Developing and demonstrating improved techniques for climate projection downscaling and hydrologic impacts assessment:

Thinking ahead to SECURE 2016

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Disclaimer: Results in this presentation are preliminary and subject to change

Improved techniques for climate projection downscaling and hydrologic impacts assessment

Gap(s) Addressed

2.03 Information on the strengths and weaknesses of downscaled data…

3.03 Basis for culling or weighting climate projections …

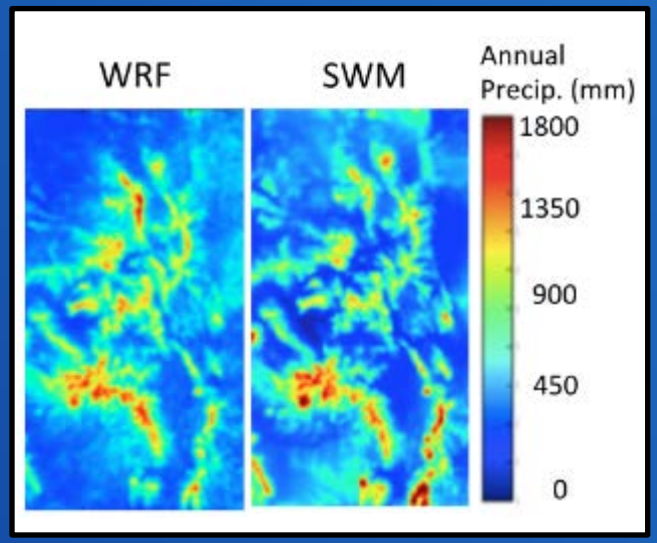
4.01 Guidance on strengths and weaknesses of watershed hydrologic models/methods …

4.02 Understanding how climate change should impact potential evapotranspiration and how it is represented in watershed hydrologic models.

7.02 Uncertainty information on regional climate projections …

7.04 …uncertainty information on system science and associated ways of portraying this science in a system model and the observations used to customize a model for a specific system.

Graphic



Precipitation from WRF & Simple Weather Model (SWM)

Research Question(s)

1. How can we make greater use of projected changes in climate dynamics to downscale output from multiple GCMs?
2. How can we improve continental-scale hydrology simulations and better characterize hydrologic model uncertainty?
3. What is the relative importance of different sources of uncertainty in the portrayal of climate change impacts on hydrology

Collaborators/Schedule/Source of Support

- Reclamation, US Army Corps of Engineers
- Schedule:
  - *Fall 2013 – Baseline simulations and development of modeling infrastructure*
  - *Summer 2014 – Prototypes for intermediate-complexity downscaling and multi-model hydrology simulations*
  - *Summer 2015 – Information for the SECURE report*
- Funding: Reclamation, US Army Corps of Engineers; complemented by NSF

RECLAMATION

Outline

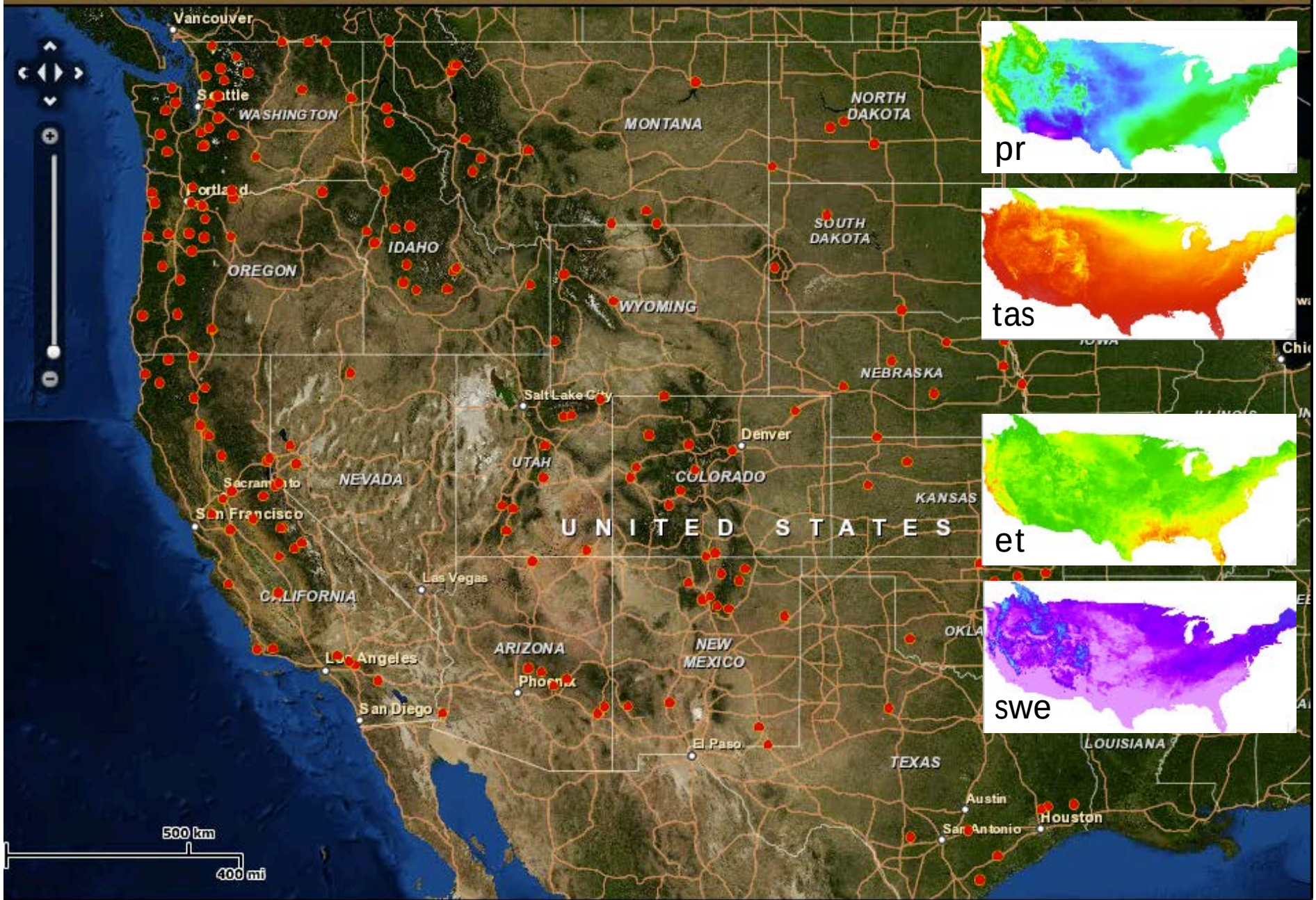
- Baseline portrayals of climate change impacts on hydrology from CMIP5
  - Modeling approach
  - Analysis of model performance
- Improving hydrologic models
  - Initial modeling infrastructure
  - Integrating parameterizations and architectures from multiple models
- Improving downscaling methods
  - Reviewing “new” traditional techniques
  - Circulation-based statistical downscaling
  - The Simple Weather Model
- Summary & Discussion

CMIP5 VIC Runs

- NCAR generated 100 CMIP5 scenario based daily forcings and VIC CONUS hydrology datasets, together with a brief descriptive report. The tasks associated with this effort are the following.
  1. Generate daily weather sequences (precipitation and temperature minima and maxima) from the 100 downscaled "run 1" members of the CMIP5 climate projection archive over the 1/8th degree CONUS grid.
  2. Using the parameter sets and global control files from the prior effort, run all forcing scenarios through the VIC hydrology model. Translate the hydrometeorological outputs into netCDF-based daily and monthly summary formats.
  3. Assess and document climatological statistics sufficient to evaluate the performance of the downscaling and hydrologic simulation.
     1. Before running the hydrological simulations, investigate and document the source and quality of the existing streamflow calibrations
     2. Improve the model calibrations where warranted.
- Initial timeline: 6 months from NCAR acceptance of award (Aug 2013)
- Status: running/routing VIC simulations this week, transferring to GDO

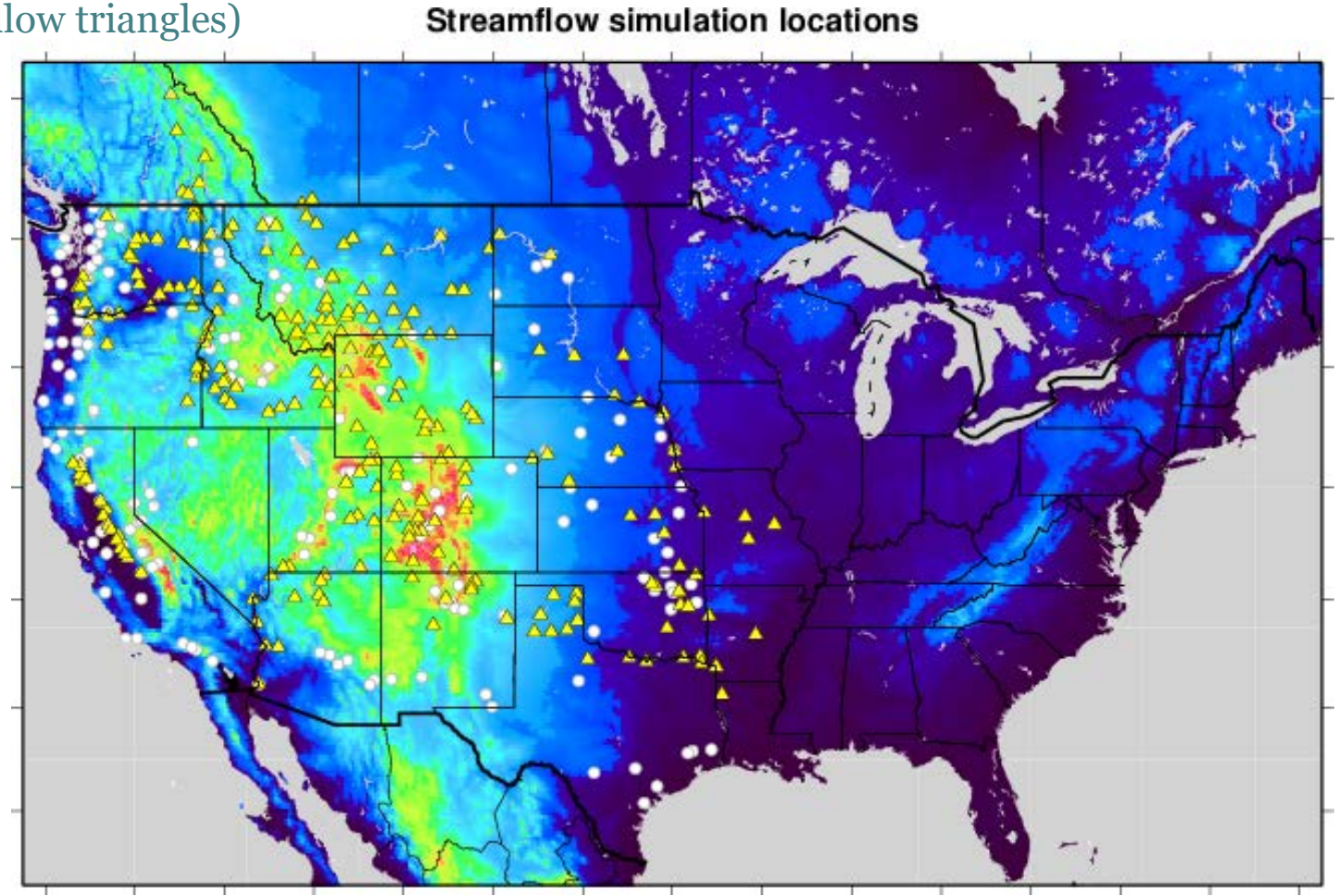
Streamflow Projections for the Western United States

RECLAMATION
Managing Water in the West



Streamflow simulations

- Former locations
  - WWCRA: 154 HCDN + 43 USBR + 9 'MISC' (white circles)
- New locations
  - UW West-wide Forecast locations (240) – in general, bigger basins with naturalized flows (yellow triangles)



VIC run outputs for GDO

Step 2.4: Select Projection Sets (Green text indicates projection set form completed)

- [ ] BCSD-CMIP3-Climate-monthly
- [x] BCSD-CMIP5-Climate-monthly
- [ ] BCCA-CMIP3-Climate-daily
- [ ] BCCA-CMIP5-Climate-daily
- [x] BCSD-CMIP3-Hydrology-monthly

BCSD-CMIP3-Climate-monthly | BCCA-CMIP3-Climate-daily | **BCSD-CMIP3-Hydrology-monthly** | **BCSD-CMIP5-Climate-monthly** | BCCA-CMIP5-Climate-daily

Step 2.5: Variables -- monthly projections ?

