Extra slides

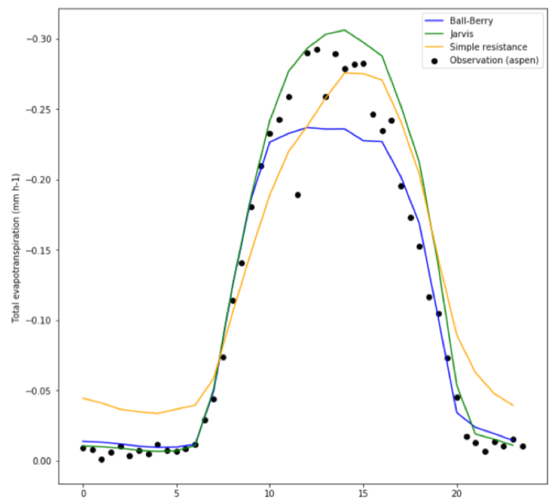
Tooling and workflow capabilities

PySUMMA: Object-Oriented Python wrapper for SUMMA

```
In [39]: # defind observation data
         obs = df_gp_hr.groupby('level_0').mean()
         observation_data = obs['Observation (aspen)']

In [40]: # analyze validtation between BallBerry simulation and observation data.
         validation.analysis(observation_data, BallBerry_simulation)

         Mean Absolute Error: 0.014720
         Mean Squared Error: 0.000434
         Root Mean Squared Error: 0.020833

In [41]: # analyze validtation between Jarvis simulation and observation data.
         validation.analysis(observation_data, Jarvis_simulation)

         Mean Absolute Error: 0.019703
         Mean Squared Error: 0.000915
         Root Mean Squared Error: 0.030249

In [42]: # analyze validtation between Simple resistance simulation and observatio
         validation.analysis(observation_data, Simple_resistance_simulation)

         Mean Absolute Error: 0.033234
         Mean Squared Error: 0.001449
         Root Mean Squared Error: 0.038060
```

4.5) Plotting output of three different stomatal resistance parameterizations and observation data

```
In [36]: # create plot with three different stomatal resistance parameterizations
         ET_Combine_Graph = ET_Combine.plot(color=['blue', 'green', 'orange'])
         # invert y axis
         ET_Combine_Graph.invert_yaxis()
         # plot scatter with x='xvals', y='Observation (aspen)'
         ET_Combine_Graph.scatter(xvals, df_gp_hr['Observation (aspen)'], color='black')
         # add x, y label
         ET_Combine_Graph.set(xlabel='Time of day (hr)', ylabel='Total evapotranspiration (mm h-1) ')
         # show up the legend
         ET_Combine_Graph.legend()
         jtplot.figsize(x=10, y=10)
```



CHOI, Y., J. Goodall, J. Sadler, A. Bennett, B. Nijssen, A. M. Castronova, M. Clark, D. Tarboton (2018). Prototyping a Python wrapper for the Structure for Unifying Multiple Modeling Alternatives (SUMMA) hydrologic modeling framework, HydroShare, http://www.hydroshare.org/resource/759cd9b74753462c9efc26c6d146e0d6

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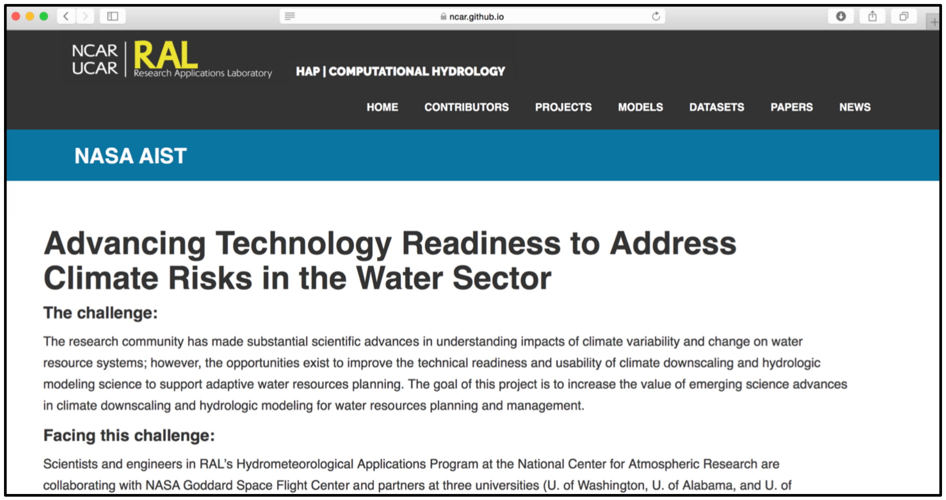
Findings and Accomplishments, Task 4

