WRF-Hydro: A hydrological modeling extension package for the Weather Research and Forecasting System

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National Center for Atmospheric Research

Outline:

1. Basic concepts and rationale
2. WRF-Model Overview…(brief)
3. WRF-Hydro Overview (Structure and physics)
4. WRF-Hydro Requirements
   – Pre-processing
5. Hands-on Practice (tomorrow)

What is WRF-Hydro:

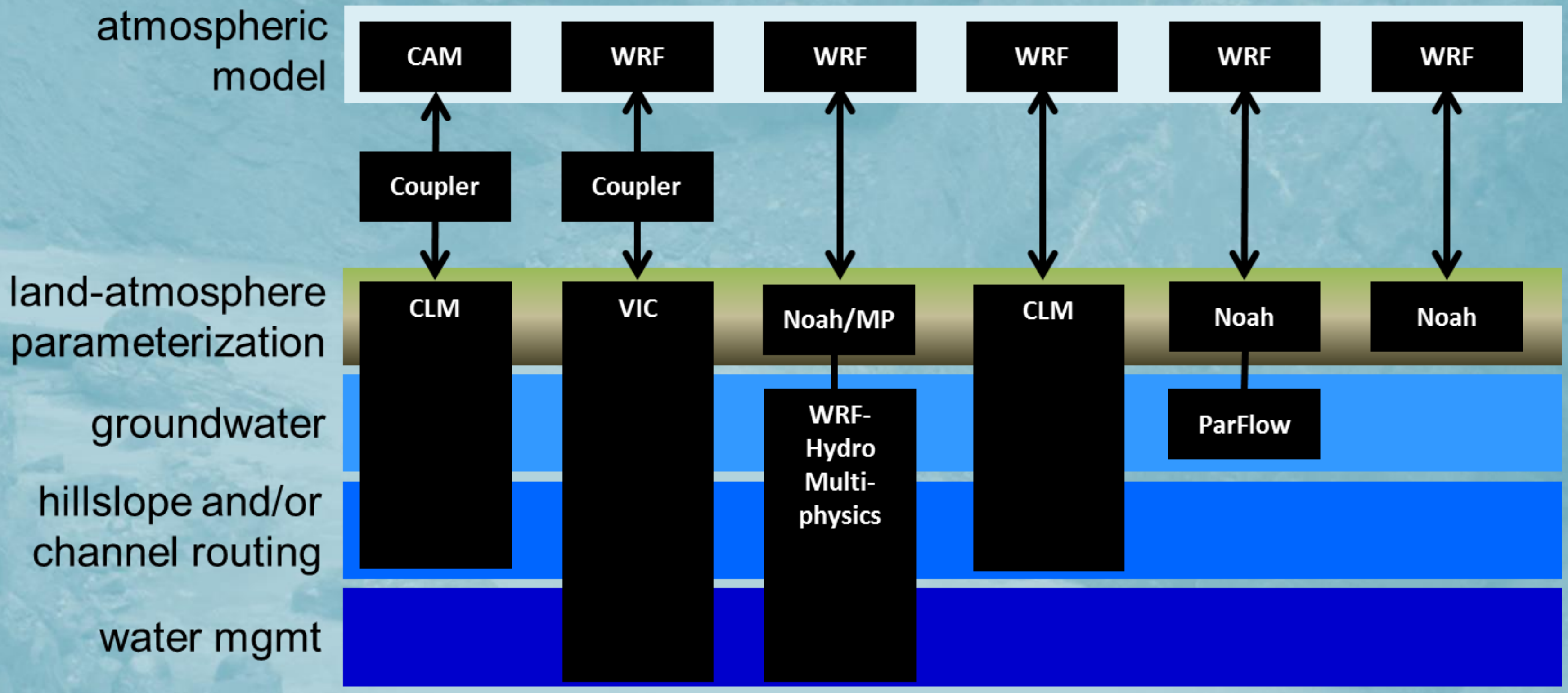
WRF-Hydro is a community-based, supported coupling architecture design to couple multi-scale process models of the atmosphere and terrestrial hydrology

It also seeks to provide:

1. A capability to perform coupled and uncoupled multi-physics simulations and predictions
2. Fully utilize high-performance computing platforms
3. Leverage existing and emerging standards in data formats and pre-/post-processing workflows
4. An extensible, portable and scalable environment for hypothesis testing, sensitivity analysis, data assimilation and observation impact research

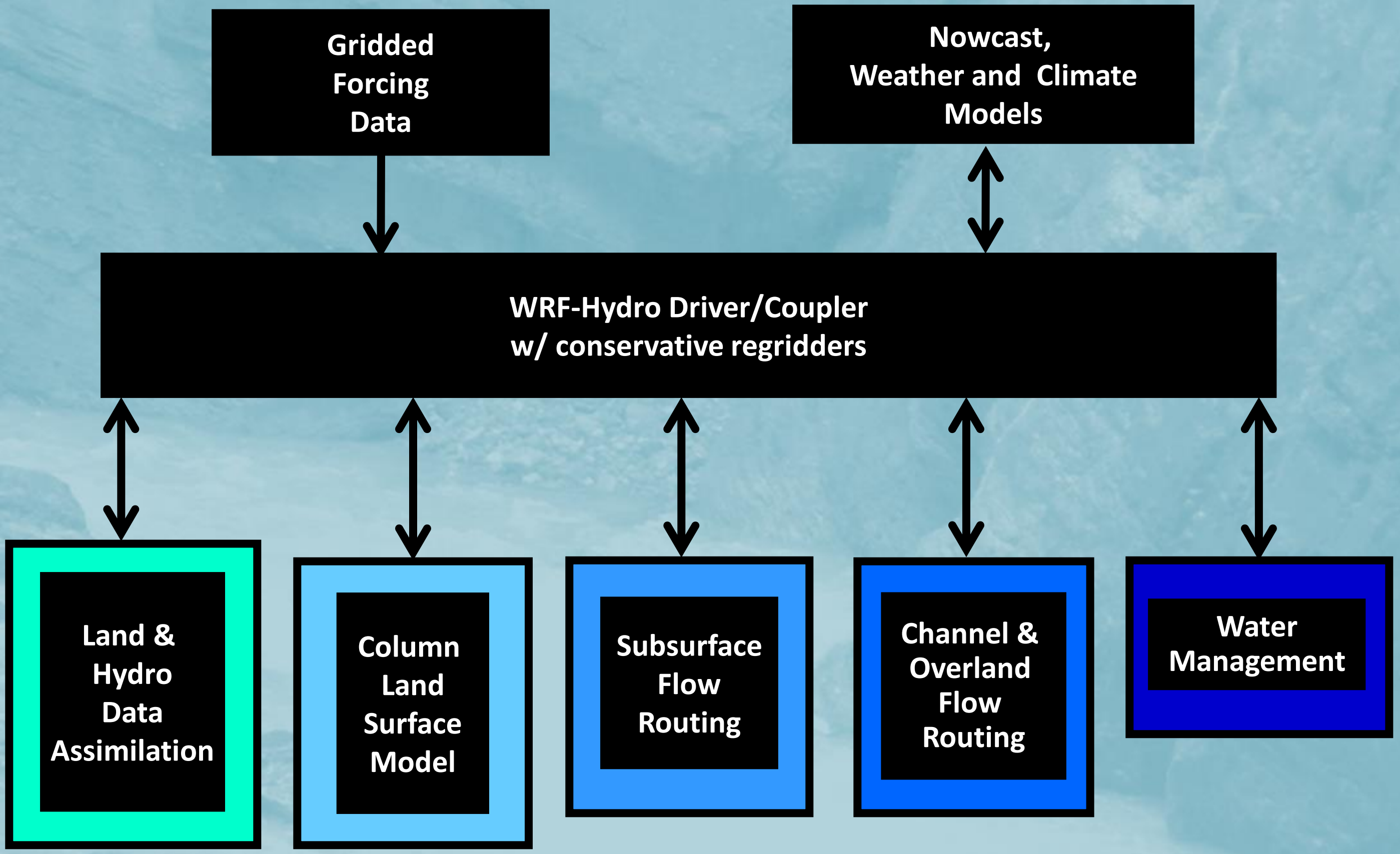
Motivation for WRF-Hydro:

- Problem Statement: Components of Earth Systems Models are often stove-piped by geoscience domains which limits inter-operability with other domains



Conceptualization of WRF-Hydro:

- Multi-scale/Multi-physics modeling…



Introduction to the Weather Research and Forecasting Model (WRF)

12 June, 2014

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Weather Research and Forecasting Model (WRF):

- Modeling system for atmospheric research and operational prediction

- Provide many core functionalities:
  - Data pre-processing (model initialization and boundary conditions)
  - 3-d non-hydrostatic, multi-physics, multi-scale atmospheric model
  - Fully-parallelized for high performance computing applications
  - Data assimilation frameworks (EnKF, grid nudging, 3d/4d variational analysis)
  - Post-processing to produce standardized datasets for ingest into many analysis and visualization software

- Directly ingestible into the Model Evaluation Tools (MET) software for verification

WRF Model Structure:

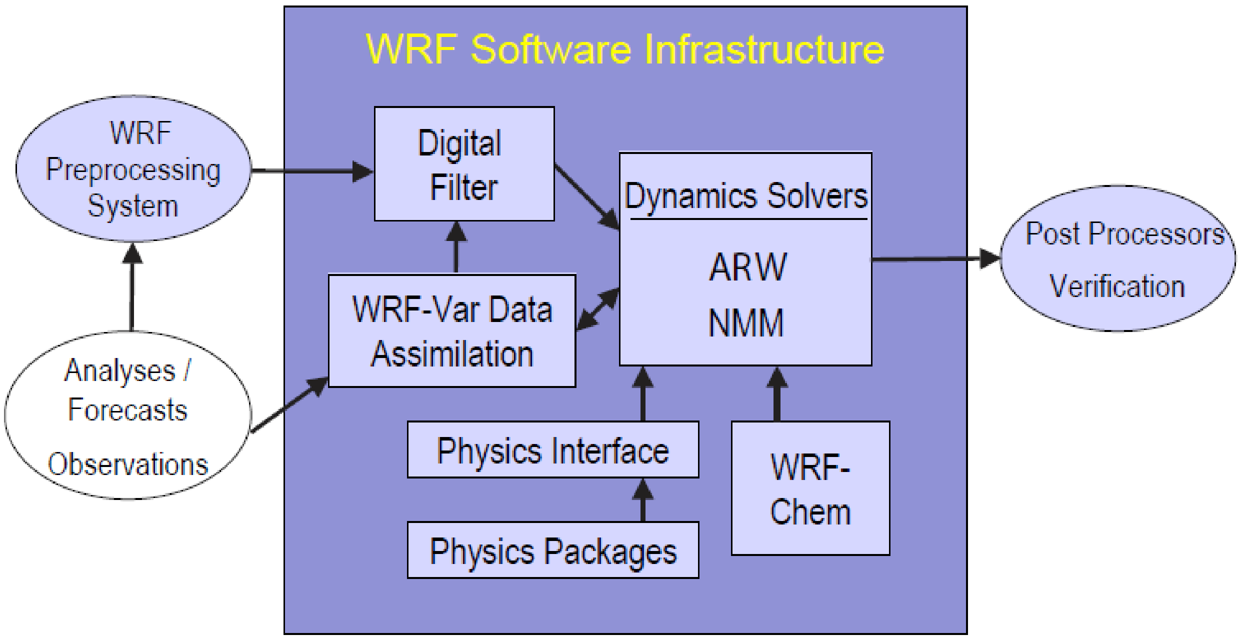

Figure 1.1: WRF system components.

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Model Structure: Model Physics

- Microphysics: Schemes ranging from simplified physics suitable for idealized studies to sophisticated mixed-phase physics suitable for process studies and NWP.
- Cumulus parameterizations: Adjustment and mass-flux schemes for mesoscale modeling. (dx > ~5km)
- Surface physics: Multi-layer land surface models ranging from a simple thermal model to full vegetation and soil moisture models, including snow cover and sea ice.
- Planetary boundary layer physics: Turbulent kinetic energy prediction or non-local K schemes.
- Atmospheric radiation physics: Longwave and shortwave schemes with multiple spectral bands and a simple shortwave scheme suitable for climate and weather applications. Cloud effects and surface fluxes are included.

Model Structure: Model Domain

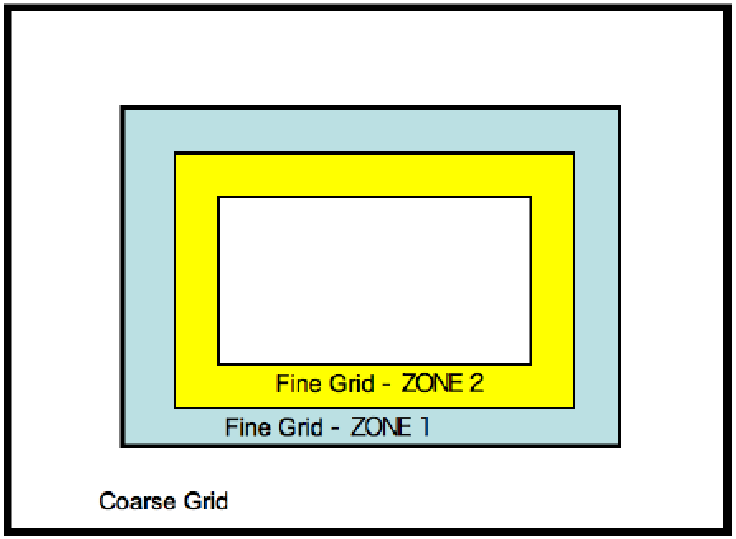
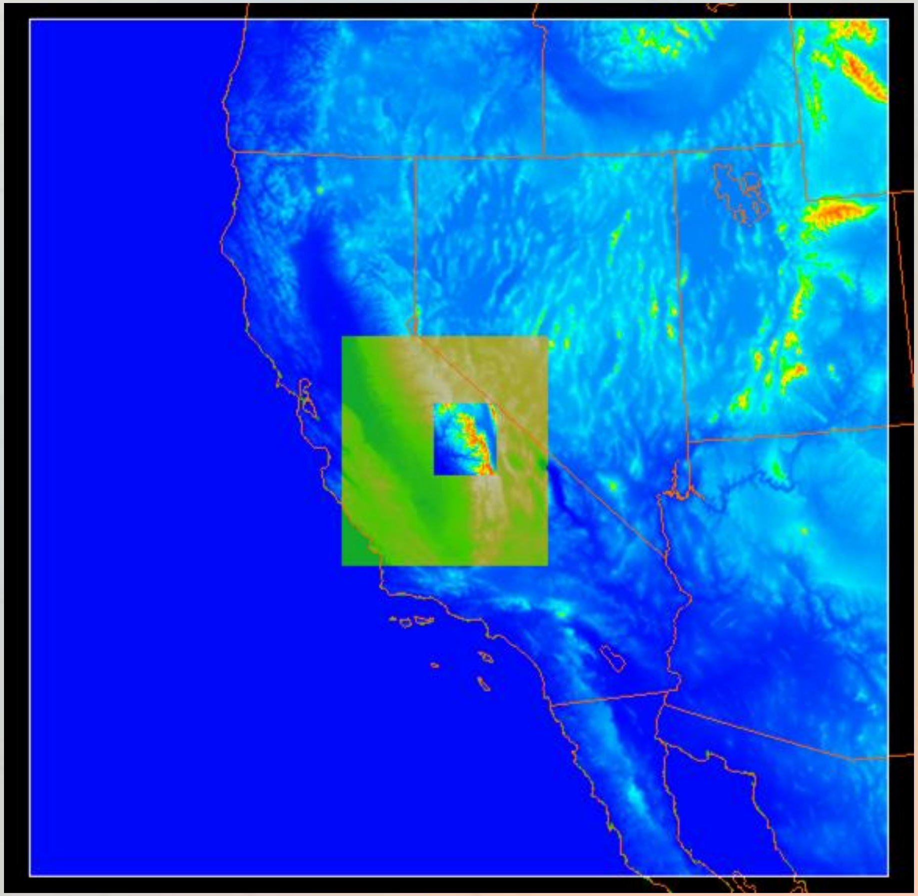
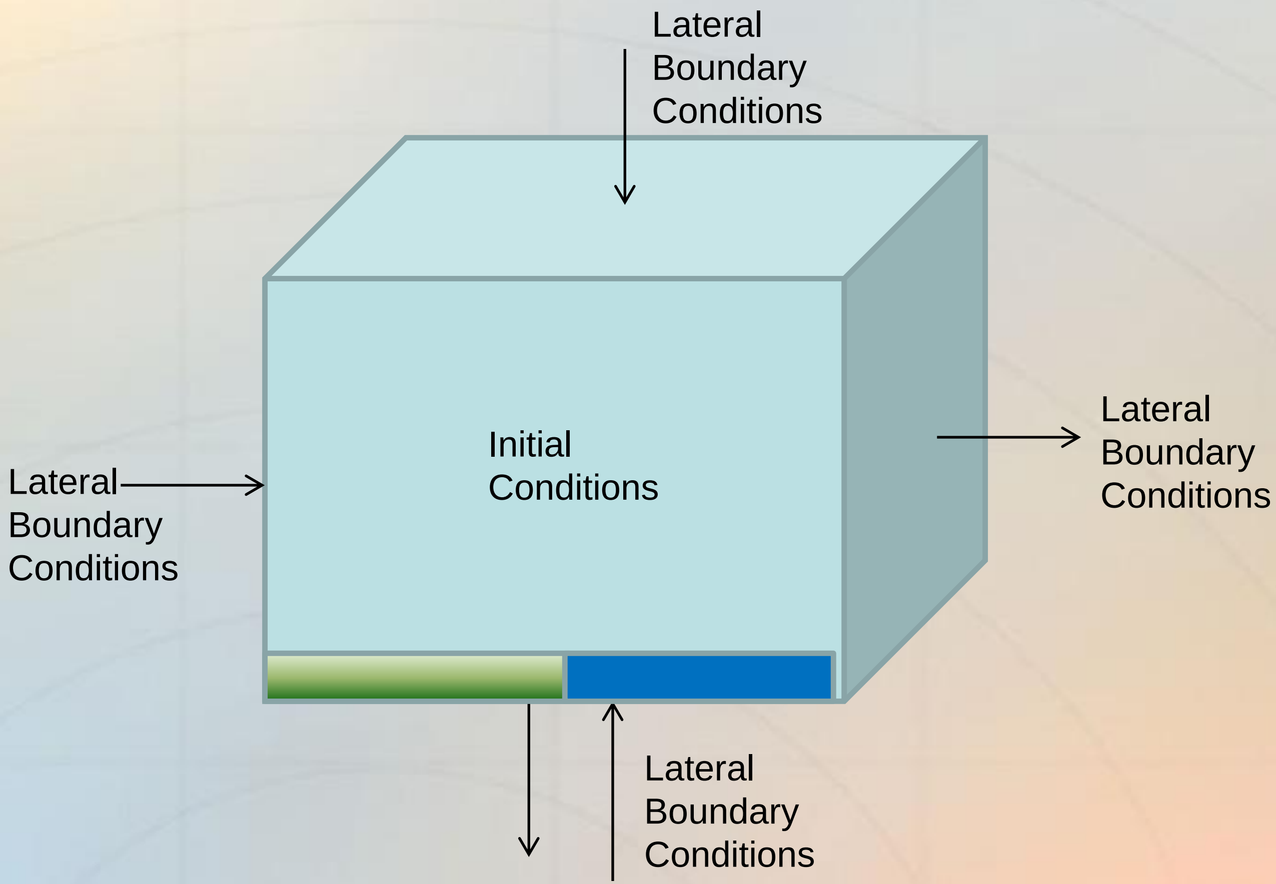