- [ ] Precipitation (mm/m)
- [ ] Maximum Air Temperature (deg C)
- [ ] Minimum Air Temperature (deg C)
- [ ] Wind Speed (m/s)
- [ ] Soil Moisture Content (mm -- 1st day of month)
- [ ] Snow Water Equivalent (mm -- 1st day of month)
- [ ] Total runoff (mm/m)
- [ ] Evapotranspiration - Actual (mm/m)
- [ ] Evapotranspiration - Potential, natural veg (mm/m)
- [ ] Evapotranspiration - Potential, open water (mm/m)
- [ ] Evapotranspiration - Potential, tall reference (mm/m)
- [ ] Evapotranspiration - Potential, short refernece (mm/m)

Step 2.6: Emissions Scenarios, Climate Models and Runs ?

De-select all runs | None | None | None

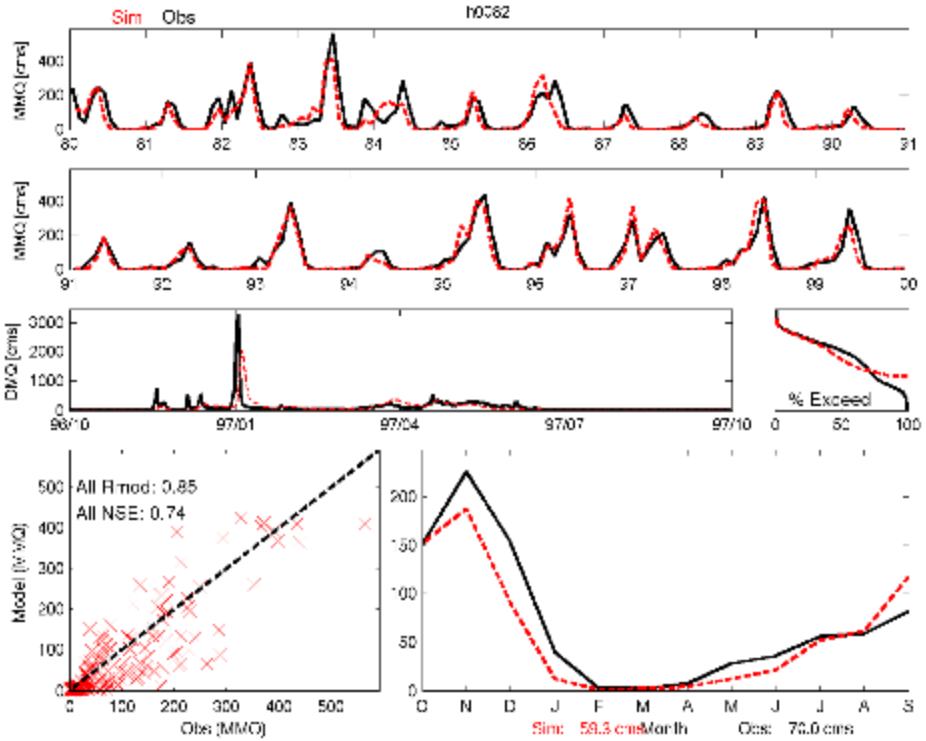
Also:

- daily netcdf and ascii forcings (ascii archived by basin)
- daily runoff and baseflow (and their total) for routing
- daily and monthly streamflow simulations, historical and CMIP5

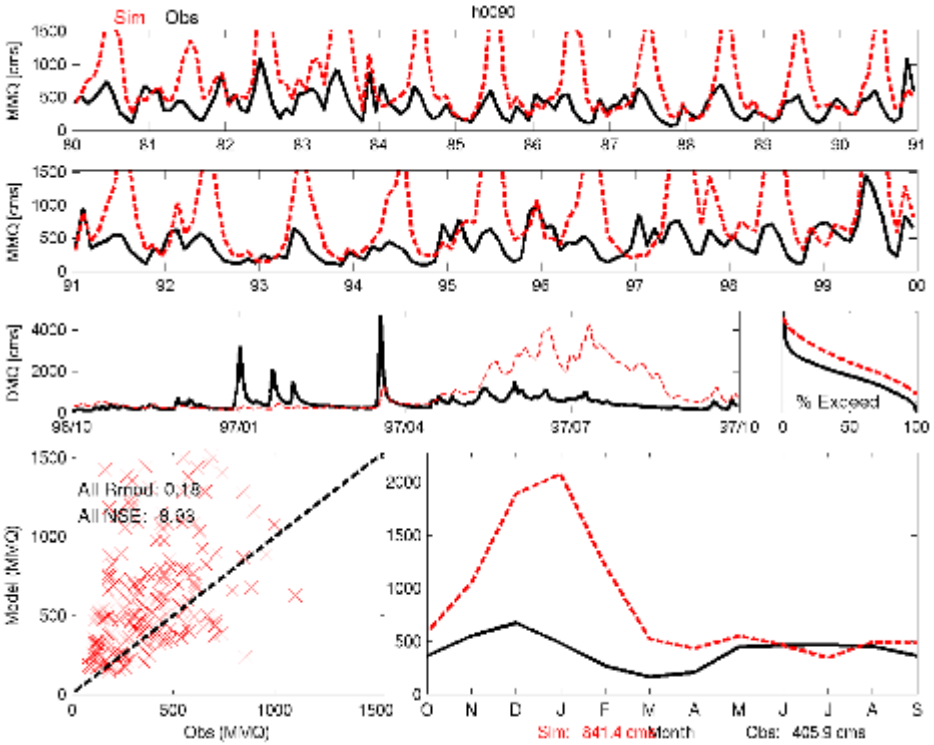
Sample small site calibrations (existing)

Wide range of performance …

Cole C nr Salt Springs Dam



Dungeness River near Sequim



Recalibration effort used single-objective SCE applied to six VIC soil parameters

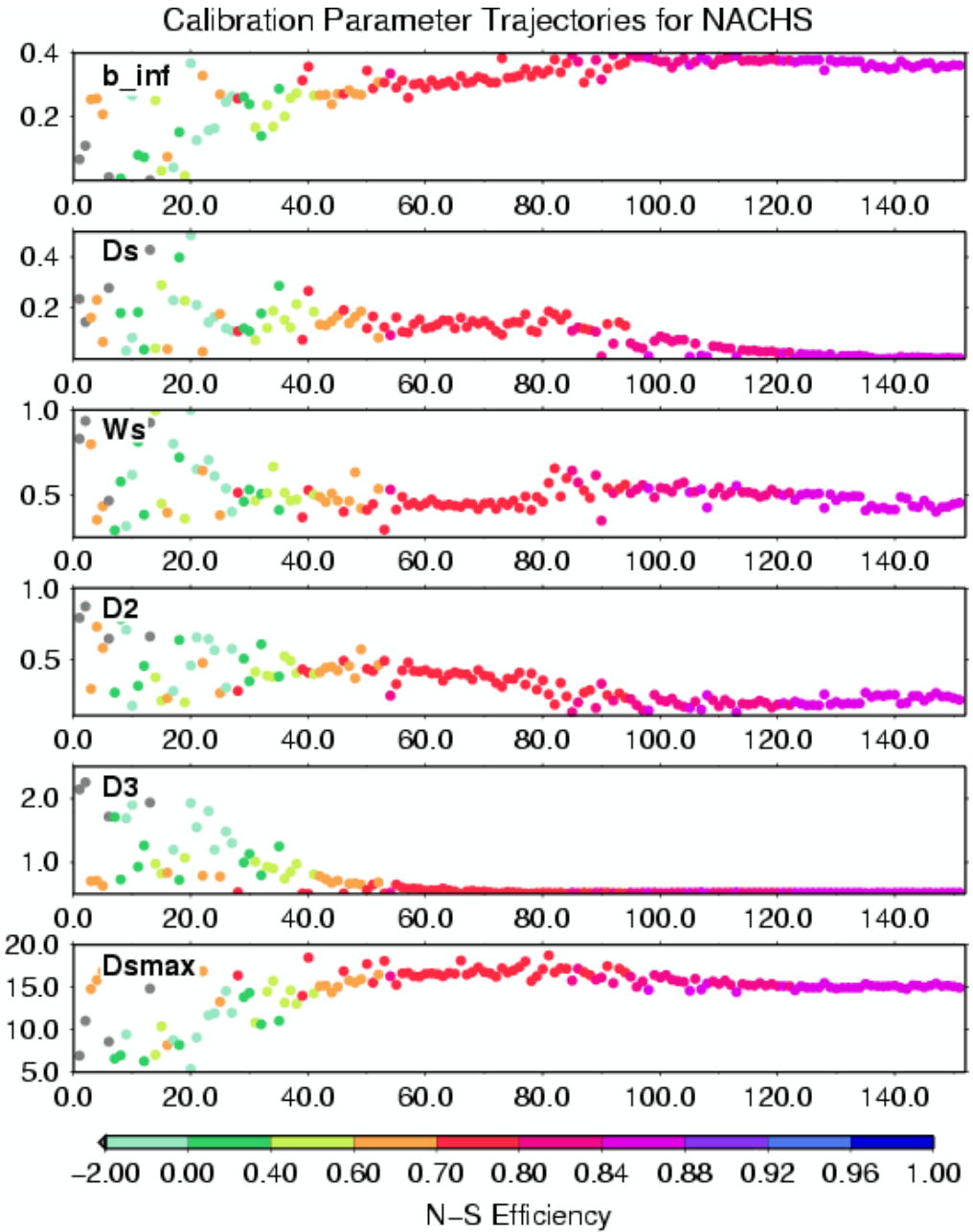
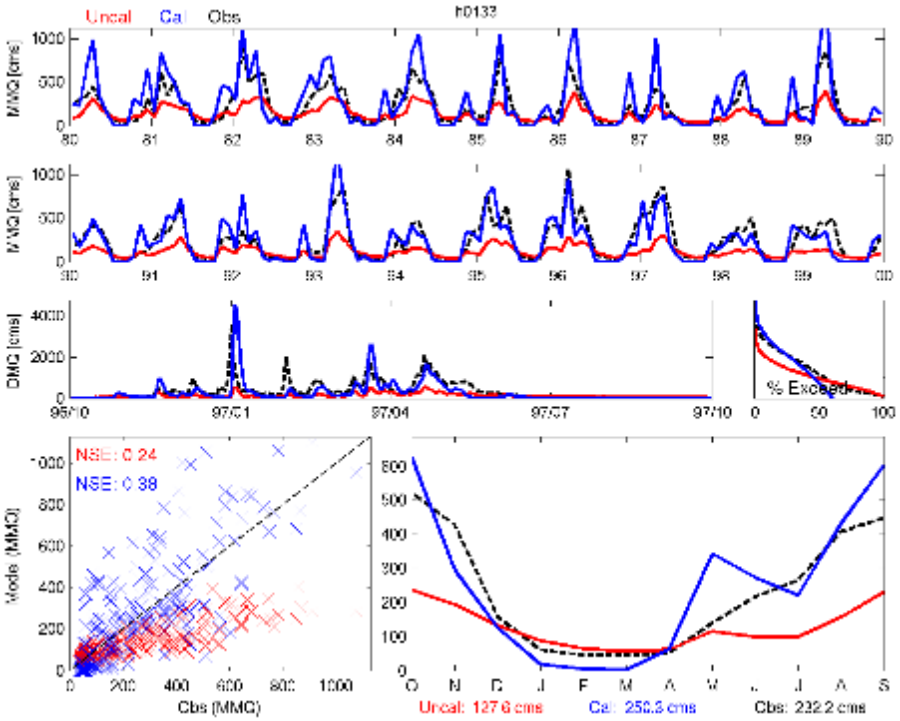