Materials for sharing AIST project updates and outcomes.



ncar.github.io

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HAP | COMPUTATIONAL HYDROLOGY

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NASA AIST

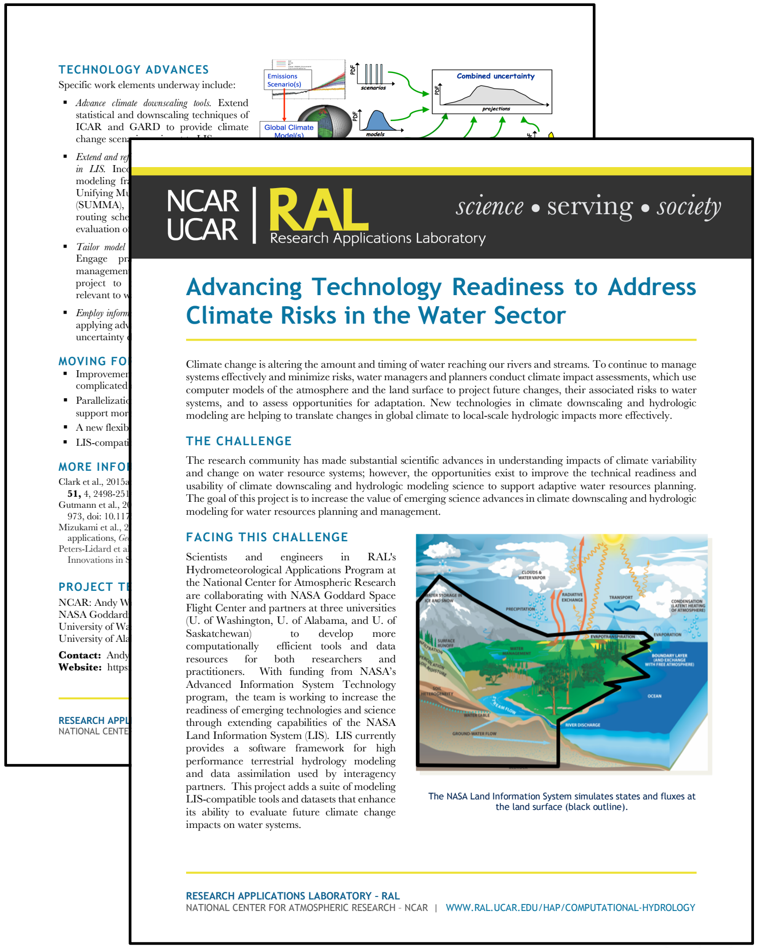
Advancing Technology Readiness to Address Climate Risks in the Water Sector

The challenge:

The research community has made substantial scientific advances in understanding impacts of climate variability and change on water resource systems; however, the opportunities exist to improve the technical readiness and usability of climate downscaling and hydrologic modeling science to support adaptive water resources planning. The goal of this project is to increase the value of emerging science advances in climate downscaling and hydrologic modeling for water resources planning and management.

Facing this challenge:

Scientists and engineers in RAL's Hydrometeorological Applications Program at the National Center for Atmospheric Research are collaborating with NASA Goddard Space Flight Center and partners at three universities (U. of Washington, U. of Alabama, and U. of



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Advancing Technology Readiness to Address Climate Risks in the Water Sector

Climate change is altering the amount and timing of water reaching our rivers and streams. To continue to manage systems effectively and minimize risks, water managers and planners conduct climate impact assessments, which use computer models of the atmosphere and the land surface to project future changes, their associated risks to water systems, and to assess opportunities for adaptation. New technologies in climate downscaling and hydrologic modeling are helping to translate changes in global climate to local-scale hydrologic impacts more effectively.

THE CHALLENGE

The research community has made substantial scientific advances in understanding impacts of climate variability and change on water resource systems; however, the opportunities exist to improve the technical readiness and usability of climate downscaling and hydrologic modeling science to support adaptive water resources planning. The goal of this project is to increase the value of emerging science advances in climate downscaling and hydrologic modeling for water resources planning and management.