Figure 7.6: Zones of topographic blending for a fine grid. In the fine grid, the first zone is entirely interpolated from the coarse grid topography. In the second zone, the topography is linearly weighted between the coarse grid and the fine grid.

Model Structure: Model Domain



Model Structure: Model Domain



Model Structure: Initial and Boundary Conditions

- Initial conditions: Provides the initial ‘state’ of the atmosphere and land surface at time = 0.

- Lateral boundary conditions: Provides ‘forcing’ to the regional domain from the ‘sides’ of the model, necessary condition for any forward-integrating numerical modeling problem

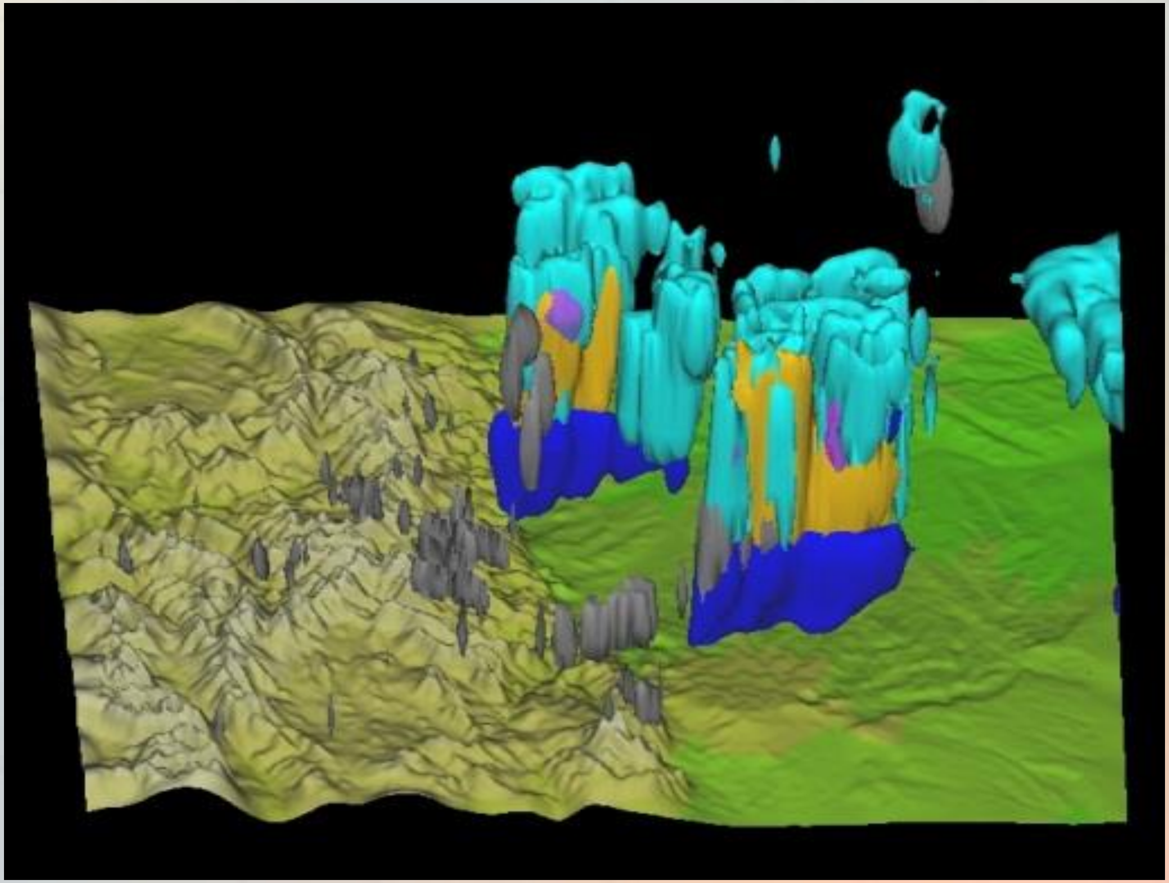
- The impacts of initial conditions can be very important or not very important depending on the problem and the variable of interest.
  - NWP – ‘initial value problem’, meaning the impact of initial conditions plays a ‘dominant’ role in the model solution along with model physics
  - ‘Climate modeling’ – ‘boundary value problem’, meaning the final solution is not as sensitive to initial conditions but, instead, more sensitive to boundary forcing and the model physics

WRF Model Workflow:

1. Pull/point to data for 'geogrid.exe' execution: this is the WRF-WPS database
2. Dynamically edit the 'namelist.wps' file
3. Execute 'geogrid.exe' to create surface data
4. Get meteorological boundary condition data from a global server
5. Pull/point to data for 'metgrid.exe'
6. Run 'ungrib.exe' from the WPS directory to prepare data for metgrid.
7. Execute 'metgrid.exe' to prepare atmospheric boundary conditions
8. Edit principle WRF model namelist for model setup (namelist.input)
9. Run executables: 'real.exe; and 'wrf.exe'
10. Post-process results…

WRF Model Products:

- Detailed, physically-robust depictions of atmospheric phenomena for research and prediction applications



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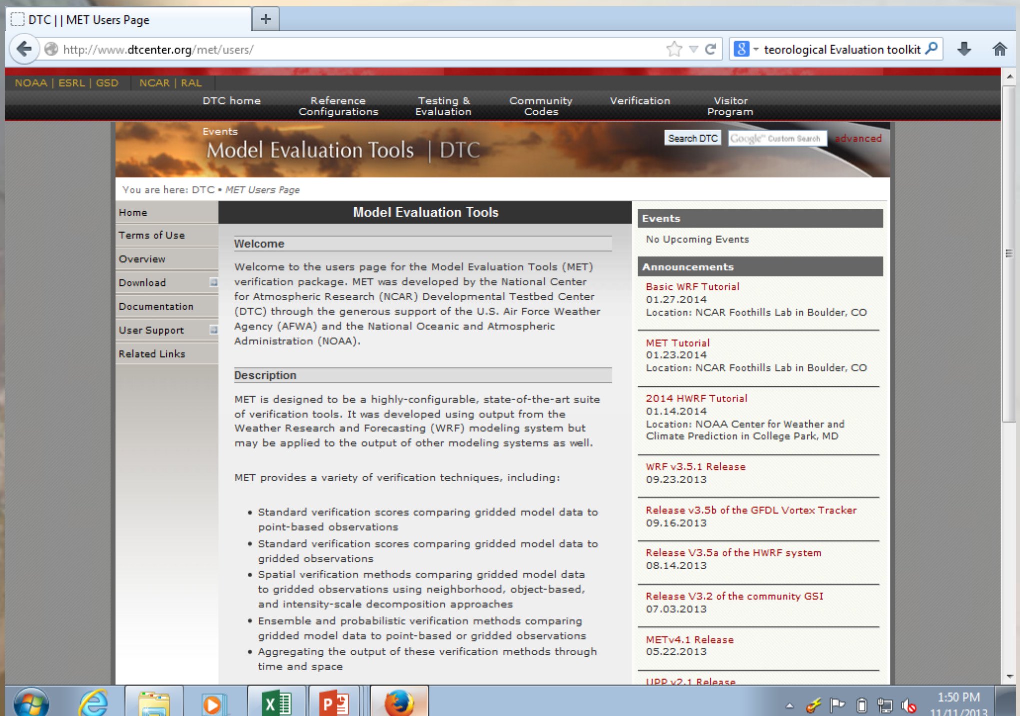
MET for all things Verification:



- Suite of data processing and analysis tools to provide:

- Standard verification scores comparing *gridded model data to point-based observations*
- Standard verification scores comparing *gridded model data to gridded observations*
- *Spatial verification methods* comparing gridded model data to gridded observations using neighborhood, object-based, and intensity-scale decomposition approaches
- *Ensemble and probabilistic verification* methods comparing gridded model data to point-based or gridded observations

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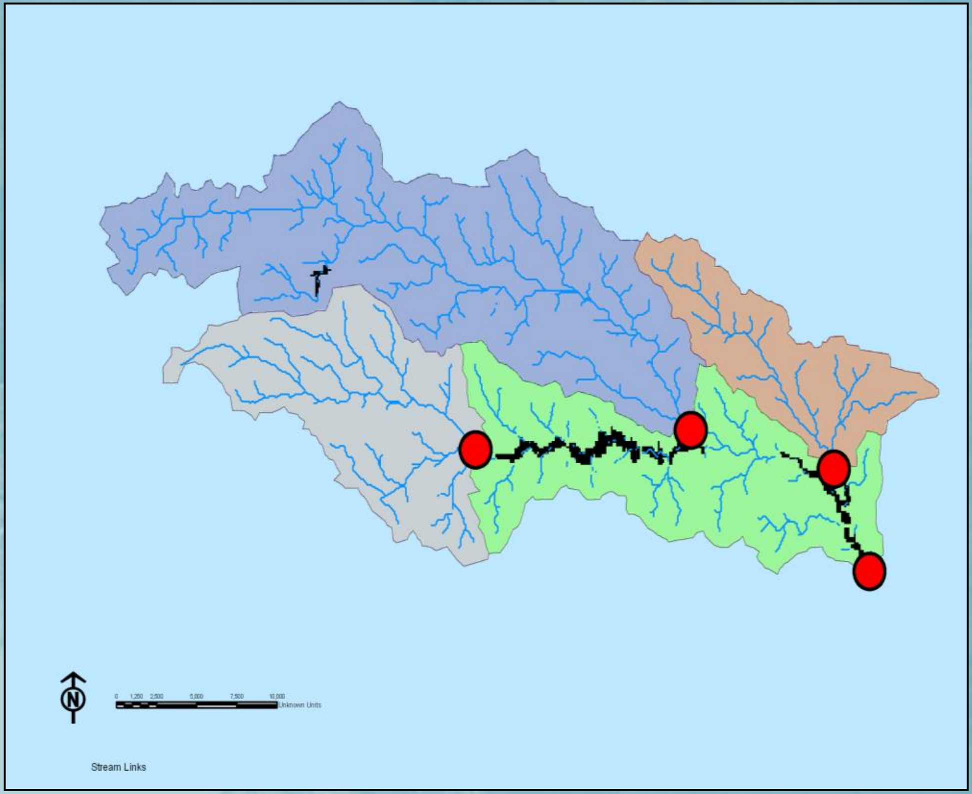
http://www.dtcenter.org/met/users/

3. Conceptualizations of Land Surface vs. Traditional Hydrological Models

Description of traditional hydrological models:

- Discrete spatial elements:
  - Catchments
  - Hillslopes
  - Aquifers
  - Reservoirs
  - River networks
  - Often as ‘objects’



Description of traditional hydrological models:

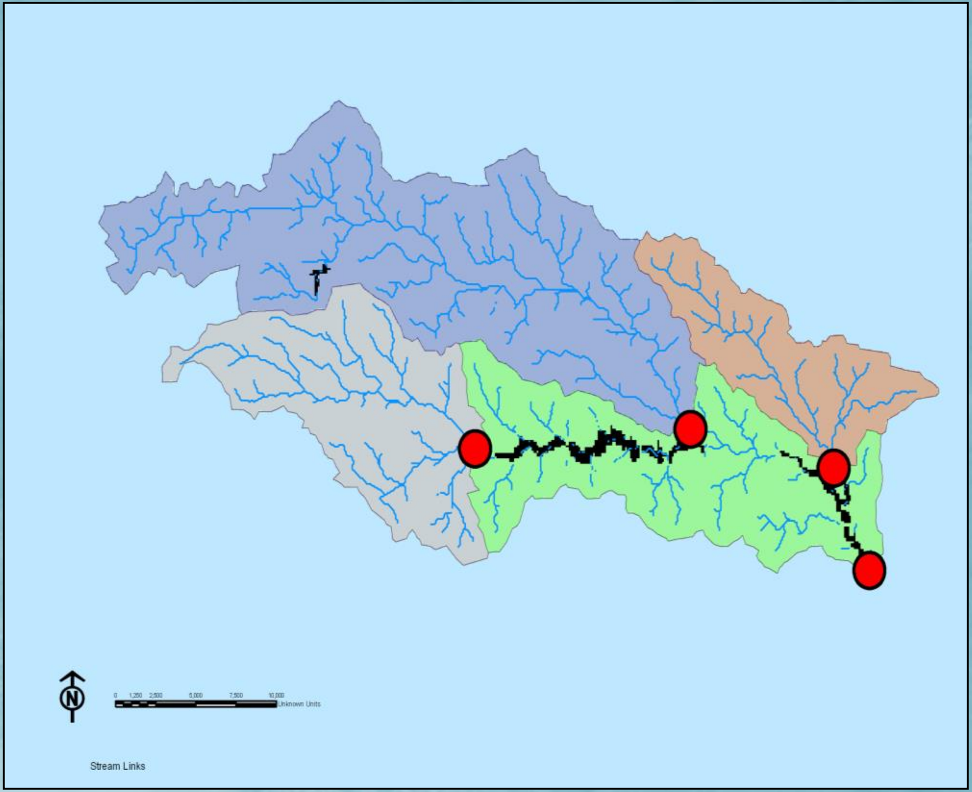
- Traditional/engineering hydrologists often viewed the world as catchments of ‘black boxes’:
- Rational method:

$$Q_{Peak} = CA\bar{R}$$ ca. 1851

C = coefficient/scaling parameter
A = catchment area
R = avg precip intensity

- Curve Numbers:

$$Q = \frac{(P - \lambda S_{max})}{P + (1 - \lambda)S_{max}}$$

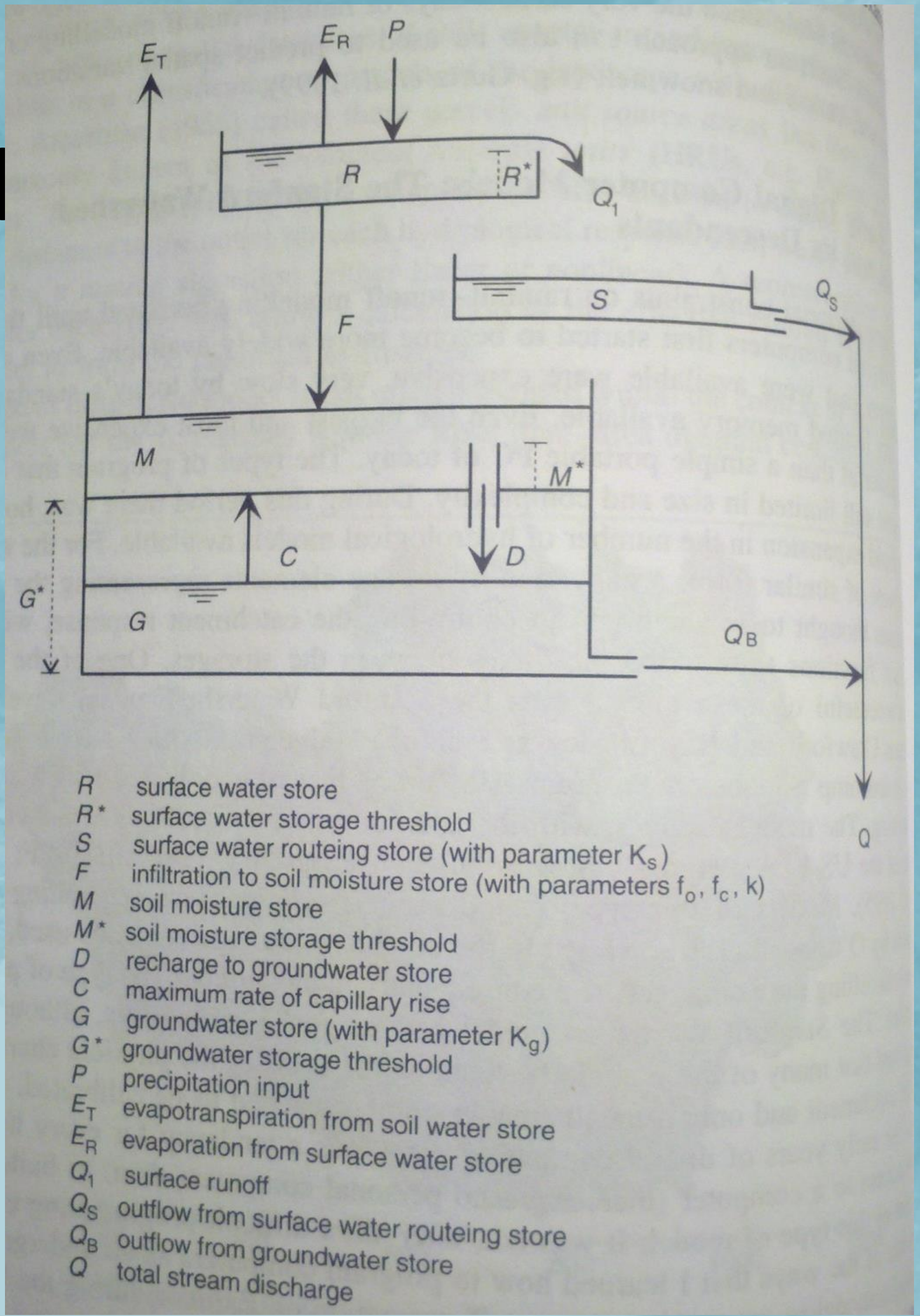


Q = total runoff volume
P = volume of precipitation
Smax = empirical maximum storage volume ~ $\left(\frac{100}{CN} - 1\right)$
CN – Curve number, empirical for land cover/land use, adjusted for antecedent moisture conditions
λ = empirical coefficient

Description of hydrological model

- Traditional/engineering hydrologists often viewed the world as catchments of 'black boxes':

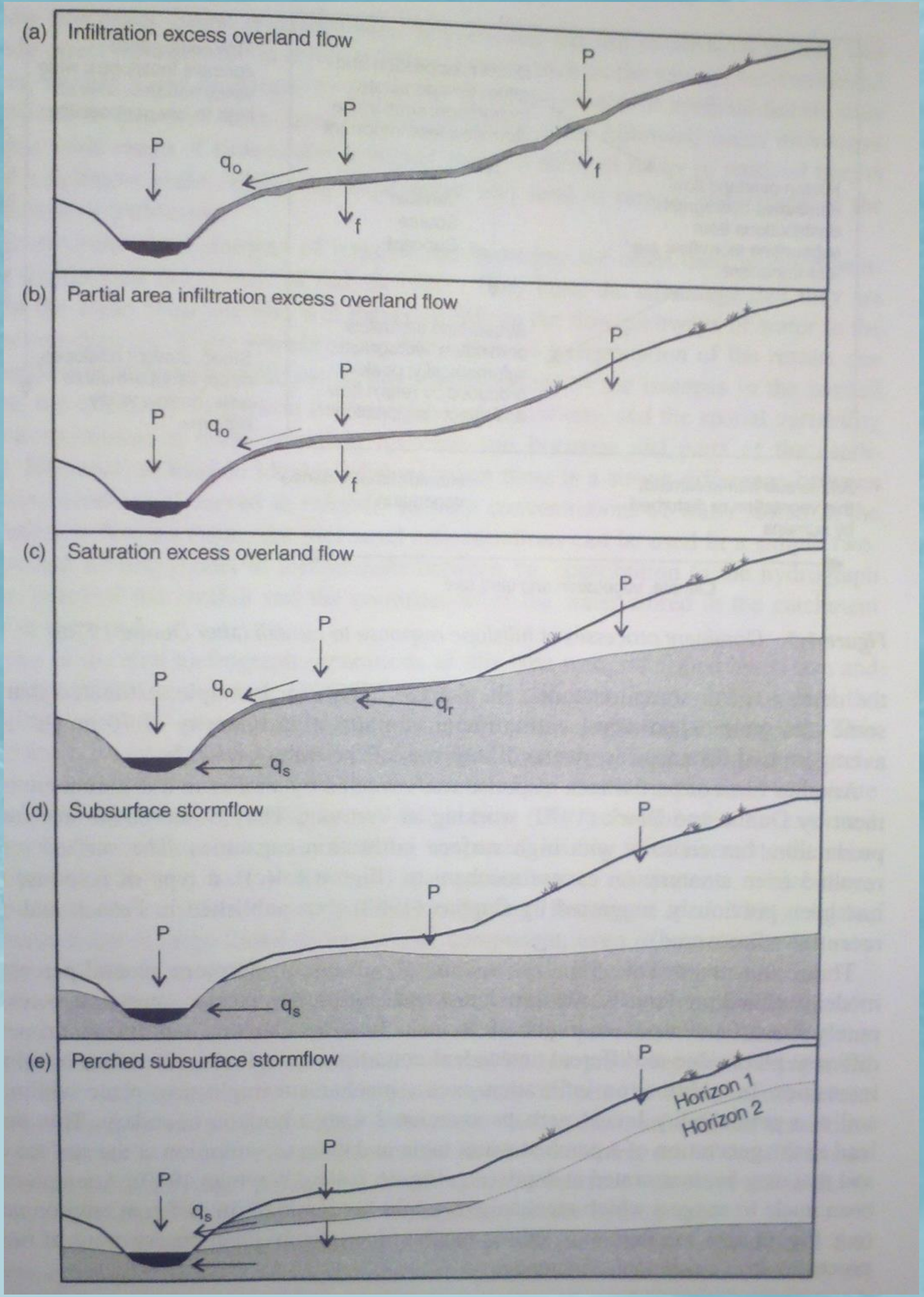
- 'Stanford Model (soil moisture accounting):
  - Series of storages (buckets)
  - Movement between buckets
  - Discharge/ET from buckets



Beven, 2003

Description of hydrological models:

- Modern hydrologists attempt to 'move water' around based on spatial gradients and coupled energy and water fluxes…
  - 'Hillslope hydrology'
  - River channel hydraulics
  - Ecosystem/atmo interactions
  - Biogeochemistry



Beven, 2003

Description of hydrological models:

- Fundamental surface flow equations expressed in terms of the St. Venant Equations:

$$-\frac{\partial A\rho g h}{\partial x} + \rho g A S_o - \tau P = \frac{\partial \rho A v}{\partial t} + \frac{\partial \rho A v^2}{\partial x}$$

along channel change in hydrostatic pressure + Loss in Potential energy + Friction loss + Local time Rate of change in momentum + Along channel Change in momentum

- Fundamental sub-surface flow equations expressed in terms of Darcy-Richard's Equations:

$$\frac{\partial \rho \theta}{\partial t} = \nabla \left[\rho K(\theta) \nabla \psi\right] + \frac{\partial \rho K(\theta)}{\partial z} - \rho E_T(x, y, z, t)$$

Time rate of Change of soil moisture

Divergence of Soil moisture expressed In terms of Darcy's law Due to soil matric potiential

Add vertical flux Due to hydrostatic forces

Sink of moisture Due to ET

Generational view of land surface models:

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

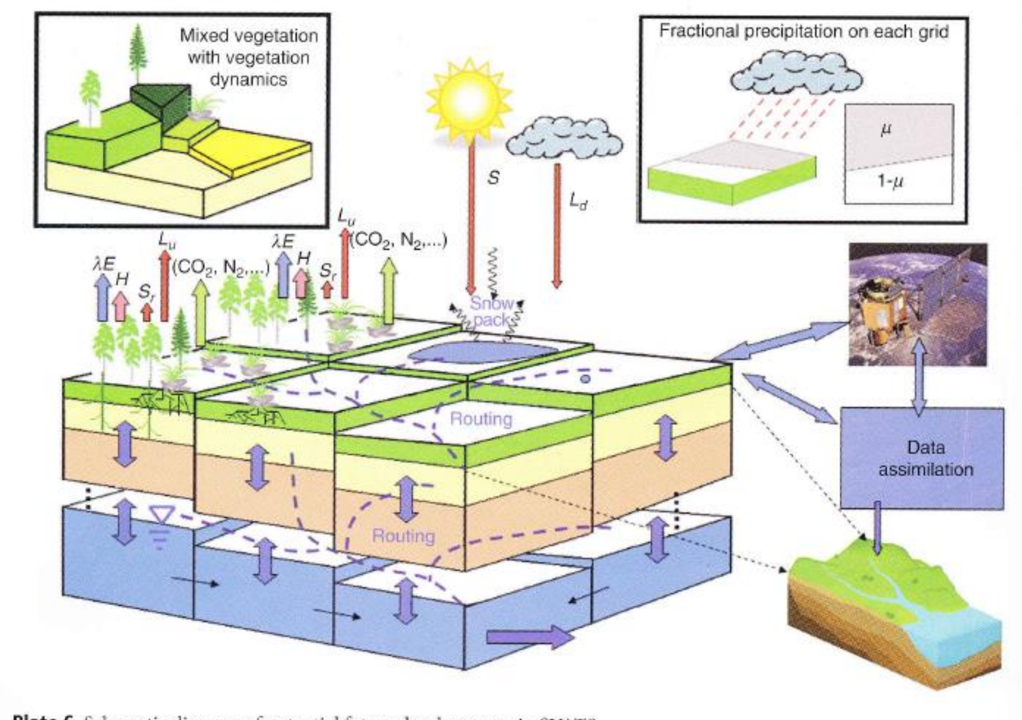
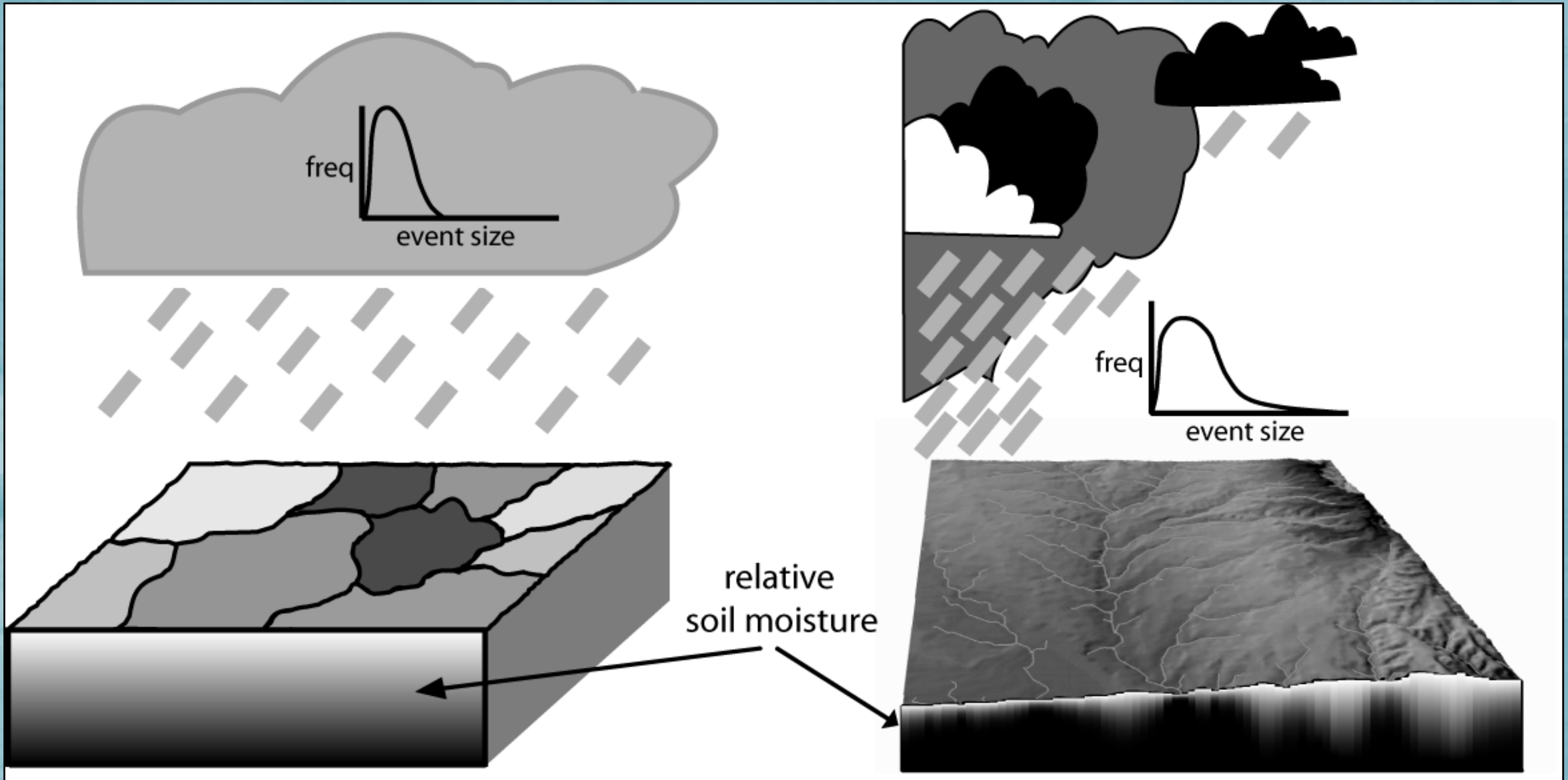


Plate 6 Schematic diagram of potential future developments in SVATS.

Shuttleworth, 2011

Getting things back to the atmosphere….'Land surface models'

- Goal: To linking multi-scale process models in a consistent Earth System Modeling framework



a. Existing climate models

b. Conceptualization of nature

Land surface parameterizations:

Table 24.1 Requirements in a Soil-Vegetation-Atmosphere Transfer (SVAT) scheme: (A) Basic variables that must be calculated at each model time step by a SVAT if it is used in a meteorological model; (B) Additional required calculations to allow representation of the hydrological impacts of climate; (C) Additional required calculations to allow representation of changes in CO_2 (and perhaps other trace gases) in the atmosphere.

