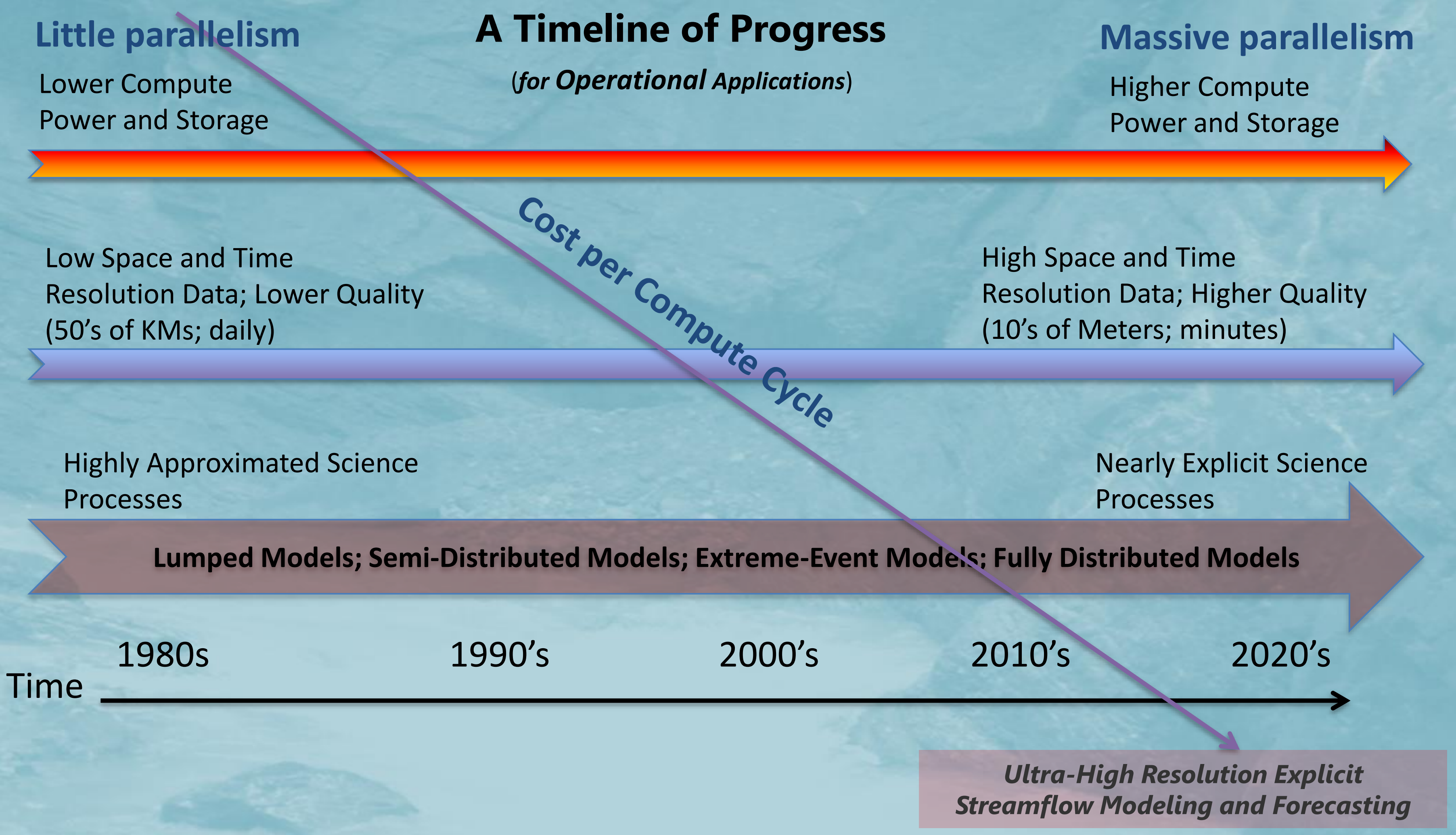
Multi-scale water cycle predictions using the community WRF-Hydro modeling system

Sept 7, 2017

D. Yates, D. Gochis, W. Yu, A. Dugger, J. McCreight, K. Sampson, A. RafieeiNasab, L. Karsten, L. Read, L. Pan, Y. Zhang

National Center for Atmospheric Research

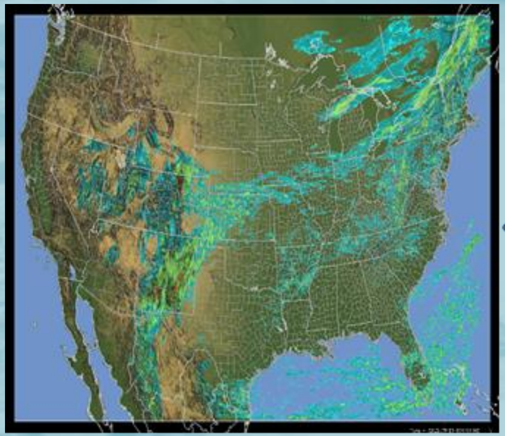
State-of-Science Hydrological Forecasting Across Scales



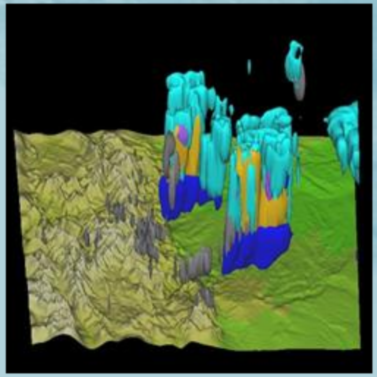
Overarching WRF-Hydro System Objectives

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

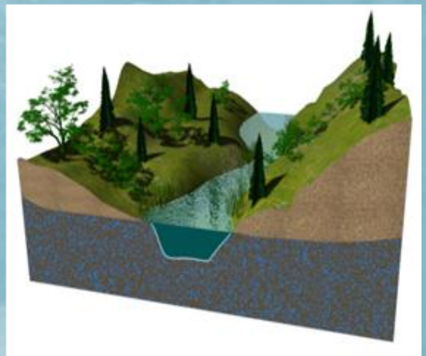
1. An extensible *multi-scale & multi-physics* land-atmosphere modeling capability for conservative, coupled and uncoupled *assimilation & prediction* of major water cycle components such as <u>precipitation, soil moisture, snowpack, groundwater, streamflow, inundation</u>
2. ‘Accurate’ and ‘reliable’ streamflow prediction across scales (from 0-order headwater catchments to continental river basins & minutes to seasons)
3. A robust framework for land-atmosphere coupling studies



1-10’s km



100’s m - 1’s km

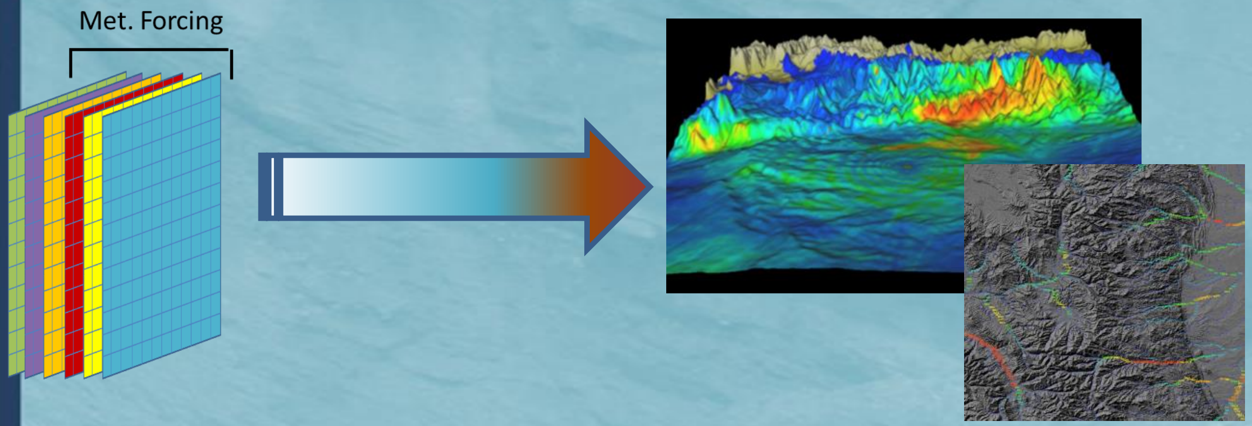


1-10’s m

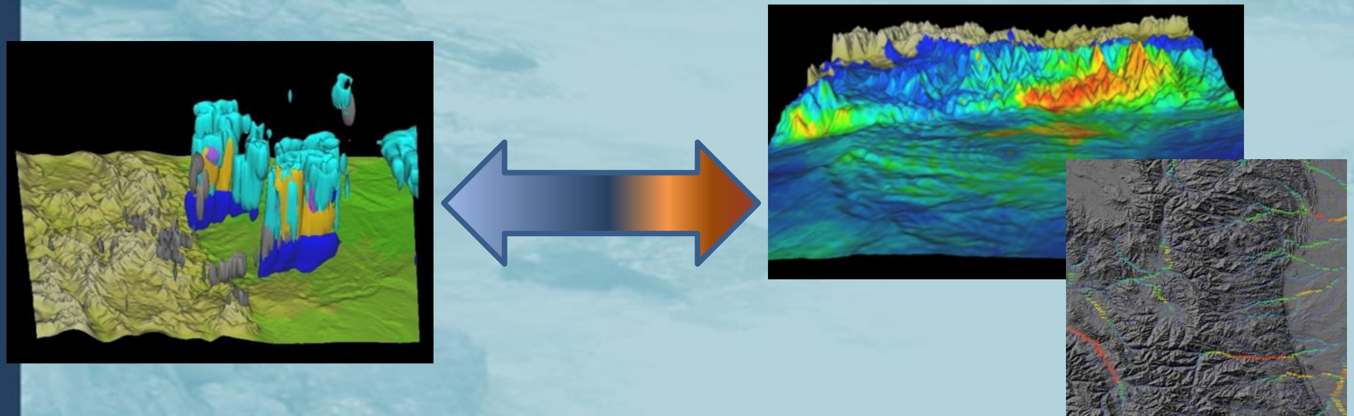
The National Center for Atmospheric Research