FACING THIS CHALLENGE

Scientists and engineers in RAL's Hydrometeorological Applications Program at the National Center for Atmospheric Research are collaborating with NASA Goddard Space Flight Center and partners at three universities (U. of Washington, U. of Alabama, and U. of Saskatchewan) to develop more computationally efficient tools and data resources for both researchers and practitioners. With funding from NASA's Advanced Information System Technology program, the team is working to increase the readiness of emerging technologies and science through extending capabilities of the NASA Land Information System (LIS). LIS currently provides a software framework for high performance terrestrial hydrology modeling and data assimilation used by interagency partners. This project adds a suite of modeling LIS-compatible tools and datasets that enhance its ability to evaluate future climate change impacts on water systems.

The NASA Land Information System simulates states and fluxes at the land surface (black outline).

RESEARCH APPLICATIONS LABORATORY - RAL
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH - NCAR | WWW.RAL.UCAR.EDU/HAP/COMPUTATIONAL-HYDROLOGY

Accomplishment: Information sharing platforms being developed in ways that will help them align with existing climate change information ecosystem.

Team Members: PIs, Students Post-Docs, Personnel

Andy Wood
PI, NCAR/RAL
Role: hydrology modeling / water applications

Bart Nijssen
Co-I, UW
Role: hydrology modeling / information theory

Christa Peters-Lidard
Co-I, NASA/GSFC
Role: LIS supervision / science advising

Jeff Arnold
Co-I, USACE
Role: water management, science advising

Ethan Gutmann
Co-I, NCAR/RAL
Role: climate downscaling

Martyn Clark

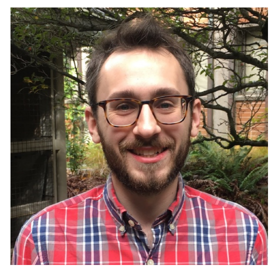
Original PI, Faculty, Univ. of Saskatchewan

Role: hydrology modeling

Sujay Kumar

Co-I, NASA/GSFC

Role: LIS implementation



Andrew Bennett

Ph.D. student, UW

Role: hydrology modeling, information theory

Naoki Mizukami

Personnel, NCAR

Role: hydrology modeling

Joseph Hamman

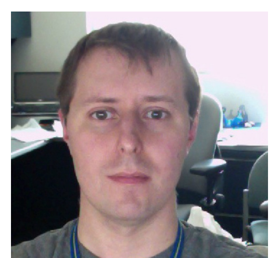
Personnel, NCAR/CGD

Role: downscaling

Julie Vano

Personnel, NCAR/RAL

Role: project management, engagement with water managers



Grey Nearing

Faculty, University of Alabama

Role: information theory

Kristine Verdin, NASA/GSFC
Role: hydrologic routing

James Geiger, NASA/GSFC
Role: LIS implementation

Scott Rheingrover, NASA/GSFC
Role: project management

Publications

Bennett, A., B. Nijssen, G. Ou, M. Clark, and G. Nearing, 2018: Quantifying process connectivity with transfer entropy in hydrologic models. Water Resources Research, in review.

Nearing, G., B. Ruddell, M. Clark, B. Nijssen, and C. Peters-Lidard, 2018: Benchmarking and Process Diagnostics of Land Models. J. Hydrometeor. doi:10.1175/JHM-D-17-0209.1, in press.

Acronyms

AMCE: AIST Managed Cloud Environment

CONUS: The contiguous USA

En-GARD: Ensemble Generalized Analog Regression Downscaling

GSFC: Goddard Space Flight Center

HYEENNA: Hydrologic Entropy Estimators based on Nearest Neighbor Approximations

HyMAP: Hydrological Modeling and Analysis Platform

ICAR: Intermediate Complexity Atmospheric Research model

LIS: The NASA Land Information System

NCAR: National Center for Atmospheric Research

SUMMA: The Structure for Unifying Multiple Modeling Alternatives

Augmentation opportunity and proposal

Motivation

- The Earth Science community is increasingly focusing on the potential use of advanced statistical techniques such as machine learning (ML) and artificial intelligence (AI) across the geosciences.
- Early results show that ML models can be more efficient predictors of certain terrestrial water and energy fluxes than traditional process-oriented hydrology and land surface models.