A. Basic requirements in meteorological models

1. *Momentum absorbed from the atmosphere by the land surface* – requires the effective area-average aerodynamic roughness length.
2. *Proportion of incoming solar radiation captured by the land surface* – requires the effective area-average, wavelength average solar reflection coefficient or albedo.
3. *Outgoing longwave radiation* (calculated from area-average land surface temperature) – *requires the effective area-average, wavelength average emissivity of the land surface.*
4. *Effective area-average surface temperature* of the soil-vegetation-atmosphere interface - required to calculate longwave emission and perhaps energy storage terms.
5. *Area-average fraction of surface energy leaving as latent heat (with the remainder leaving as sensible heat)* - to calculate this other variables such as soil moisture and/or measures of vegetation status are often required, these either being prescribed or calculated as state variables in the model.
6. *Area-average of energy entering or leaving storage* in the soil-vegetation-atmosphere interface (required to calculate the instantaneous energy balance).

B. Required in hydro-meteorological models to better estimate area-average latent heat and to describe the hydrological impacts of weather and climate

7. *Area-average partitioning of surface water* into evapotranspiration, soil moisture, surface runoff, interflow, and baseflow.

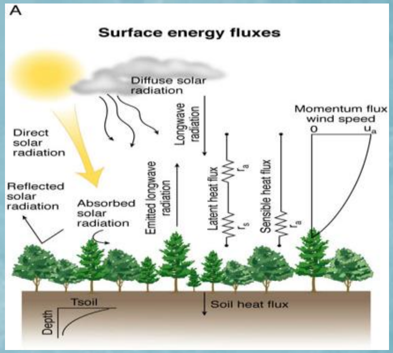
C. Required in meteorological models to describe indirect effect of land surfaces on climate through their contribution to changes in atmospheric composition

8. Area-average exchange of carbon dioxide (and possibly other trace gases).

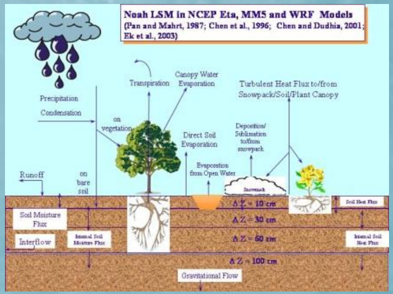
Shuttleworth, 2011

Community land surface model development at NCAR

1. Community Land Model (CLM):
   a) Designed for climate/Earth system modeling
   b) Emphasizes biogeochemical (C/N) and ecosystem complexity
   c) Coupled to CCSM and regional climate models where *timescale of terrestrial dynamics is relevant for climate behavior*



2. Community 'Noah' land surface model:
   a) Designed for use in numerical weather prediction
   b) Relatively simple, robust and efficient, emphasizing computational efficiency for operational forecasting
   c) Coupled to NCEP NAM, GFS and NCAR WRF



3. Both models have an open and mature working group structure comprised of scientists from many disciplines (though clearly biased towards atmospheric sciences)

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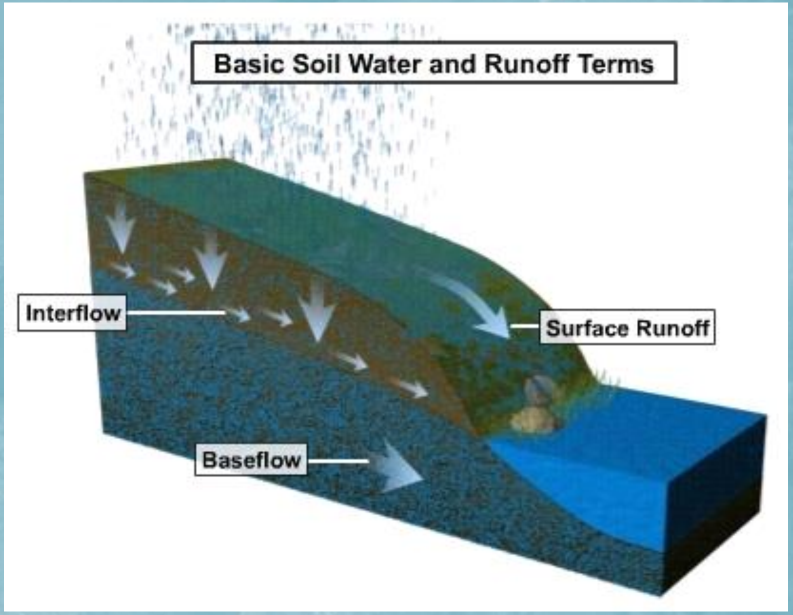
'Moving Water Around': Scale and process issues

- Terrain features affecting moisture availability (scales ~1km)
  - Routing processes: the redistribution of terrestrial water across sloping terrain
    - Overland lateral flow (dominates in semi-arid climates)
    - Subsurface lateral flow (dominates in moist/temperate climates)
    - Shallow subsurface waters (in topographically convergent zones)
  - Channel processes
  - Built environment/infrastructure
  - Water management
  - Other land surface controls:
    - Terrain-controlled variations on insolation (slope-aspect-shading)
    - Soil-bedrock interactions

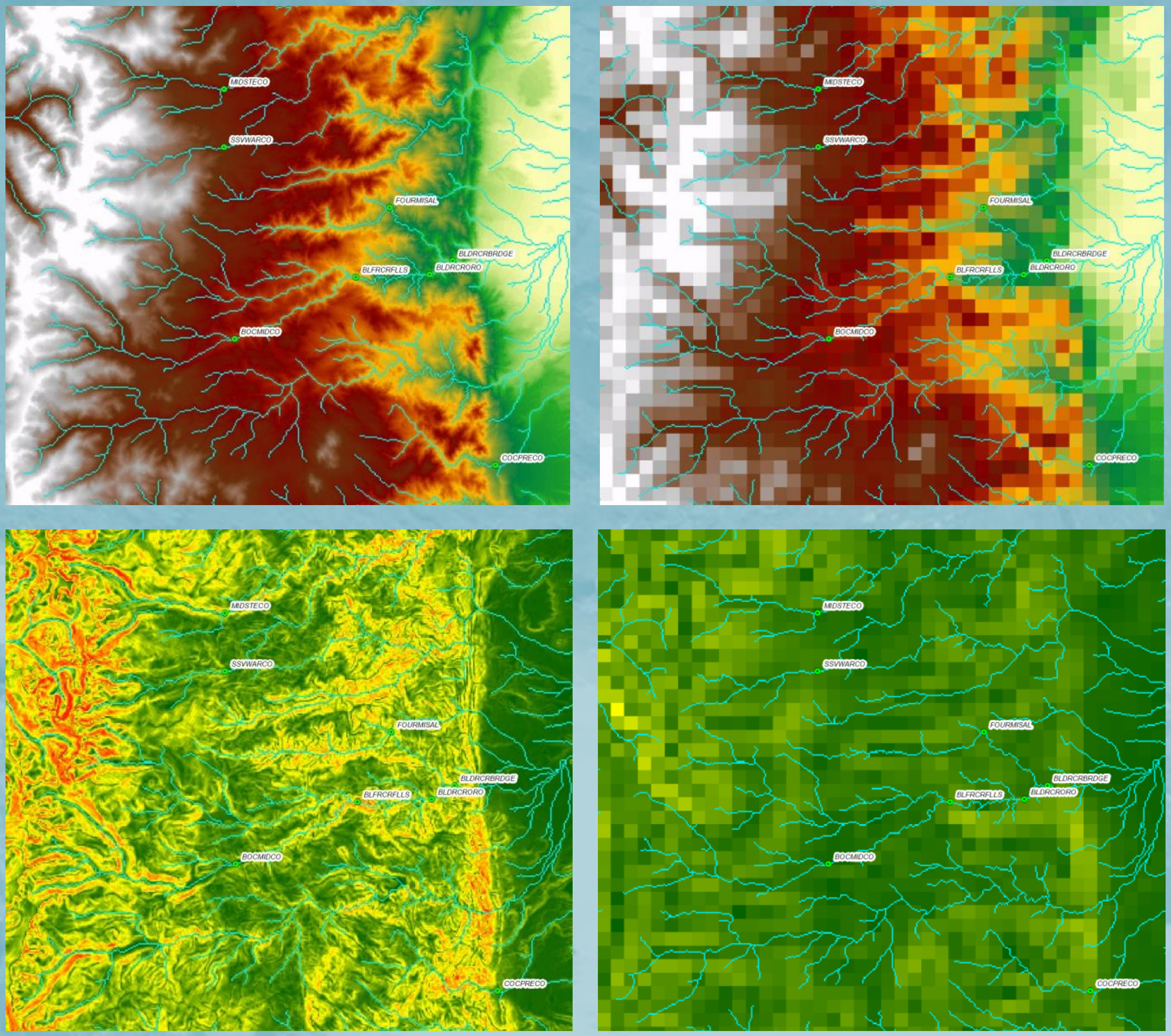


Courtesy the COMET Program

Scale dependence of potential energy (terrain slope):

100m Terrain

1 km Terrain



Terrain slope (0-45 deg)

Review:

- Rationale
- Structure of WRF Model
- Structure of traditional hydrological models
- How land surface models have evolved
- Time for fusion…

WRF-Hydro Component Overview

12 June, 2014

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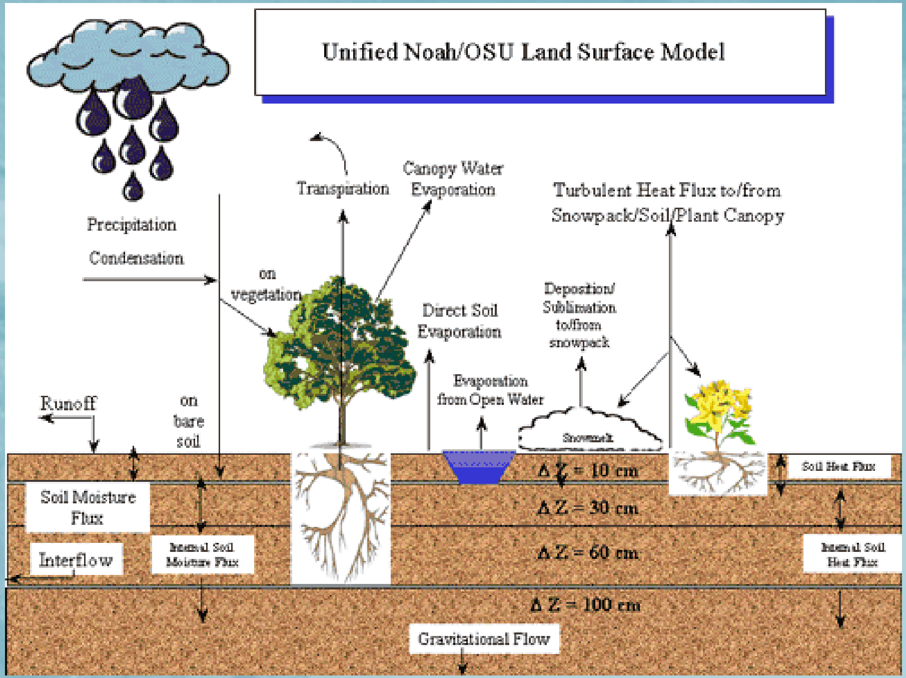
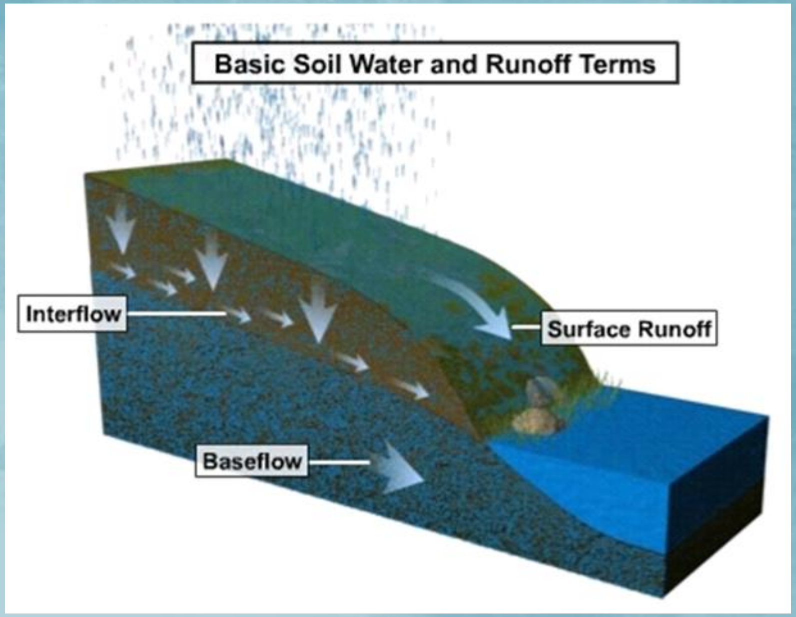
Outline:

- Basic Concepts
- Conceptualization of WRF-Hydro
- Model Architecture & Requirements

Basic Concepts:

- Linking the column structure of land surface models with the 'distributed' structure of hydrological models in a flexible, HPC architecture….





Conceptualization of WRF-Hydro:

- Atmospheric coupling perspective and serving the WRF research and forecasting and CESM communities

- Oriented towards existing NCAR-supported community models, but expanding:
  - Not fully genericized coupling which has pros/cons associated…
  - Also aimed at cluster & HPC architectures

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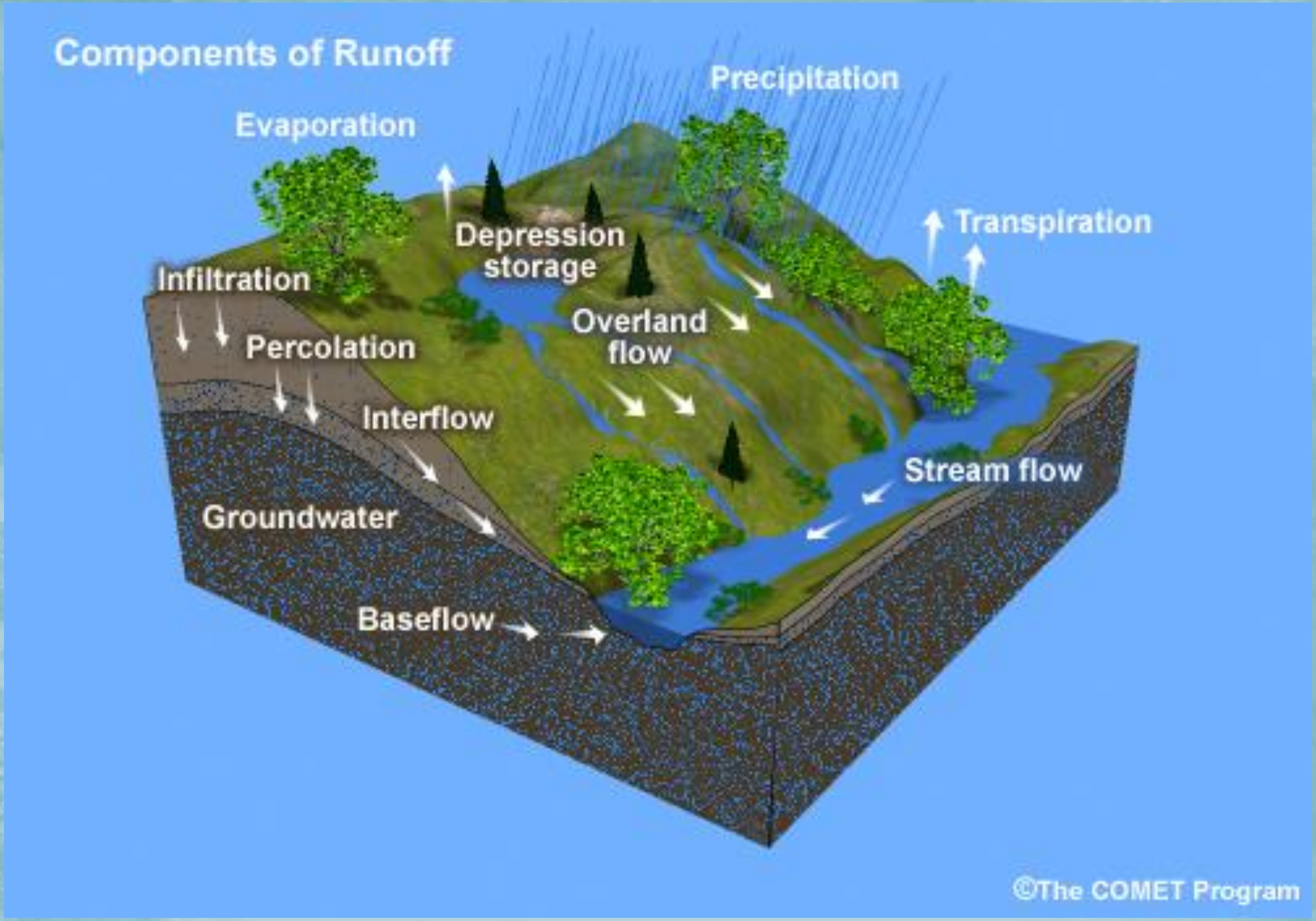
WRF-Hydro Development Goals:

1. Improve prediction skill of hydrometeorologial forecasts using science-based numerical prediction tools
2. Build and support an extensible, multi-scale coupling architecture to link weather and climate models with hydrological component models
3. Foster a community development environment for hypothesis testing and algorithm development

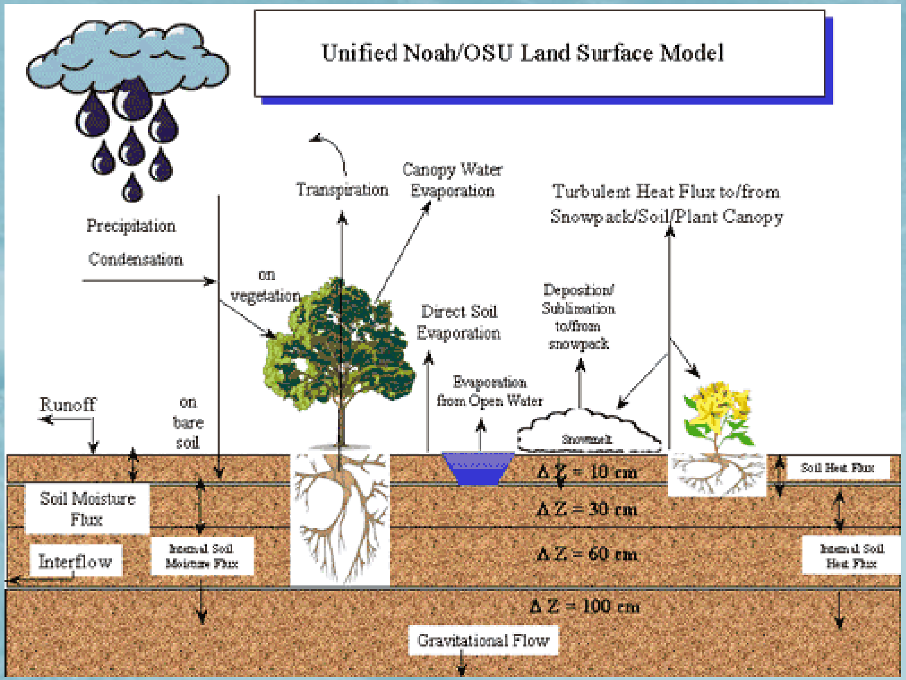
WRF-Hydro v2.0 Physics Components:

- Goal…

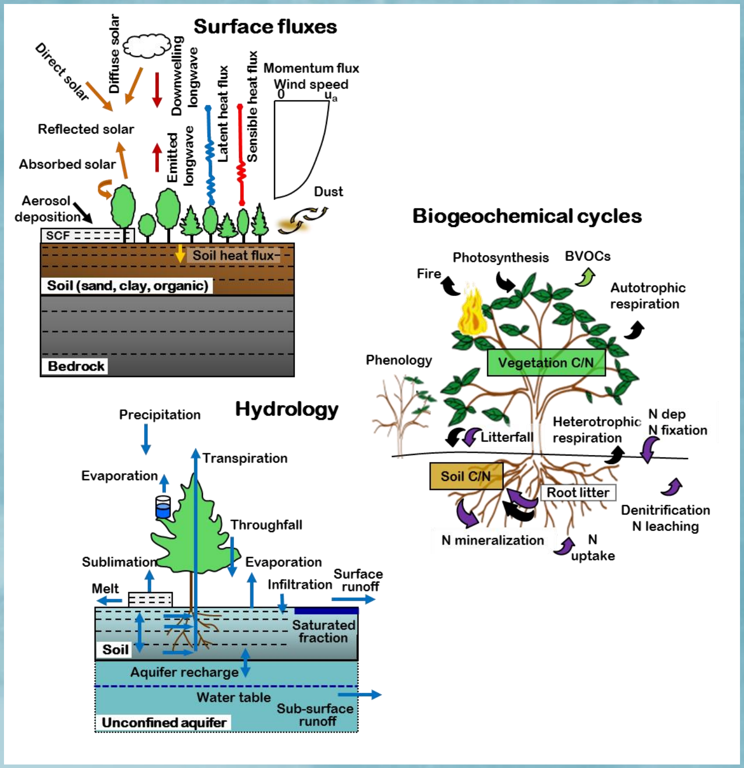


WRF-Hydro v2.0 Physics Components:

- Current Land Surface Models:
  - Column physics & land-atmosphere exchange



Noah LSM v3.5 & Noah-MP

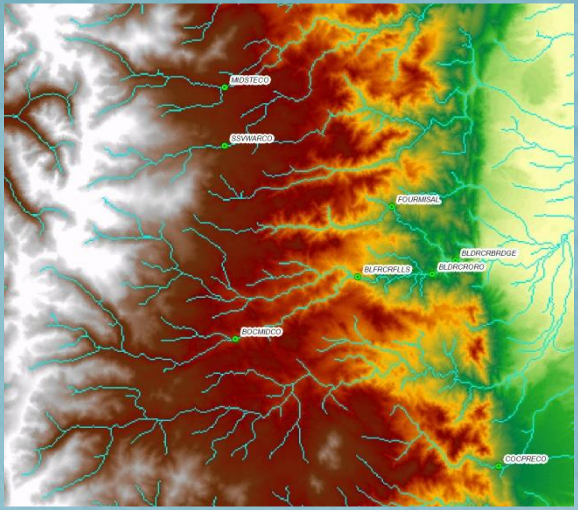


CLM v4.5

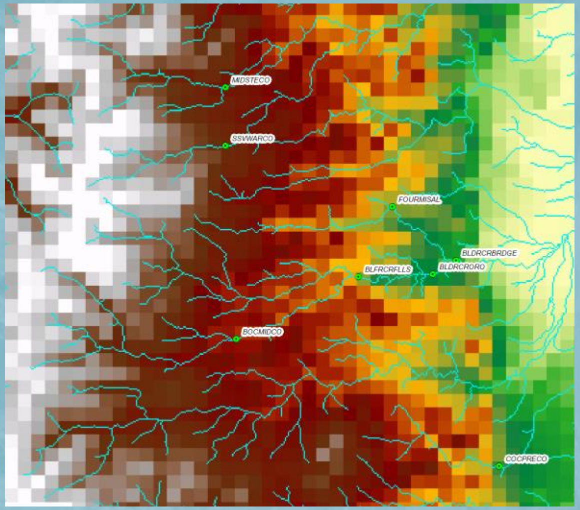
WRF-Hydro v2.0 Physics Components:

- Multi-scale aggregation/disaggregation:

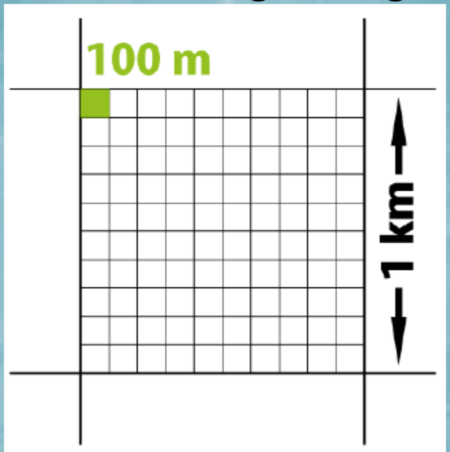
100m Terrain

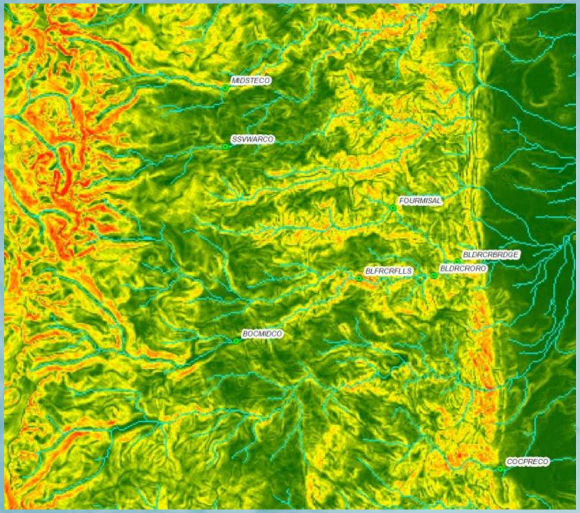


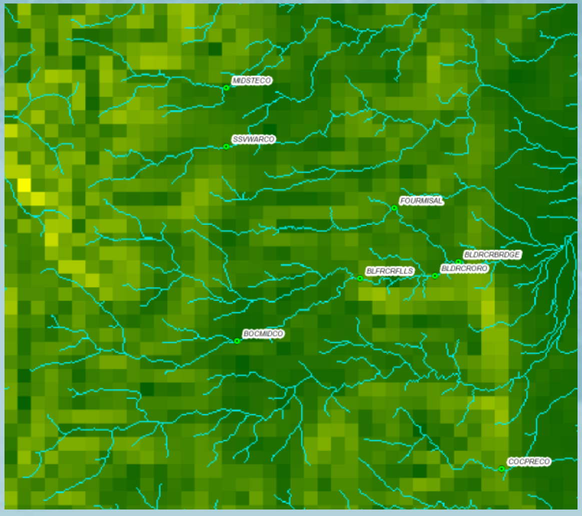
1 km Terrain



Current 'Regridding'

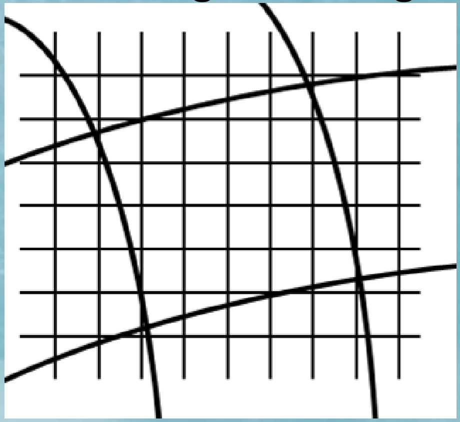






Terrain slope (0-45 deg)

Implementing ESMF Regridders



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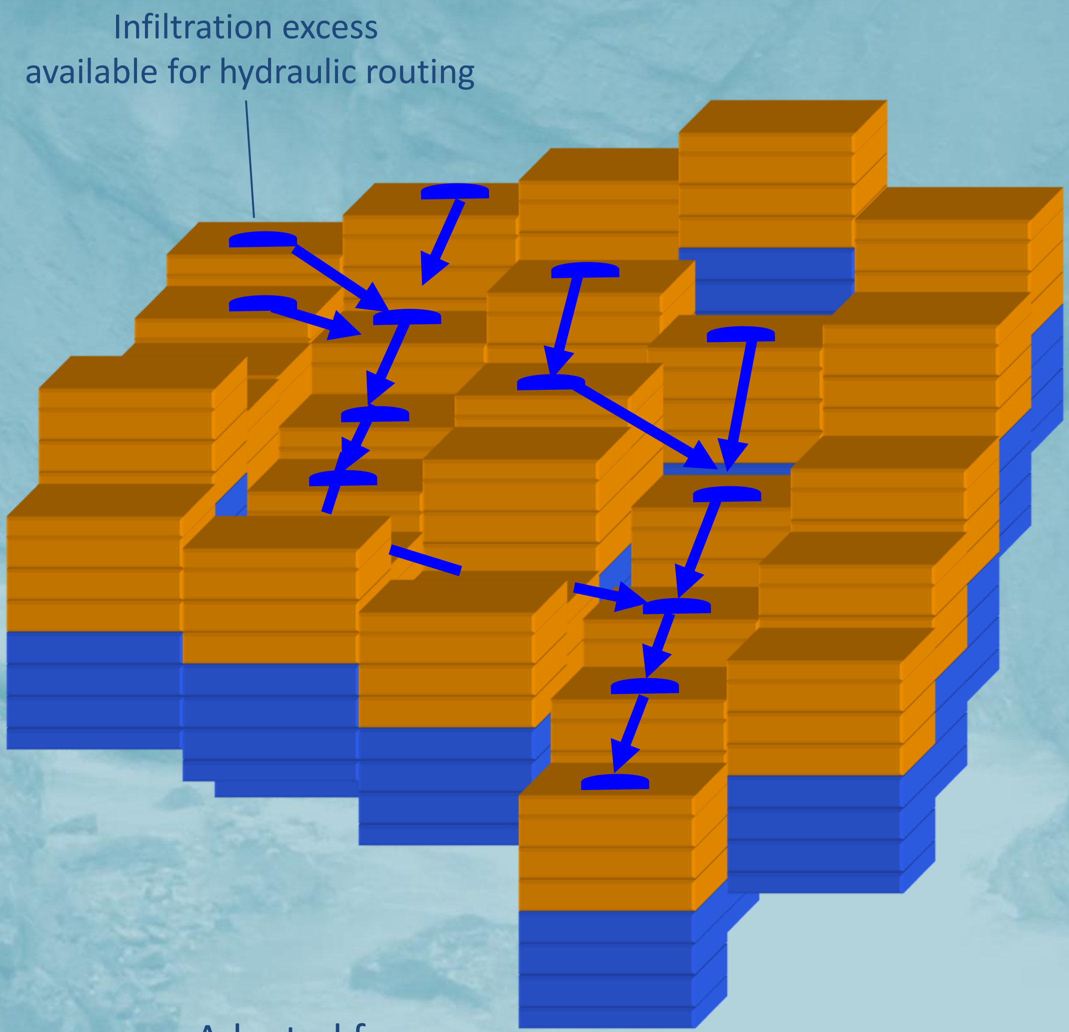
WRF-Hydro v2.0 Physics Components:

- Surface routing:



Adapted from:
Julian et al, 1995 – CASC2D, GSSHA

- Pixel-to-pixel routing
  - Steepest descent or 2d
  - Diffusive wave/backwater permitting
  - Explicit solution
- Ponded water (surface head) is fully-interactive with land model
- Sub-grid variability of ponded water on routing grid is preserved between land model calls

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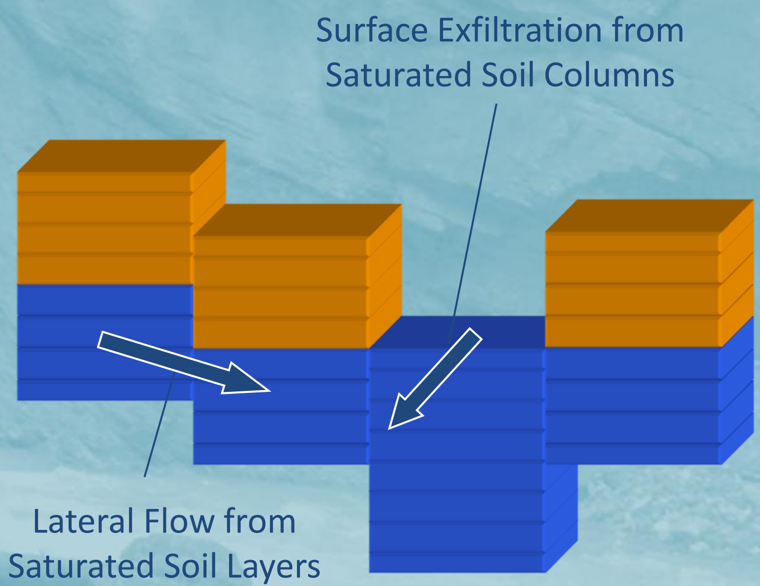
WRF-Hydro v2.0 Physics Components:

- Subsurface routing:



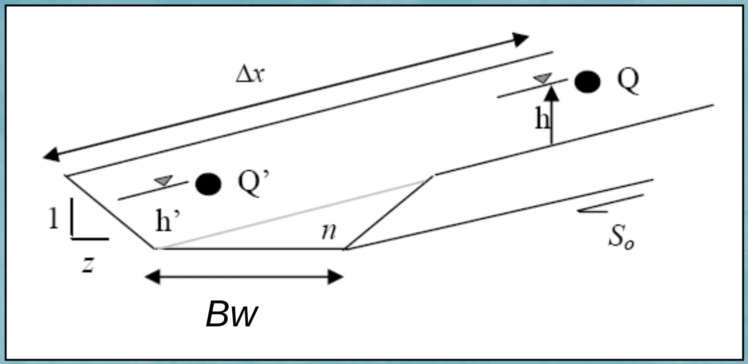
Adapted from:
Wigmosta et. al, 1994

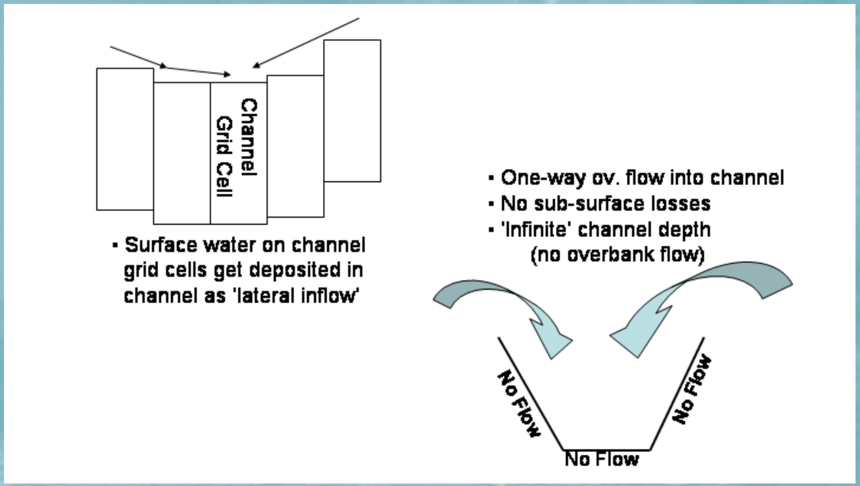
- Quasi steady-state, Boussinesq saturated flow model
- Exfiltration from fully-saturated soil columns
- Anisotropy in vertical and horizontal Ksat
- No 'perched' flow
- Soil depth is uniform

- Critical initialization value: water table depth

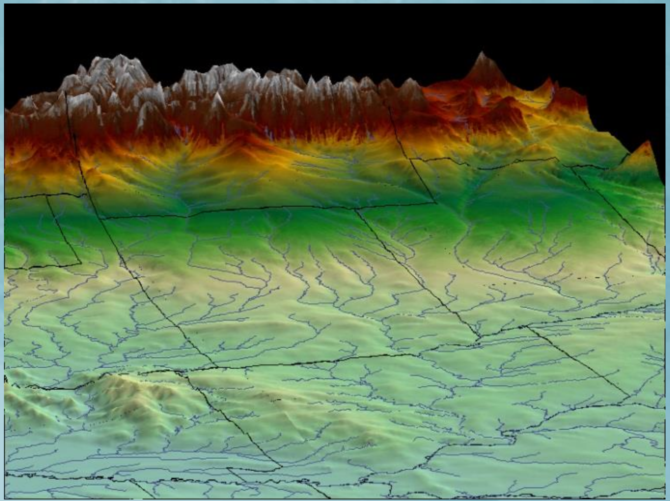
WRF-Hydro v2.0 Physics Components:

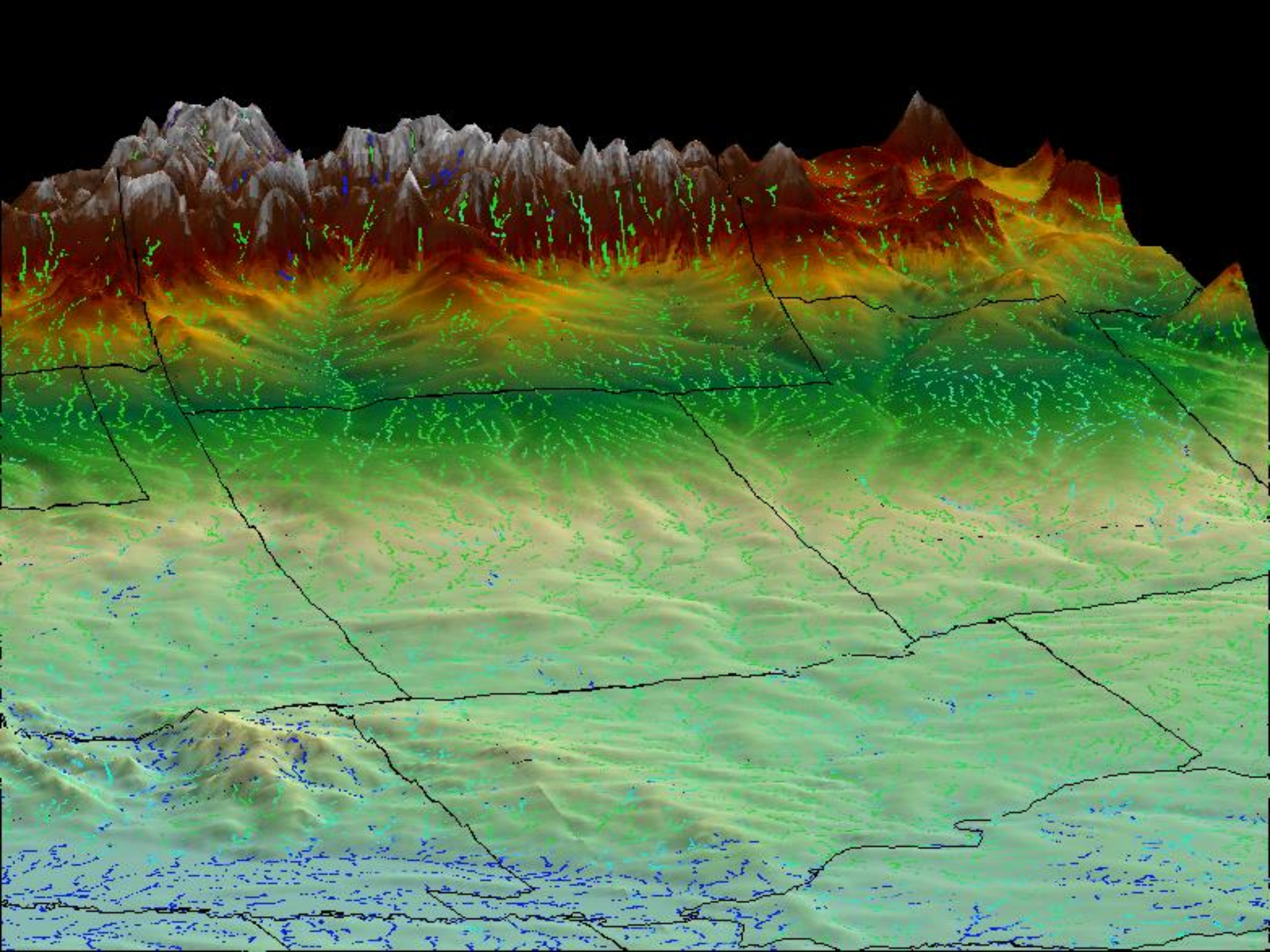
- Channel routing: Gridded vs. Reach-based





- Solution Methods:
  – Gridded: 1-d diffusive wave: fully-unsteady, explicit, finite-difference
  – Reach: Muskingam, Muskingam-Cunge *(much faster)*
- Parameters:
  – A priori function of Strahler order
  – Trapezoidal channel (bottom width, side slope)





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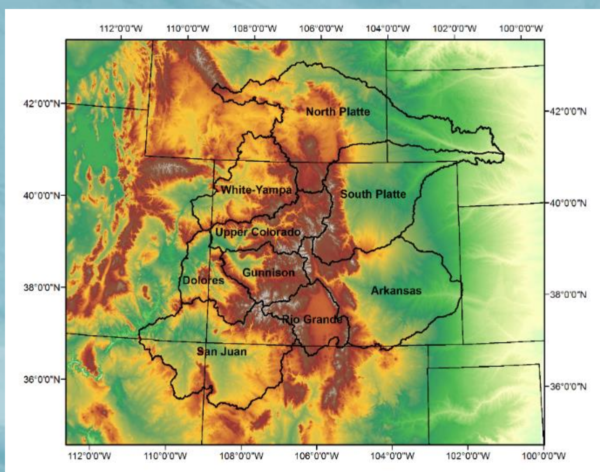
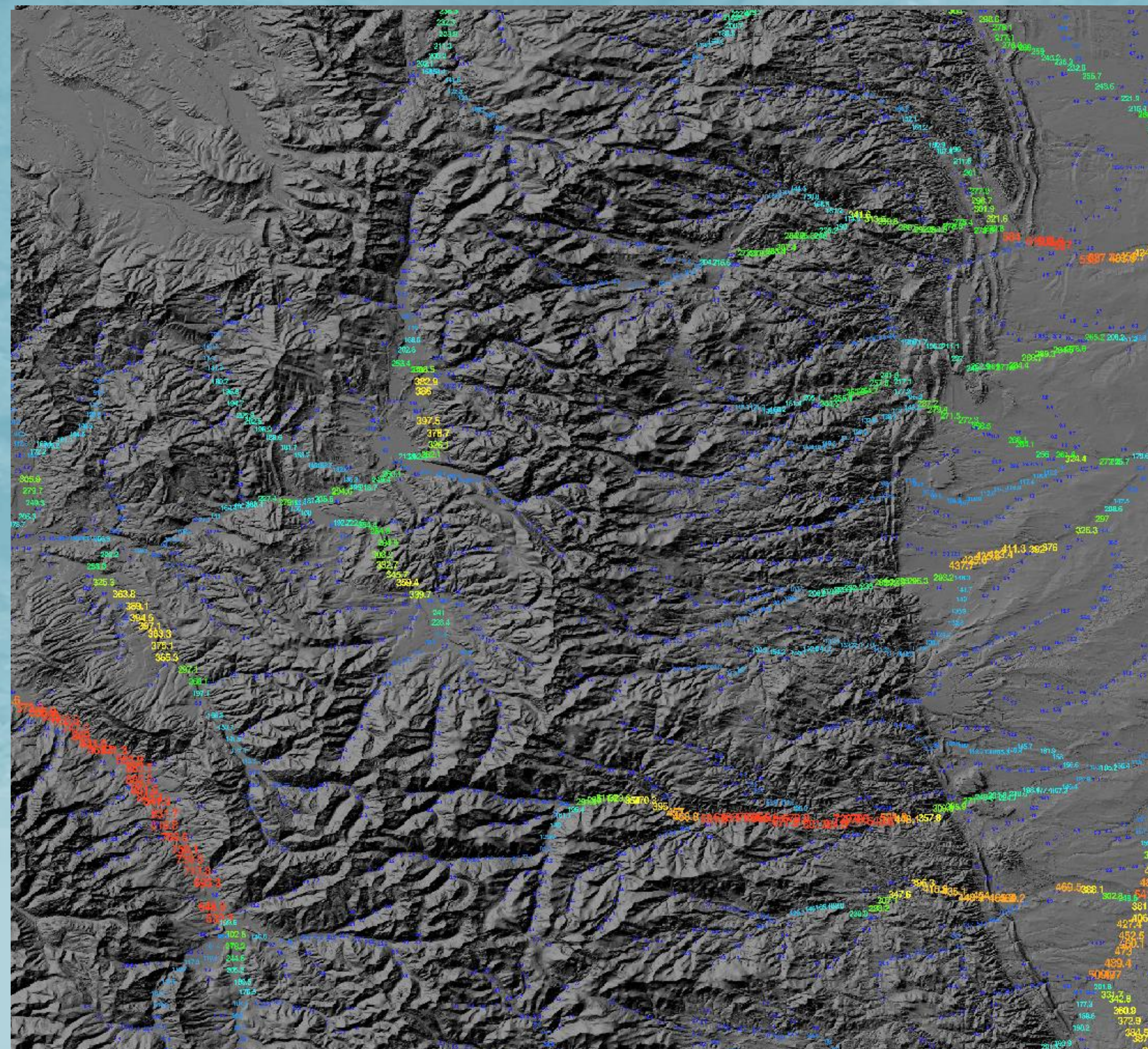
Multi-scale modeling and visualization:





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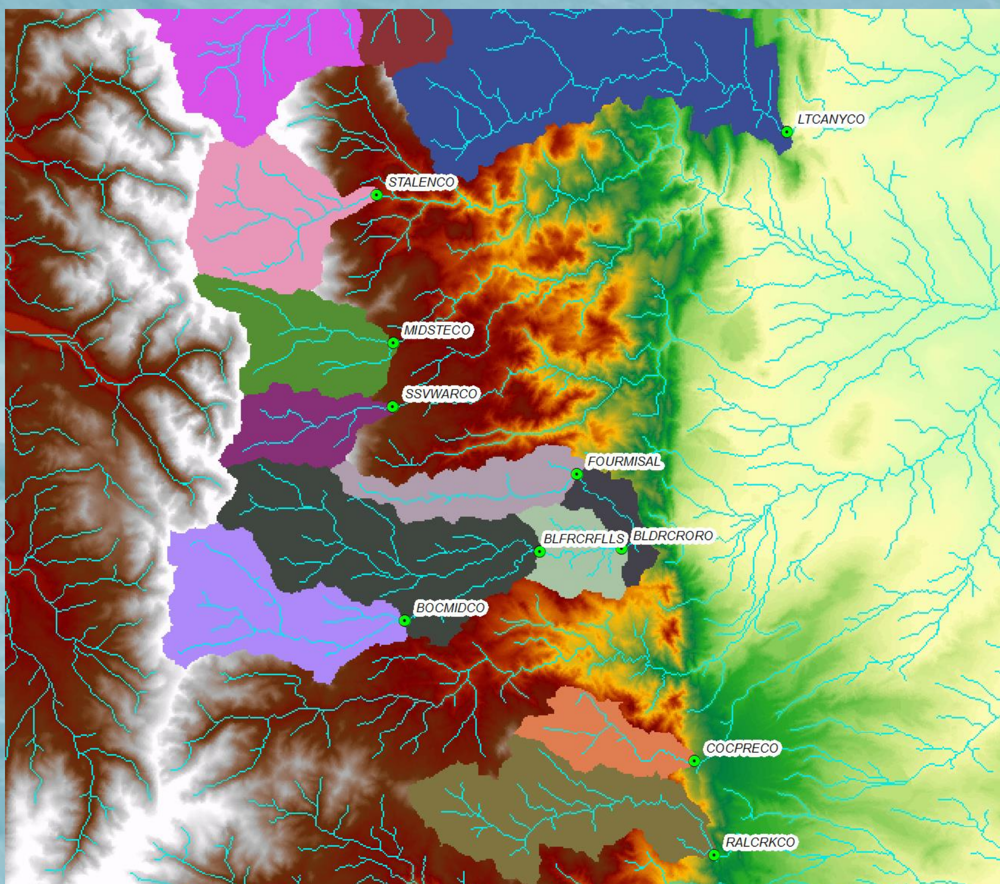
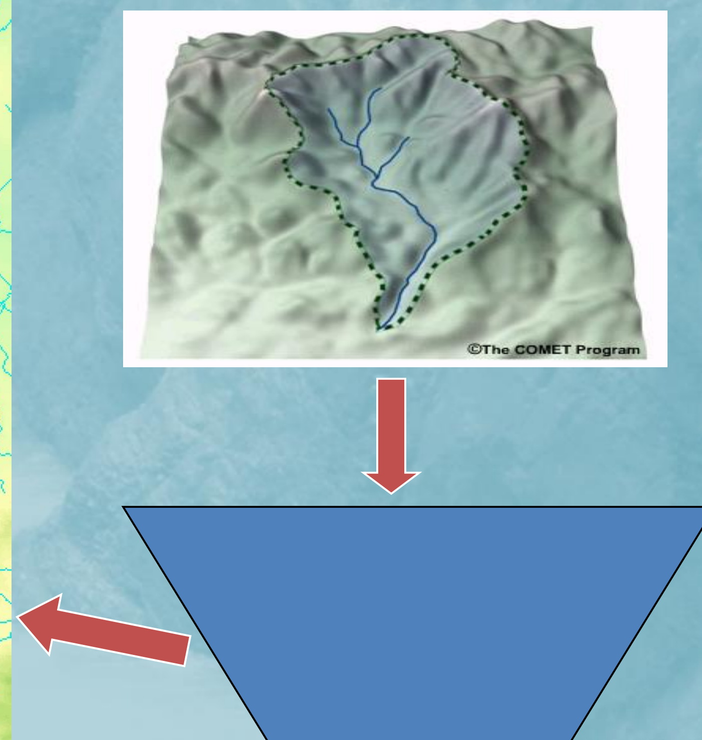
WRF-Hydro v2.0 Physics Components:

- Optional conceptual ‘baseflow’ model:
  - Used for continuous (vs. event) prediction
  - Simple pass-through or 2-parameter exponential model
  - Bucket discharge gets distributed to channel network





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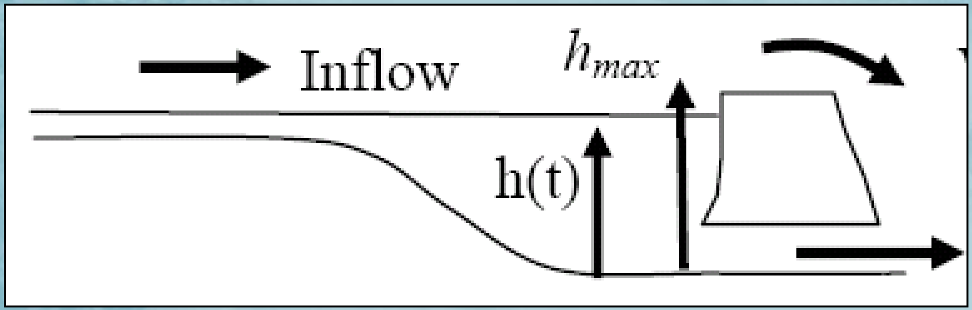
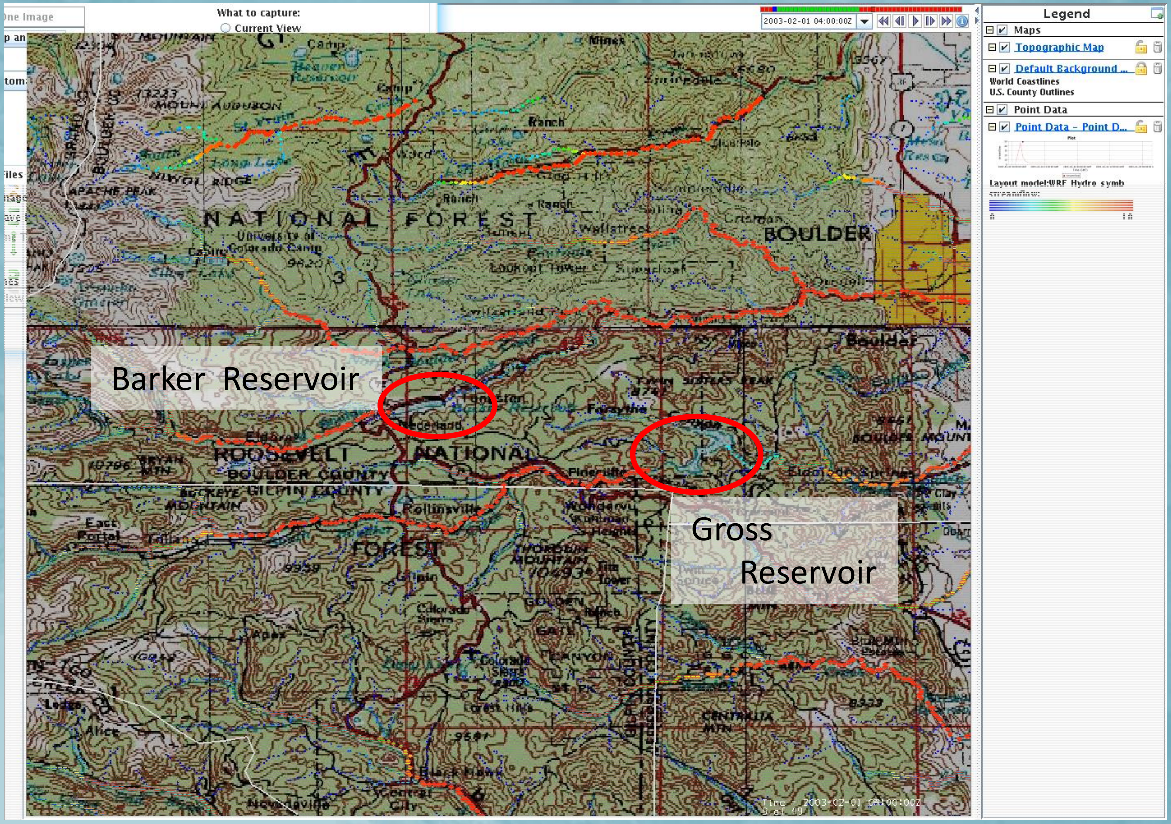
WRF-Hydro v2.0 Physics Components:

- Optional lake/reservoir model:
  - Level-pool routing (i.e. no lagging of wave or gradient in pool elevation)
  - Inflows via channel and overland flow
  - Discharge via orifice and spillway to channel network
  - Parameters: lake and orifice elevations, max. pool elevation, spillway and orifice characteristics; specified via parameter table
  - Active management can be added via an operations table
  - Presently no seepage or evaporative loss functions

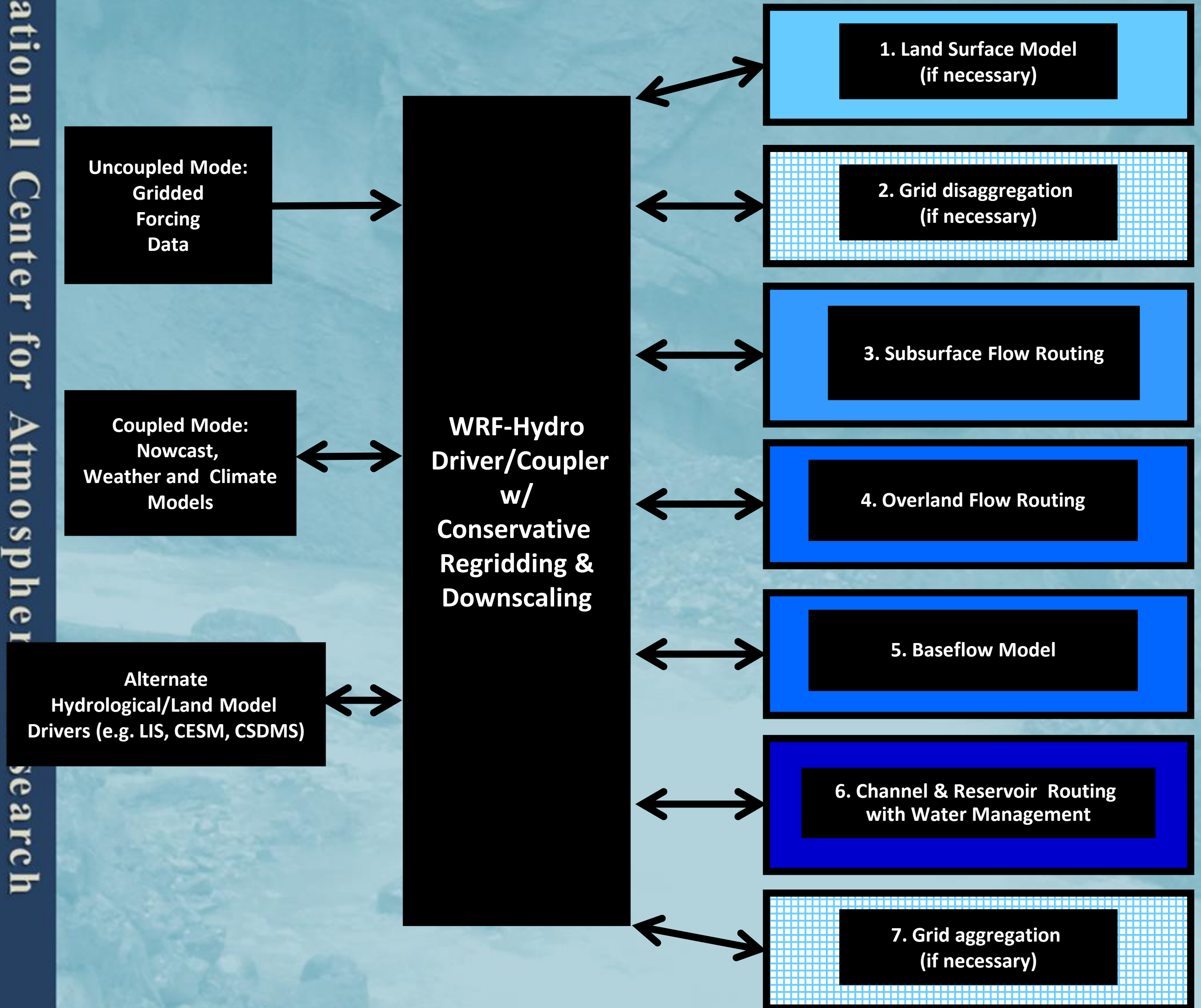


Implementing lakes and reservoirs in WRF-Hydro

1. Visualization of lake impacts



WRF-Hydro Architecture Description:



- Model physics components….
- Multi-scale components….
  - Rectilinear regridding
  - ESMF regridding
  - Downscaling

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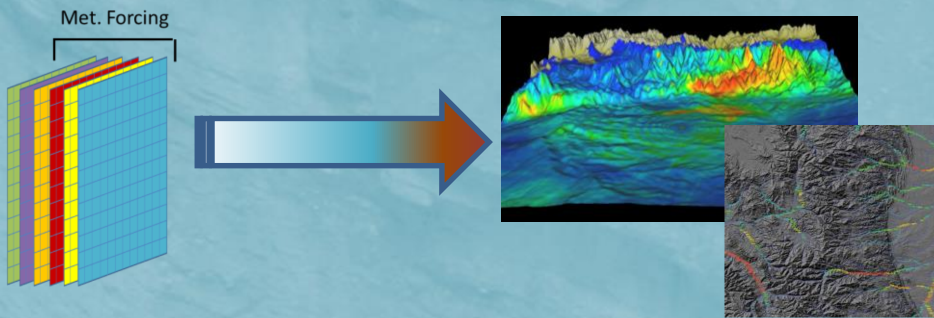
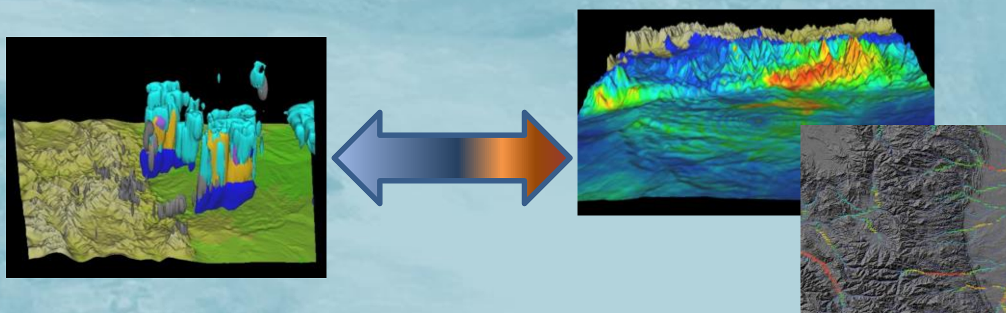
Architecture Description: Basic Concepts

One-way (‘uncoupled’) →



Two-way (‘coupled’) ↔



- Modes of operation..1-way vs. 2-way
- Model forcing and feedback components:
  - Forcings: T, Press, Precip., wind, radiation, humidity, BGC-scalars
  - Feedbacks: Sensible, latent, momentum, radiation, BGC-scalars

'WRF-Hydro' Software Features:

- Modularized F90 (and later) and integrated in the WRF ARW & NMM and CESM systems and NASA-LIS
- Coupling options are specified at compilation and WRF-Hydro is compiled as a new library in WRF
- 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

Wei Yu (RAL) – lead engineer

Data Grids

- Three Data Grids

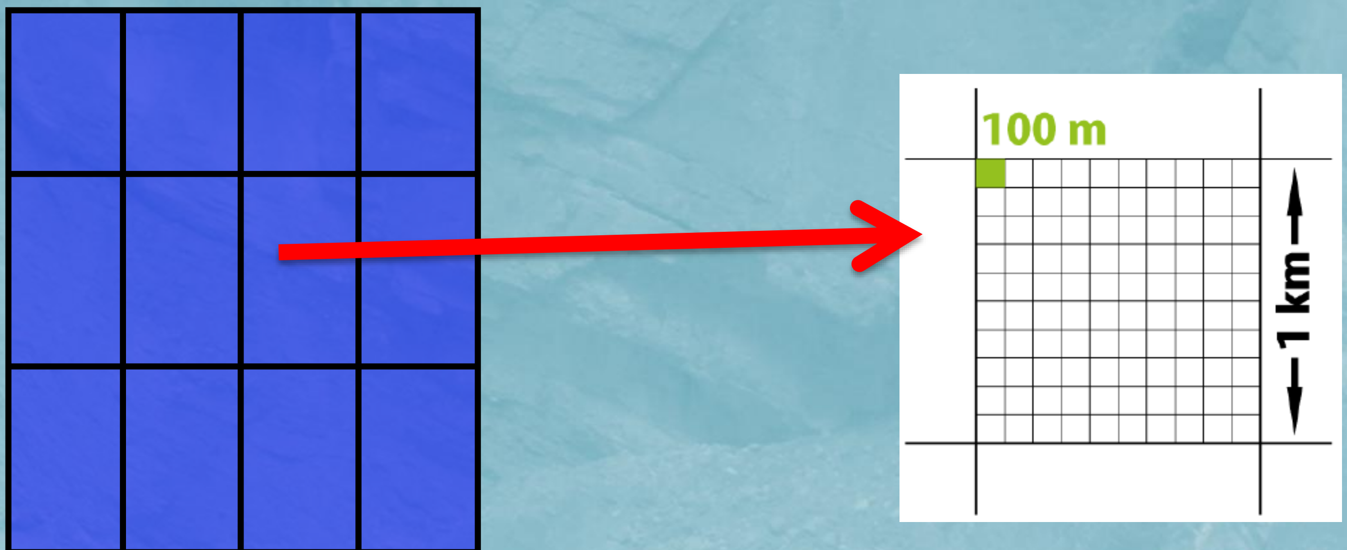
    Land Grids: (ix,jx), (ix,jx, n_soil_layer)

    Land Routing: (ixrt,jxrt), (ixrt,jxrt,n_soil_layer)

    Channel Routing: (n_nodes), (n_lakes)

- Parallel Scheme
    - Two dimensional domain decomposition
    - Distributed system only

WRF-Hydro Multi-Grids Domain Decomposition

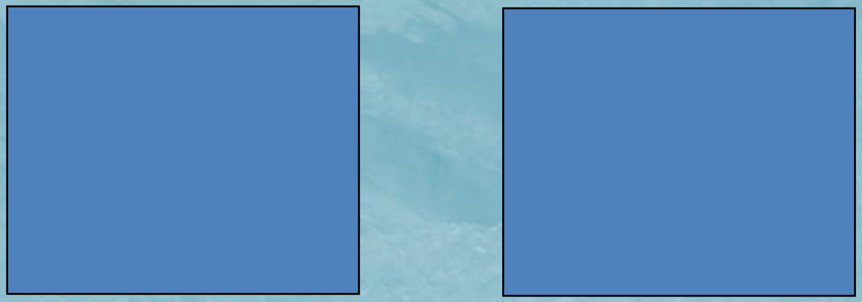


Land grid

Land routing grid cell: regridding

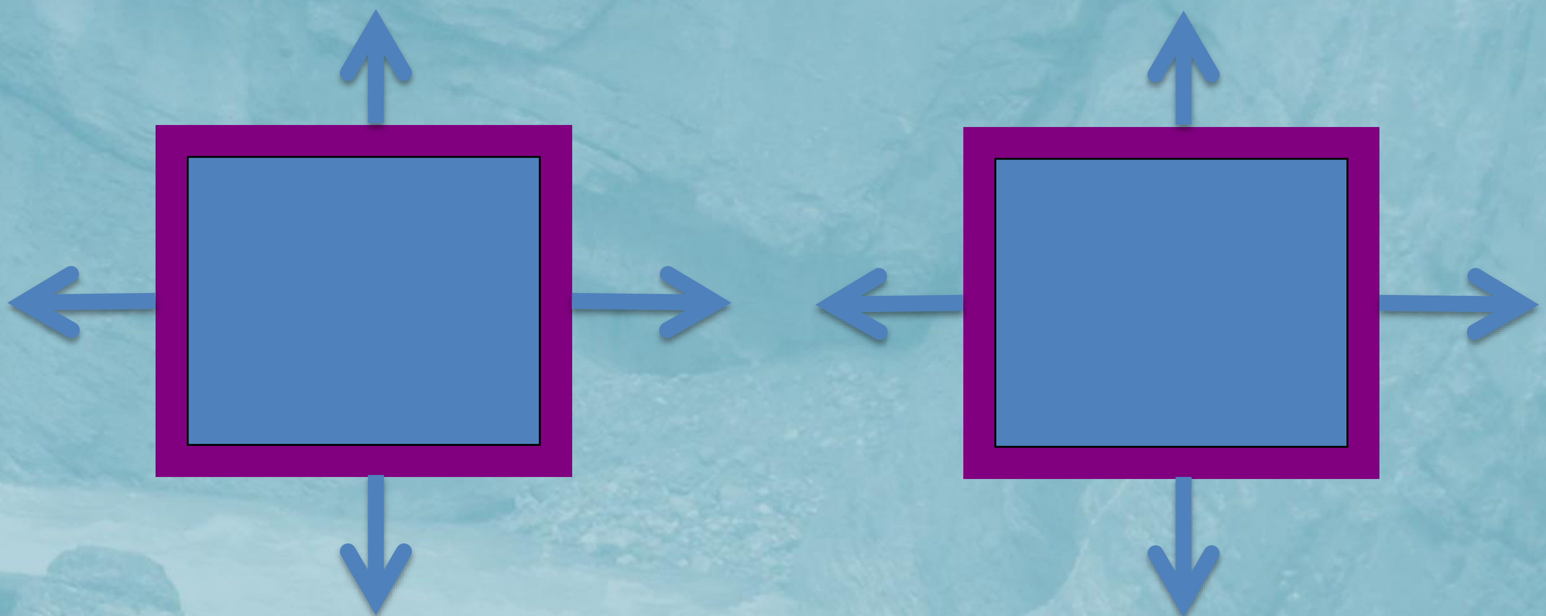
One CPU: Land grid, land routing grid cell, and channel routing nodes.

