Building Resilience to a Changing Climate:

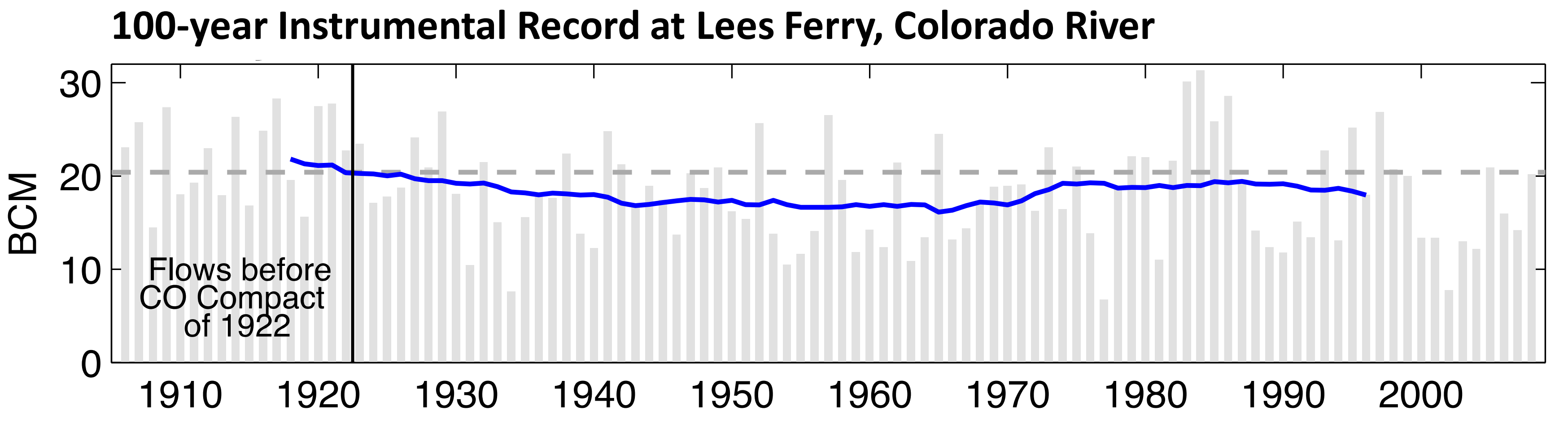
A Technical Training in Water Sector Utility Decision Support

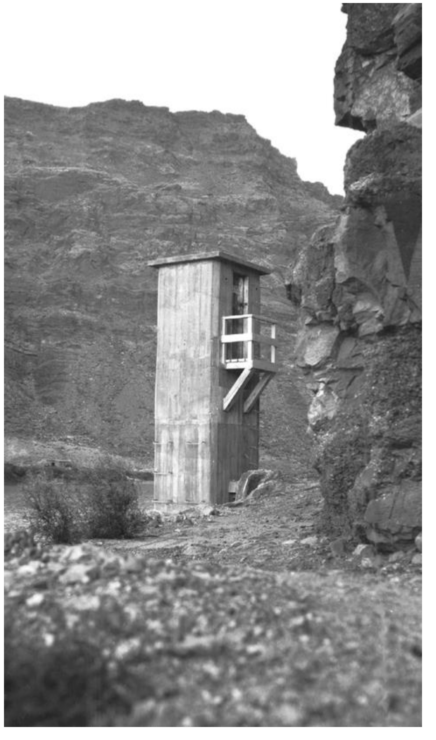
WUCA
Water Utility Climate Alliance

A Practical Look at Downscaling, Bias Correction, and Translating Climate Science into Hydrology

