Integrated Hydrometeorological Prediction with WRF-Hydro and WRF

Current Uncoupled and Coupled Model Applications

David Gochis, David Yates, Kevin Sampson, Aubrey Dugger, James McCreight, Arezoo RafieeiNasab, Yongxin Zhang, Ryan Cabell, Katelyn Fitzgerald, Matt Casali, Joe Grim, Amir Mazrooei, Bahram Kazaei, Ridwan Saddique

Research Applications Lab

June 2021

NCAR

WRF-Hydro
MODELING SYSTEM

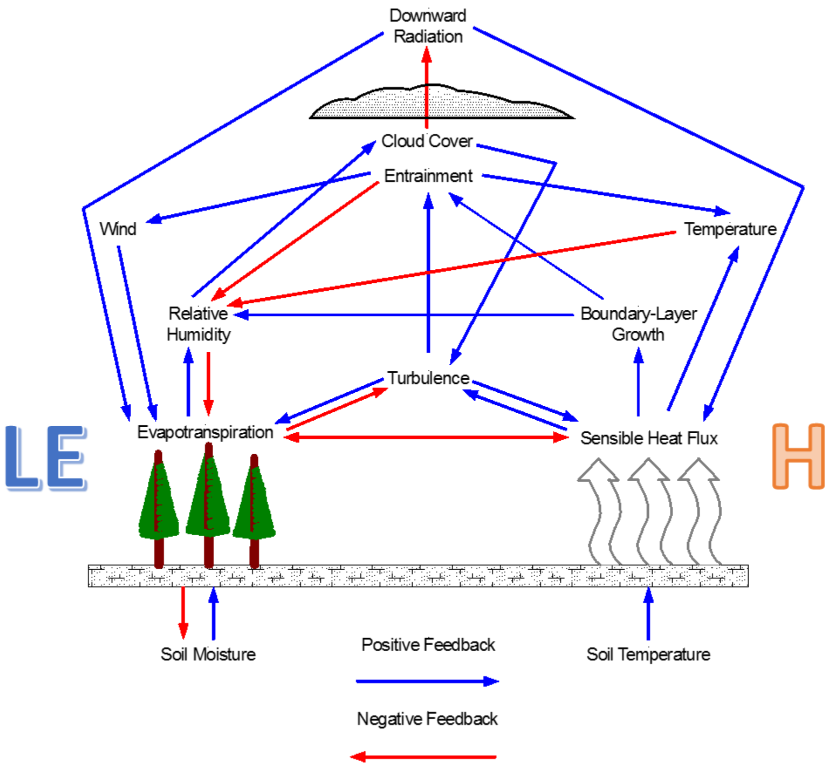
Outline

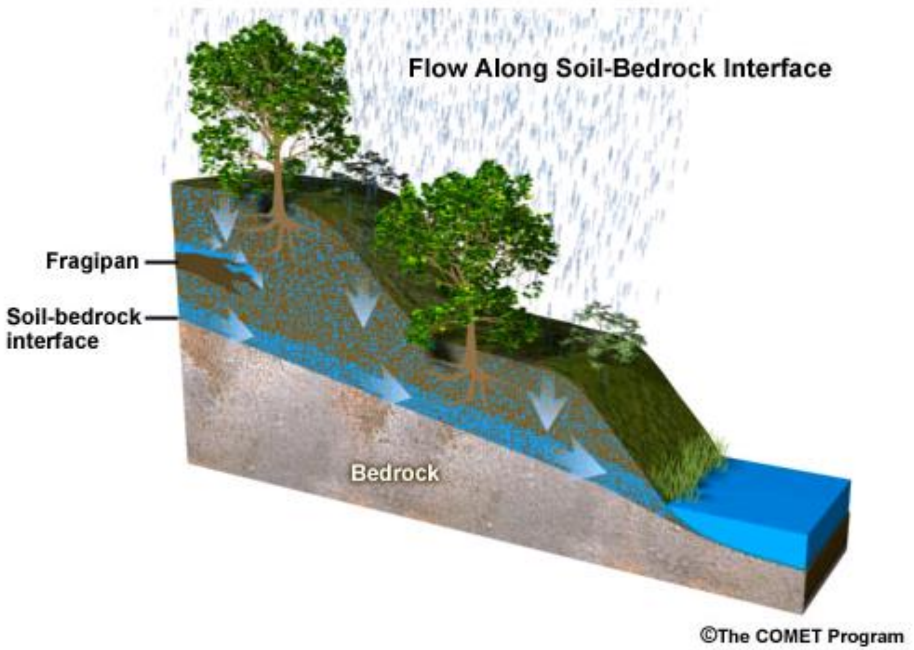
- History with the community WRF-Hydro System
  - Started in 2003, first full community version in ~2006
  - Global community of over 5,000 users
  - Deployed model as national forecasting system for 4 nations, including U.S. NOAA National Water Model (NWM)
    - More than doubled skill of NWM forecasts in less than 4 years
  - Publications hosted on community WRF-Hydro website

- Motivation: Scale issues in hydrology
  - Oftentimes column land surface models are not enough…
- Conceptualization: WRF-Hydro System Description
- Application

Motivation:

- Surface Energy Flux Partitioning…





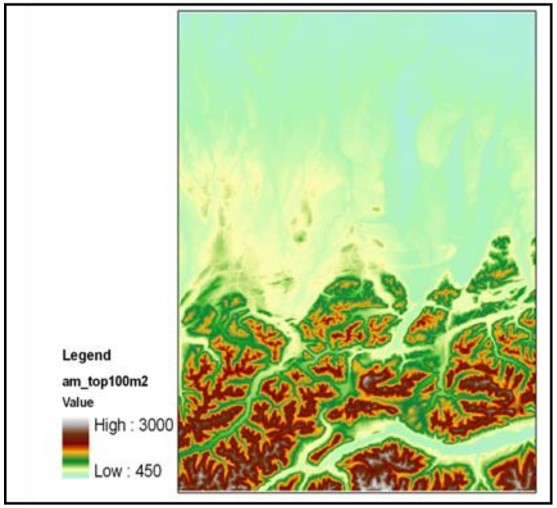
Horizontal transfer matters….

- Timing, distribution and availability of water
- Predominantly responsible for flooding impacts

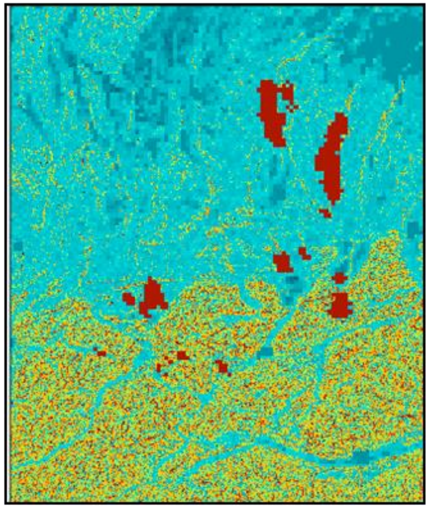
Motivation:

- Terrain-driven organization of spatial variability

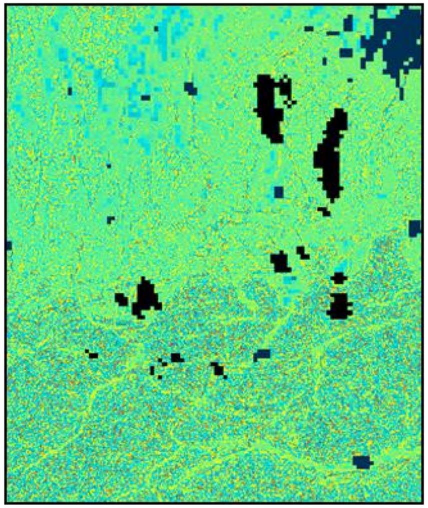
DEM:
100 m



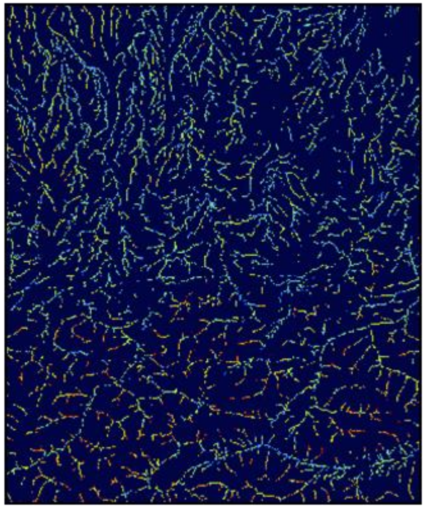
Water table
depth (m)