WRF-Hydro Operates in 2 Major Modes: Coupled or Uncoupled to an Atmospheric Model

One-way ('uncoupled') →

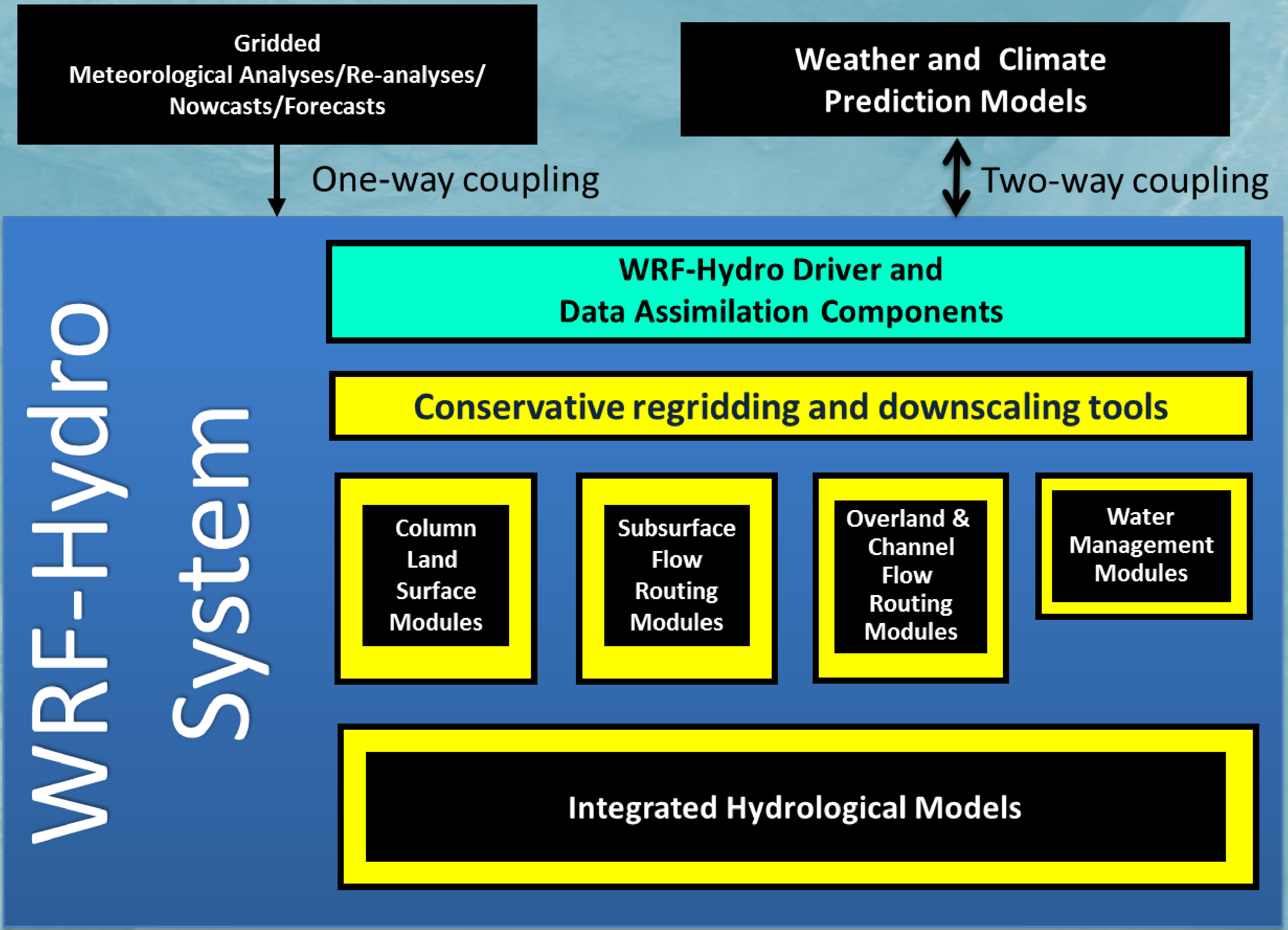


Two-way ('coupled') ↔



- Uncoupled mode critical for spinup, data assimilation and model calibration
- Coupled mode critical for land-atmosphere coupling research and long-term predictions
- Model forcing and feedback components mediated by WRF-Hydro:
  - Forcings: T, Press, Precip., wind, radiation, humidity, BGC-scalars
  - Feedbacks: Sensible, latent, momentum, radiation, BGC-scalars

The National Center for Atmospheric Research

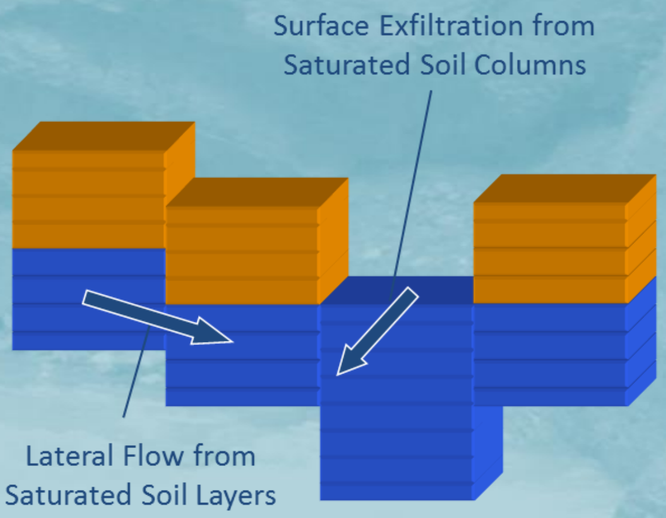


The National Center for Atmospheric Research

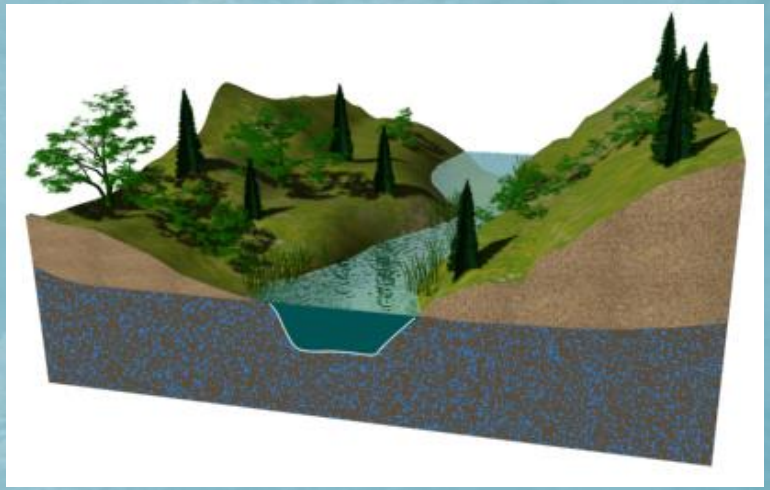
Version 4.0 physics components:

- physics-based runoff processes

Overland Flow -
Diffusive wave
Kinematic*
Catchment aggregation*



Groundwater Flow –
Boussinesq flow
Catchment aggregation*

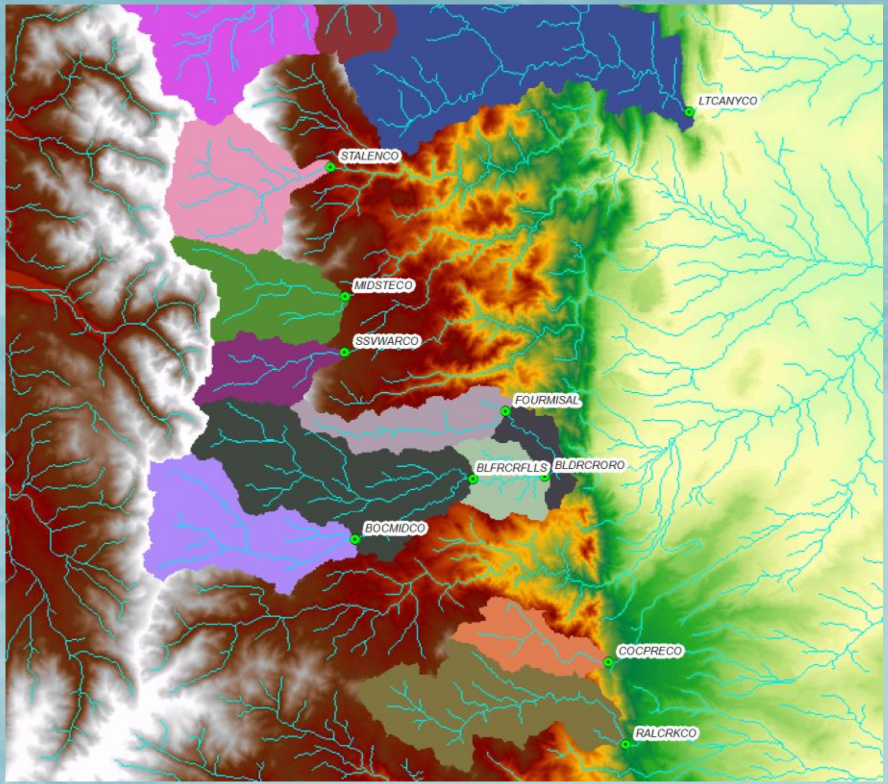


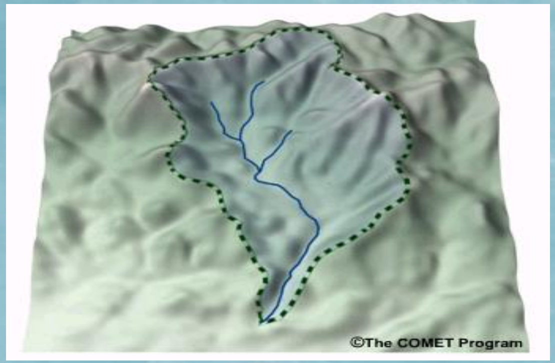
Channel Flow –
Diffusive wave
Kinematic*
Reach-based Muskingam*