Objectives

To add useful new ML-based capabilities to the LIS ecosystem

- develop and demonstrate LIS-compatible open-source ML modeling tools for bechmarking and evaluating dynamical models
- improved online visualization and analysis capabilities (using Jupyter notebooks)
- comparison of ML and dynamical models in future climate context

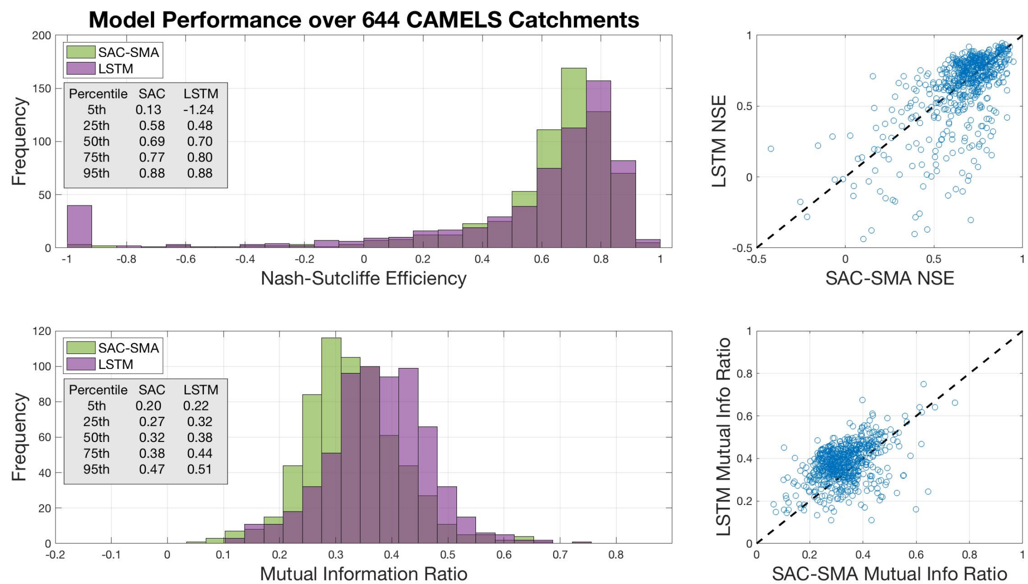


Figure 1: *Comparison between LSTMs and calibrated conceptual SAC-SMA watershed models for streamflow simulations over 644 catchments*

Scope

Existing partners, 1 year extension, $240K

NCAR

ESTO Earth Science Technology Office

Parallelization: River network decomposition

- Assign pfafstetter code to river reaches/HRUs
- Pfafstetter code based domain decomposition.

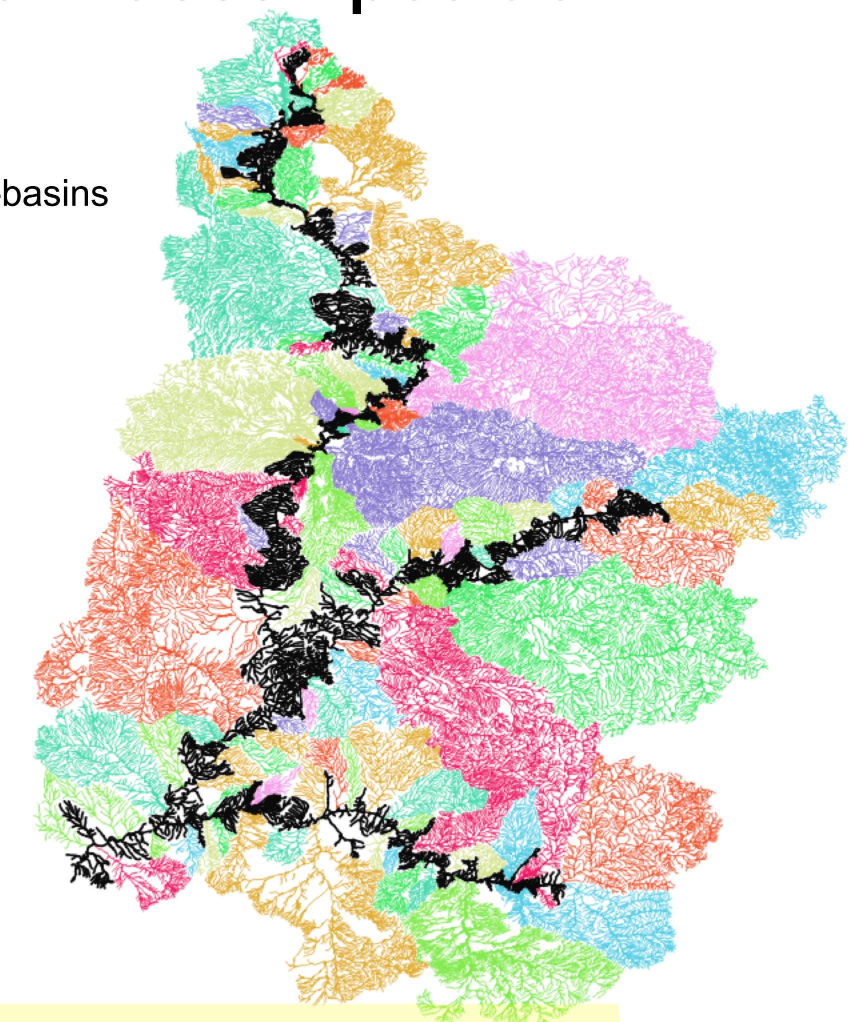
Split river networks into ”tributary basins” and “inter-basins (mainstem)”