Distributed Memory Communications
Land Grid



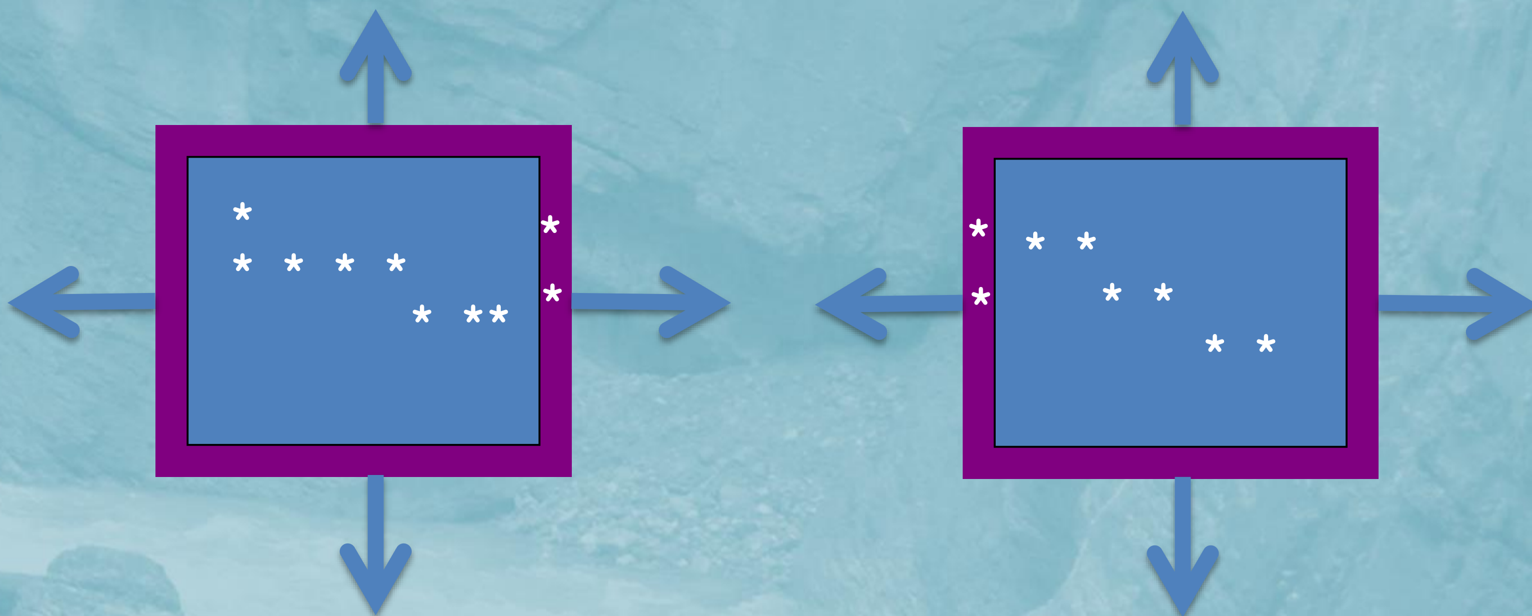
Stand alone columns require no memory communication between neighbor processors

Distributed Memory Communications
Land Routing Grid



Lateral routing DOES require memory communication between neighbor processors

Distributed Memory Communications
Channel Routing

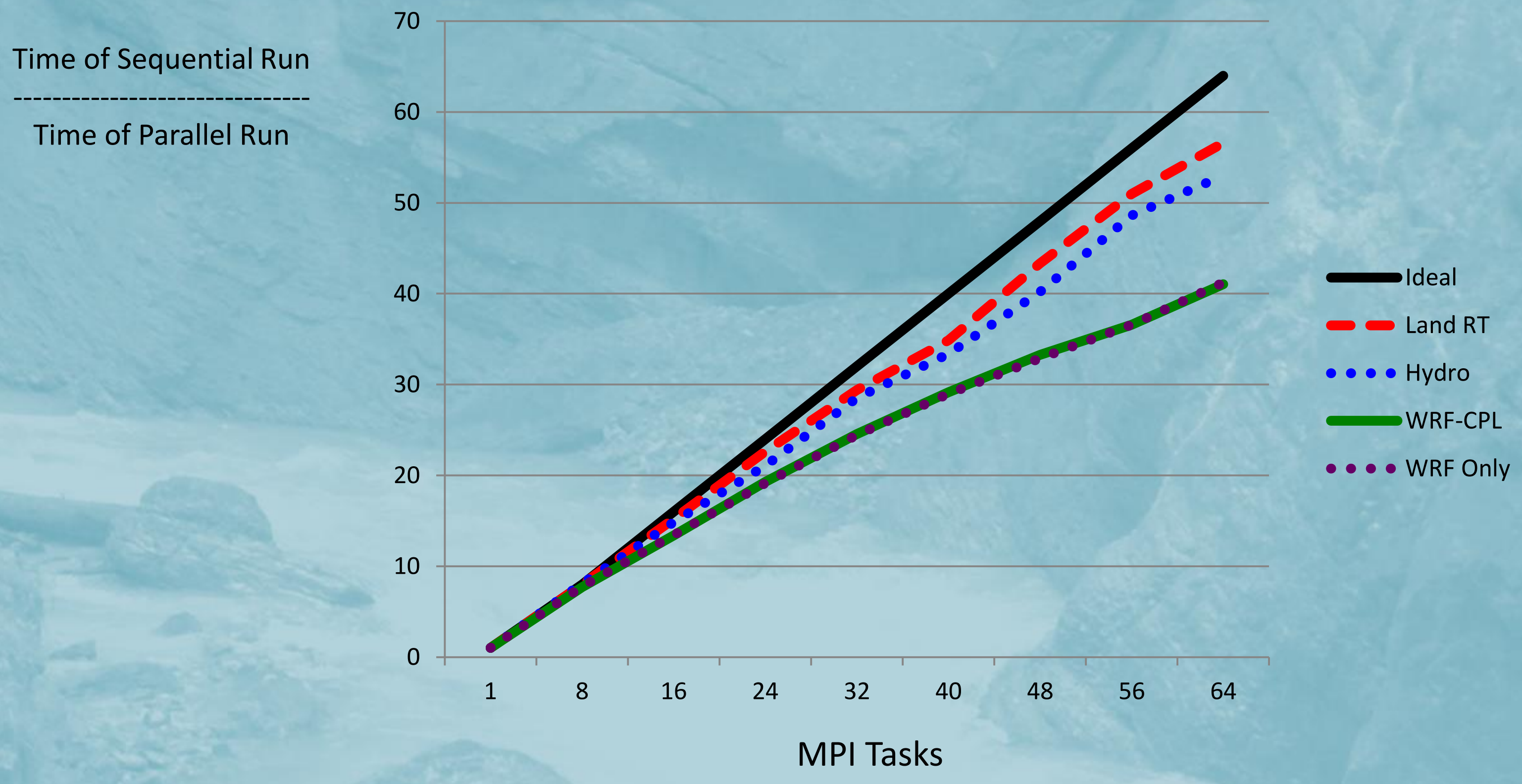


Lateral channel routing DOES require memory communication between neighbor processors, although the arrays are reduced to the sparse matrix of the channel elements

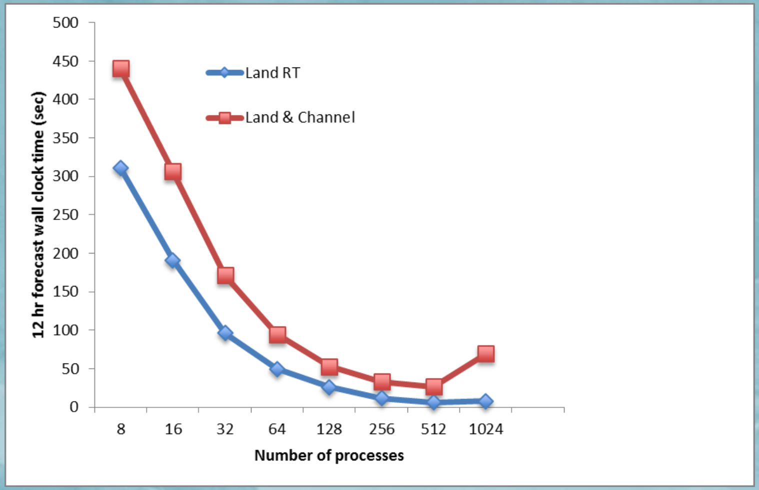
WRF-Hydro Coupling

- Coupled with WRF
- ‘Un-coupled’ with HRLDAS (1-d Noah land model driver, working on Noah-MP)
- Coupled with LIS
- Coupled with CLM under CESM coupler (working on recent release of CLM in WRF)

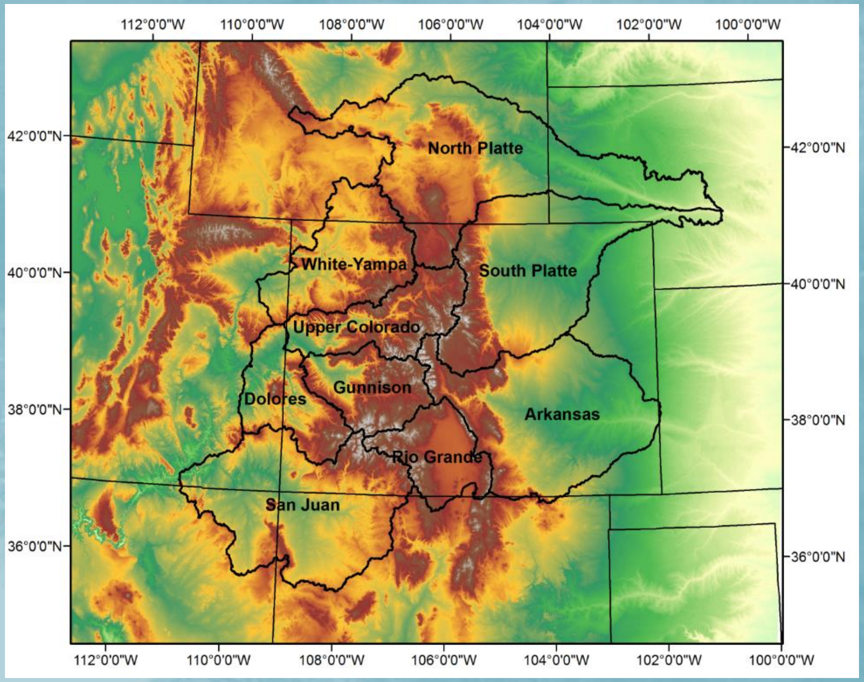
WRF-Hydro Performance Speedup



Large Domain Computational Benchmarking



4 km dx ~500x500



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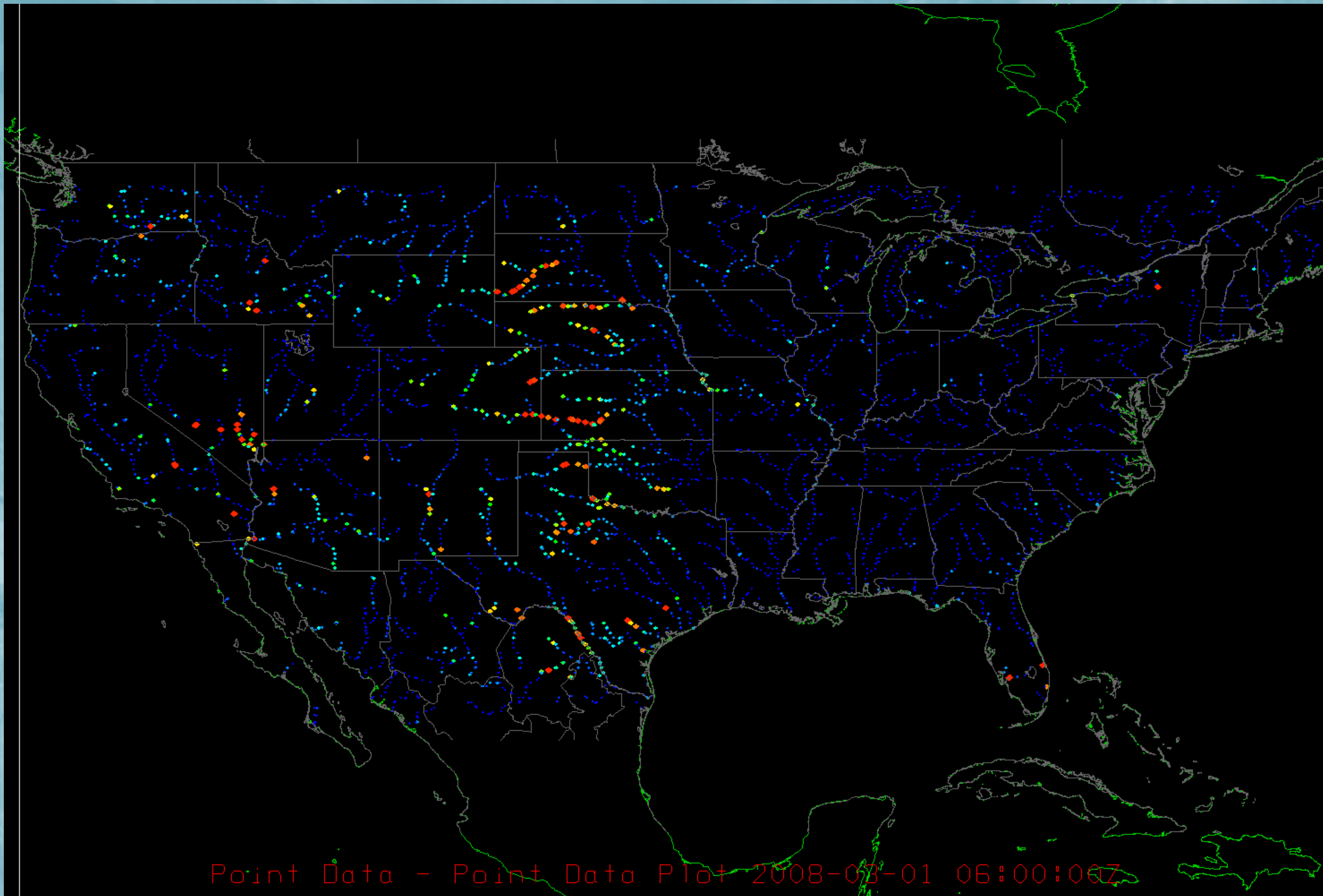
Large Domain Computational Benchmarking



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Thank you!

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WRF-Hydro: http://www.ral.ucar.edu/projects/wrf_hydro/

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