Soil moisture

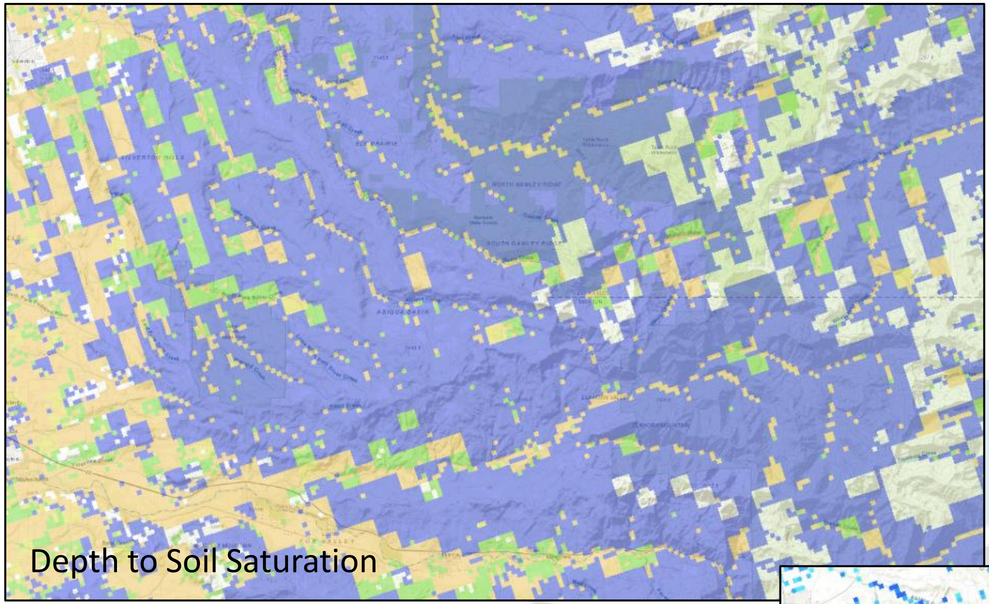


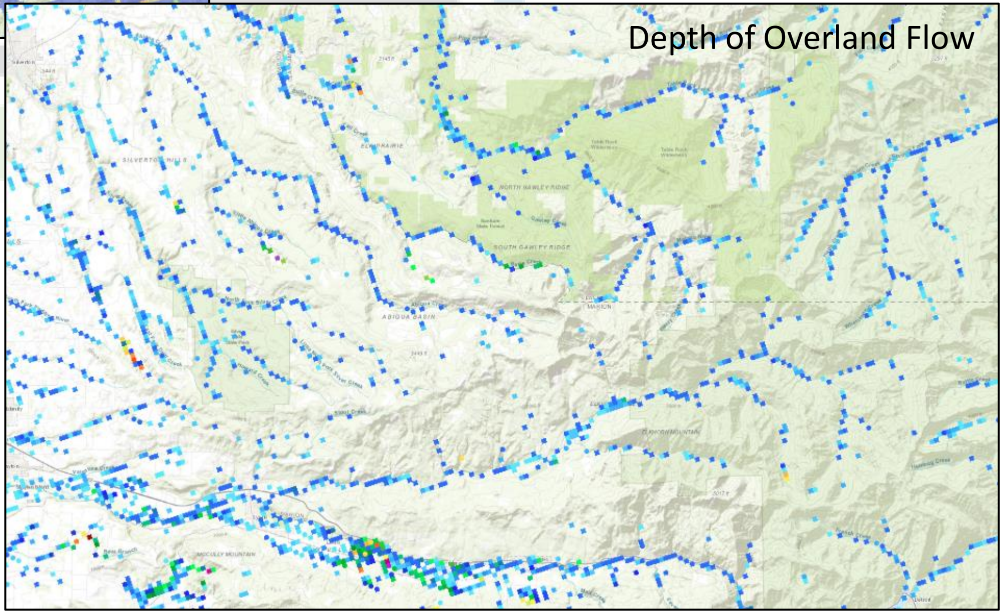
Stream channel
inflows



**Northern Alps :
Germany
Domain:
~140x220 km**

Motivation:



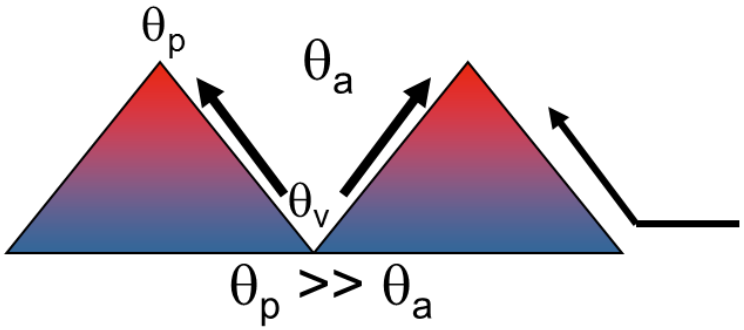


- Soil column saturation
- Exfiltration to surface
- Overland flow production

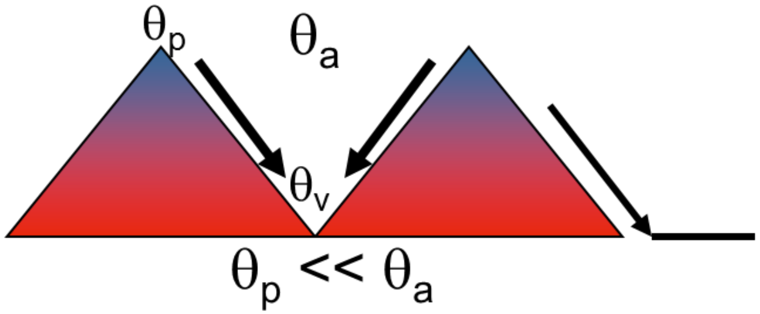
Motivation:

Foundational questions…

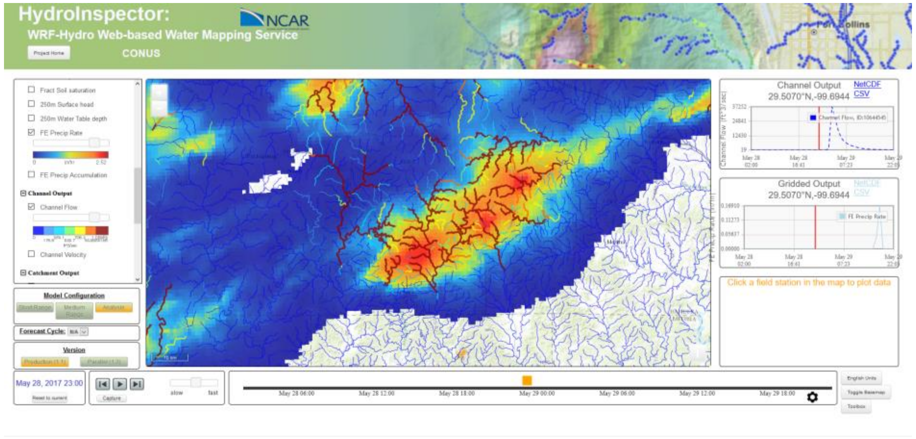
- How do hydrologic routing processes influence background mesoscale circulations?



- At what spatial and temporal scales do routing processes become significant?



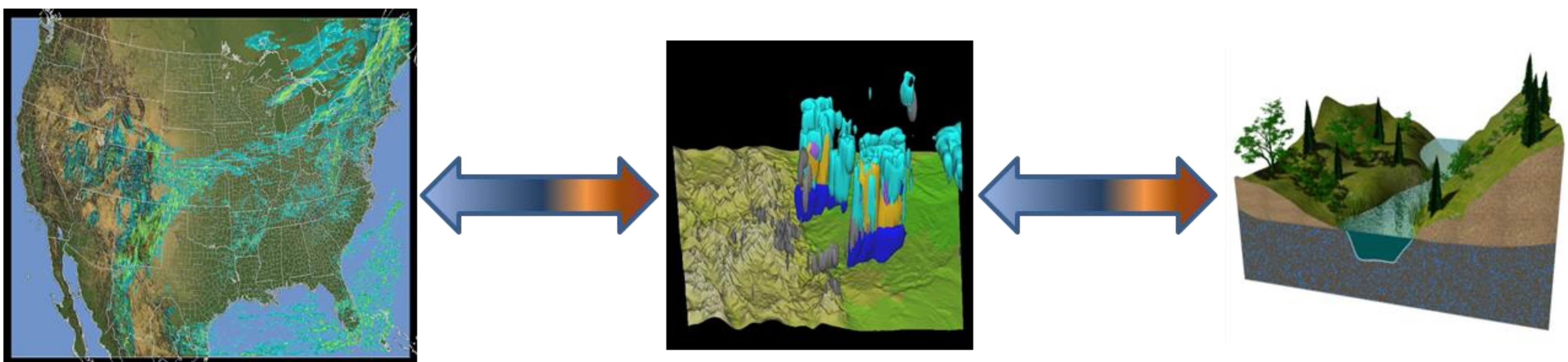
- What are the sources of error and limits on predictability of extreme hydrologic events?



WRF-Hydro Modeling System

A community-based, supported coupling architecture designed to provide:

1. An extensible *multi-scale & multi-physics* land-atmosphere modeling capability for conservative, coupled and uncoupled *assimilation & prediction* of major water cycle components such as precipitation, soil moisture, snowpack, groundwater, streamflow, inundation
2. 'Accurate' and 'reliable' streamflow prediction across scales (from 0-order headwater catchments to continental river basins & minutes to seasons)
3. Research modeling testbed for evaluating and improving physical process and coupling representations



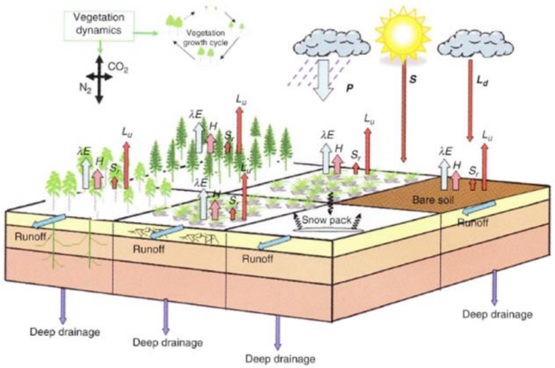
1-10's km **100's m - 1's km** **1-10's m**

Can be run fully-coupled with WRF or in an offline mode, driven by prescribed meteorological data