Node assignment (11 nodes)

- 1
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

1–10: “Large” tributary

- 0 Mainstems + “small” tributary



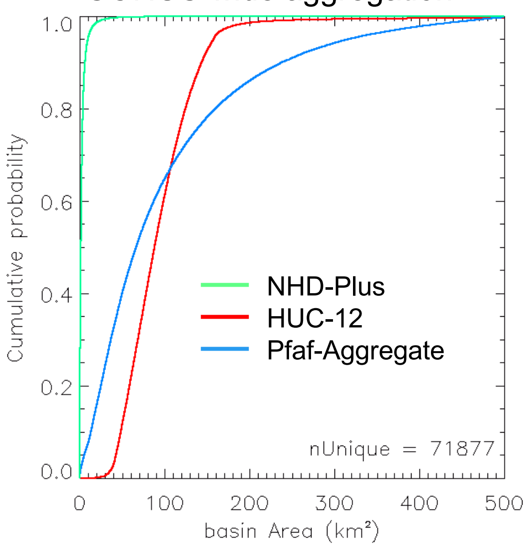
Accomplishment: Domain decompositions and initial MPI implementation

Findings and Accomplishments, Task 2

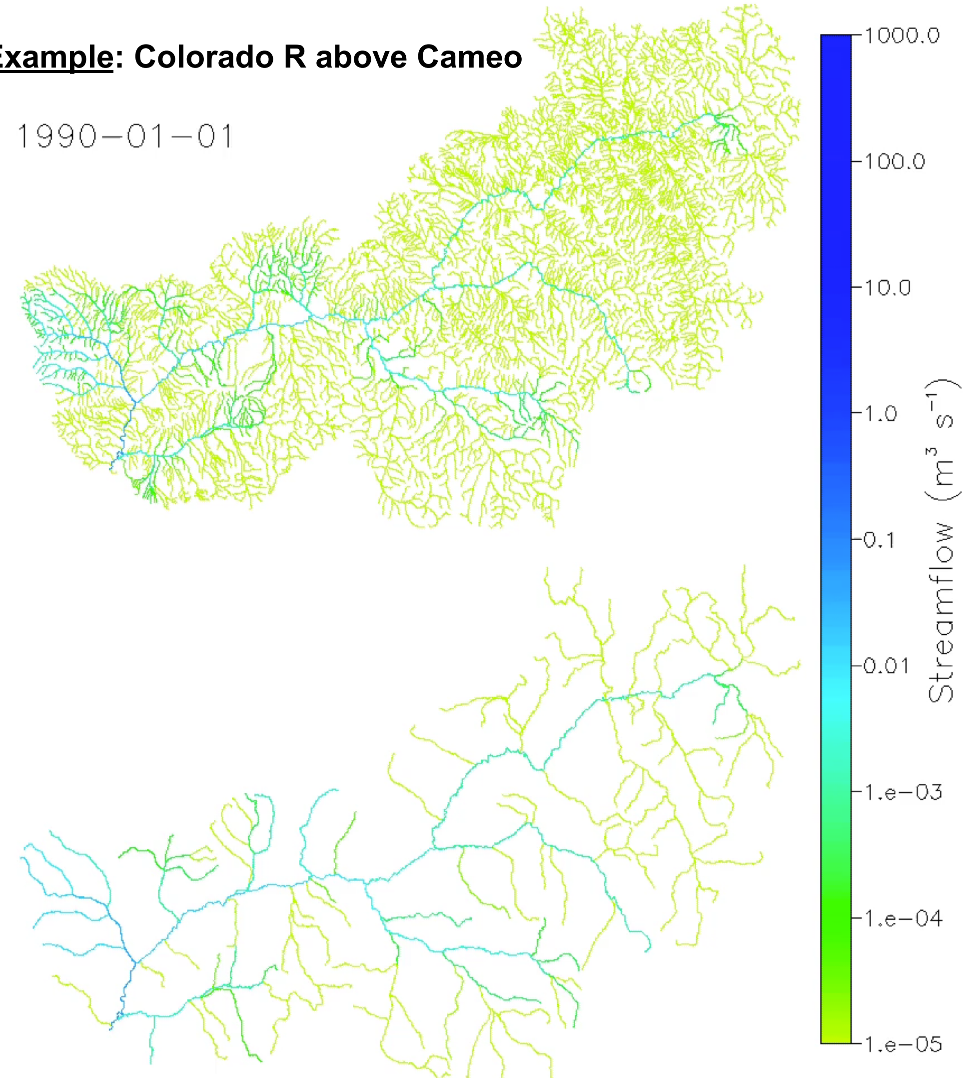
Aggregate basins at a given Pfafstetter level, and route using the same underlying network