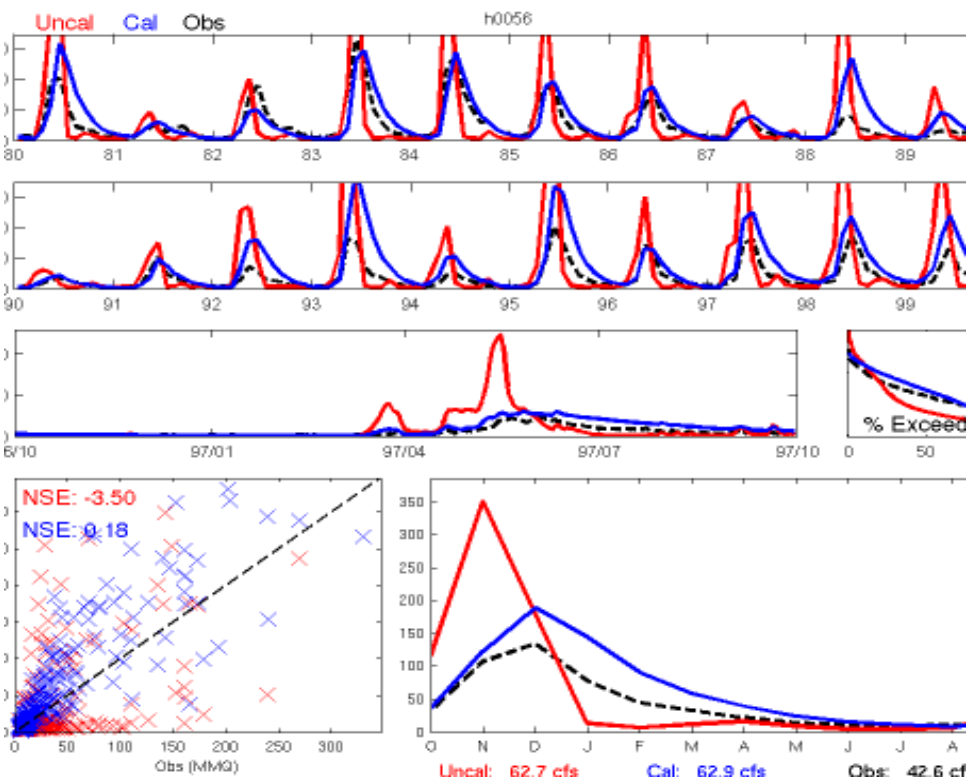
Figure at right (from prior work) illustrates process

Recalibration results

Primary recalibration focus was on HCDN sites with constraint of avoiding degrading existing larger basin calibrations

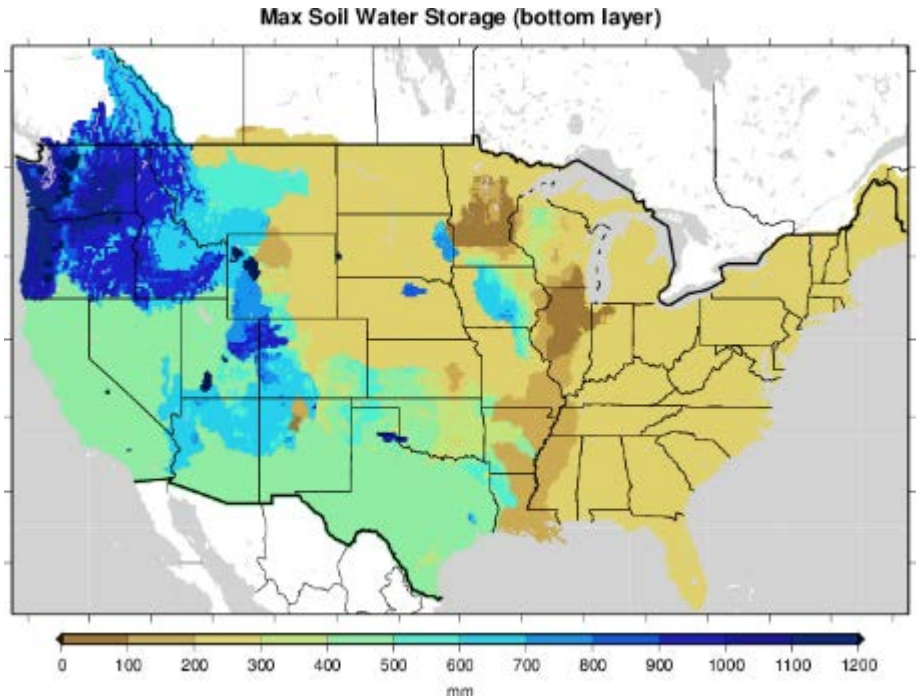
- of 153 evaluated, 77 were targeted for calibrations
- of these, approximately half were improved enough to warrant incorporation into the CONUS-wide soil file

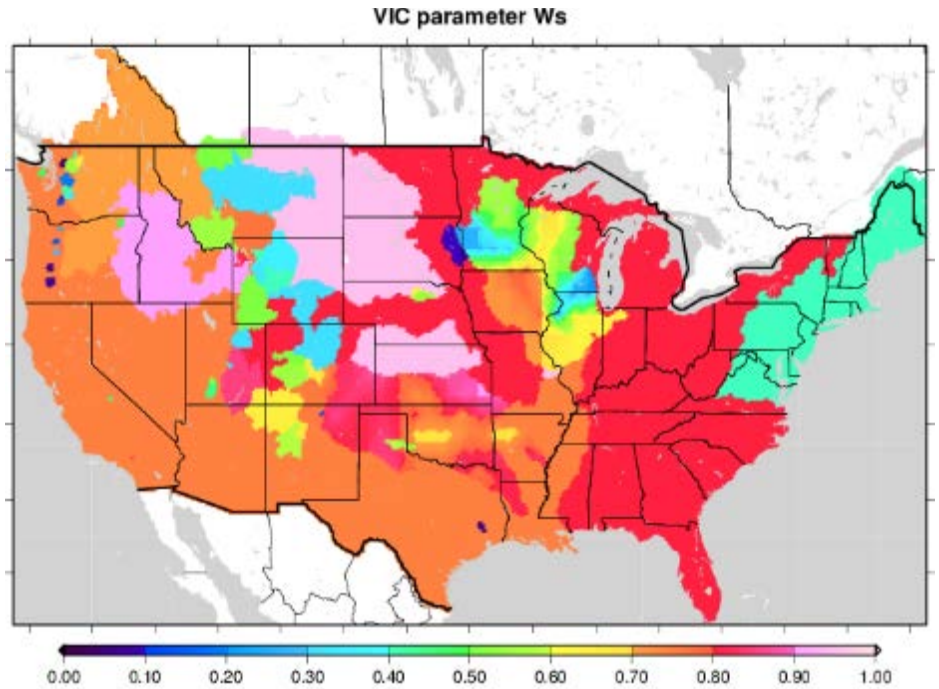




Recalibration results

- Further inspection of parameter variations argued against implementing traditional piece-meal approach toward calibration fixes
- Instead, the **original** WWCRA effort parameters were used for the VIC simulations
  - Work to date (eg flow & routing datasets) to be applied to NCAR's upcoming broader regional calibration efforts
  - Streamflow simulation performance documented for users





Other run details

- Other streamflow simulation locations were added or initiated to support follow-on efforts
  - over 1000 adjusted monthly flow time-series were obtained through contacts at NRCS National Water and Climate Center – for future calibration use
  - Eastern US 1/8th degree routing networks and upgraded parameters are being obtained from Princeton University and NCEP EMC.

- Run times
  - CONUS forcing generation – 10 hours/scenario on 16 CPUs
  - CONUS VIC run – 8 hours per run on 64 CPUs
  - daily, monthly netcdf conversions – ½ hour to 1 hour per run on up to 150 processors

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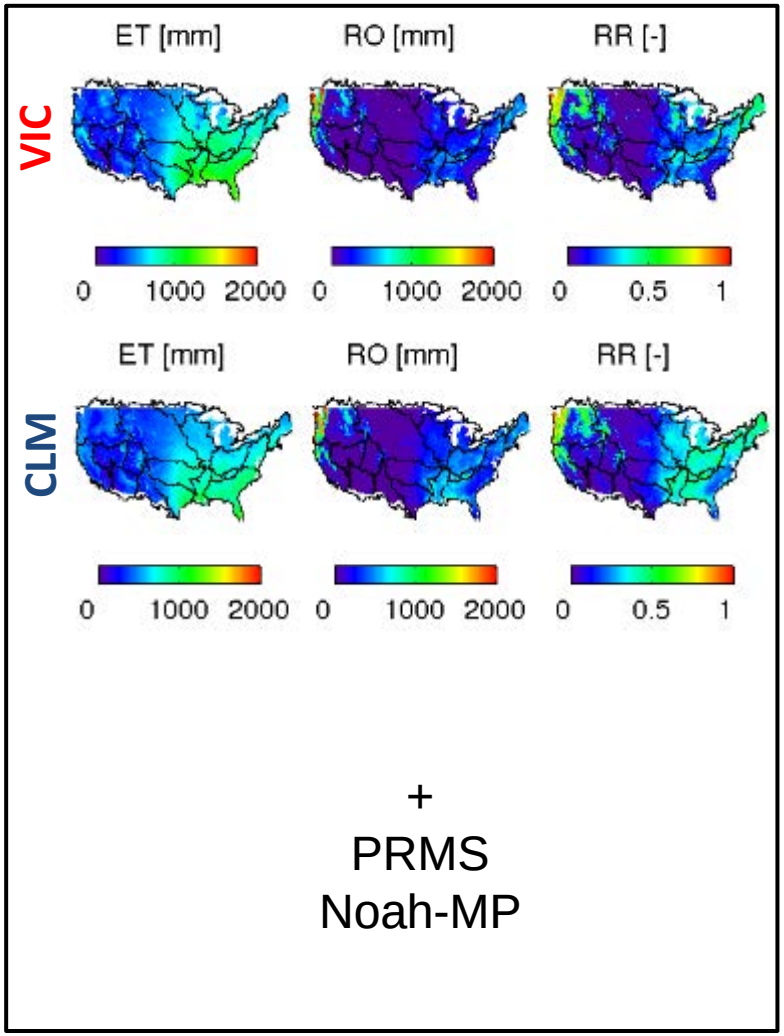
Timeline for hydrologic modeling

- Current practice
  - Single semi-calibrated hydrologic model
  - Sub-optimal model fidelity and no characterization of uncertainty
- Medium-term deliverables (for SECURE 2016)
  - HRU implementation of existing hydrologic models (using the USGS geospatial fabric), with network-based routing models
  - Focus on estimation of model parameters (multi-objective, regionalized, and probabilistic)
  - Evaluate methods to cull ensembles to produce a relatively small representative subset of hydrologic scenarios
- Long-term modeling ambitions
  - Model fidelity: Integrate best modeling approaches from existing models into a common framework, and improve estimates of model parameters
  - Model uncertainty: Characterize uncertainty using ensembles of physics options (where ambiguity exists) and ensembles of model parameters
  - Use findings from the longer-term research effort to “correct” the trajectory of medium-term projects