Website: https://www.ral.ucar.edu/projects/wrf_hydro

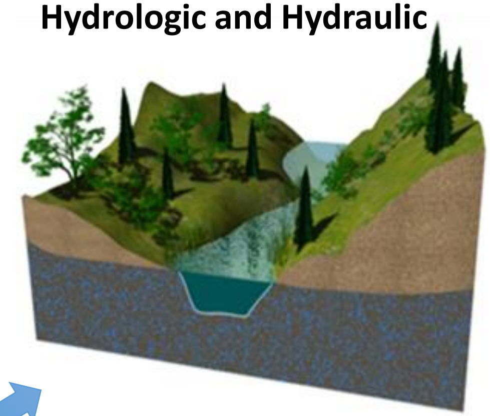
WRF-Hydro system description

Column Land Surface Models:
Noah/NoahMP/SAC-HTET*

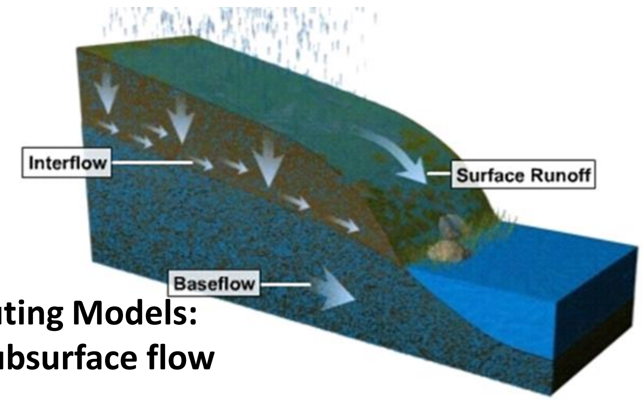


Output Variables:
Evapotranspiration
Soil moisture/Soil Ice
Snowpack/snowmelt
Runoff
Radiation Exchange
Energy Fluxes
Plant Water Stress

Channel & Reservoir
Routing Models:
Hydrologic and Hydraulic



2-way coupling



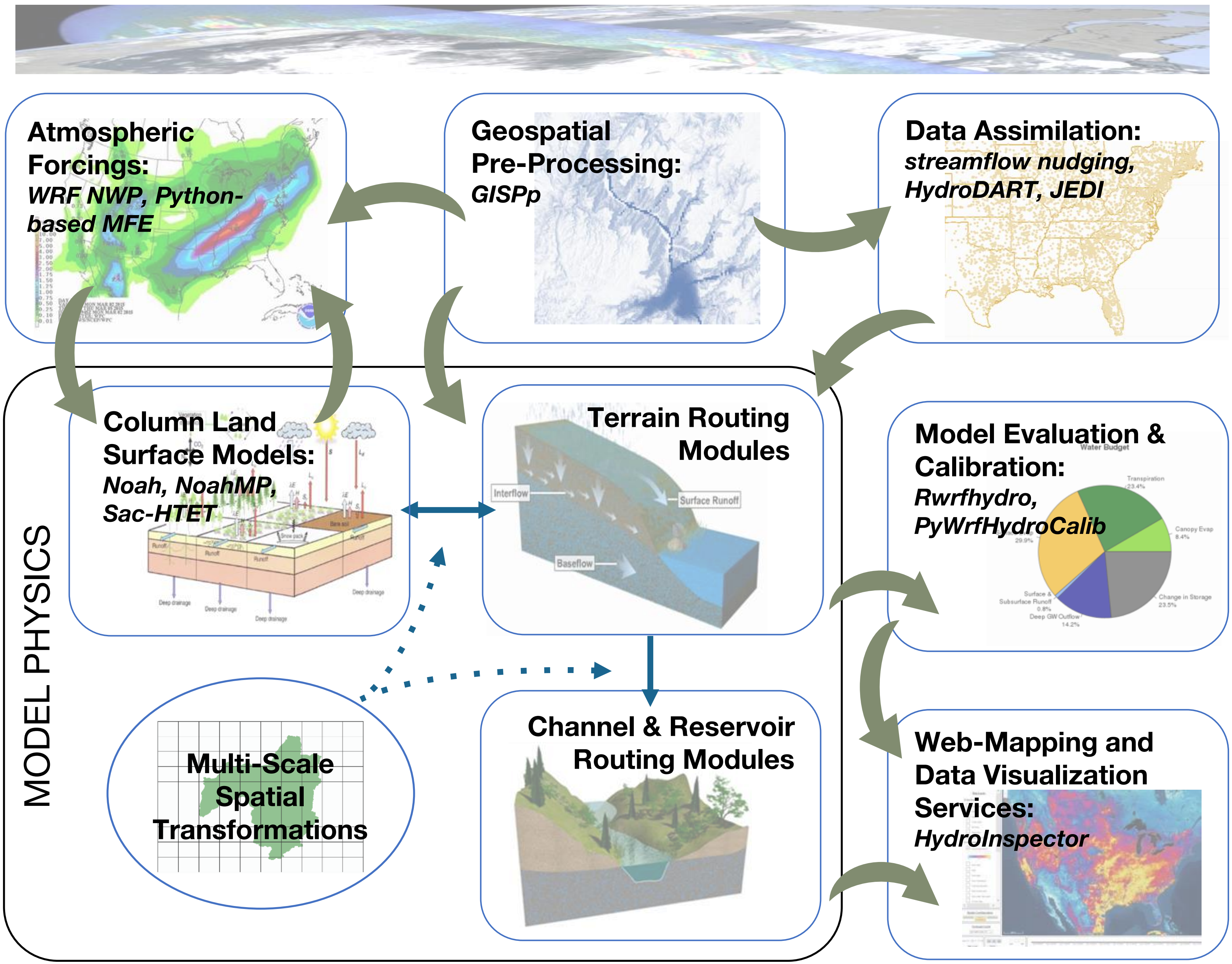
1-way coupling or
2-way coupling

Output Variables:
Streamflow
River Stage
Flow Velocity
Reservoir Storage
& Discharge

Terrain Routing Models:
Overland, subsurface flow

Output Variables:
Stream Inflow, Surface Water Depth, Groundwater Depth, Soil Moisture

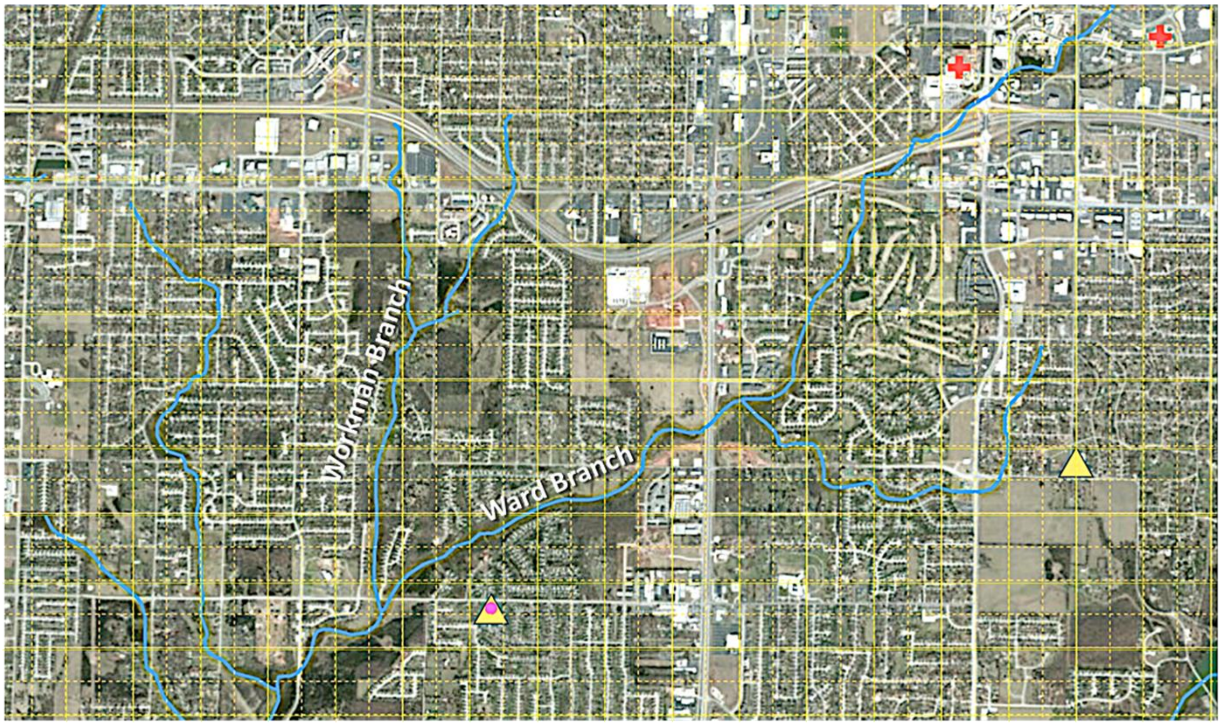
WRF-Hydro Community Model Ecosystem



WRF-Hydro V5.0 Multi-scale Physics Coupling

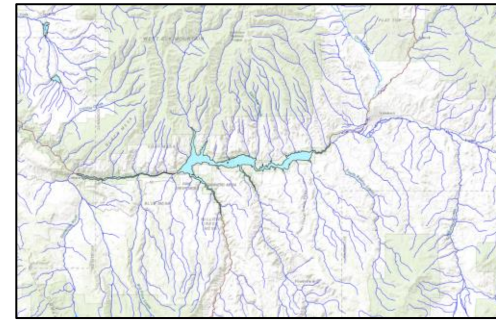
- Multi-scale aggregation/disaggregation:

Explicit refined mesh modeling:
(Soil moisture, groundwater, surface inundation)