- *Aggregation is basin-specific, so have greater resolution in specific areas (adaptive in time, e.g., as a storm passes through)*
- *Supports "computationally frugal" model instantiations (for ensemble forecasting, parameter estimation trials, etc.)*

CONUS-wide aggregation



<u>Example</u>: Colorado R above Cameo



Entry and Exit TRL

Entry TRL: 3

- Improve downscaling (Task 1)
- Develop watershed-based configurations in NASA-LIS (Task 2)
- Refine hydrologic model configurations in NASA-LIS (Task 3)

Advance to TRL: 4

- Connect downscaled climate scenarios to NASA-LIS (Task 1)
- Ensure prototyping implementations conform (Task 2)
- Thorough test prototyping in representative environment (Task 3)

Advance to TRL: 5

- Develop tailored products for water management community for engineering feasibility (Task 4)
- Applications of information theory and machine learning to further demonstrated and refine actual system applications (Task 5)

Exit TRL: 6

Entry and Exit TRL for Subsystems

Entry TRL: 3

	En-GARD/ICAR	LIS	mizuRoute
Advance to TRL: 4	Improved downscaling, Task 1	Refactoring, Task 2 (running, validation underway)	Watershed based configurations, Task 3
Advance to TRL: 5	Connect output to LIS Task 1	Ensure Prototype Implement., Task 2	Thorough test prototype in represent env, Task 3

------------Tailored products, Task 4--------------------

---Information theory, machine learning, Task 5----

Exit TRL: 6

Project Effort

Project tasks	2017		2018				2019	
	3	4	1	2	3	4	1	2
1. Advance large-domain climate downscaling tools.								
1a. Simplify pre-processing. Develop configurable scripts to download climate model output and produce inputs for ICAR and En-GARD.	x	x						
1b. Simplify configuration and testing. Develop configuration scripts and integration and unit tests for En-GARD and ICAR.	x	x	x					
1c. Improve robustness and extensibility. Add internal error checking and documentation to the ICAR and En-GARD code.		x	x	x				
1d. Document user options. Develop extensive documentation for input and output files for ICAR, En-GARD and related scripts			x	x				
Milestone A. Application of En-GARD and ICAR over the contiguous USA, forced with 20 climate scenarios.				x				
2. Extend hydrologic modeling capabilities in LIS.								
2a. Terrain analysis. Develop terrain analysis tools to delineate landscape features and define hillslope characteristics.	x	x						
2b. Develop workflow to quickly formulate and evaluate hypotheses. Incorporate alternative spatial configurations in SUMMA.		x	x	x				
2c. Integrate watershed-based land model configurations into the NASA-LIS Land Data Toolkit (LDT).			x	x				
2d. Generalize the production of digital river networks to accommodate multiple streamflow routing models.		x	x					
2e. Integrate workflow for these generalized digital river networks into the pre-processing suite for NASA-LIS, LDT.			x	x				
Milestone B. NASA-LIS simulations using watershed-based land model configurations for the contiguous USA.				x				
Milestone C. NASA-LIS network routing for the contiguous USA.				x				
3. Refine the hydrologic modeling simulations from LIS.								
3a. Calibrate land and stream parameters using MPR-flex.				x	x	x		
3b. Produce an ensemble of parameter configurations.					x	x		
3c. Update NASA-LIS/LDT to accept parameters from MPR-flex.					x	x		
3d. Assemble streamflow time series that can be used for streamflow bias correction on a continental domain.				x	x			
3e. Generalize bmorph and incorporate bmorph into mizuRoute workflow to account for network topology in bias correction.					x	x		
Milestone D. Ensemble of parameter sets for SUMMA within NASA-LIS.						x		
Milestone E. Application of bmorph to produce hydrologic storylines for 100 climate-hydrology model combinations.						x		
4. Tailor model outputs.								
4a. Engage with stakeholders to develop a set of metrics and outputs.	x	x	x	x	x	x	x	x
4b. Tailor model output. Iterate with stakeholders to modify plots.	x	x	x	x	x	x	x	x
4c. Interactive displays. Integrate key metrics (e.g. return intervals) into a database to enable interactive plotting.			x	x	x	x		
4d. Provide online access to underlying NetCDF files.				x	x	x		
Milestone F. Summary information in a form usable by water managers.								x
5. Information theory and machine learning.								
5a. Acquire evaluation data and identify representative watersheds for process-level analyses.				x	x			
5b. Train benchmarking neural networks and perform uncertainty decompositions in representative watersheds.					x	x	x	
5c. Perform network analysis to identify process-level tradeoffs on various SUMMA configurations in different environments.						x	x	x
Milestone G. Identify process-level deficiencies.								x