Initial modeling infrastructure

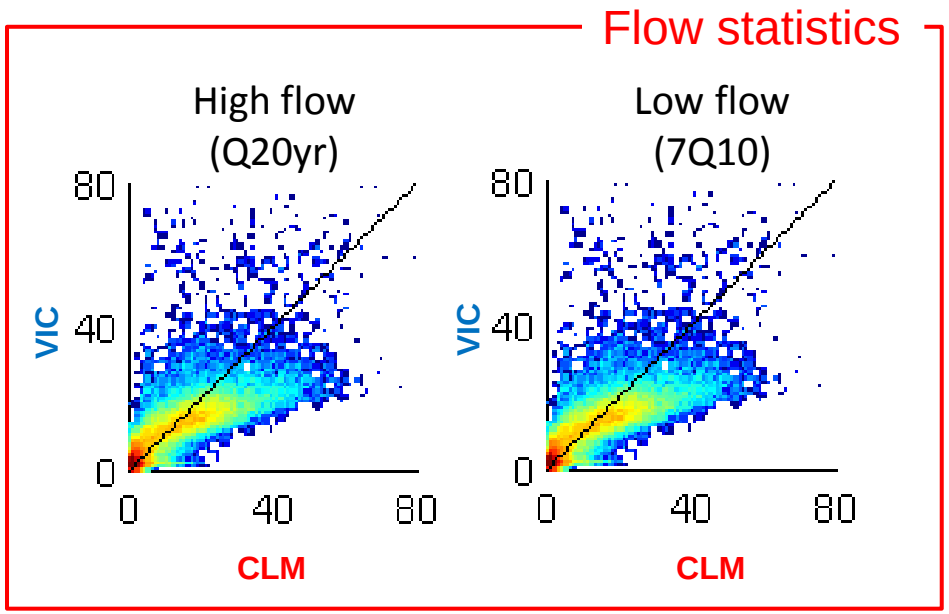
Move from single-model to multi-model approaches

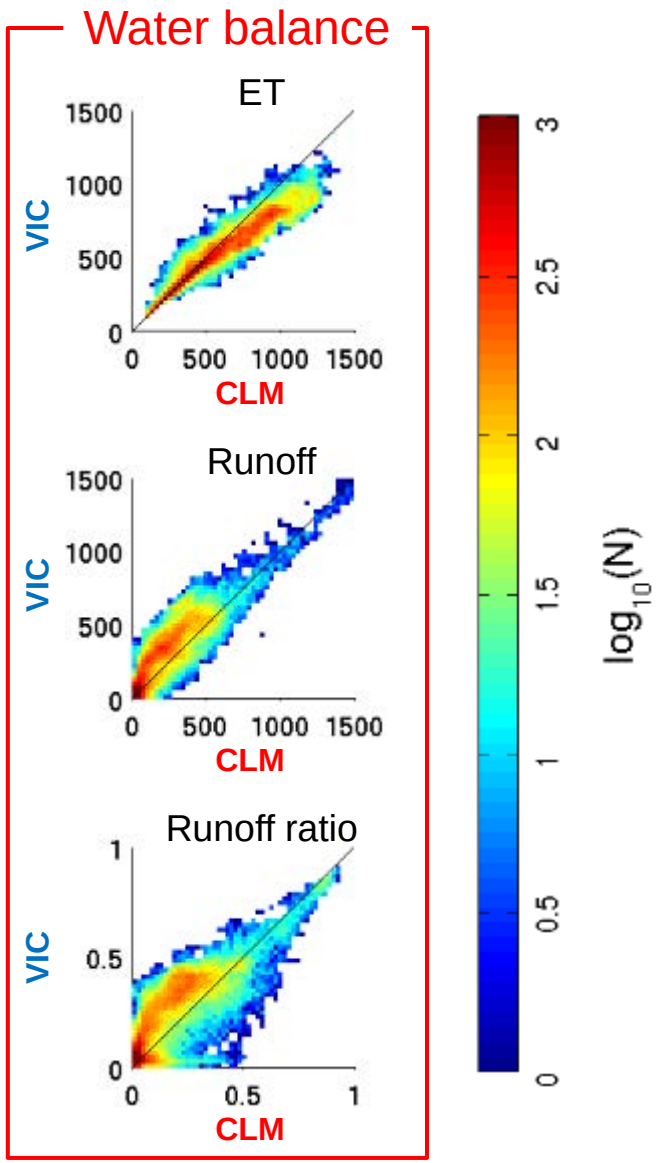
- Continental-scale application of existing 1-d hydrologic and land-surface models
  - Models applied on either Hydrologic Response Units (HRUs) or grids
- Routing using the USGS river network topology from the Geo-spatial Fabric
  - Simulate streamflow at all USGS stream segments
    - Simple time-delay routing models (like used in VIC)
    - Lagrangian kinematic wave routing model
    - (more)
- Use of default model parameters



Inter-model differences

- Large inter-model differences in
  - Partitioning of precipitation between ET and runoff
  - Flow statistics
- Outstanding questions…
  - Is the difference among models symptomatic of poor fidelity in one (or both) models?
  - Is the inter-model difference a good proxy for model uncertainty?
- More generally…
  - How can we improve hydrologic model fidelity and better characterize model uncertainty?





HRU implementation of macro-scale hydrologic models

- Hydrologic Response Units (HRUs) define areas of the landscape that exhibit a similar hydrologic response to external forcing
  - The USGS geo-spatial fabric delineates HRUs for the contiguous USA
- Macroscale hydrologic models have been configured to run for the USGS HRUs, coupled with a network-based Lagrangian kinematic wave routing model.

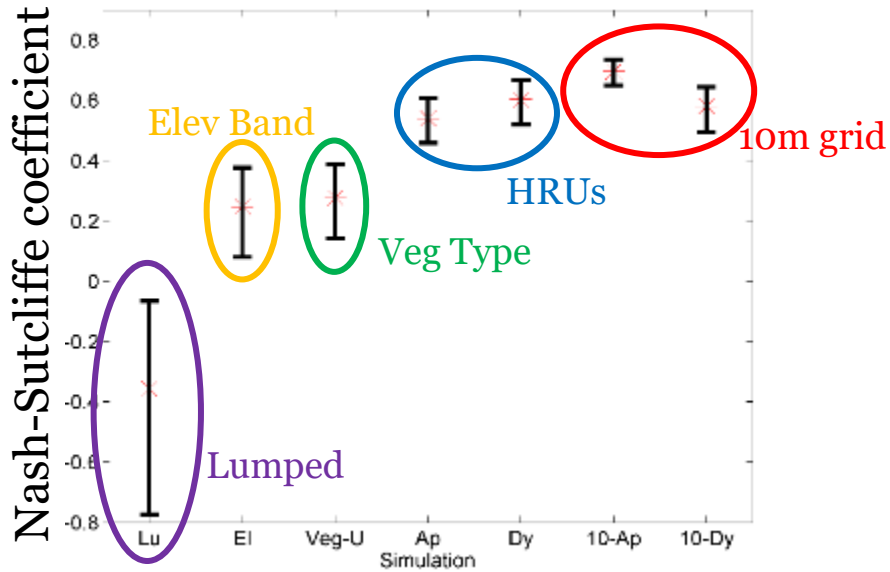
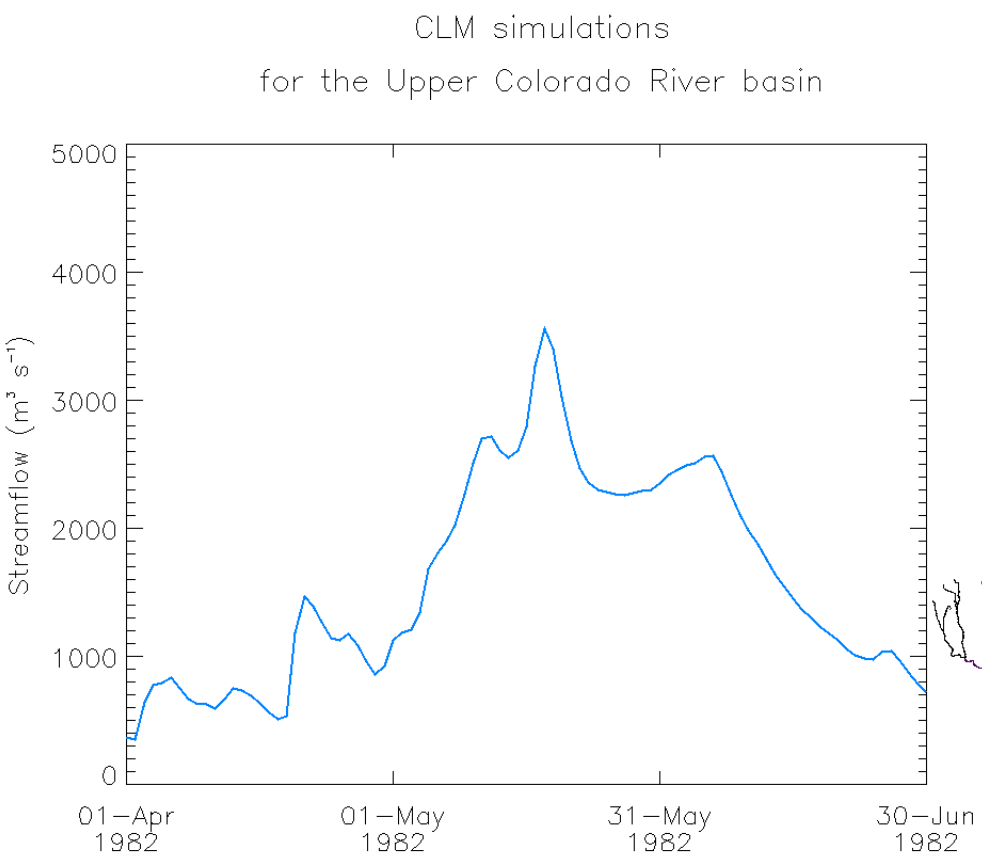
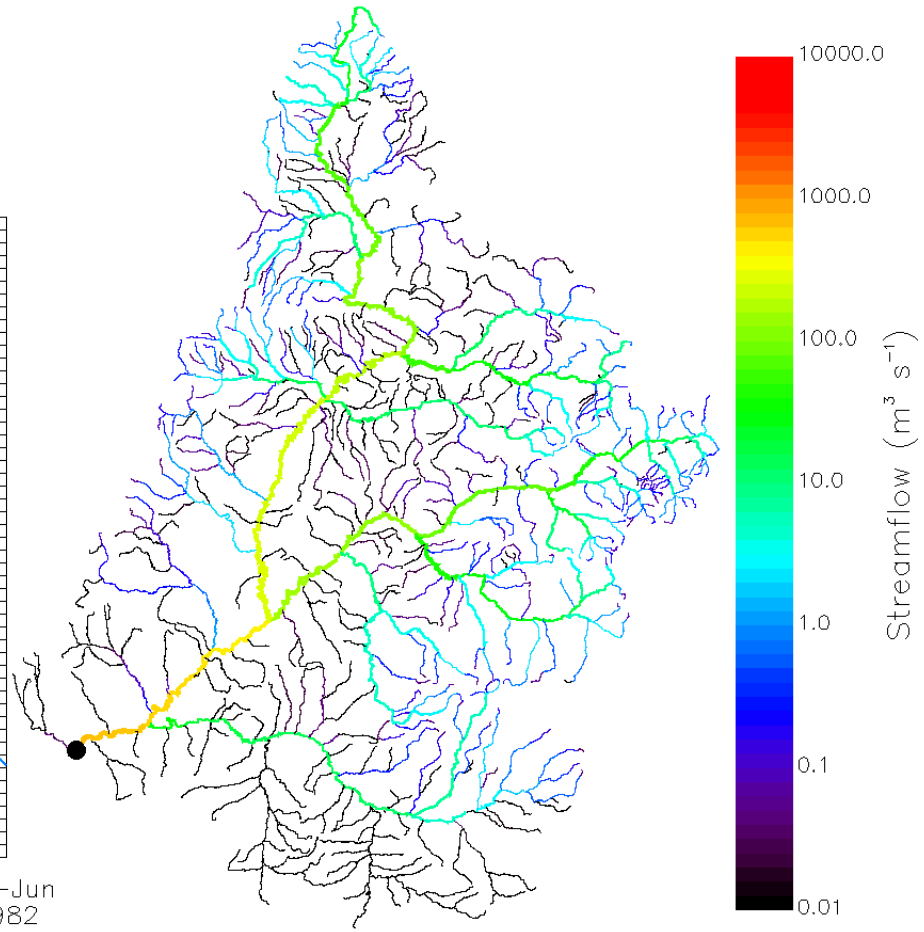


Figure above shows that the accuracy of hydrologic simulations on a 10-m grid is similar to the accuracy obtained where the basin is delineated into HRUs, and much higher where the basin is delineated into elevation bands and vegetation type. The lumped simulations have negative skill.