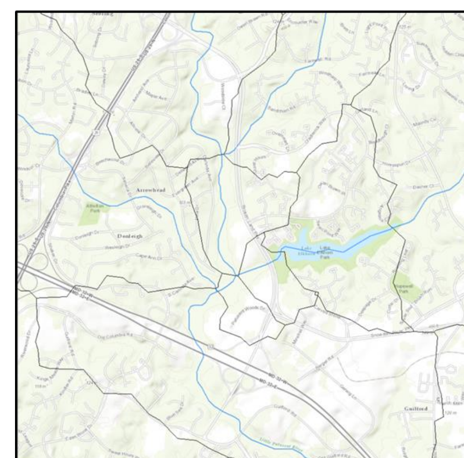


18 km

Explicit channel network and water body representation



Watershed/catchment flux aggregation

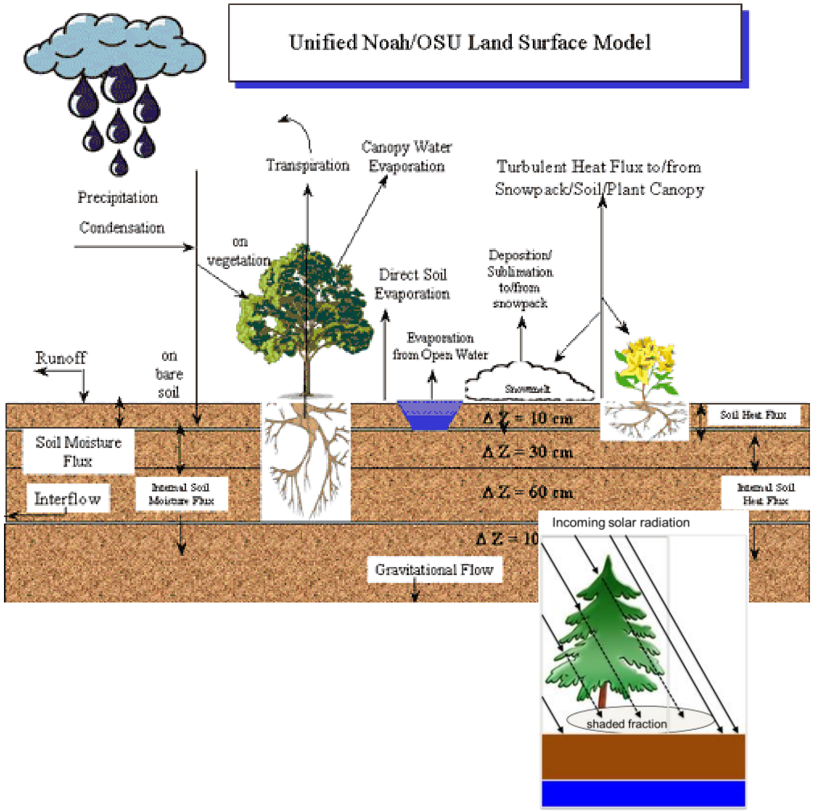


WRF-Hydro V5.0 Physics Components

NoahMP Column Physics:

Noah-MP contains several options for land surface processes:

1. Dynamic vegetation/vegetation coverage (4 options)
2. Canopy stomatal resistance (2 options)
3. Canopy radiation geometry (3 options)
4. Soil moisture factor for stomatal resistance (3 options)
5. Runoff and groundwater (4 options)
6. Surface layer exchange coefficients (4 options)
7. Supercooled soil liquid water/ice fraction (2 options)
8. Frozen soil permeability options (2 options)
9. Snow surface albedo (2 options)
10. Rain/snow partitioning (3 options)
11. Lower soil boundary condition (2 options)
12. Snow/soil diffusion solution (2 options)



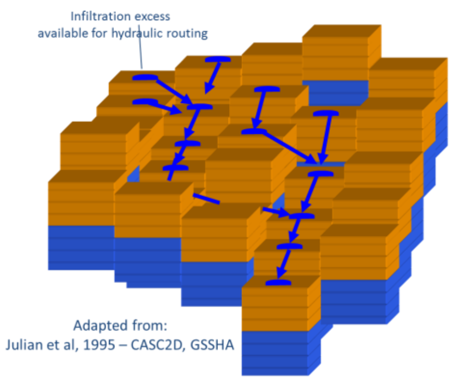
Noah/NoahMP development lead by M. Barlage and F. Chen, NCAR

Total of ~50,000 permutations can be used as multi-physics ensemble members

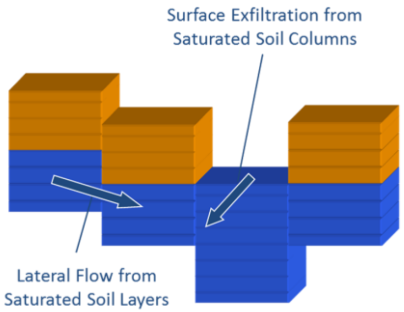
WRF-Hydro V5.0 Physics Components

Runoff and Routing Physics:

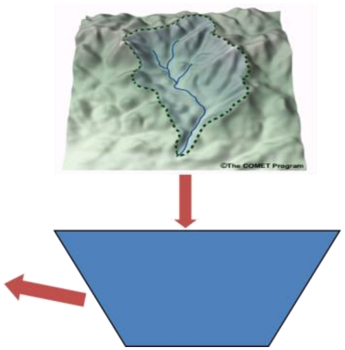
Overland Flow



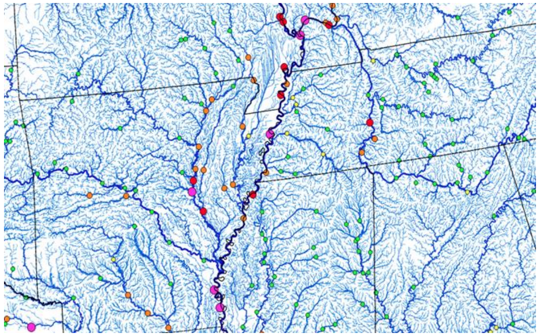
Lateral Subsurface Flow



Simplified Baseflow Parameterization

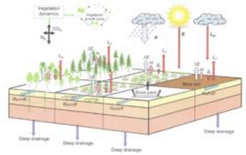
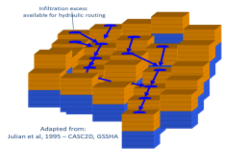
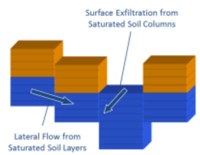
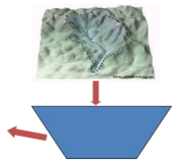
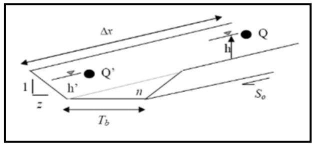
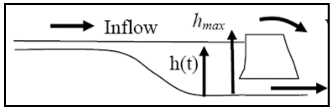
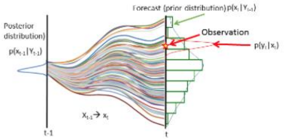


Channel Hydraulics



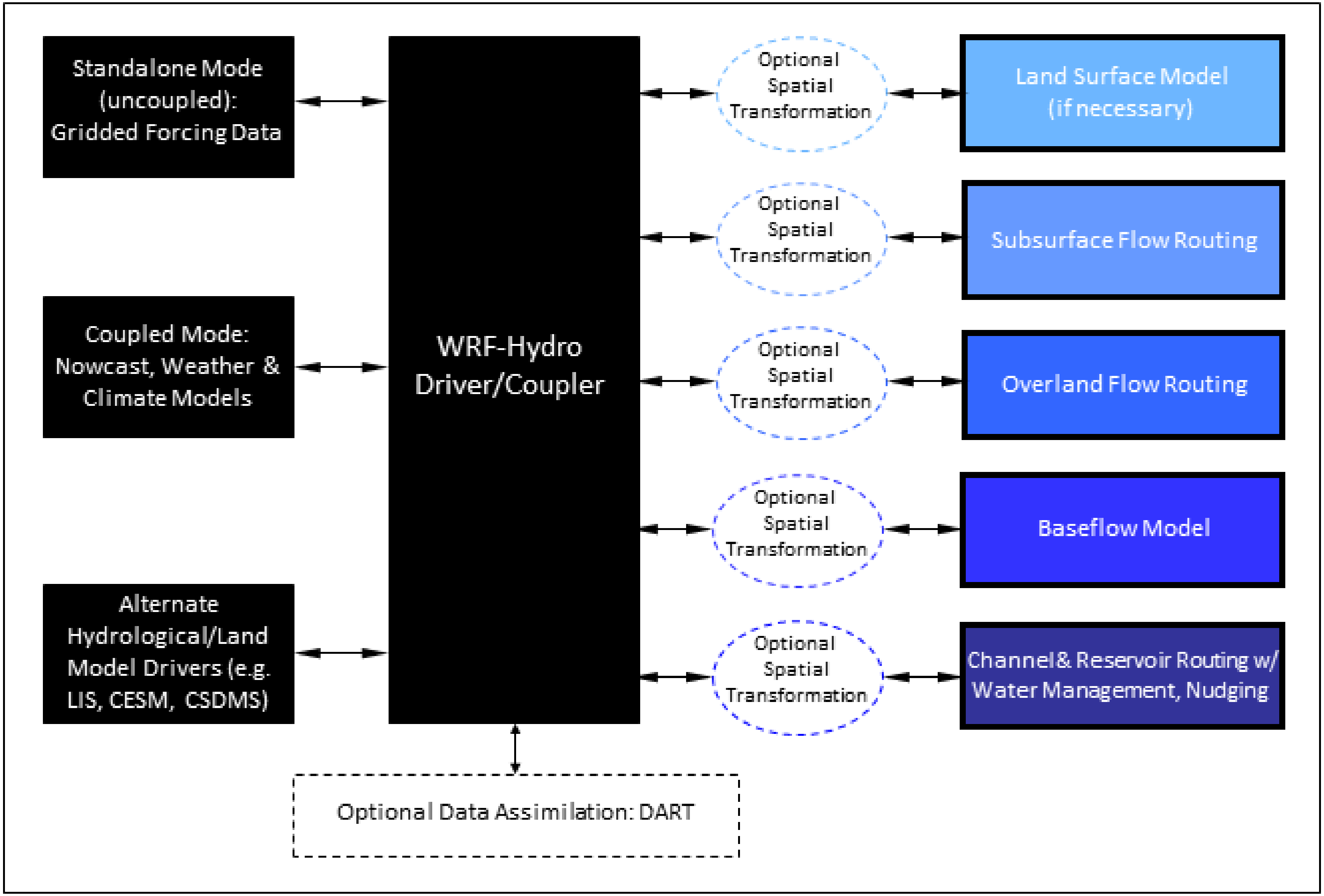
Simple Water Management

WRF-Hydro Community Model Multi-Physics Options

		WRF-Hydro Options	**Current NWM**
Column Land Surface Model		2 column land models: Noah, NoahMP	NoahMP
Overland Flow Module		3 surface routing schemes: diffusive wave, kinematic wave, direct basin aggregation	diffusive wave
Lateral Subsurface Flow Module		2 subsurface routing scheme: Boussinesq shallow saturated flow, 2d aquifer model	Boussinesq shallow saturated flow
Conceptual Baseflow Parameterizations		2 groundwater schemes: direct aggregation storage-release: pass-through or exponential model	exponential model
Channel Routing/ Hydraulics		5 channel flow schemes: diffusive wave, kinematic wave, RAPID, custom-network Muskingum or Muskingum-Cunge	custom-network (NHDPlus) Muskingum-Cunge model
Lake/Reservoir Management		2 lake routing schemes: level-pool, w/ or w/o persisted release option	level-pool w/ persisted release
Data Assimilation		4 DA options: streamflow nudging, supplemental forecasts, HydroDART, JEDI	streamflow nudging, RFC supplemental reservoir forecasts