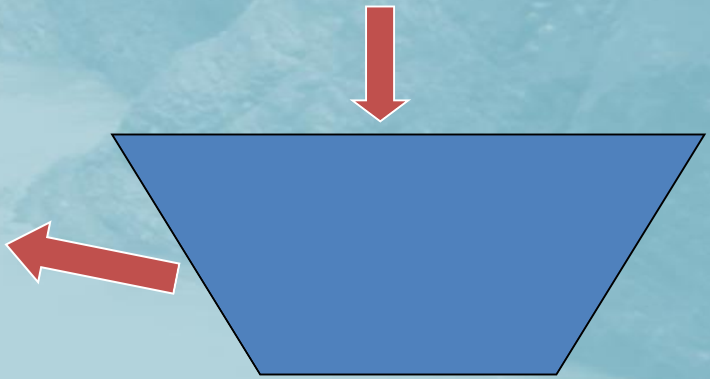
The National Center for Atmospheric Research

WRF-Hydro v4.0 Physics Components:

- Optional conceptual ‘catchment’ modeling support:
  - Benchmarking simple versus complex model structures
  - Enable very rapid ‘first-guess’ forecasts with reduced runtime/computational demand
  - Bucket discharge gets distributed to channel network channel routing (e.g. NWM & RAPID coupling)







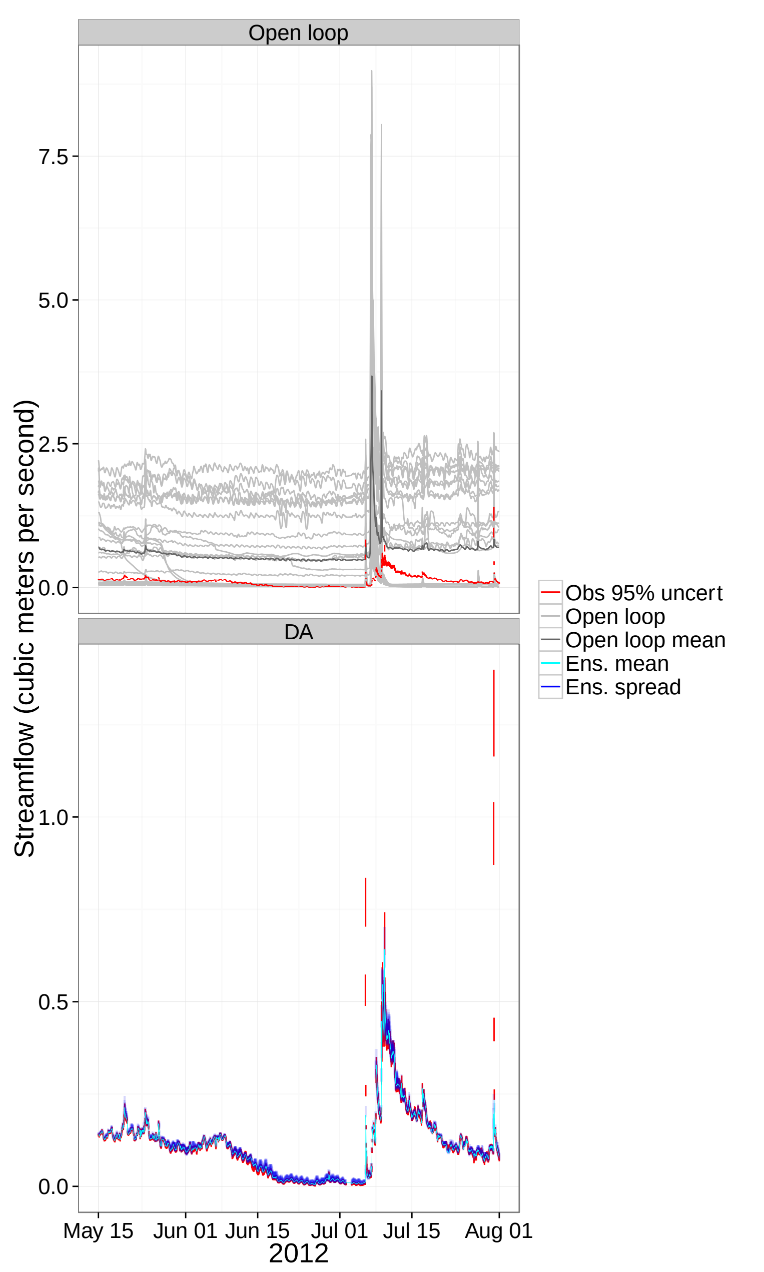
DA with WRF Hydro

Current capabilities

- Ensemble DA:
  - Offline WRF Hydro + DART = "HydroDART"
- Ensemble generation:
  - Initial state & parameter perturbation, ensemble runs

Future capabilities

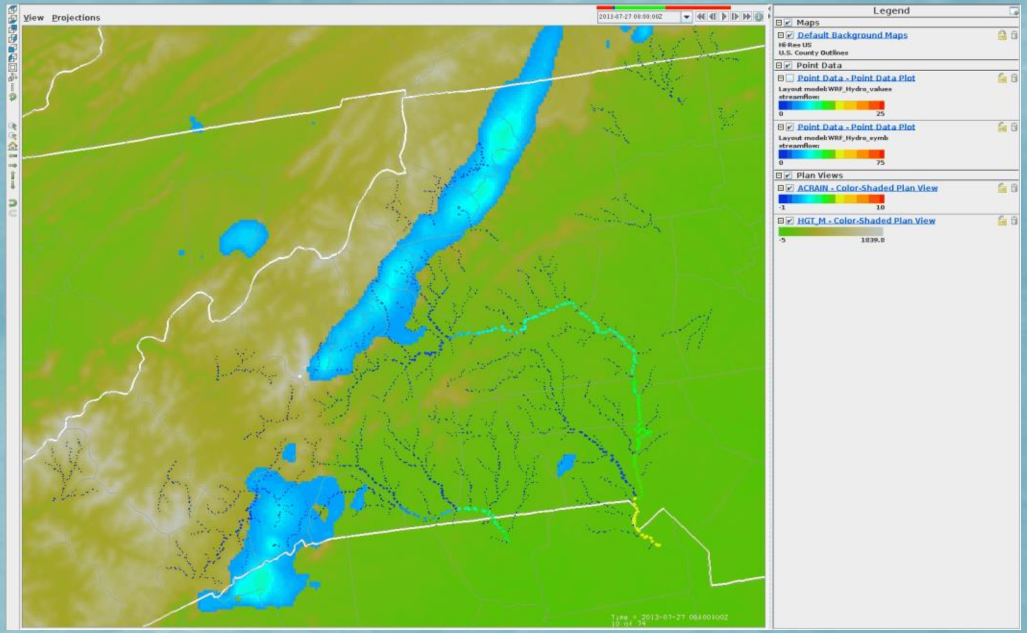
- Variational DA and/or nudging:
  - Faster & computationally cheaper for large-scale applications.
  - Variational DA not rank-deficient
- Other kinds of DA (hybrid, MLEF, …)
- Bias-aware filtering / Two-stage bias estimation (Friedland, 1969; Dee and de Silva, 1998; De Lannoy et al., 2007)



‘WRF-Hydro’ Process Permutations and System Features:

- ~180 possible ‘physics’ component configurations for streamflow prediction:
  - 3 up-to-date column physics land models (Noah, NoahMP, CLM)
  - 3 overland flow schemes (Diffusive Wave, Kinematic Wave, Direct basin aggregation)
  - 4 lateral/baseflow groundwater schemes (Boussinesq shallow-saturated flow, 2d aquifer model, Direct Aggregation Storage-Release: pass-through or exponential model
  - 5 channel flow schemes: Diffusive wave, Kinematic Wave, RAPID-Muskingam, Custom Network Muskingam/Muskingam Cunge

- Simple level-pool reservoir with management
- Data Assimilation:
  - DART, filter-based hydrologic data assimilation
  - Nudging-based streamflow



Ensemble Flood Forecasting in the Southeast U.S. with WRF-Hydro
***2014 WRF User’s Workshop*, K. Mahoney (NOAA-ESRL)**

WRF-Hydro System-Level Coupling Capabilities

Completed:

- Stand-alone, 'Un-coupled' (1-d Noah & NoahMP land model driver)
- Coupled with the Weather Research and Forecasting Model WRF-ARW)
- Coupled with LIS (WRF-Hydro v1.0, LISv6.1)
- Coupled into DART…

In Progress:

- NOAA/NEMS (NOAA Environmental Modeling System-Cecilia DeLuca)
- Update of LIS coupling to LIS v7/WRF-Hydro v2.1
- Coupled with CLM under CESM coupler (working on recent release of CLM in WRF)

The National Center for Atmospheric Research

'WRF-Hydro' Software Features:

- Modularized FORTRAN
- Coupling options are specified at compilation and WRF-Hydro is compiled as a new library in WRF when run in coupled mode
- 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 (e.g. NCAR supercomputer) and 'good' scaling performance
- Ported to Intel, IBM and MacOS systems and a variety of compilers (pg, gfort, ifort)