Figure from Newman et al., JHM (in press)

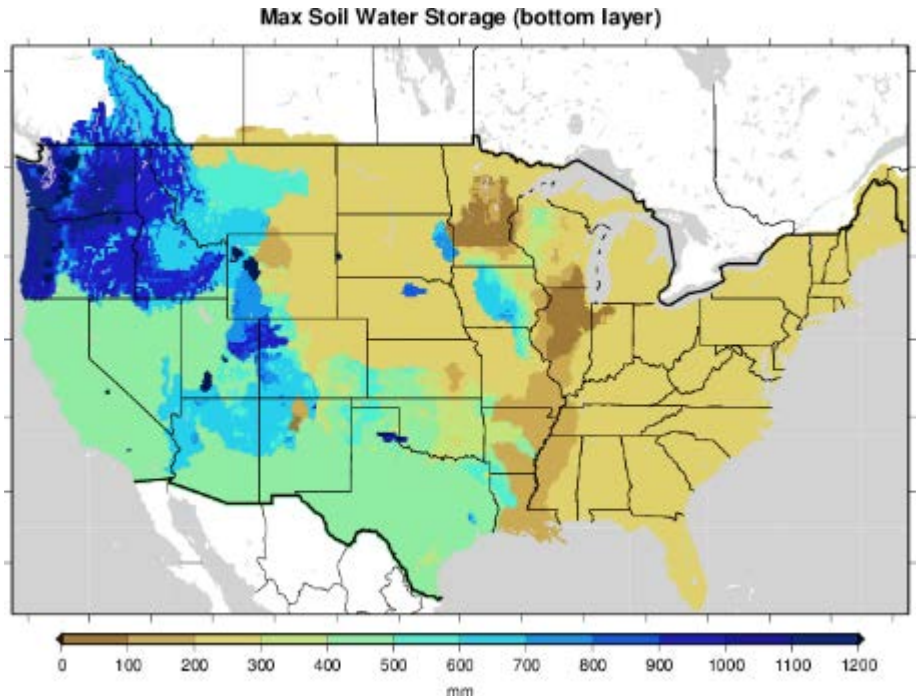
CLM simulations coupled with network-based routing model configured for the USGS geospatial fabric

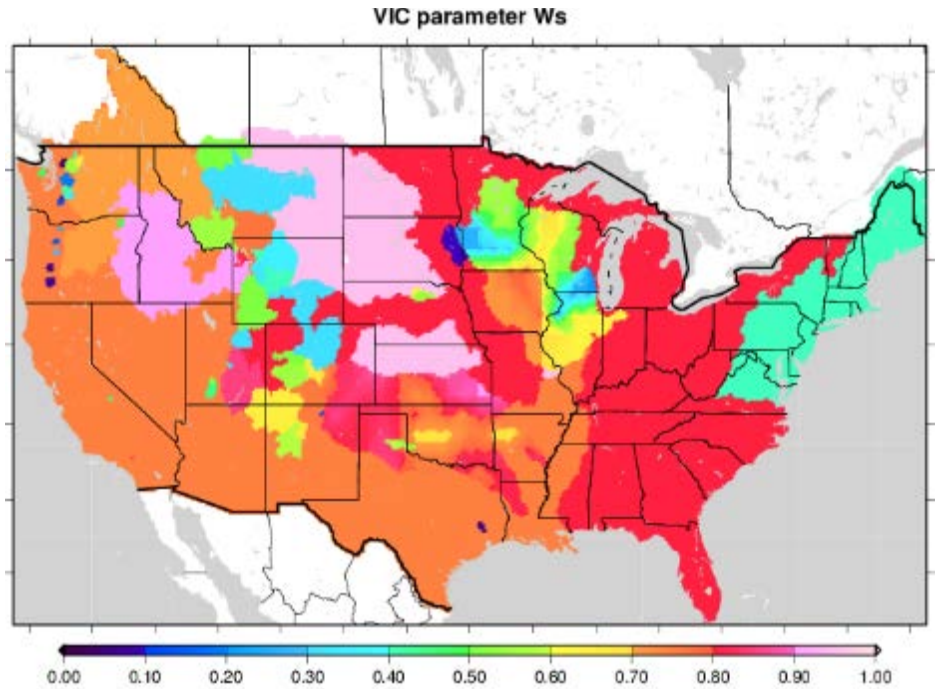




Parameter estimation

- Understand sensitivity of model parameters to multiple objectives
  - *Re-code models to increase flexibility of models to represent spatial heterogeneity and model uncertainty*
- Use regionalized probabilistic multi-objective parameter estimation methods
  - *Avoid the unphysical "patchwork quilt" parameter maps that plague basin-by-basin parameter estimation methods*





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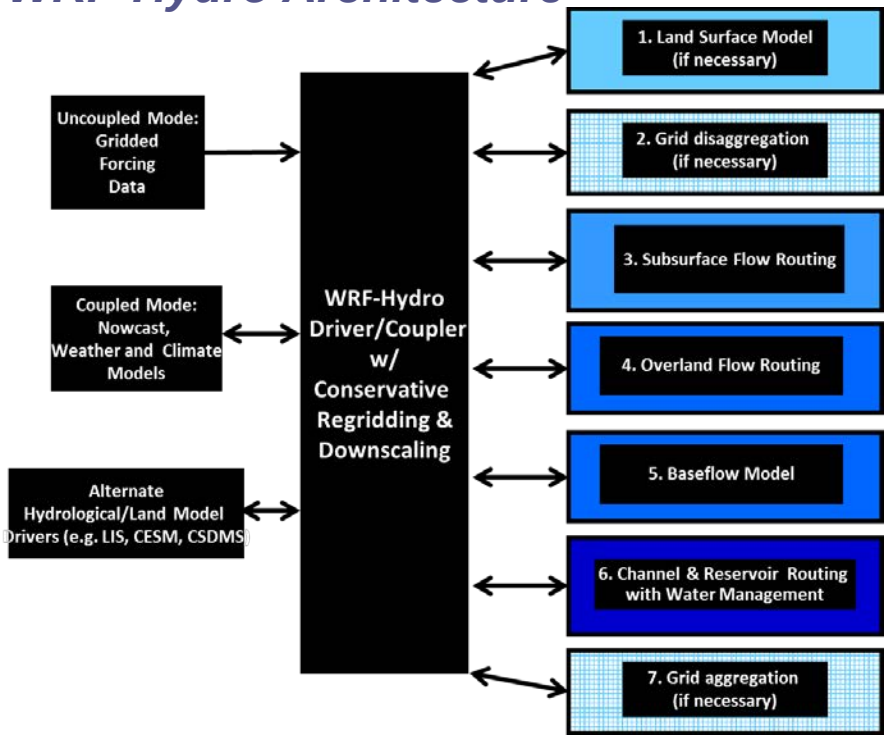
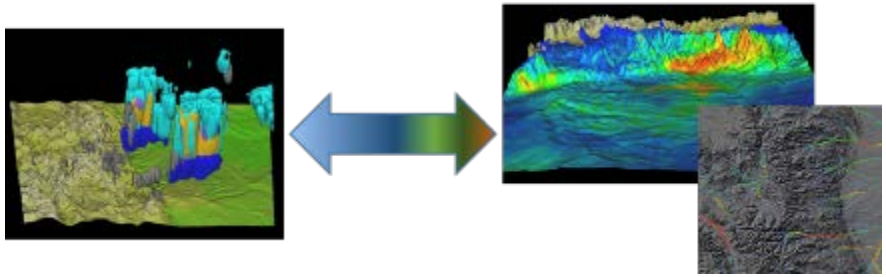
Enable component coupling across scales and levels of process complexity

WRF-Hydro Architecture



Two-way ('coupled') ↔



Explicit representation of dominant physical processes at the scales in which they operate (km's for atmosphere 10s of m's for land)

<u>Motivation</u>: Provide framework for understanding and predicting interaction of hydrologic and atmospheric processes

<u>Approach</u>: Design a flexible, extensible architecture for performing multi-scale, two-way coupled process modeling of hydrology and meteorology/climate

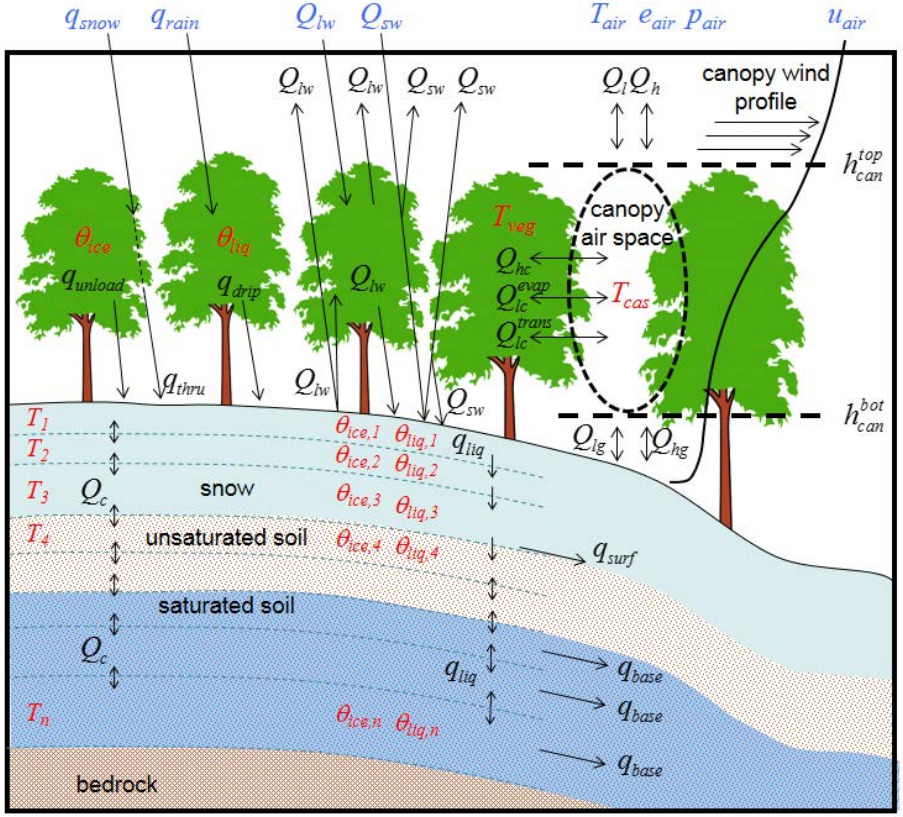
- *Capitalize on existing, portable community modeling architectures and increases in computing resources*
- *Maximize use of data standards to aid in pre-/post-processing*

<u>Desired Outcomes</u>: adaptable and portable platform for hydrometeorological/ hydroclimate analysis and prediction

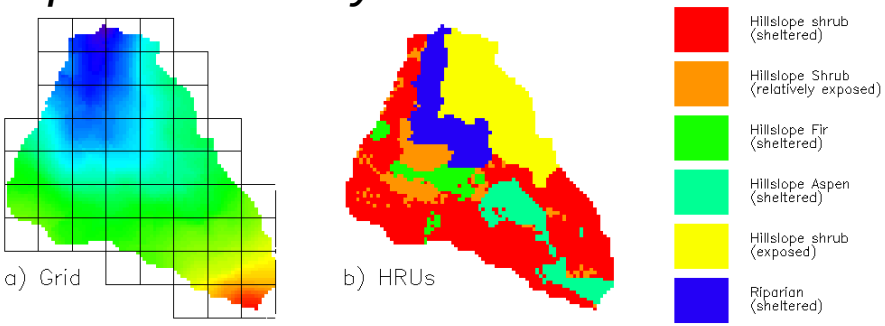
- *Better understanding of land-atmosphere coupling behavior across the time-space continuum*
- *Integrated prediction system design that conserves mass and energy between all components*
- *Programming environment that is amenable to augmentation and experimentation*

Systematic analysis of process-based hydrologic models

1-d column physics



Spatial variability



Downslope flow of water across the landscape (flow from discontiguous HRUs to a contiguous riparian zone)