WRF-Hydro System Specifics

WRF-Hydro Modular Calling Structure

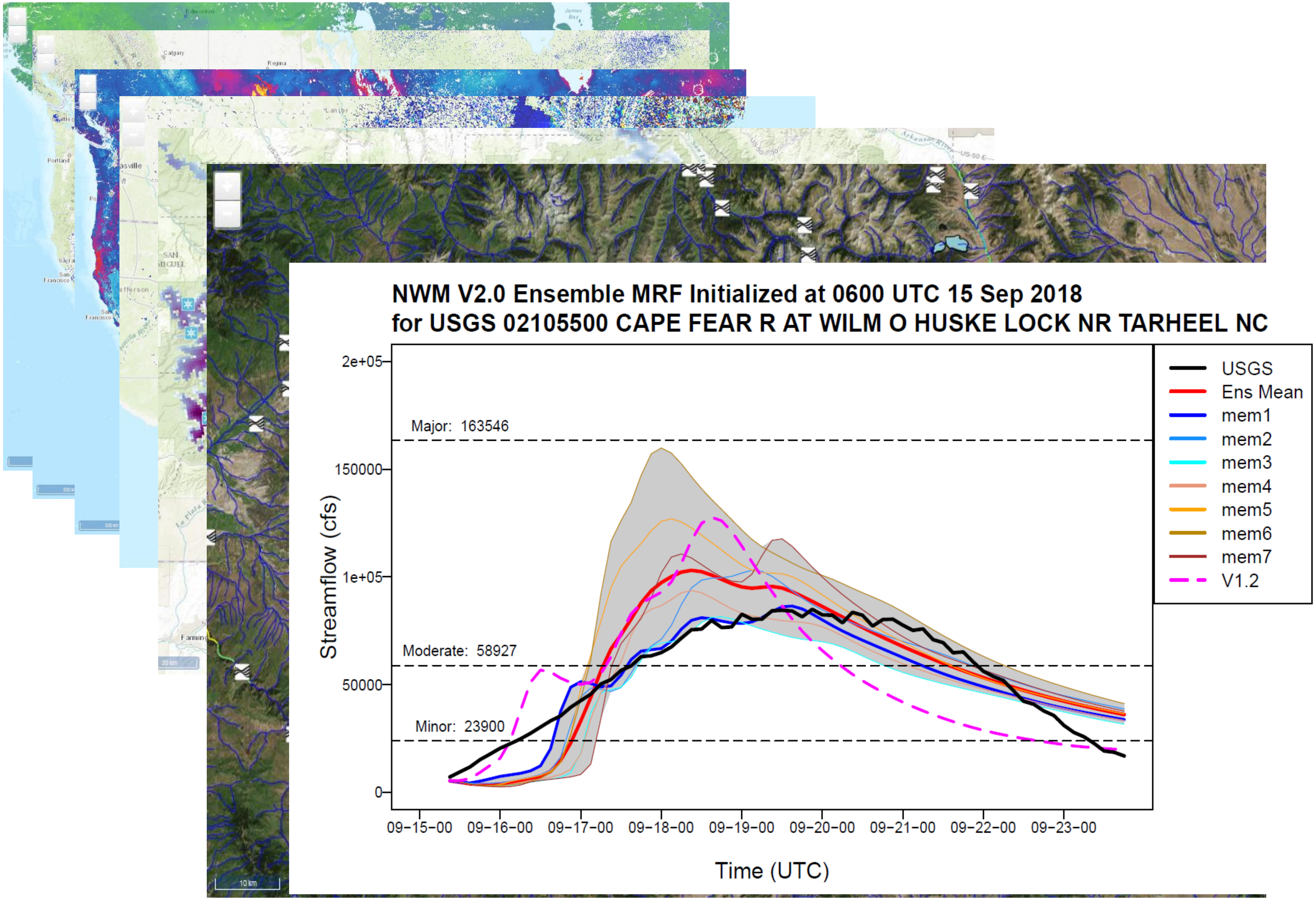


WRF-Hydro Software Features

- Modularized Fortran
- Physics options are switch-activated though a namelist/configuration file
- Options to output sub-grid state and flux fields to standards-based netcdf point and grid files
- **Fully-parallelized** to HPC systems
- Ported to Intel, IBM and MacOS operating systems and a variety of compilers (pg, gfort, ifort, cray)
- Containerized using Docker
- Cloud-ported onto AWS (all training conducted on cloud)
- Extensive library of Jupyter Notebooks for WRF-Hydro ecosystem components