1. Advance large-domain climate downscaling tools, **2017 to mid-2018**
2. Extend hydrologic modeling capabilities in LIS, **2017 to mid-2018**
3. Refine the hydrologic modeling simulations from LIS, **2018**
4. Tailor model outputs, **2017 to 2019**
5. Information theory and machine learning, **2018 to 2019**

Science / ESD Value

Applicability to NASA Earth Science

1. Innovation breakthroughs to understand global change
    - applying uncertainty estimates
    - integrating automation and workflow tools
    - predicting and modeling extreme water-related events
    - formulating and evaluating hypotheses quickly

2. Technology enhancements for applied science application
    - developing new, potentially game-changing capabilities for water resource planning in the USACE

Tooling and workflow capabilities

Hydrologic Entropy Estimators based on Nearest Neighbor Approximations (HYEENNA)

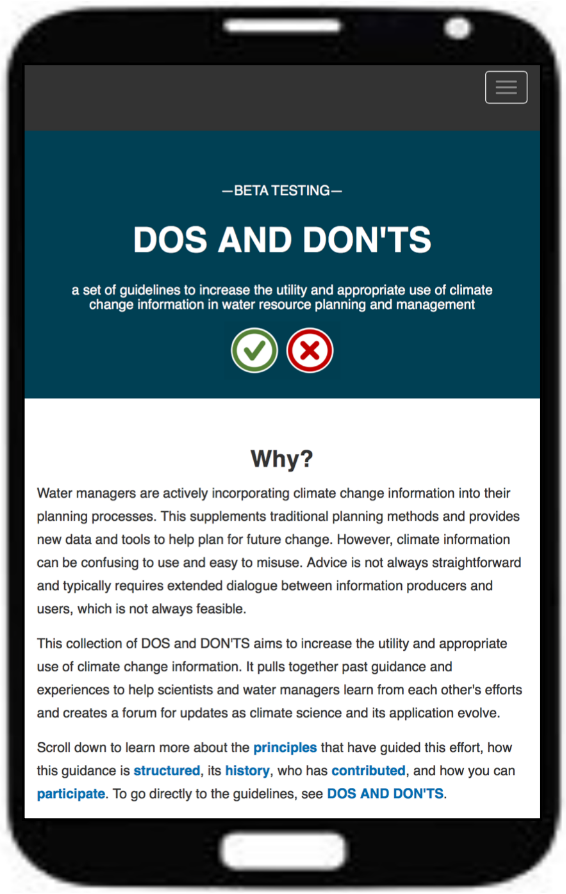
- Implements network estimation and plotting, timescale estimation, and statistical tests
- Implements both standard and advanced quantity calculations
- Scalable and efficient methods
- Focused on usability and standardization
- Python-based library

```
hy.entropy(precip)
hy.mutual_info(precip, swe)
hy.transfer_entropy(precip, swe)
hy.estimate_network([precip, swe, runoff, evap, sm],
                    ['P', 'SWE', 'R', 'ET', 'SM'])
hy.plot_chords([precip, swe, runoff, evap, sm],
               ['P', 'SWE', 'R', 'ET', 'SM'])
```

```
import hyeenna as hy
st = hy.shuffle_test(estimator=hy.transfer_entropy,
                     data={'X': precip, 'Y': swe},
                     params={'tau': 3, 'omega': 1, 'k': 1, 'l': 1},
                     nruns=20, sample_size=3000)
```

Accomplishment: HYEENNA was developed and can be used to decompose uncertainty at the process level.