- <u>Motivation</u>: Model inter-comparison experiments have not provided many insights on reasons for inter-model differences
  - Differences in model behavior caused by differences in parameter values, process parameterizations, model architecture, and numerical solution
  - Different modeling options/parameter values are highly inter-dependent, making it difficult to *attribute* differences in model performance to specific modeling decisions
- <u>Approach</u>: Conduct a systematic analysis of process-based hydrologic models
  - Recognize that different (process-based) hydrologic models share the same set of governing equations – different models can be considered small permutations of a master modeling template
  - Integrate different modeling alternatives into a common framework and evaluate specific modeling decisions in a controlled way
- <u>Desired outcomes</u>: Fidelity and uncertainty
  - Improve model fidelity – identify preferable modeling approaches and parameter values
  - Better characterize model uncertainty

Example modeling options

Process	Methods	References
Canopy radiation	Beer's law Beer's law with multiple scattering Simple two-stream model Two-stream model	Beer (1852) Nijssen and Lettenmaier (1999) Mahat and Tarboton (2012) Dickinson (1983), Niu et al. (2011)
Surface albedo	Constant time decay, broadband albedo Variable time decay, wavelength dependence	Verseghy (1991), Niu et al. (2011) Yang et al. (1997), Niu et al. (2011)
Canopy turbulence	K-theory, exponential wind profile K-theory, below-canopy logarithmic wind profile Alternative canopy wind reduction formulations	Choudhury+Monteith (1988 Mahat et al. (2013) Norman et al. (1995)
Stability corrections	Asymptote to critical Richardson number Non-zero stability above the critical Richardson number Exponential stability function under stable conditions	Anderson (1976) Louis (1979) Mahrt (1987)
Stomatal resistance	Soil moisture controls Ball-Berry type formulation	Liang et al. (1994) Oleson et al. (2010), Niu et al. (2011)
Canopy interception and unloading	"Sticky snow" interception, and unloading tied to melt drip Density-dependent interception and linear unloading rate	Andreadis et al. (2009) Hedstrom and Pomeroy (1988)
Frozen soil	Van Genuchten functions for super-cooled liquid water	Harlan (1973)
Soil hydrology	Moisture form of Richards' equation Mixed form of Richards' equation Power-law transmissivity profiles	Boone and Wetzel (1996) Celia et al. (1990) Beven (1997)
Model architecture	Lumped Vegetation mosaic Conceptual baseflow reservoir Disconnected hydrologic response units Connected hydrologic response units	Chen and Dudhia (2001) Koster and Suarez (1992) Liang et al. (1994) Leavesley (1983) Wigmosta et al. (1994)

Conclusions relevant for climate impact assessments

- Improving model fidelity is possible through preferential selection of approaches from existing models – creation of the dream model
  - Numerical methods, for example
    - Prognostic canopy air space
    - Numerical error control and adaptive sub-stepping
    - Flexible hierarchal data structures
  - Physical representations, for example
    - Variably saturated flow
    - Biophysical representation of transpiration
    - Hydrologic similarity concepts to represent sub-grid variability
    - Explicit representation of lateral flow

- Improving characterization of uncertainty requires a mix of multi-physics options and parameter ensembles
  - Uncertainty in model parameters
    - Inter-model differences in parameterizations of individual processes are often overwhelmed by uncertainty in model parameters – in these cases uncertainty in process representation can be characterized using an ensemble of model parameter sets
  - Uncertainty in process parameterizations and model architecture
    - There are still cases where different modeling options have different behavior and it is impossible to distinguish among competing parameterizations based on physical considerations or experimental data – in these cases uncertainty can be characterized using an ensemble of physics options
  - Uncertainty due to missing processes
    - Models are by definition a simplification of nature, and practical considerations and lack of knowledge mean that some physical processes are missing in hydrologic models – in these cases, different models may provide the “wrong” results for the same reasons, and it is necessary to be conservative in the communication of uncertainty

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A continuum of downscaling options

increasing physical representation

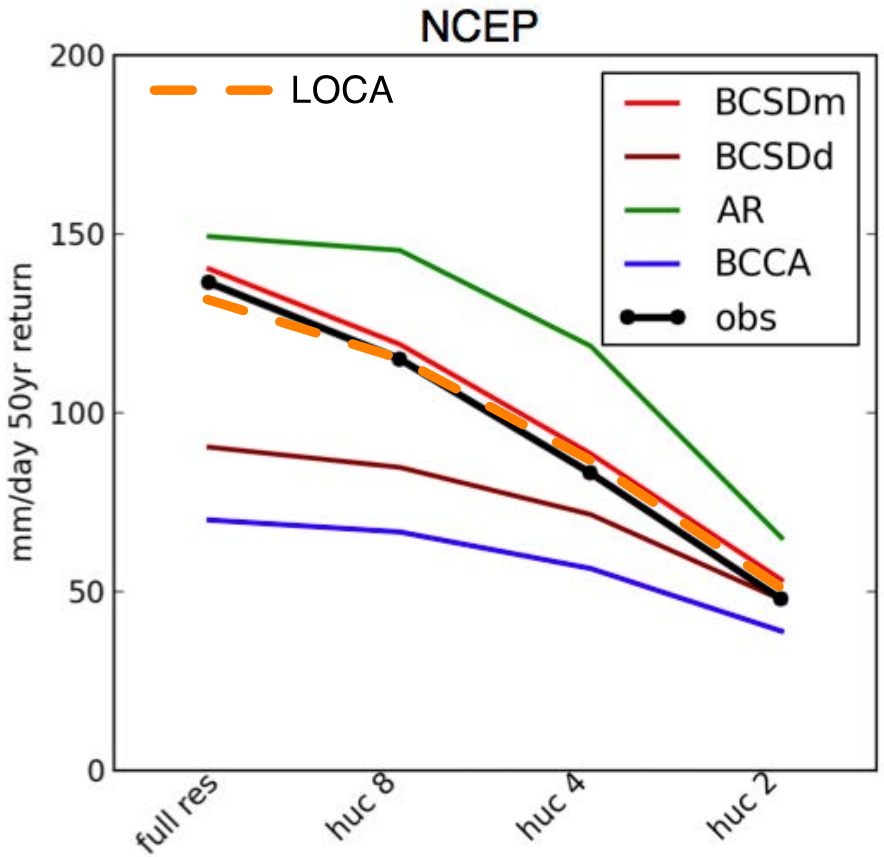
- Statistical downscaling based on GCM outputs
  - BCSD, BCCA, AR
- Statistical downscaling based on GCM dynamics (water vapor, wind, convective potential, etc.)
  - Regression-based methods
  - Analog methods
- Stochastic methods to relate the space-time variability of downscaled fields (wet day frequency, extremes, etc.) to synoptic scale atmospheric predictors
- Dynamical downscaling using simple weather models
- Dynamical downscaling using state-of-the-art RCMs

New Downscaling Methods

- Reviewing new “traditional” statistical techniques
  - LOCA, MACA, ?
- Circulation based statistical techniques
  - T, RH, wind, etc.
  - regressions with stochastic component
- Simple Weather Model
  - FAST, Simplified atmospheric physics

New Traditional Techniques : LOCA

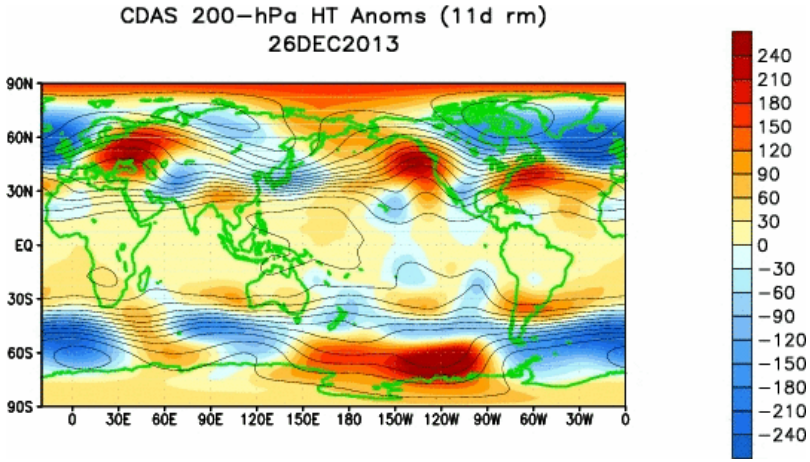
- LOCA = Locally Constructed Analog
  - Pierce and Cayan (2014)
- Develop a constructed analog for very small regions, and additional corrections
- Good spatial scaling characteristics

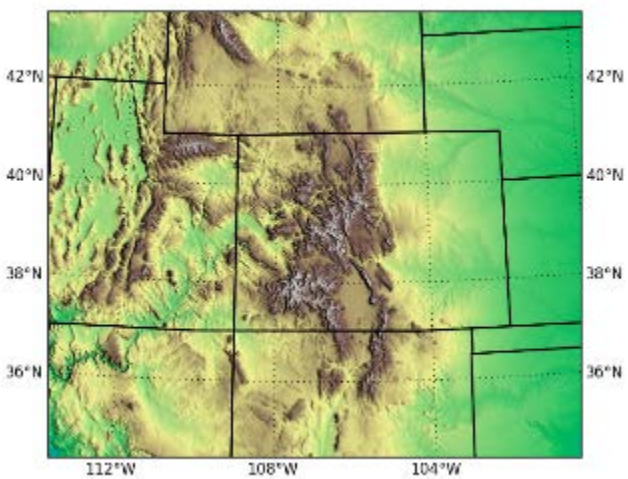


Circulation based statistics

- GCM precipitation is not reliable
  - (no topography, coarse grid)
- GCM circulation is probably more trustworthy
  - 3D: wind, humidity, temperature, pressure
- Develop regressions to calculate precipitation and other fields based on large scale atmospheric variables
- Use residuals from regression to incorporate uncertainty as a random error term
- Sample regression output with spatially correlated random numbers

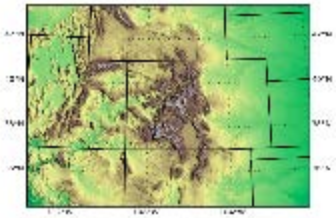
Stochastic Circulation Based Example





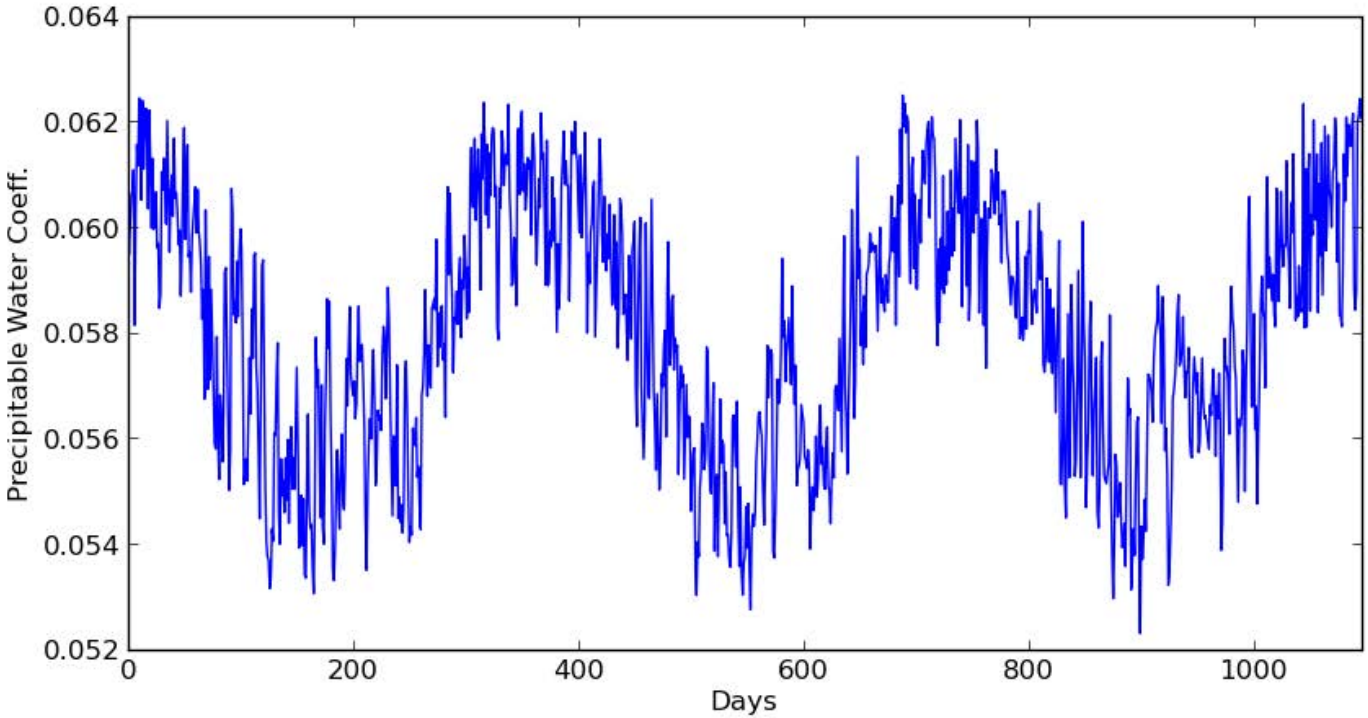
- Training data:
  - Maurer et al (12km)
- Forcing data:
  - GEFS (1°) (on left)
- Period:
  - 2001-2008
- Sub-domain:
  - Headwaters (on left)