WRF-Hydro Output Products

WRF-Hydro Model Outputs: National Water Model Configuration

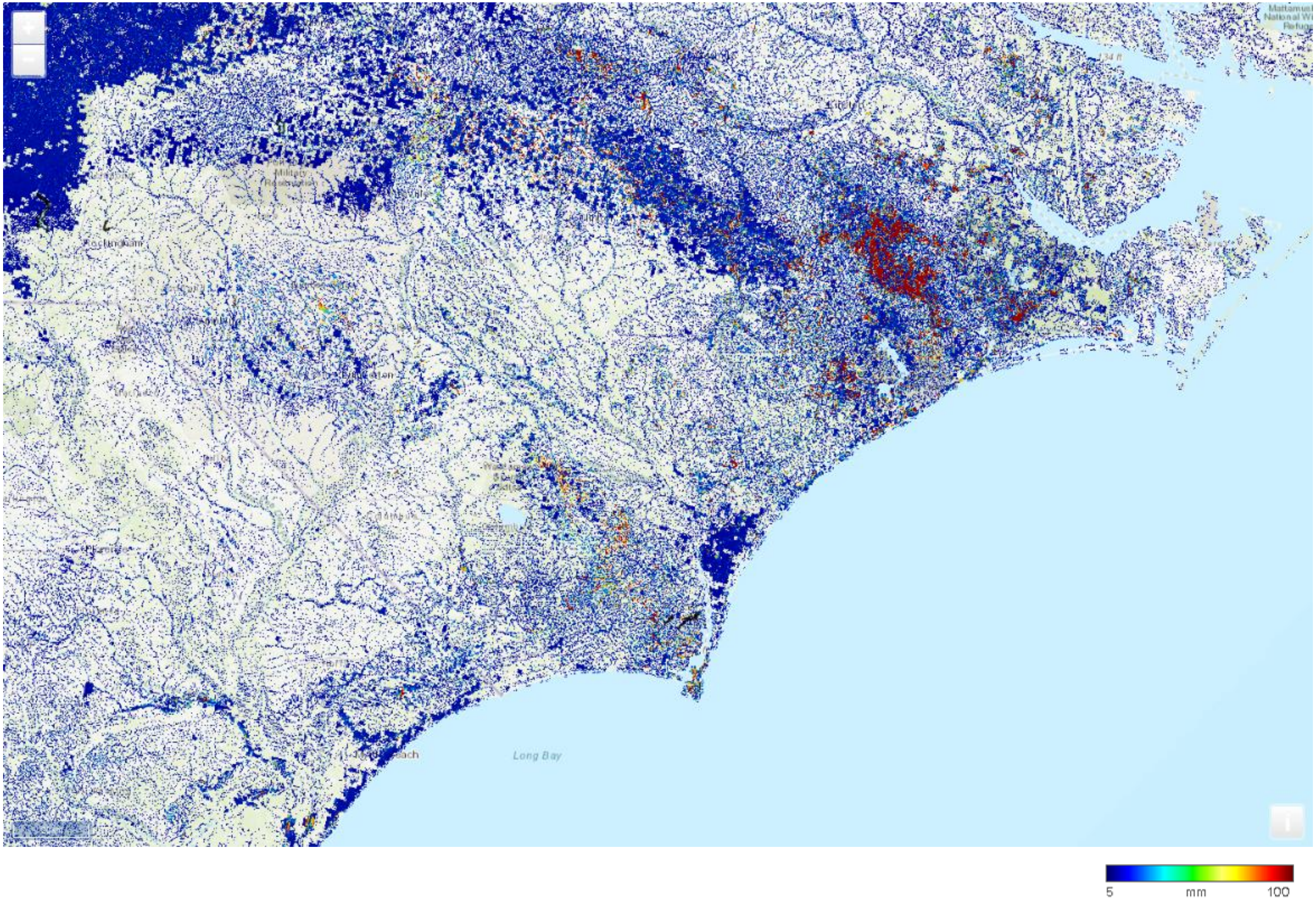


NHDPlus channel flow and velocity

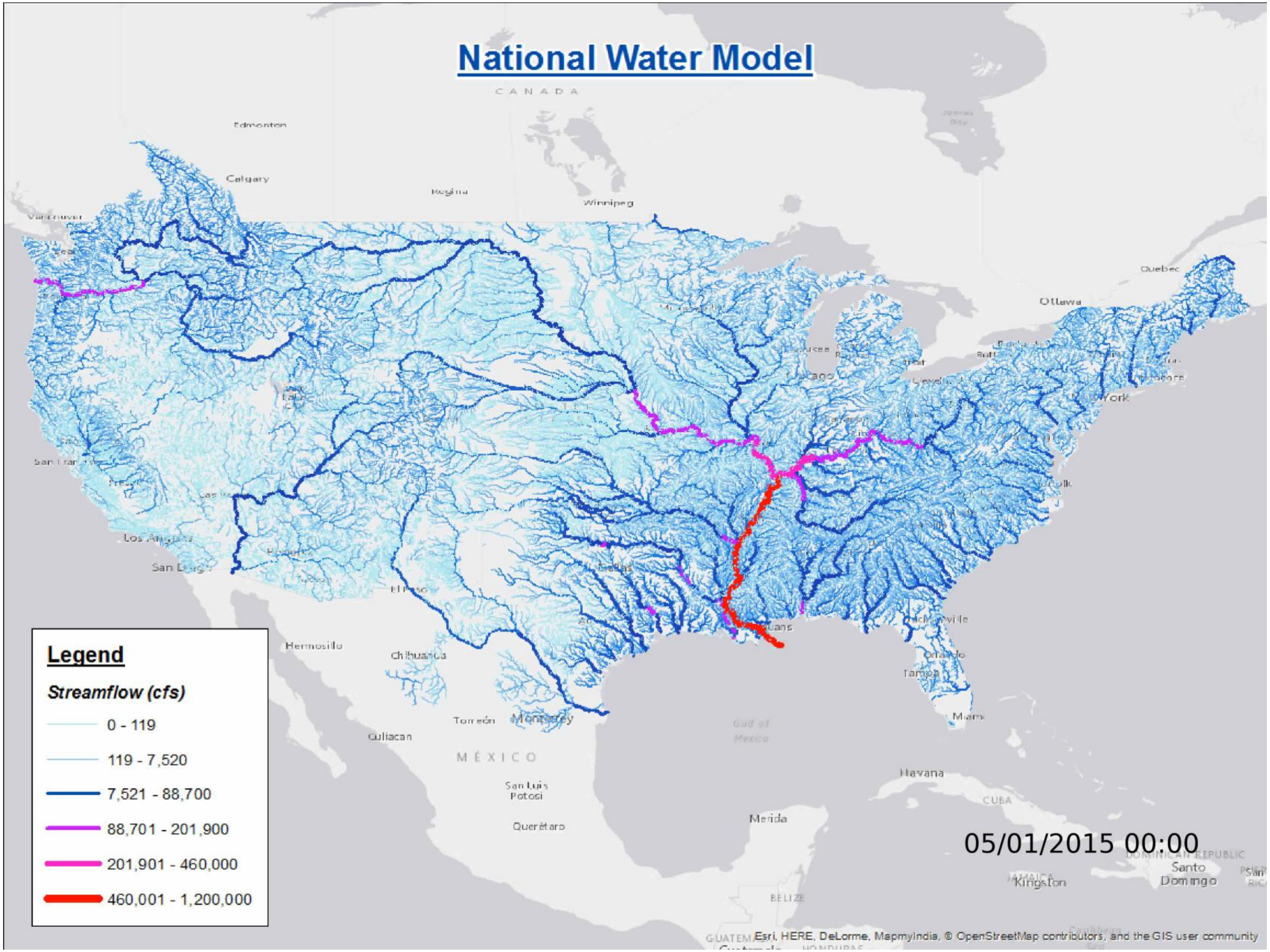
Ensemble streamflow predictions

WRF-Hydro Model Outputs

NWM v1.2 Medium Range Forecast Surface Overland Flow Water Depth (mm):
Eastern N. Carolina, Hurricane Florence….Forecast guidance up to 6 days in advance



WRF-Hydro Model Outputs

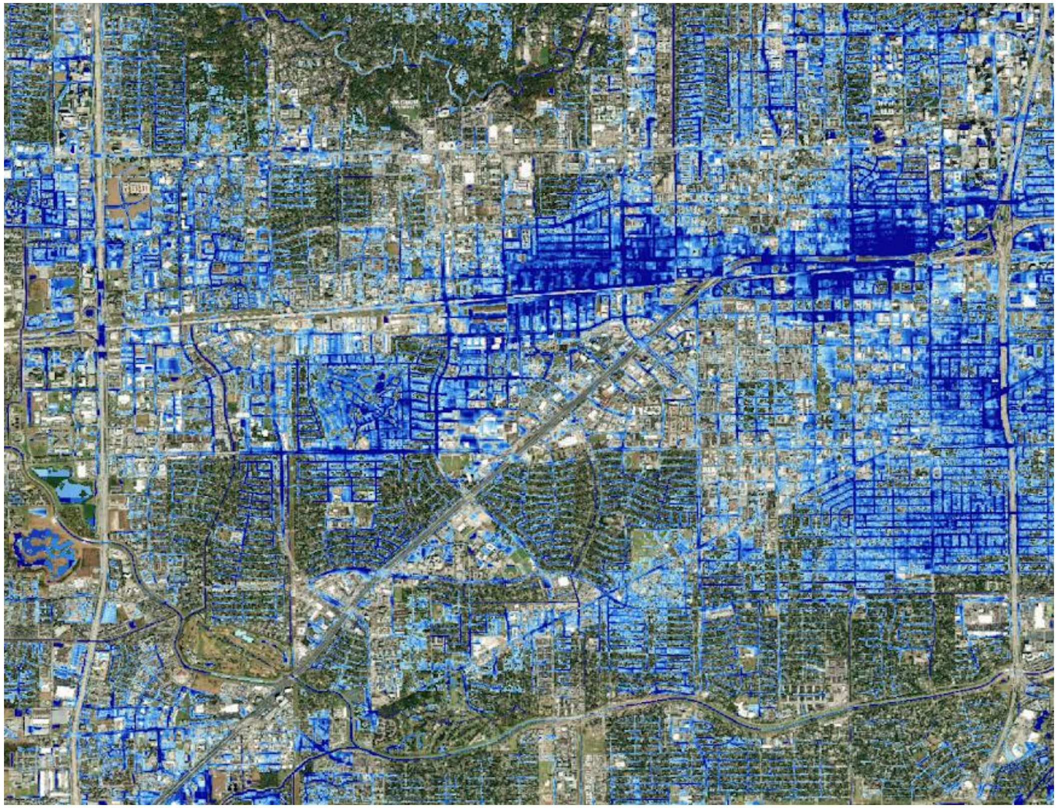


WRF-Hydro Research: Flood Inundation Products for Hurricane Harvey, 2018

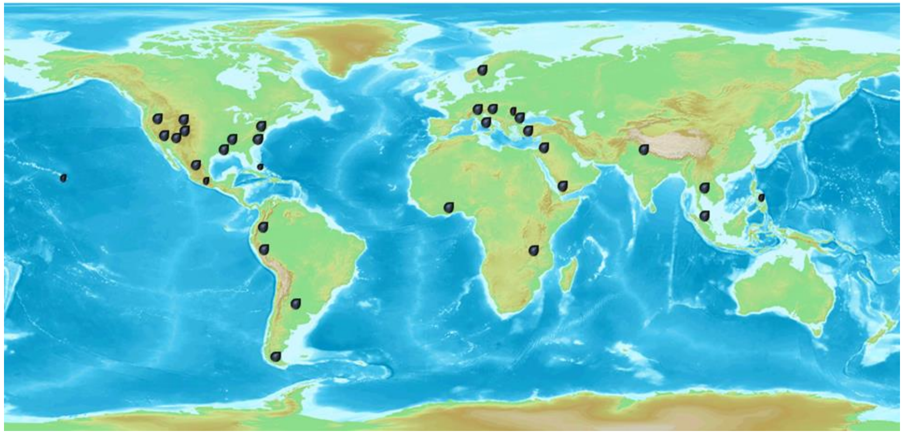
- Terrain-downscaled inundation maps

- 2-step hybrid blended product:
  - Downscaled max. overland flow depth
  - Riverine inundation
  - Utilize ensembles forecasts to make probabilistic product
  - Adopt workflow to 'on-demand' service via HydroInspector

- Applications in:
  - Operational prediction
  - Long term risk analysis



WRF-Hydro® Applications Around the Globe



Operational Streamflow Forecasting

- U.S. National Weather Service National Water Model (NOAA/NWS, National Water Center, USGS, CUAHSI)
- Israel National Forecasting System (Israeli Hydrological Service)
- State of Colorado Upper Rio Grande River Basin Water Supply Forecasting (Colorado Water Conservation Board, NOAA/NSSL)
- NCAR-STEP Hydrometeorological Prediction (NCAR)
- Italy reservoir inflow forecasting (Univ. of Calabria)
- Romania National Forecasting System (Baron)

Streamflow Prediction Research

- Flash flooding in Black Sea region of Turkey (Univ. of Ankara)
- Runoff production mechanisms in the North American Monsoon (Ariz State Univ.)
- Streamflow processes in West Africa (Karlsruhe Inst. Tech.)