Wei Yu (RAL) – lead engineer

Land surface models: Implementation of plant/canopy resistance formulations

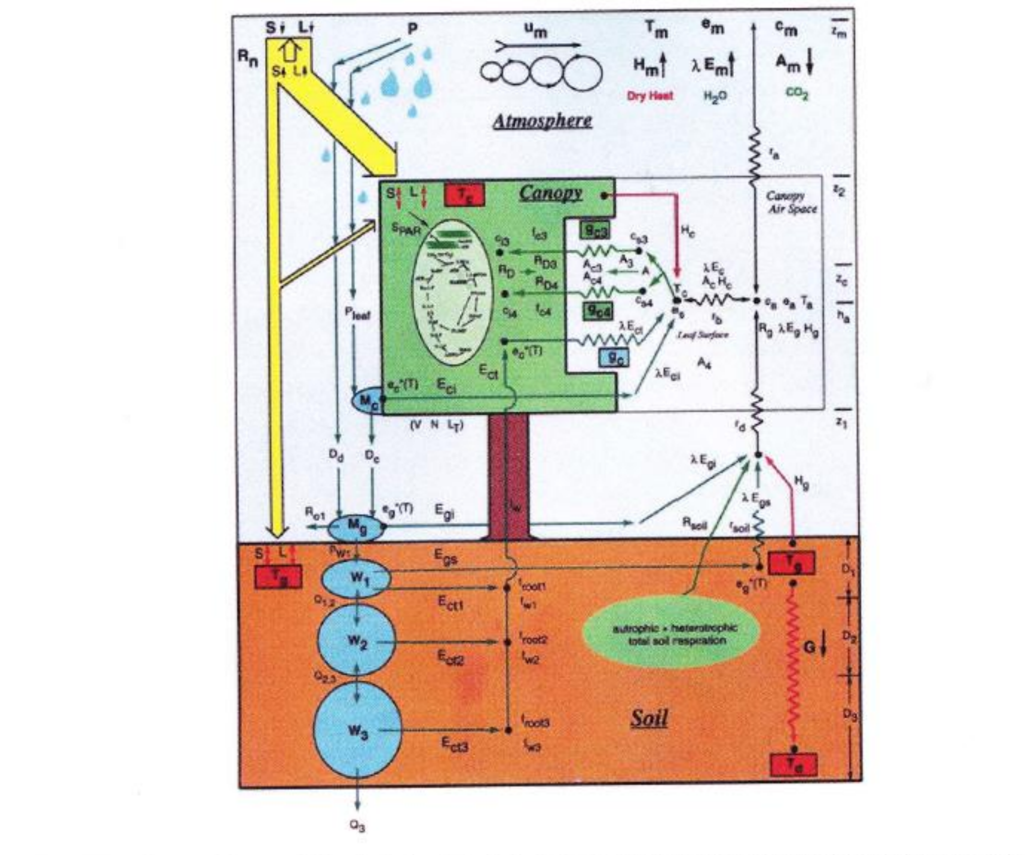


Plate 2 A schematic diagram of the physical and physiological processes represented in the second generation Simple Biosphere (SiB2) soil vegetation atmosphere transfer scheme. (From Colello *et al.*, 1998, published with permission.)

- Akin to Ohm's law for electrical circuits
- Reduces flux based on a variety of factors:
  - Plant cover fraction
  - Quality and amount of solar radiation
  - Atmospheric vapor pressure deficit
  - Leaf temperature
  - Soil moisture status

Jarvis-Stewart Model: $\frac{1}{r_s} = g_s = g_0 g_c g_R g_D g_T g_M$

The National Center for Atmospheric Research

Generational view of land surface models:

- 2nd Generation land models: P-M-style canopy resistance formulations

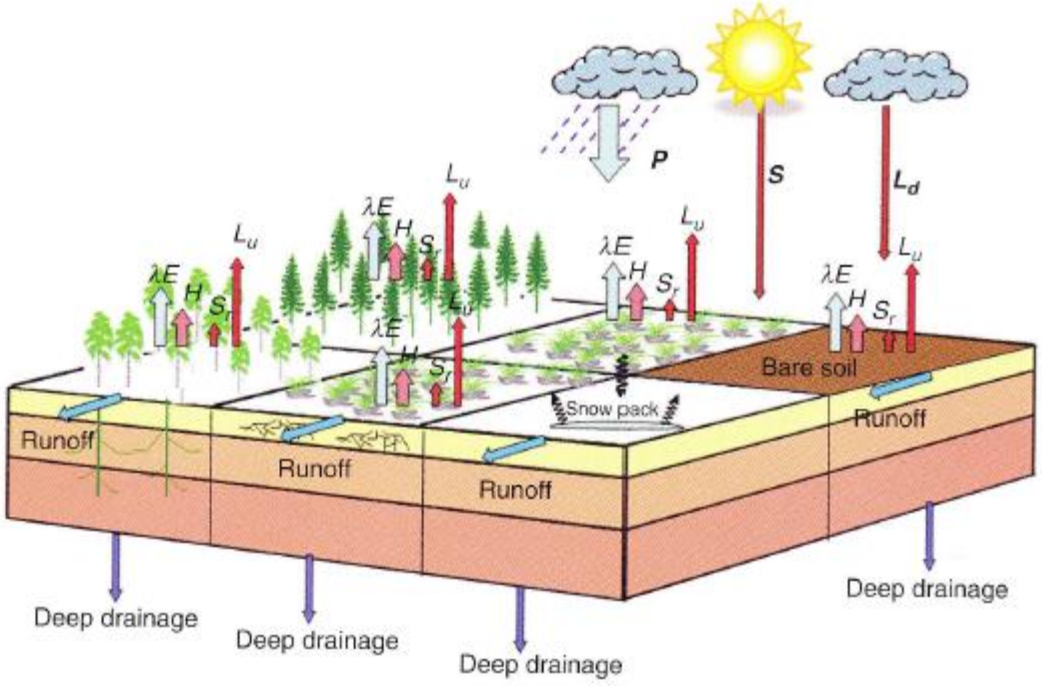


Plate 3 Schematic diagram of second generation one-dimensional SVATs in which a plot-scale micrometeorological model with an explicit vegetation canopy was applied at grid scale.

Shuttleworth, 2011

Generational view of land surface models:

- 3rd Generation land models:
  - Better soil hydrology: Richard's Eq., improved 'runoff'

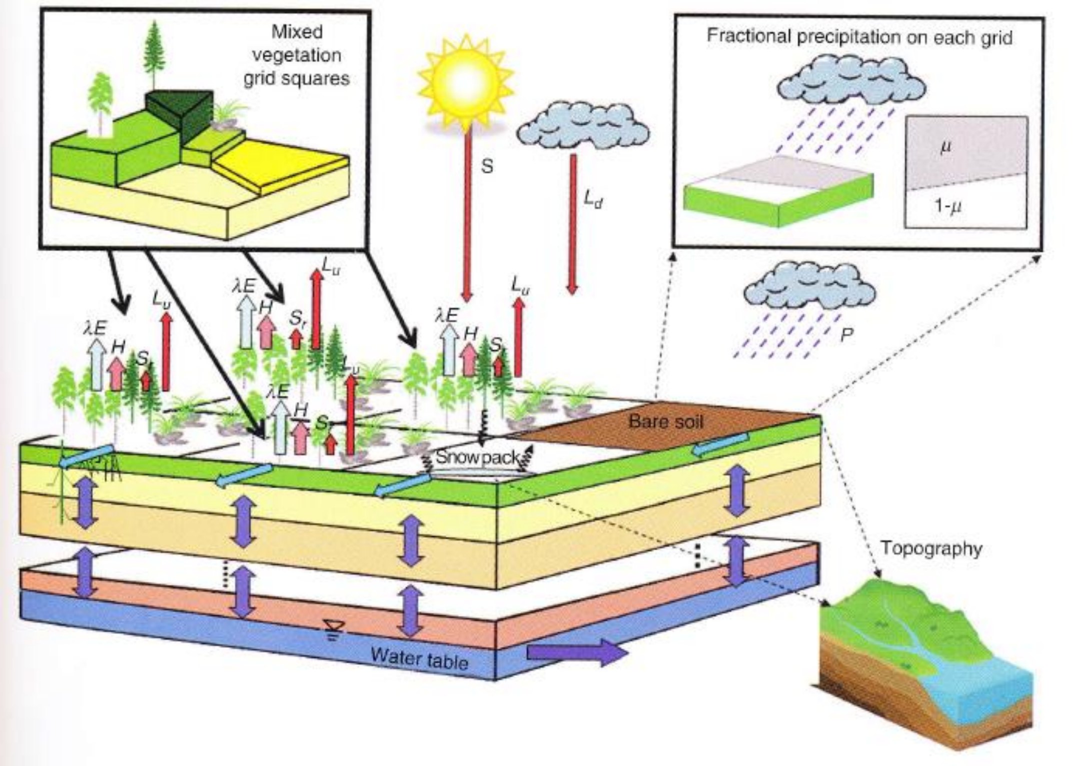


Plate 4 Schematic diagram of SVATS with improved representation of hydrologic processes.