Precipitation coefficients

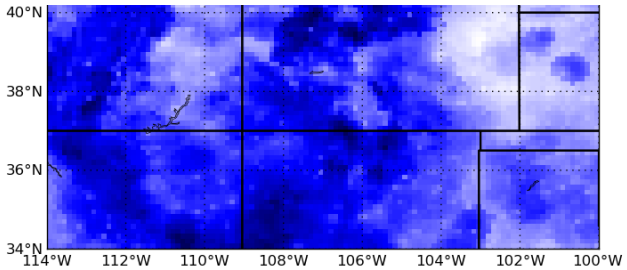


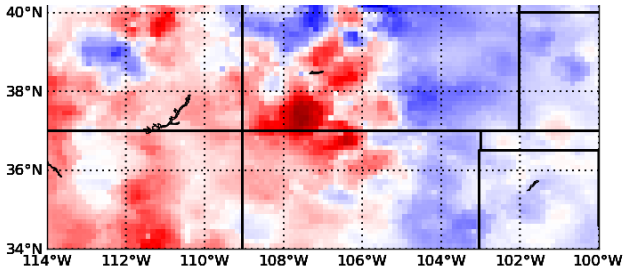
Precipitable Water
Positively correlated everywhere

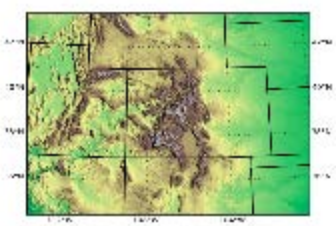
Zonal winds
Positively correlated on West slopes
Negatively correlated on East slopes



West slopes
-East slopes

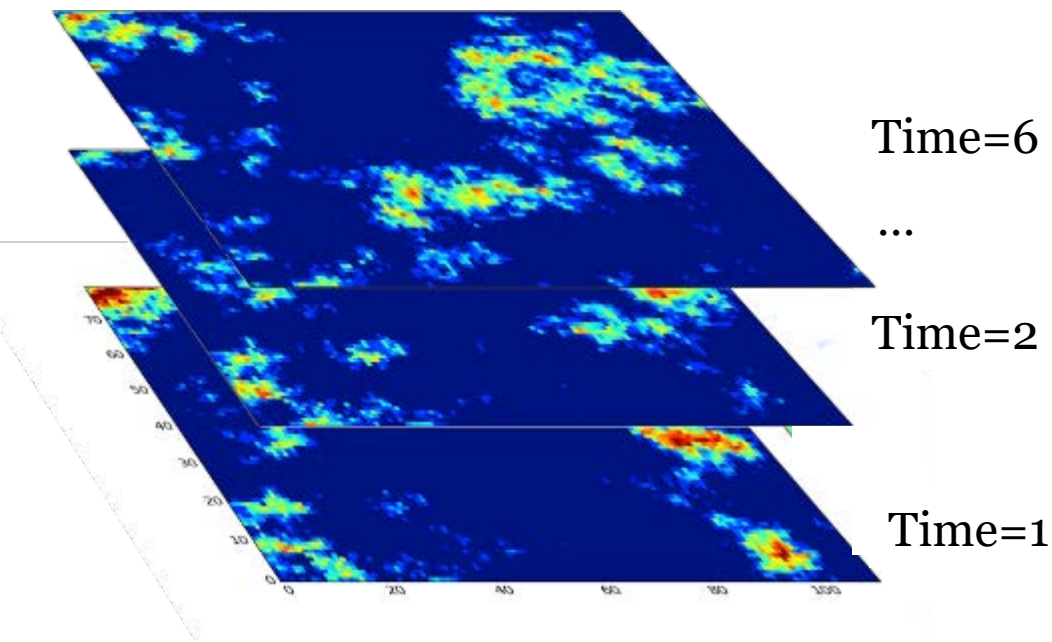


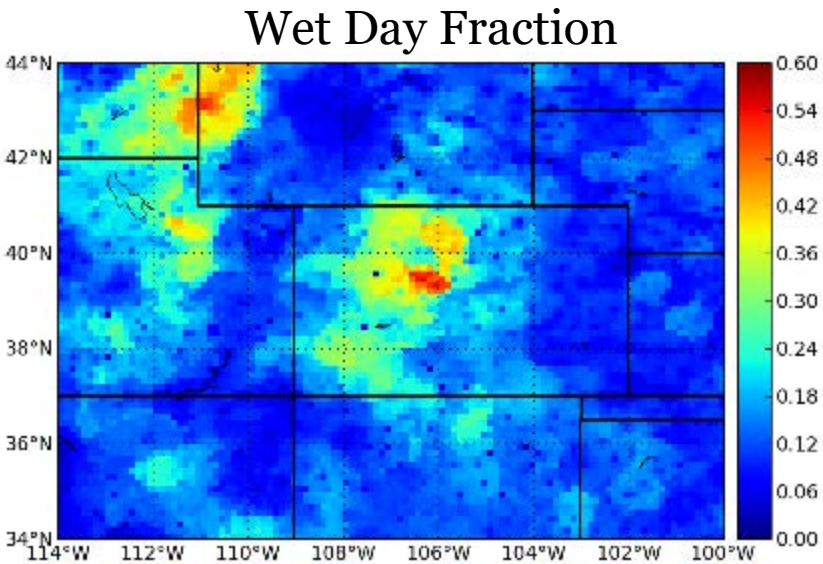




Random Spatial fields

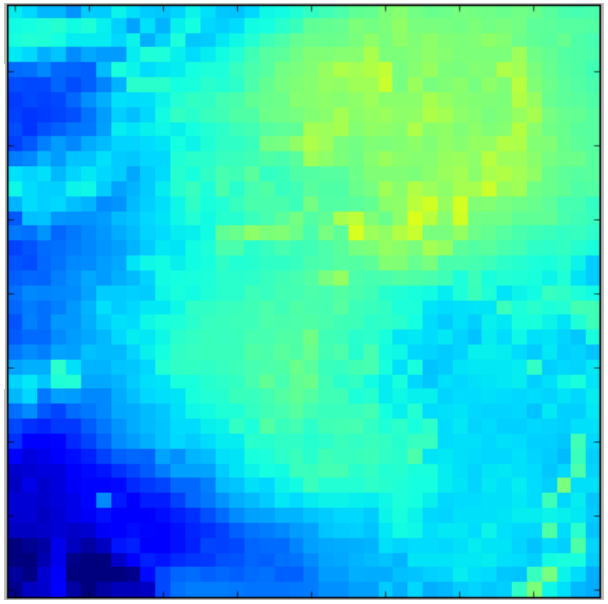
- Autocorrelated in space and time
- Provide realistic space-time variability
- Provide multiple realizations (uncertainty)





Stochastic processes

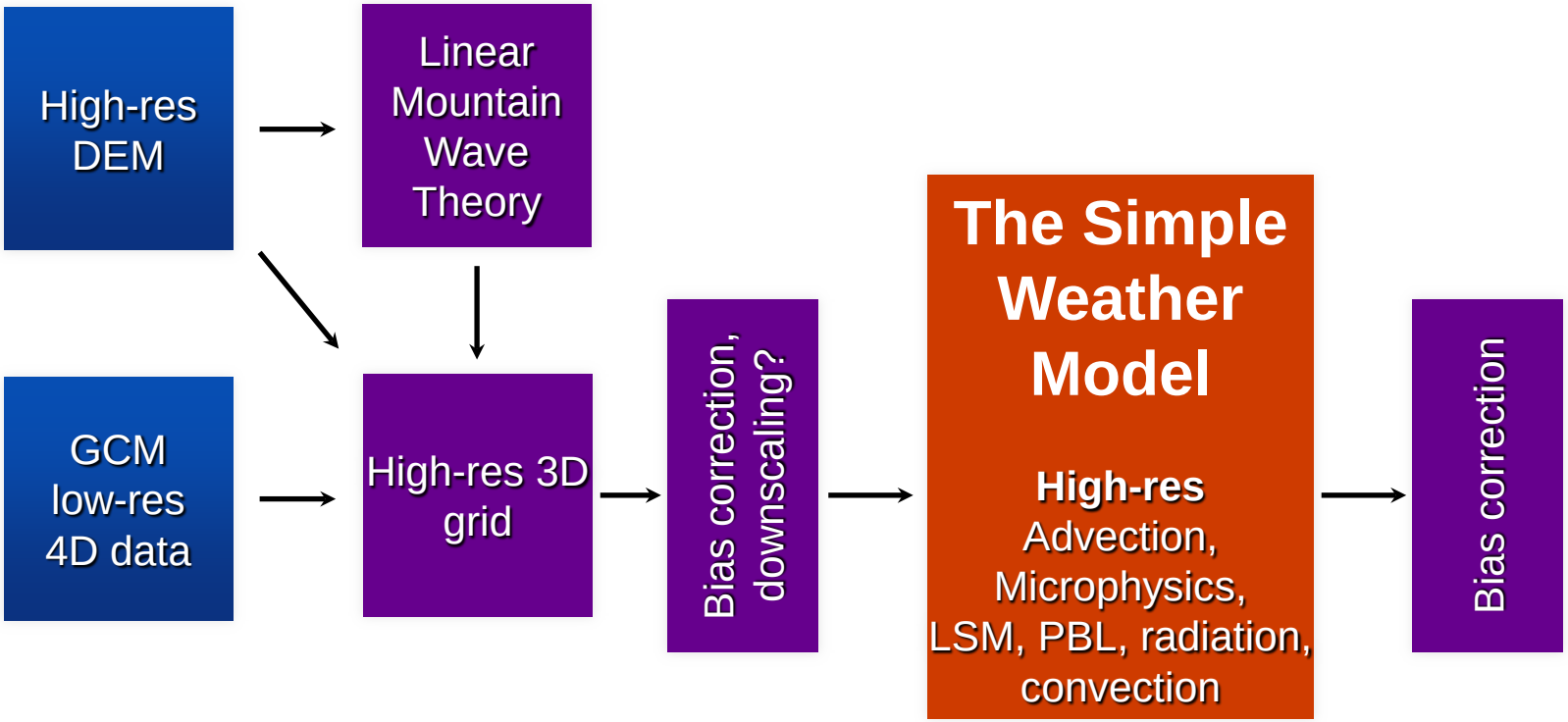
- Use of reasonably conditioned stochastic processes can improve some statistics over even the “observations”



Simple Weather Model

Statistical downscaling is computationally efficient (minus the physics)
Dynamical downscaling has loads of physics (but is too expensive)