Coupled Land-Atmosphere Processes

- Diagnosing land-atmosphere coupling behavior in mountain-front regions of the U.S. and Mexico (Arizona State Univ., Univ. of Arizona)
- Quantifying the impacts of winter orographic cloud seeding on water resources (Wyoming Board on Water Resources)
- Predicting weather and flooding in the Philippines, Luzon Region (USAID, PAGASA, AECOM)
- RELAMPAGO in Argentina (Univ. of Illinois Urbana-Champaign, NCAR)

Diagnosing Climate Change Impacts on Water Resources

- Himalayan Mountain Front (Bierknes Inst.)
- Colorado Headwaters (Univ. of Colorado)
- Bureau of Reclamation Dam Safety Group (USBR, NOAA/CIRES)
- Lake Tanganyika, Malawi, Water Supply (World Bank)
- Climate change impacts on water resources in Patagonia, Chile (Univ. of La Frontera)

Coupling WRF-Hydro with Coastal Process Models

- Italy-Adriatic sea interactions (Univ. of Bologna)
- Lower Mississippi River Valley (Louisiana State University)
- Integrated hydrological modeling system for high-resolution coastal applications (U.S. Navy, NOAA, NASA)

Diagnosing the Impacts of Disturbed Landscapes on Hydrologic Predictions

- Western U.S. Fires (USGS)
- West African Monsoon (Karlsruhe Inst. Tech)
- S. America Parana River (Univ. of Arizona)
- Texas Dust Emissions (Texas A&M Univ.)
- Landslide Hazard Modeling (USGS)

Hydrologic Data Assimilation:

- MODIS snow remote sensing assimilation for water supply prediction in the Western U.S. (Univ. of Colorado, Univ. of California Santa Barbara, NSIDC, NCAR)
- WRF-Hydro/DART application in La Sierra River basins in southeast Mexico (Autonomous National University of Mexico)

National Water Model - Operational Version Upgrades

v1.0
August 2016

Inaugural water forecasting model, 1-km/ 250-m CONUS coverage, 2.7 mil reaches, stream DA

v1.1
May 2017

Extended forecasts, parameter calibration

v1.2
March 2018

Expanded parameter calibration, improved DA

v2.0
June 2019

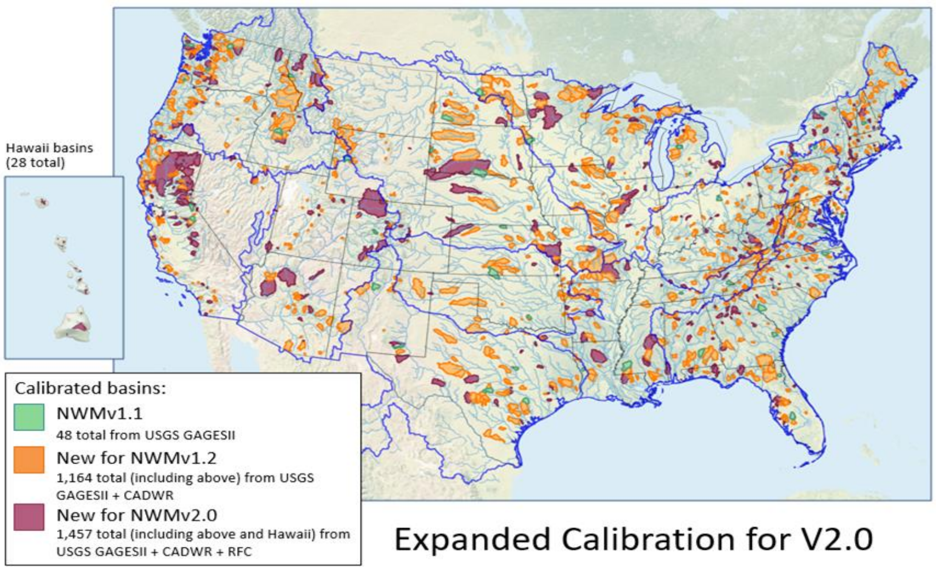
Hawaii expansion, new ensembles, compound channel, extended analysis

v2.1
In transition to ops: March 2021

Expansion to Great Lakes & PR/VI, new reservoir management modules

v3.0
Future upgrade: 2022

Expansion to Alaska, improved runoff, improved derived parameters, dynamic land cover, multi-variate calibration

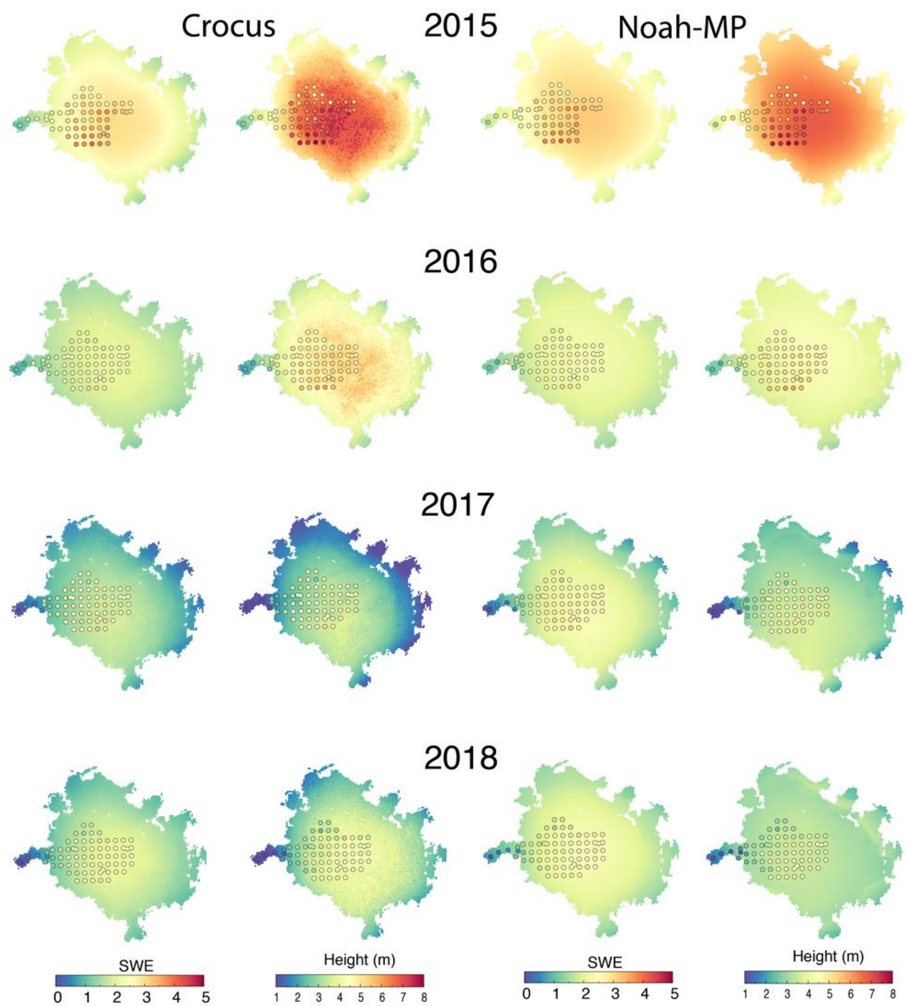


Expanded Calibration for V2.0

WRF-Hydro Research Highlight: Glacier Melt Modeling in Norway

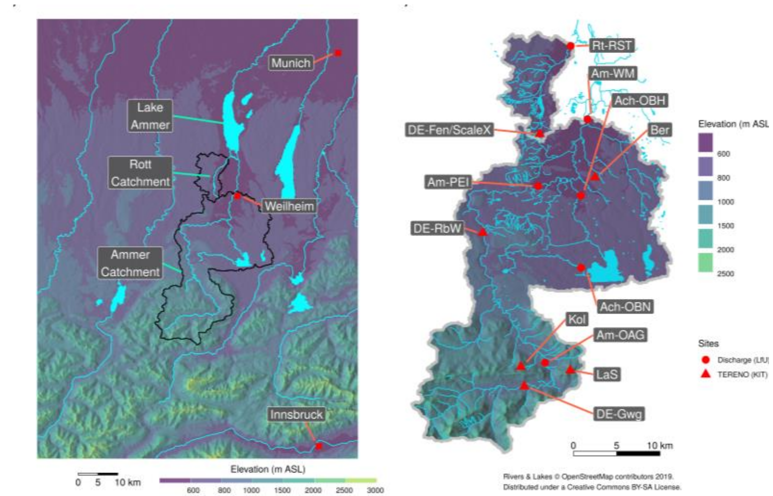
T. Eidhammer & M. Barlage

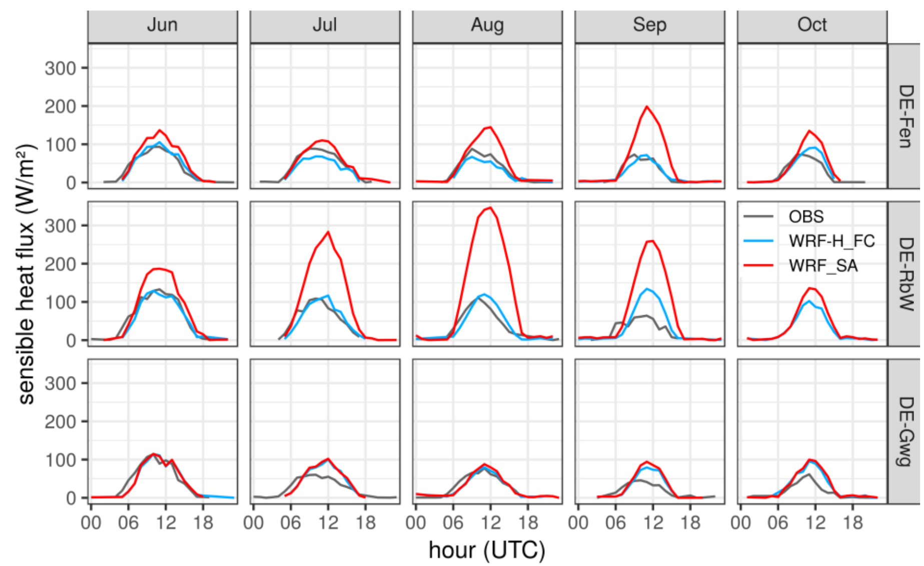
- Coupled CROCUS/NoahMP/WRF-Hydro modeling system
- CROCUS handling deeper ice layers
- Intended to handle accumulation/melt processes near glacier periphery
- Does not handle glacial flow dynamics
- Results indicate fidelity commensurate with improved accounting in seasonal growth/melt processes