Shuttleworth, 2011

Generational view of land surface models:

- 4th Generation land models: Photosynthesis and dynamic phenology

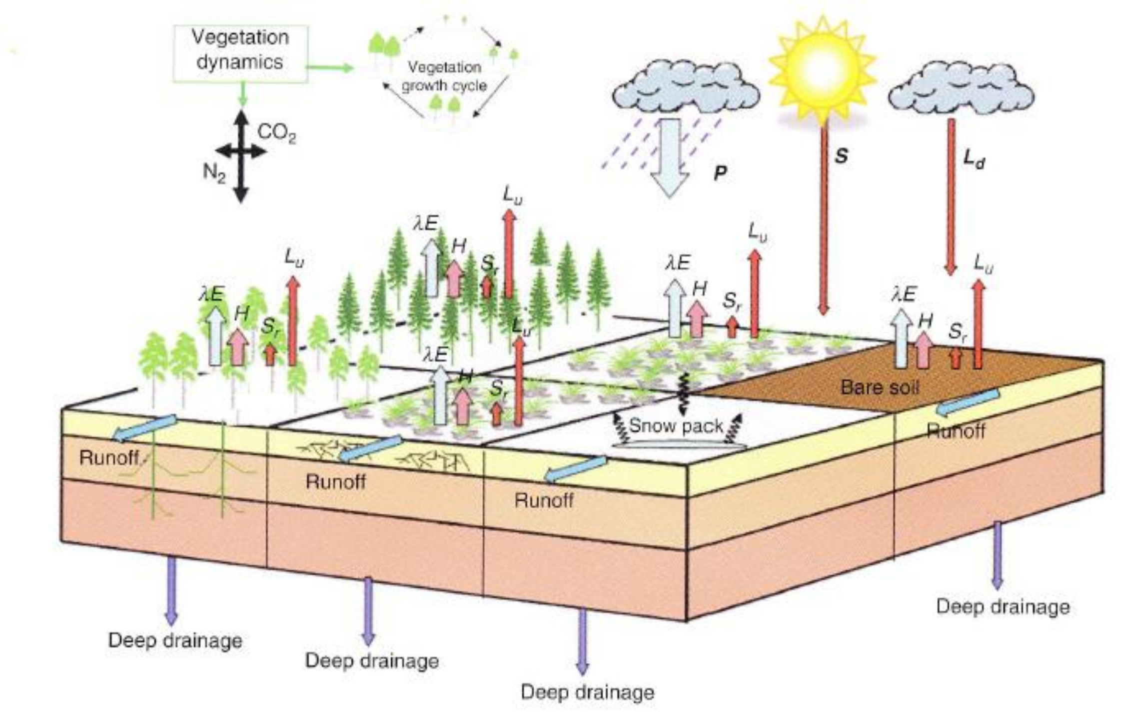


Plate 5 Schematic diagram of SVATS with improved representation of vegetation related processes, including CO_2 exchange and ecosystem evolution.

Shuttleworth, 2011

Generational view of land surface models:

- The 'greening' of land surface models:
  - Allowed for greater physiological control or specification of various plant resistance/conduction terms:
  - 'Photosynthesis-based' conductance formulation (Ball-Berry):

$$\frac{1}{r_s} = m(A_n/C_s)P_l F_e + \frac{1}{r_{s\,min}}$$

A_n – carbon assim.
C_s – CO2 concentr.
P_l – atmospheric press.
F_e – humidity stress fact.

  - Plant physiology-based 'carbon-assimilation' capacity (Farquhar)

Shuttleworth, 2011

Generational view of land surface models:

- 5th Generation land models: Sub-grid variability, distributed hydrology, data assimilation

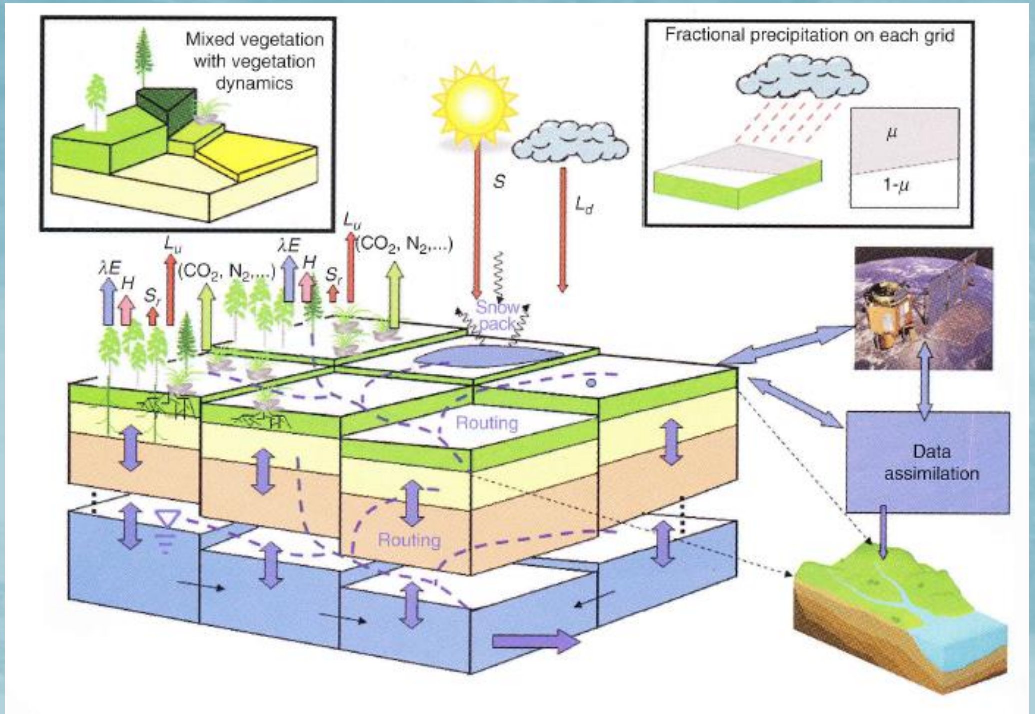
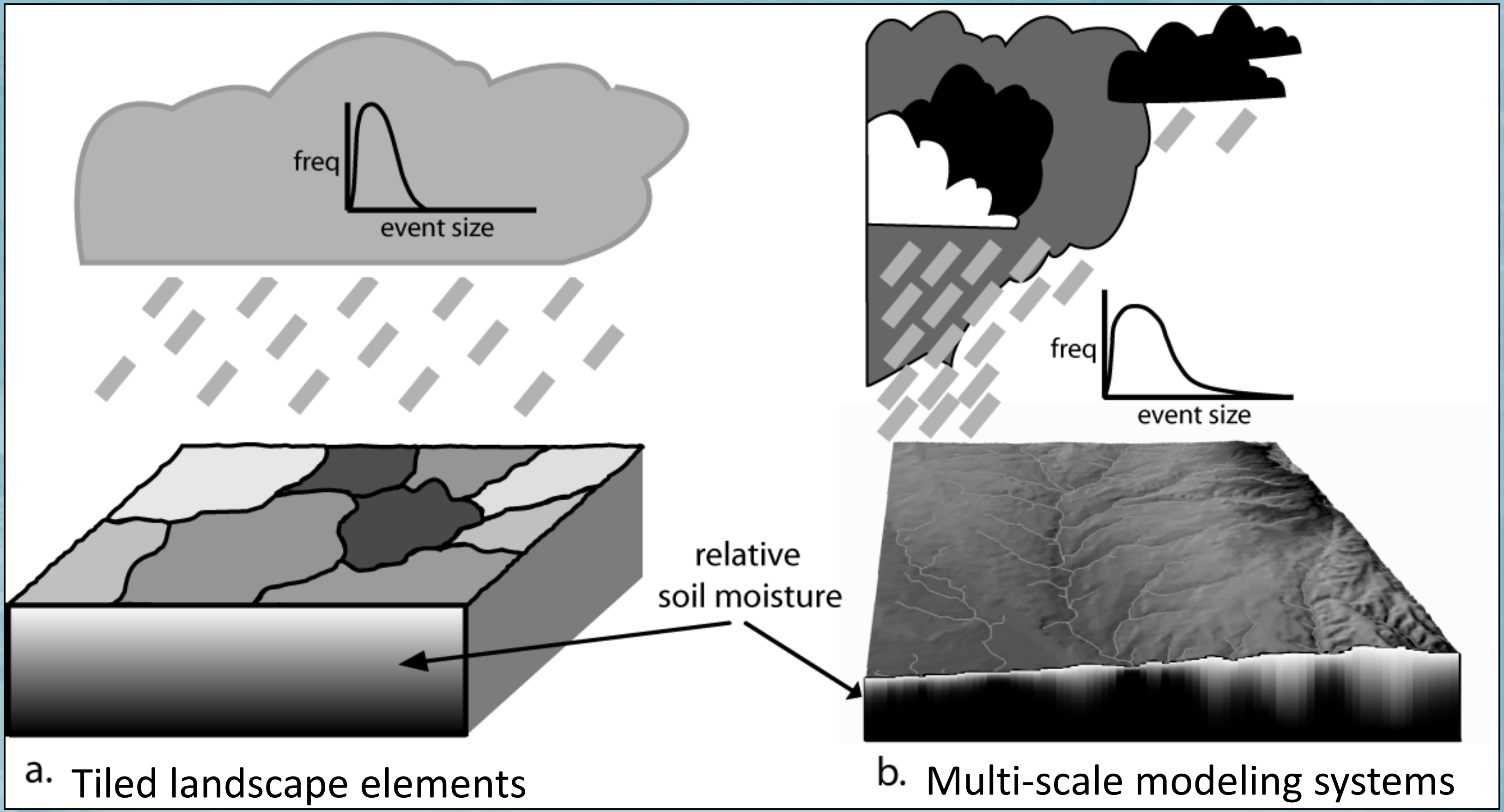


Plate 6 Schematic diagram of potential future developments in SVATS.