Findings and Accomplishments, Task 4

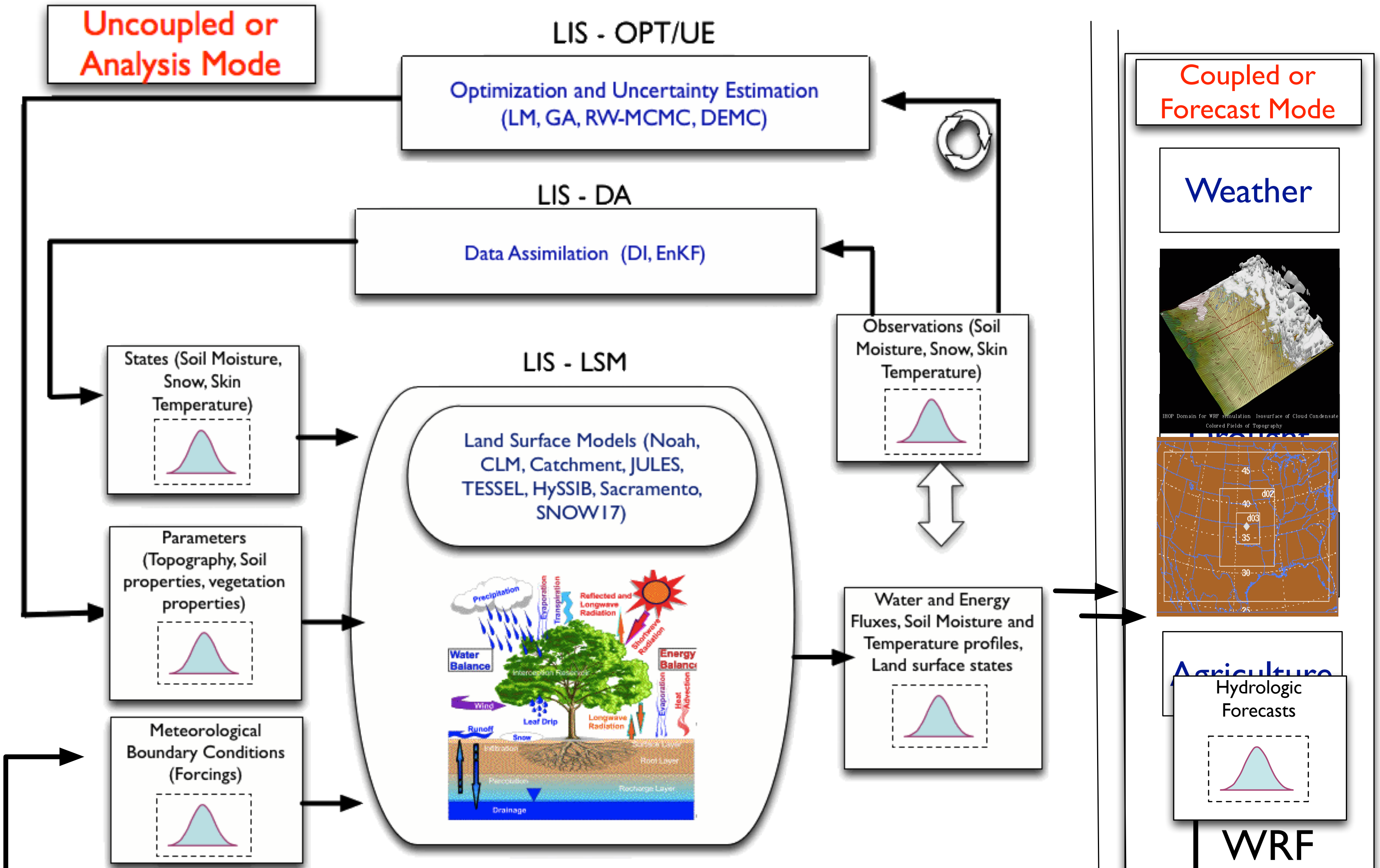


DOS AND DON'TS guidelines for using climate change information in water management and planning

- Built on previous guidance
- Promotes more understanding, applications framing helpful for research
- Fosters two-way conversation
- Provides multiple levels of engagement, designed in layers
- Allows updates that are transparent and version controlled
- Promotes a community effort
- Version 1.0 released, Version 2.0 coming soon…

https://ncar.github.io/dos_and_donts/

Background: LIS modes of operation



Kumar et al. (2006), Env. Modeling and Software, Peters-Lidard et al (2007), Innovations in Systems and Software Engineering