WRF-Hydro Research Highlight: Coupled atmo-hydro prediction in the pre-Alpine

- TERRENO-preAlpine multiscale observation campaign (southern Germany)
- Compared:
  - Traditional 1-d LSM (NoahMP)
  - Fully coupled WRF/NoahMP/WRF-Hydro
- Modeled surface energy and mass fluxes vs. field observations:
  - Fully coupled model outperformed traditional WRF-lsm configuration with respect to:
  - Evapotranspiration,
  - Sensible and ground heat fluxes
  - 2m mixing ratio, air temp
  - PBL air temp profile





Fersch et al., 2019 HESS

Current Development Activities

- Supporting coupling of WRF-Hydro in UFS (NOAA JTTI)
- Alpine glacier model enhancement (CROCUS)
- Agricultural practices - crops, irrigation, tile drainage (linkages to WRF-Crop)
- Data assimilation - snow, soil water, inundation (supporting both DART and JEDI)
- Ensemble Streamflow Prediction (ESP) for water supply
- Land cover change - fire impacts on LSM and routing processes
- Groundwater - enhanced groundwater representation (USGS-MODFLOW, Parflow)
- Water use/management - reservoirs, diversions, WRF-Lake
- Sediment transport modeling
- Water temperature modeling

WRF-Hydro Software Ecosystem

- Ecosystem overview: https://github.com/NCAR/wrfHydro
- Model: https://github.com/NCAR/wrf_hydro_nwm_public
  - Public, community model, with version control system
  - Contributing guidelines, conventions, license, code of conduct
  - Python-based (pytest) testing framework (Python API)
- Python API: https://github.com/NCAR/wrf_hydro_py
- Docker containers: https://github.com/NCAR/wrf_hydro_docker
  - Standard portable environments for working with the model
- Continuous Integration with Travis on Github (Docker + Python)
- "Discontinuous integration" at scale (cheyenne)
  - Large jobs, compilers with licenses
- ARC GIS preprocessing toolbox: https://github.com/NCAR/wrf_hydro_arcgis_preprocessor
- Analysis tool box: https://github.com/NCAR/rwrfhydro
- Training: https://github.com/NCAR/wrf_hydro_training
- Publications: https://ral.ucar.edu/projects/wrf_hydro/publications

- !! Most tools containerized and cloud-ported to AWS!!

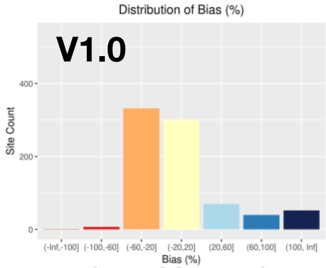
RAL WRF-Hydro/NWM Project Team

Name	Project Role
David Gochis	Project lead
Ryan Cabell, James McCreight, Katelyn FitzGerald, Ishita Srivashtava, Bill Petzke	Software engineering
David Yates, Laura Read, Bahram Khazaei	Channel and reservoir routing, water management, hyper-resolution
Kevin Sampson, Matt Casali	Geospatial framework and tools
Prasanth Valayamkunnath, Cenlin He	Land surface modeling
Yongxin Zhang, Joe Grim	Model forcings, climatology, and forecast workflows
James McCreight, Arezoo RafieeiNasab	Data assimilation
Aubrey Dugger, Katelyn FitzGerald, Arezoo RafieeiNasab, Erin Towler, Amir Mazrooei, Tom Enzminger, Ridwan Siddique	Hydrologic processes & model evaluation
Andy Gaydos	Web mapping and data services
Dave Gochis, Roy Rasmussen, Tim Schneider, Alyssa McCluskey, Aubrey Dugger, Molly McAllister	Community engagement and project management

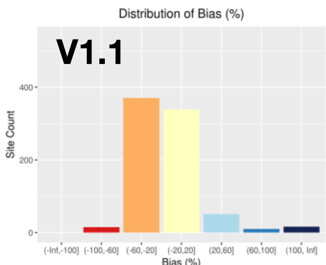
Thank you!

Dave Gochis - gochis@ucar.edu

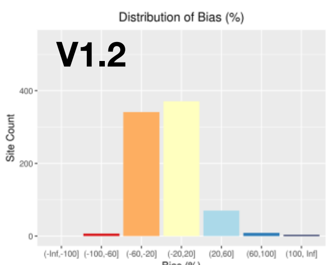
National Water Model - Operational Version Upgrades



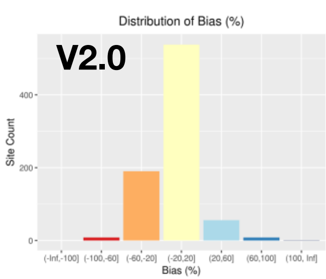
37% have bias < +/-20%



42% have bias < +/-20%



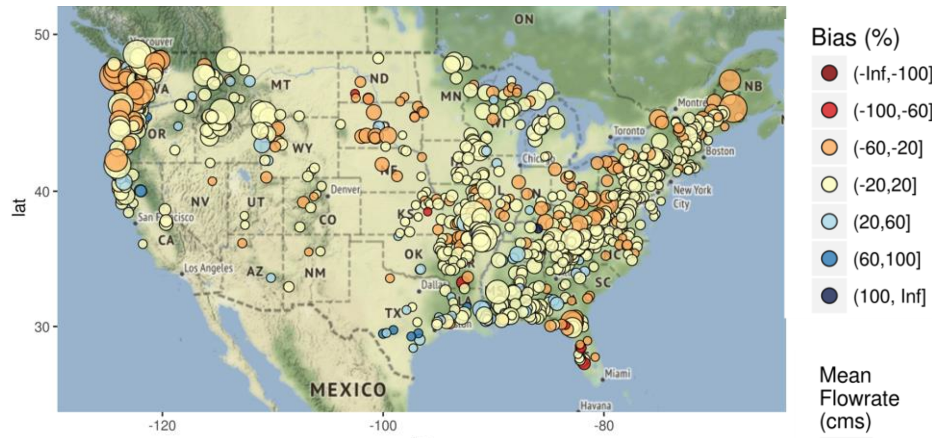
46% have bias < +/-20%

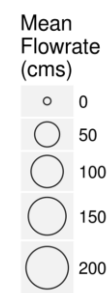


67% have bias < +/-20%

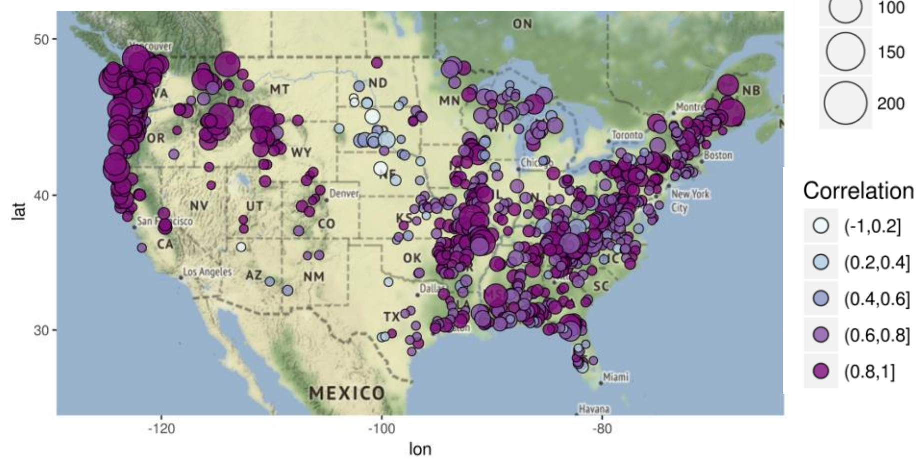
Evolution of retrospective model benchmark performance over NWM versions

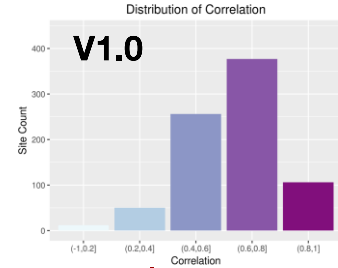
NWM v2.0 Streamflow Bias at USGS GAGES-II Reference Gauges (2011-2016)



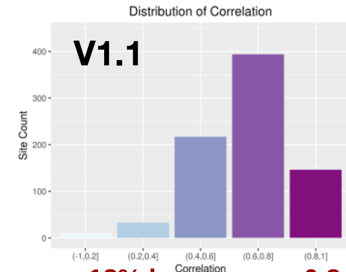


NWM v2.0 Streamflow Daily Correlation at USGS GAGES-II Reference Gauges (2011-2016)

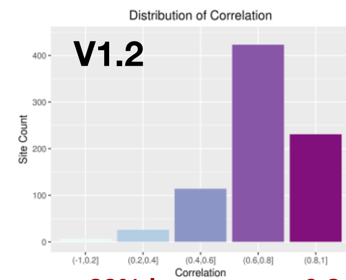




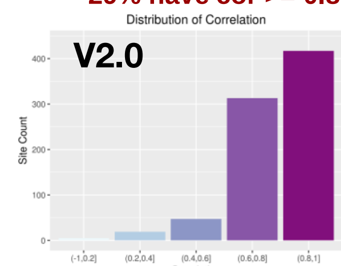
13% have cor >= 0.8



18% have cor >= 0.8



29% have cor >= 0.8



52% have cor >= 0.8