Shuttleworth, 2011

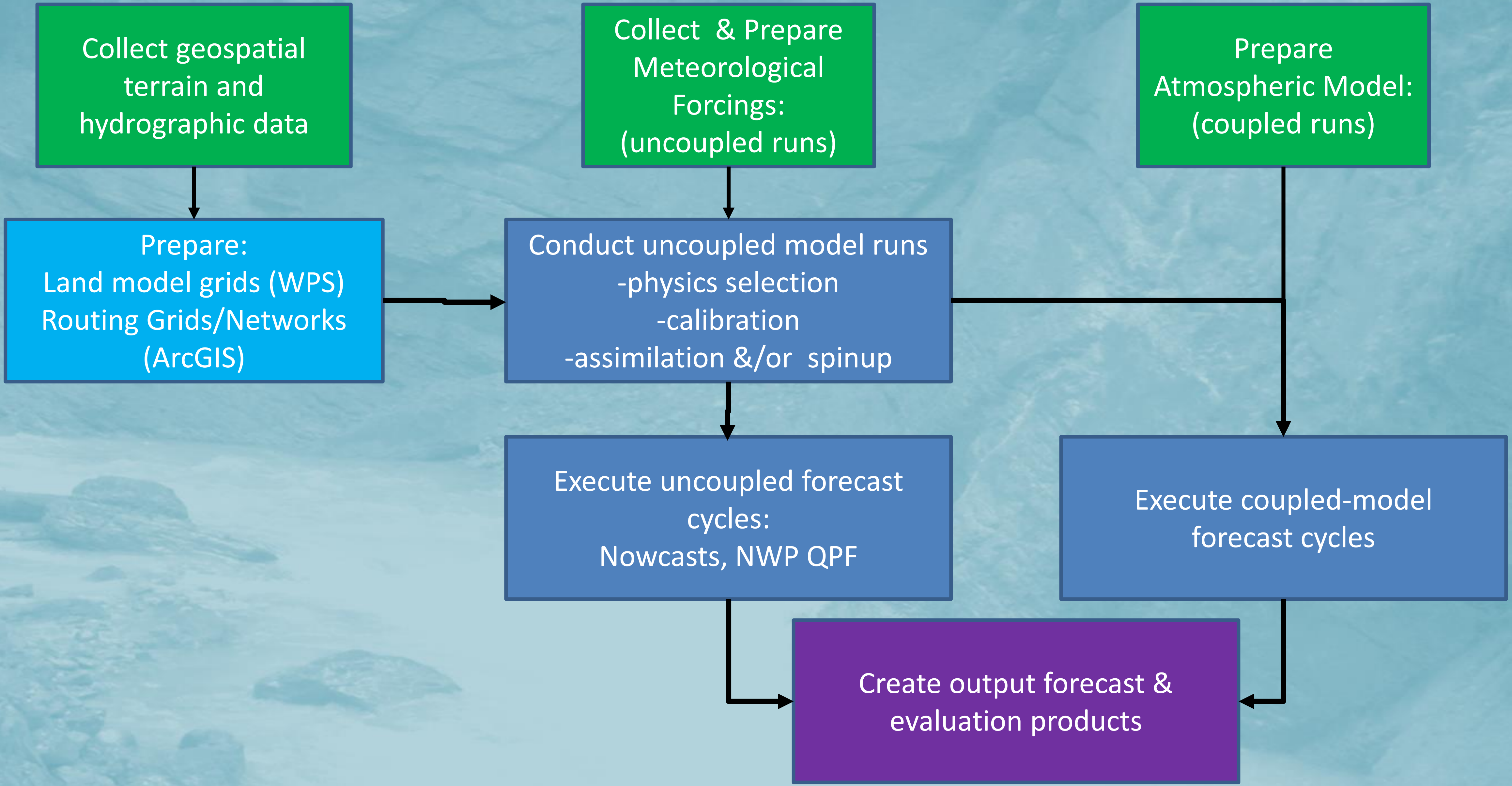
Modern integrated land surface models

- Linking multi-scale process models in a consistent Earth System Modeling framework



The WRF-Hydro Workflow

WRF-Hydro Implementation Workflow:



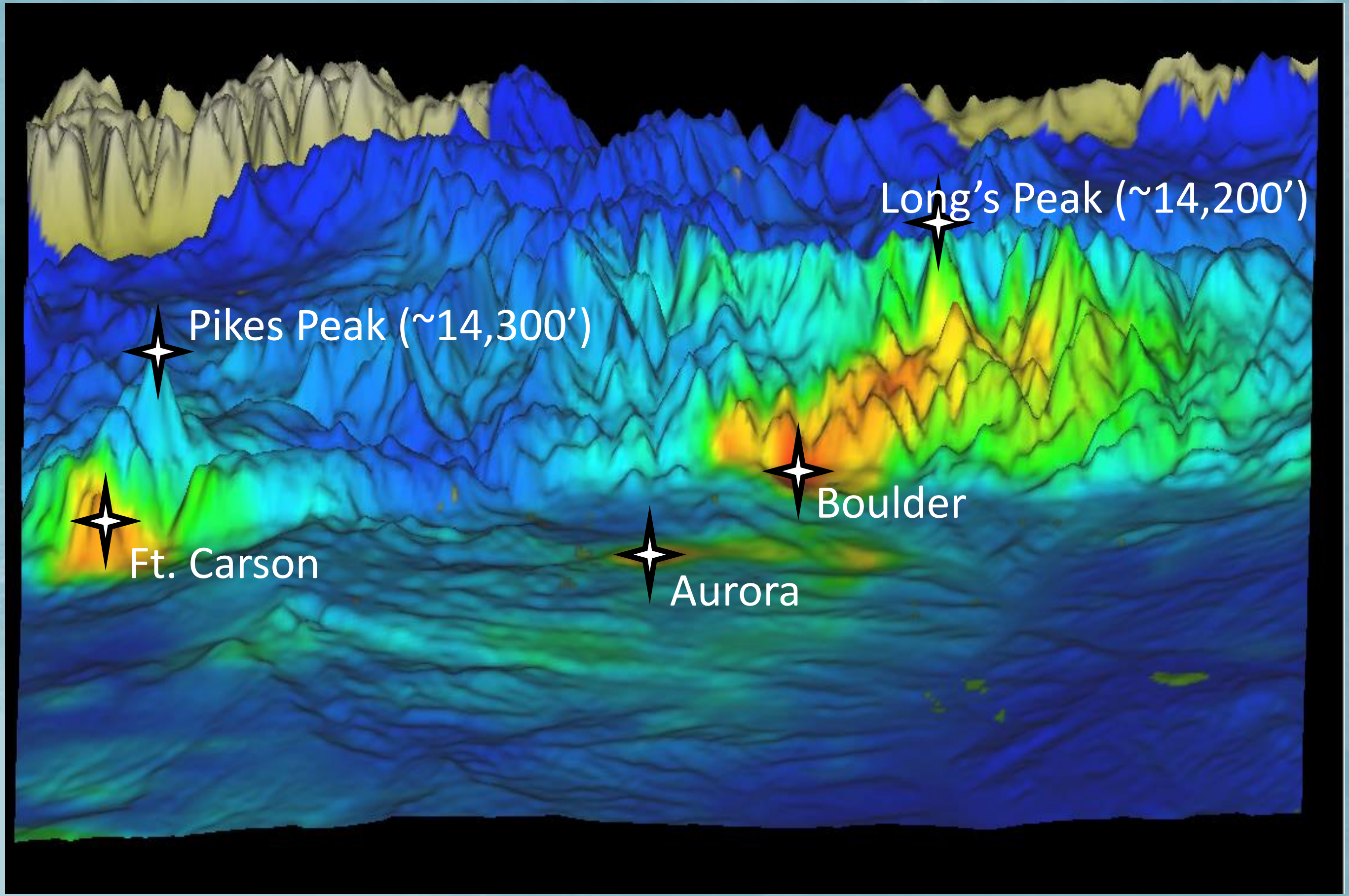
The National Center for Atmospheric Research

Model System and Components:

- GIS Pre-processor – Physiographic data processing (K. Sampson)
- Meteorological Forcing Engine (MFE) – Met. Pre-processing (D. Gochis and L .Karsten)
- *Core WRF-Hydro Model – Model physics (M. Barlage, D. Yates, D. Gochis)*
- Hydro-DART – Data assimilation (J. McCreight)
- Rwrfhydro – Analysis, verification, visualization (A. Dugger, J. McCreight, J. Mills)
- Automated Calibration (L. Karsten)

Meteorological Forcing Engine:

- NLDAS, NARR analyses
- QPE products: MPE, StgIV, NCDC-served, dual-pol, Q3/MRMS, gauge analyses, CMOPRH, TRMM, GPM
- NOAA QPF products: GFS, NAM, RAP, HRRR, ExREF
- Nowcast (NCAR Trident/TITAN)
- NOHRSC SNODAS
- ESMF/ncl regridding tools

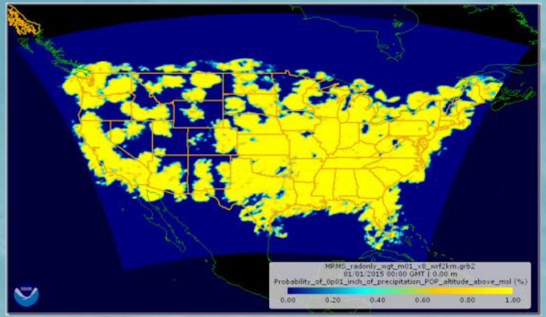


Regridded MPE precipitation during the 2013 Colorado Floods
Unidata IDV display

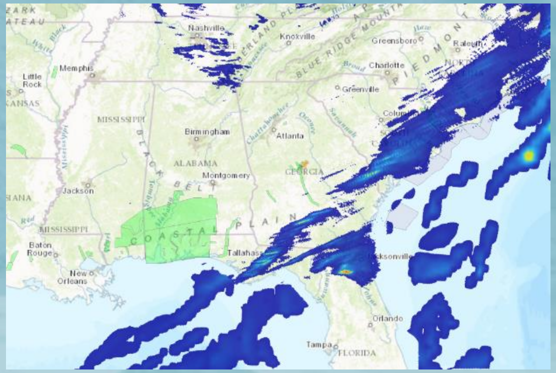
The National Center for Atmospheric Research

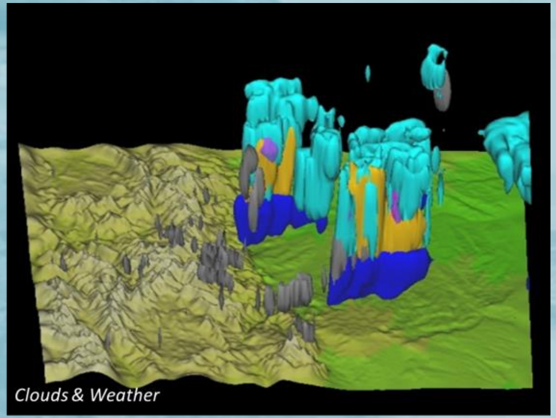
NWM: Meteorological Forcing Engine (MFE): Examples