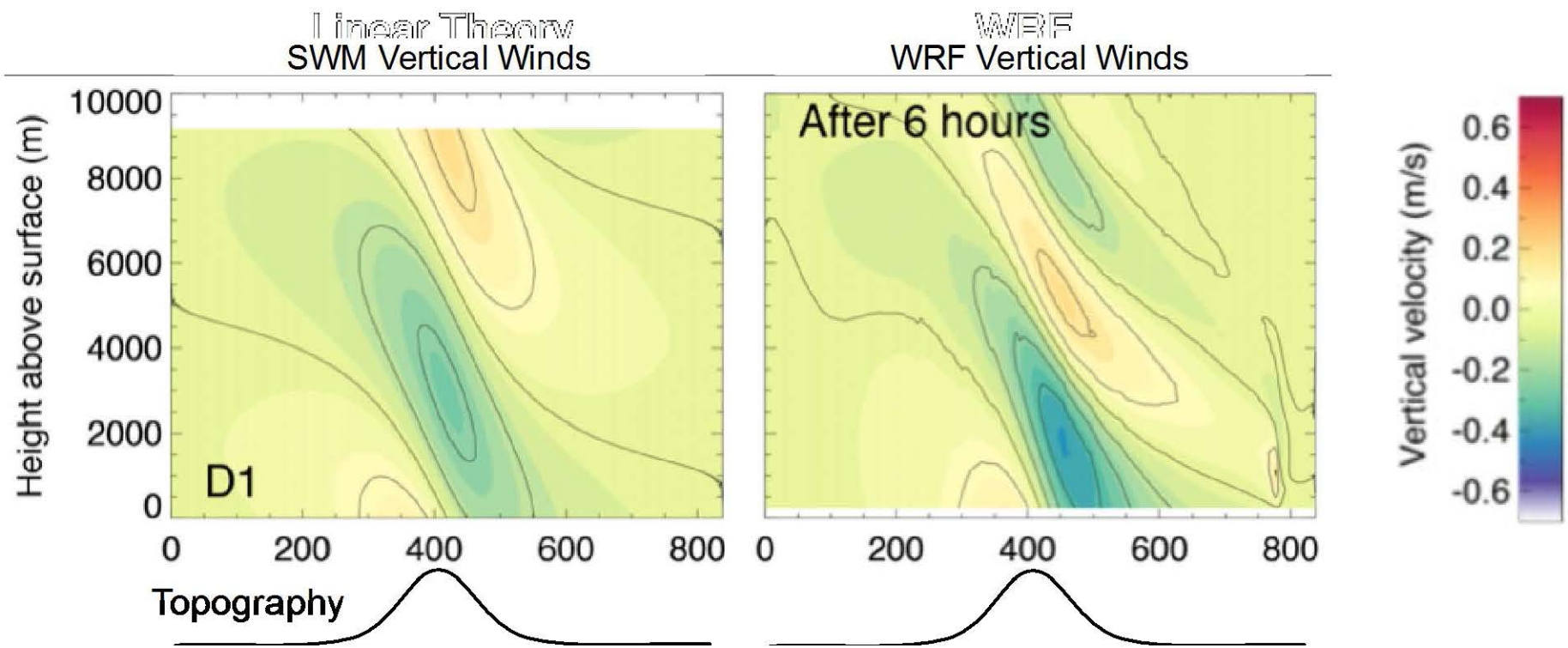
Identify the key physics and develop a simple model
GOAL: >95% of the information for <5% of the cost



Simple Weather Model Dynamics

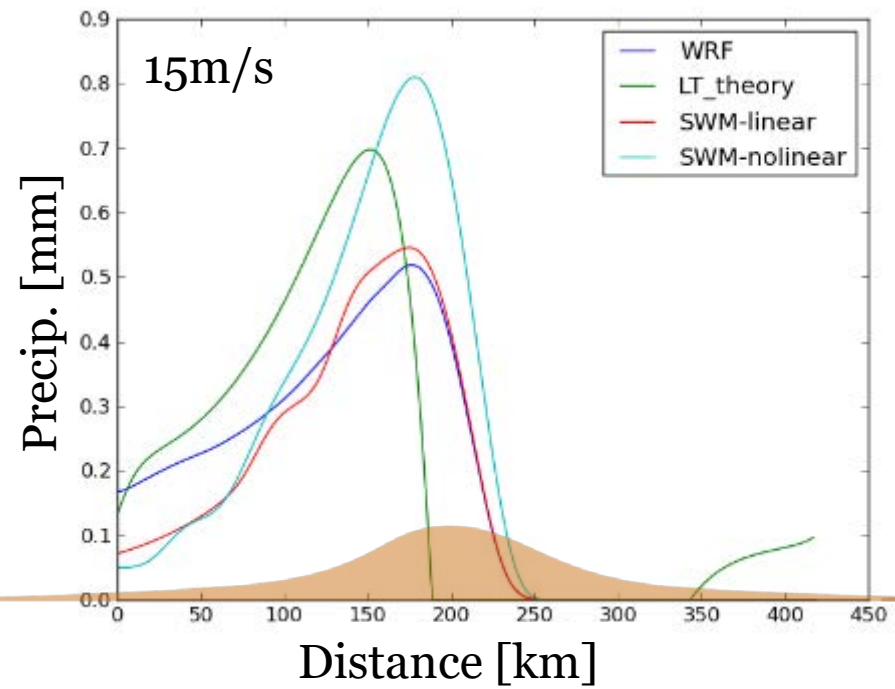
$$\hat{u}(k,l) = \frac{-m\,(\sigma k - ilf)\,i\hat{\eta}}{k^2 + l^2} \qquad \hat{v}(k,l) = \frac{-m(\sigma l + ikf)i\hat{\eta}}{k^2 + l^2}, \qquad \hat{w}(k,l) = i\sigma\,\hat{\eta}$$

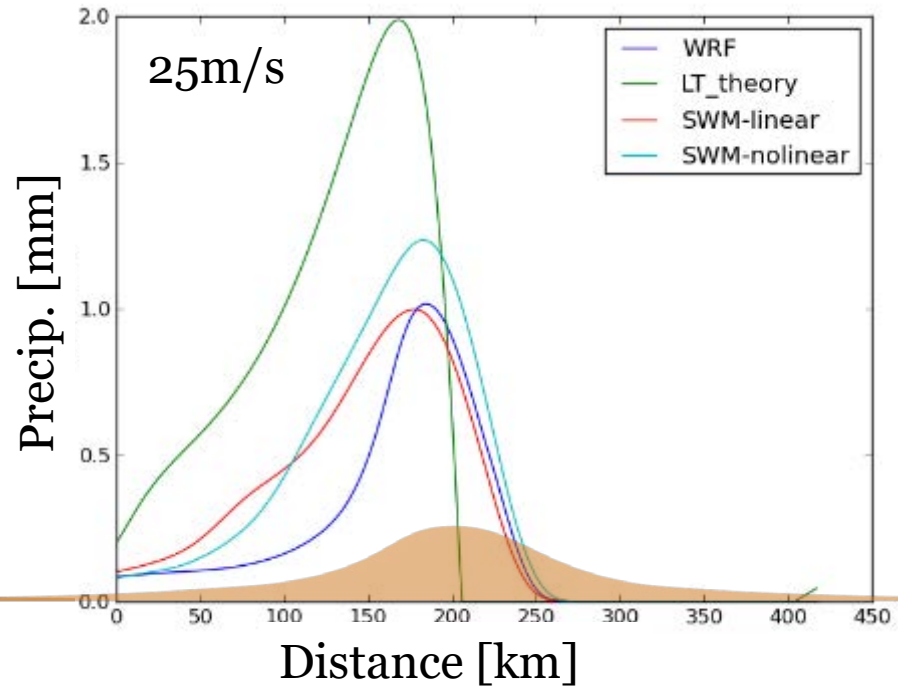
$$\hat{\eta}(k,l) = \hat{h}e^{imz}, \qquad m^2 = \frac{N^2 - \sigma^2}{\sigma^2 - f^2}(k^2 + l^2), \qquad \sigma = Uk + Vl$$



Simple Weather Model

- Changes appropriately with changing environmental conditions (e.g. wind speed)
- Also SWM (with linear winds) matches changes predicted by WRF better than pure linear theory
- Instills confidence that changes in climate will be reasonably reflected



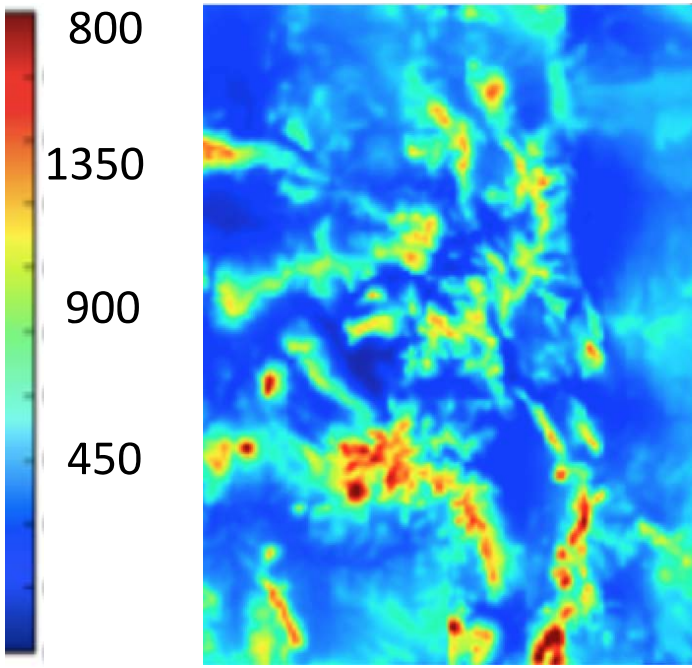


Simple Weather Model

WRF and SWM have very similar precipitation distributions.

SWM requires ~1% of the computational effort of WRF.

This enables a pseudo-dynamical downscaling for a wide variety of GCM / scenario combinations



(pre-bias correction)

Outline

- Baseline portrayals of climate change impacts on hydrology from CMIP5
  - Modeling approach
  - Analysis of model performance
- Improving hydrologic models
  - Initial modeling infrastructure
  - Integrating parameterizations and architectures from multiple models
- Improving downscaling methods
  - Reviewing “new” traditional techniques
  - Circulation-based statistical downscaling
  - The Simple Weather Model
- Summary & Discussion

Improved techniques for climate projection downscaling and hydrologic impacts assessment

Summary

- Developed baseline set of VIC runs and documented performance of current set of methods
- Developed multi-model hydrologic simulation platform for the CONUS using HRUs from the USGS geospatial fabric, coupled to a network-based routing model
- Developed simple dynamical downscaling methods that can be applied to multiple climate scenarios

Key Lessons Learned

- The semi-calibrated VIC model has poor performance for many basins across the CONUS
- Differences among hydrologic models are often overwhelmed by uncertainty in model parameters, and it is possible to characterize a large part of model uncertainty using parameter ensembles from a single model
- It is possible to greatly simplify model representations of environmental processes without large reductions in model fidelity

Next Steps/Future Work

- Improve estimates of model parameters across the CONUS for multiple hydrologic models
- Evaluate ensemble culling strategies to develop a representative set of hydrologic scenarios for SECURE2016
- Further evaluate the use of circulation-based and stochastic statistical downscaling methods, for potential inclusion in SECURE2016
- Complete the first phase of development of the Simple Weather Model (SWM), and apply SWM to a large set of GCM scenarios

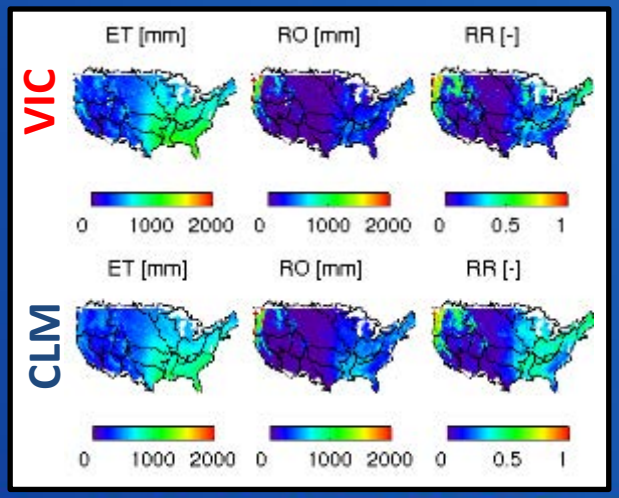


Figure: Differences in the partitioning of precipitation between ET and Runoff in CLM and VIC, when both models are forced with the Maurer et al. (2002) dataset

RECLAMATION