Seasonally-varying MRMS RQI

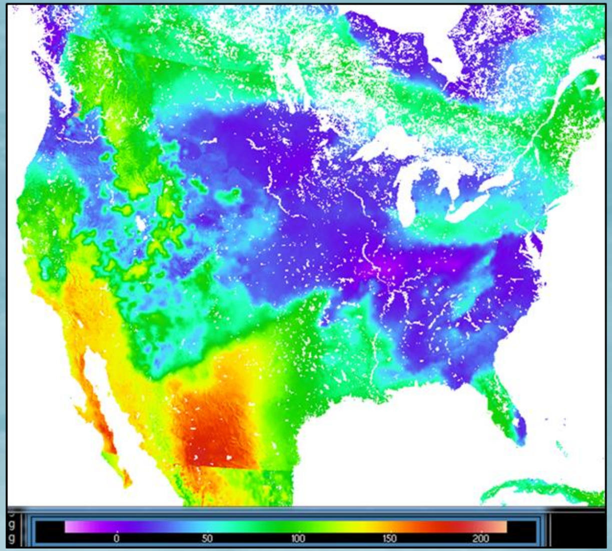


Blended MRMS-HRRR Precipitation

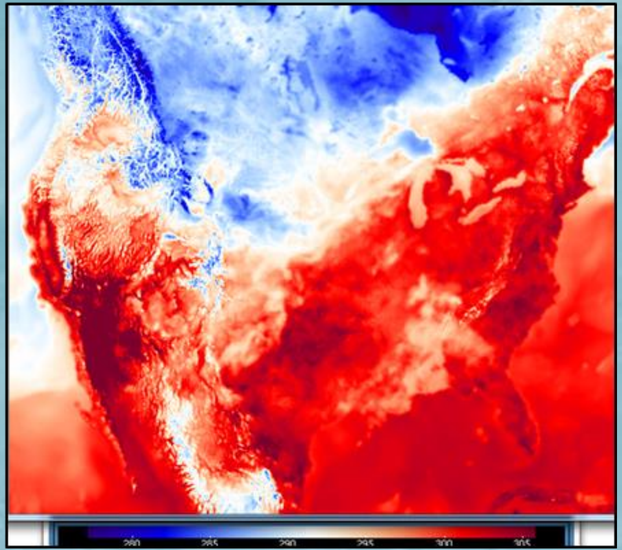




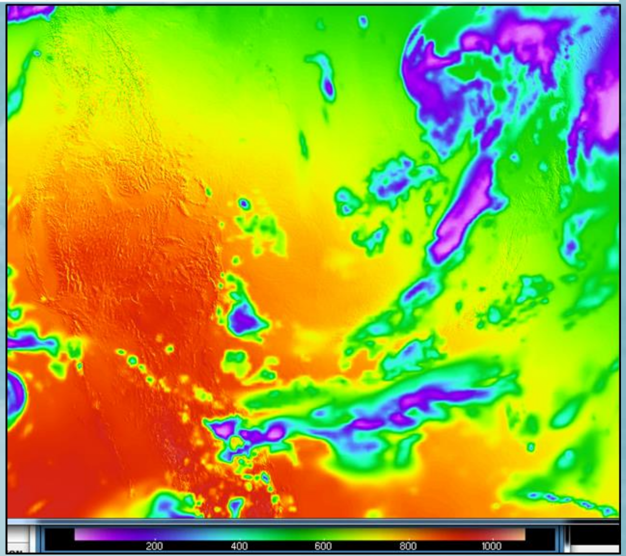
HRRR-RAP incoming longwave radiation



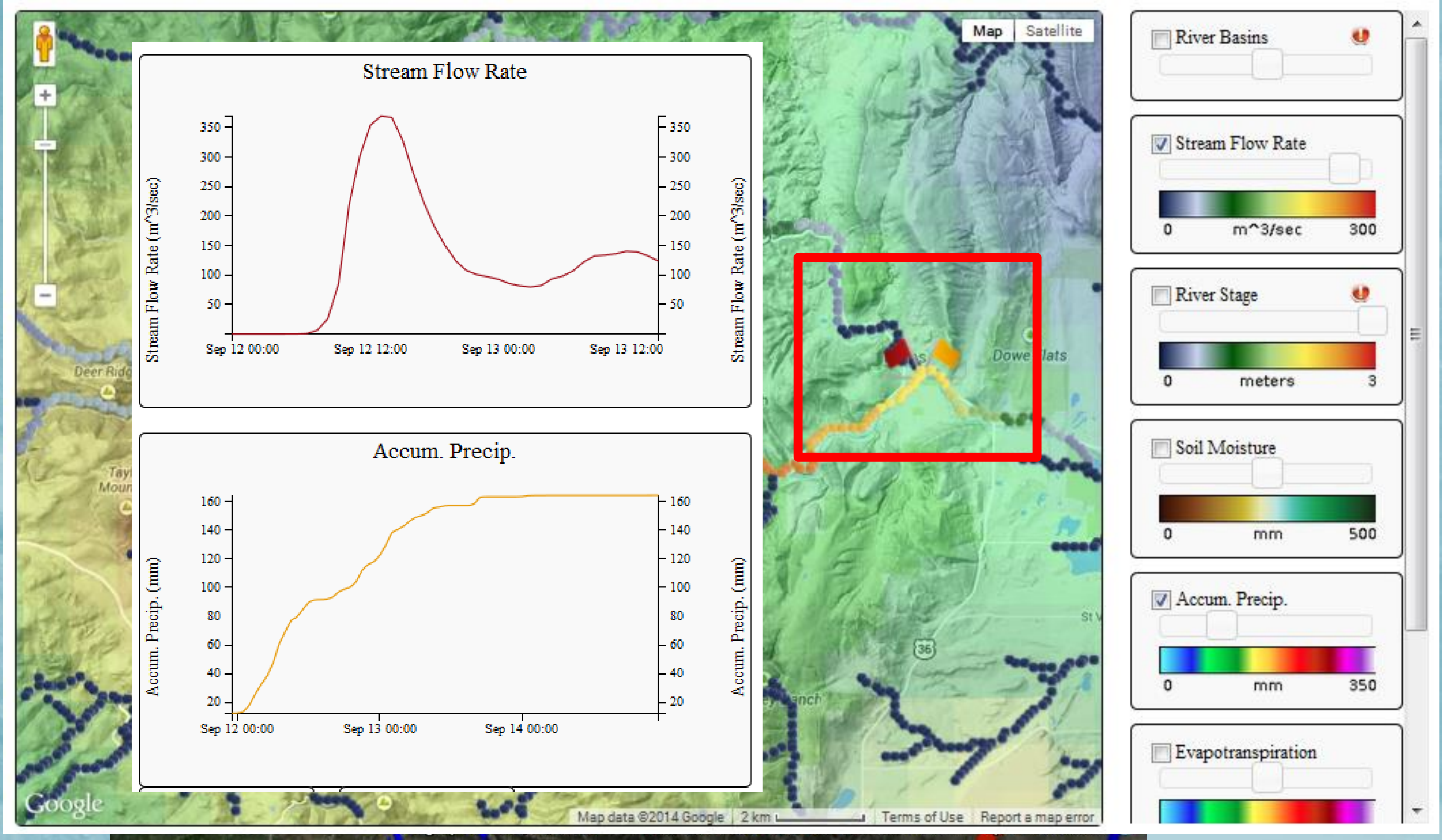
HRRR-RAP 2m Air Temperature



GFS – derived incoming shortwave radiation



Visual forecast products...Web map service interfaces: GoogleMaps/Earth , ESRI ArcGIS, OpenLayers

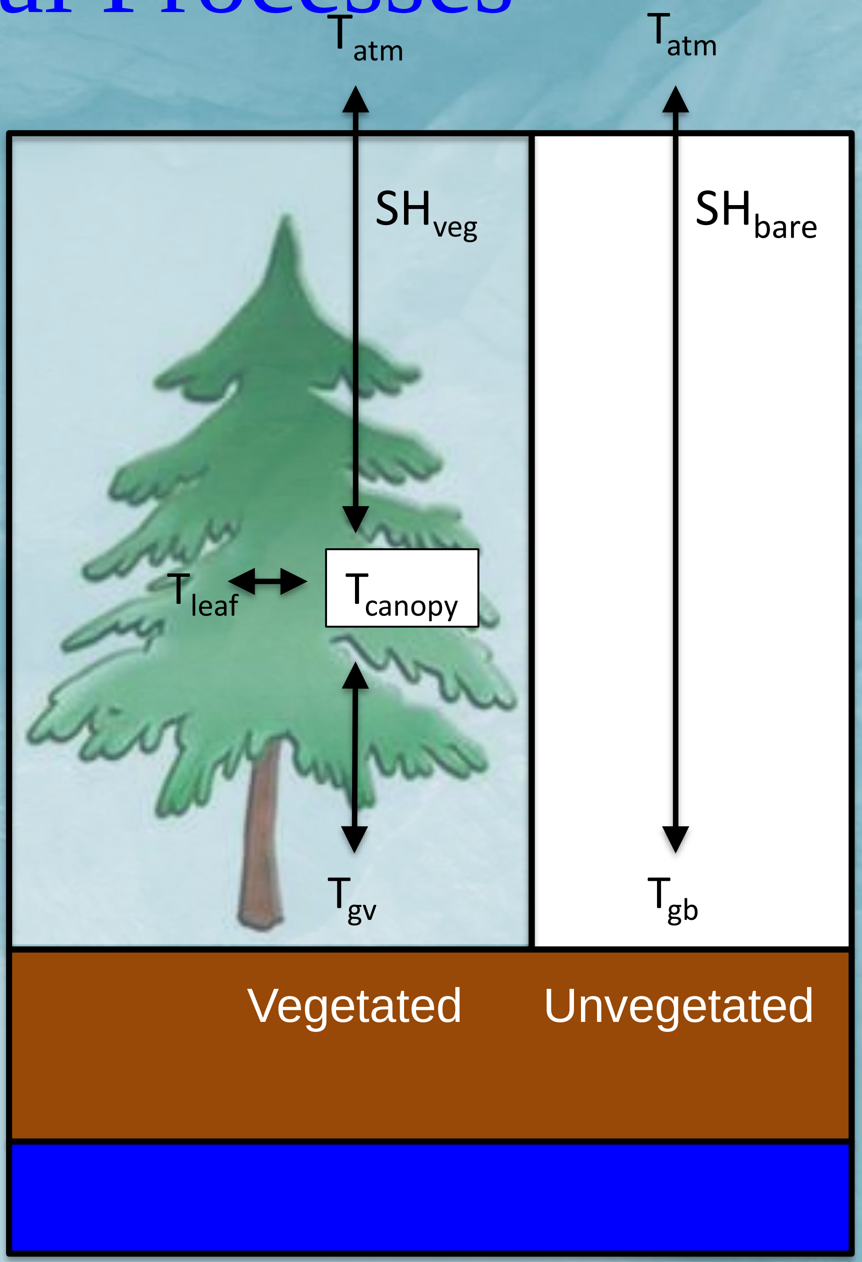


GoogleEarth, GoogleMaps. ArcGIS WMS display

Noah-MP Physical Processes

Noah-MP is a land surface model that allows a user to choose multiple options for several physical processes

- Canopy radiative transfer with shading geometry
- Separate vegetation canopy
- Dynamic vegetation
- Vegetation canopy resistance
- Multi-layer snowpack
- Snowpack liquid water retention
- Simple groundwater options
- Snow albedo treatment
- New frozen soil scheme
- New snow cover



Noah-MP: Surface Energy Budget

The National Center for Atmospheric Research

$$SW_{dn} - SW_{up} + LW_{dn} - LW_{up}\ (T_{sfc}) = SH(T_{sfc}) + LH(T_{sfc}) + G(T_{sfc})$$

SW_{dn}, LW_{dn}: input shortwave and longwave radiation (external to LSM)

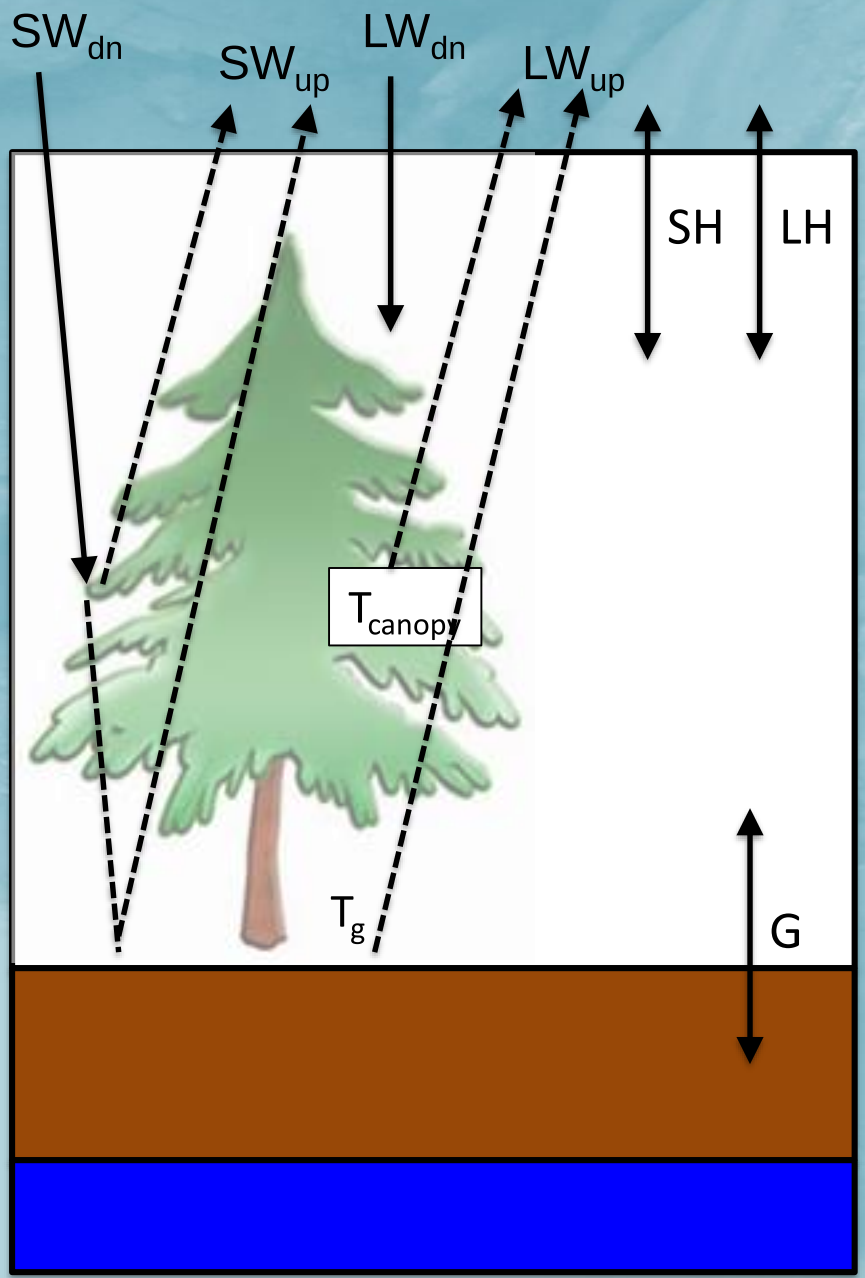
SW_{up} : reflected shortwave (albedo)

LW_{up} : upward thermal radiation

SH : sensible heat flux

LH : latent heat flux (soil/canopy evaporation, transpiration)

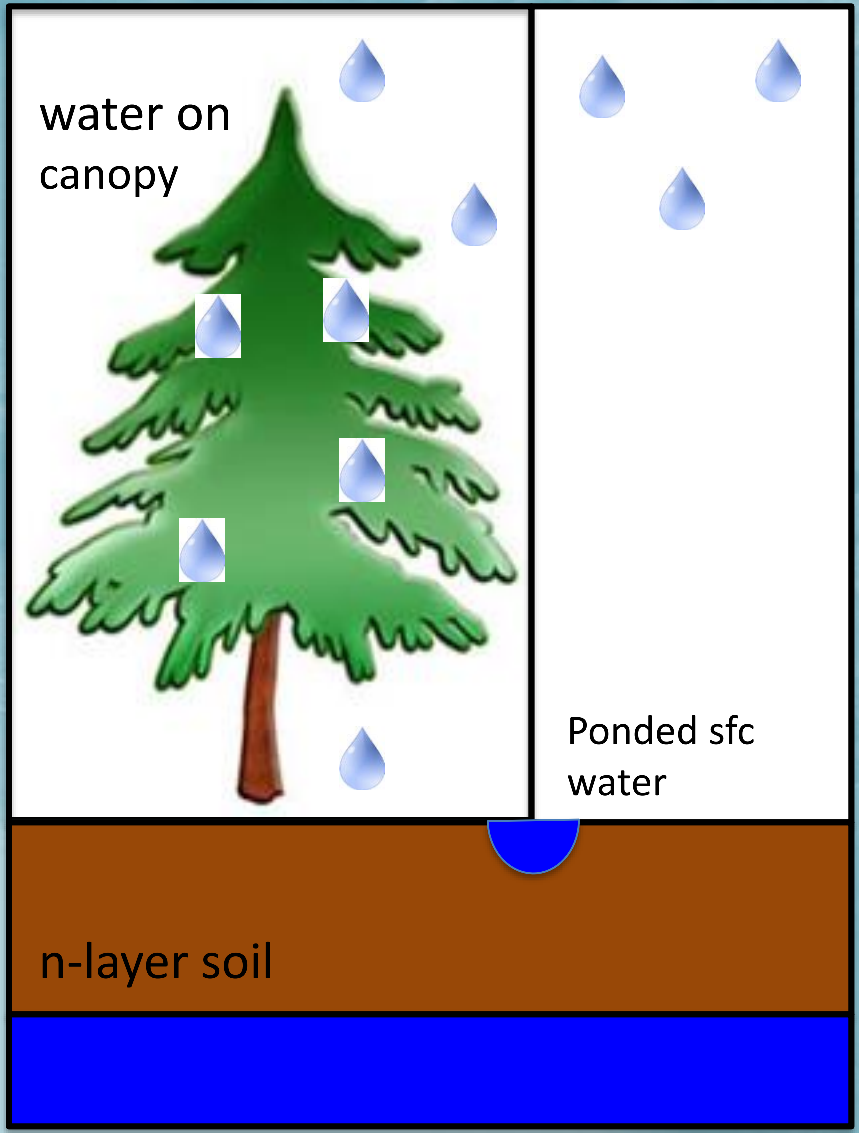
G : heat flux into the soil



Noah-MP Physical Processes

Noah-MP is a land surface model that allows a user to choose multiple options for several physical processes

- Canopy radiative transfer with shading geometry
- Separate vegetation canopy
- Dynamic vegetation
- Vegetation canopy resistance
- Multi-layer snowpack
- Snowpack liquid water retention
- Simple groundwater options
- Snow albedo treatment
- New frozen soil scheme
- New snow cover



Noah-MP Physical Processes

Noah-MP is a land surface model that allows a user to choose multiple options for several physical processes

- Canopy radiative transfer with shading geometry
- Separate vegetation canopy
- Dynamic vegetation
- Vegetation canopy resistance
- Multi-layer snowpack
- Snowpack liquid water retention
- Simple groundwater options
- Snow albedo treatment
- New frozen soil scheme
- New snow cover