Julie Vano, Aspen Global Change Institute

Tools for Understanding Future Change

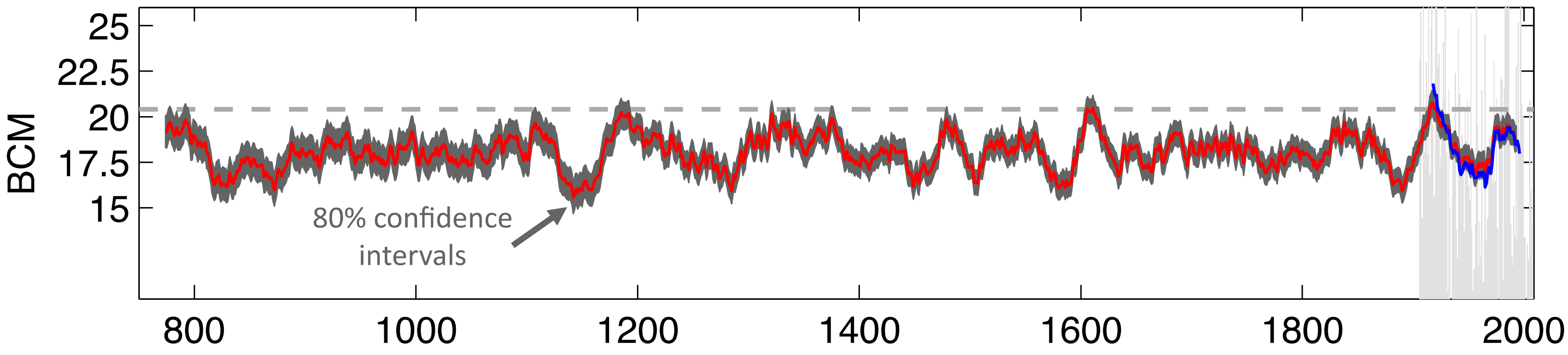


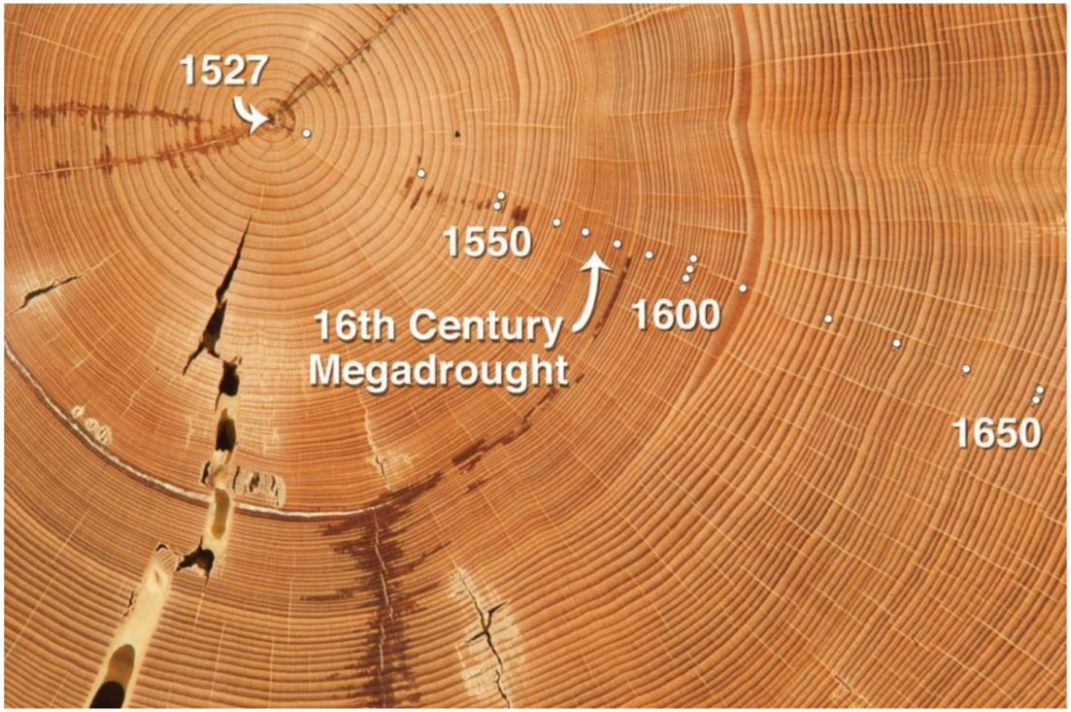


Monitoring of recent past and present

Tools for Understanding Future Change

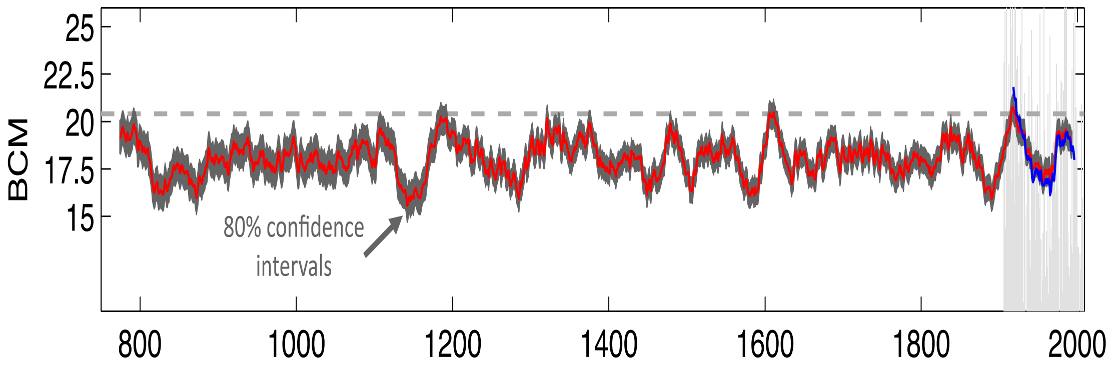
1250-year Streamflow Reconstruction

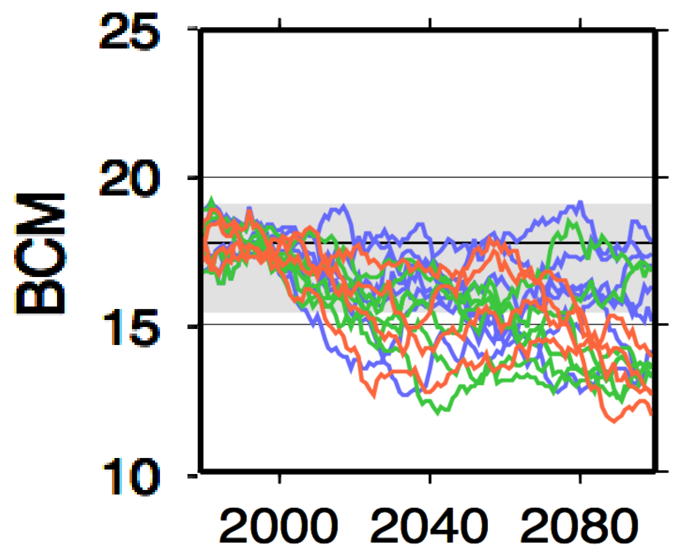


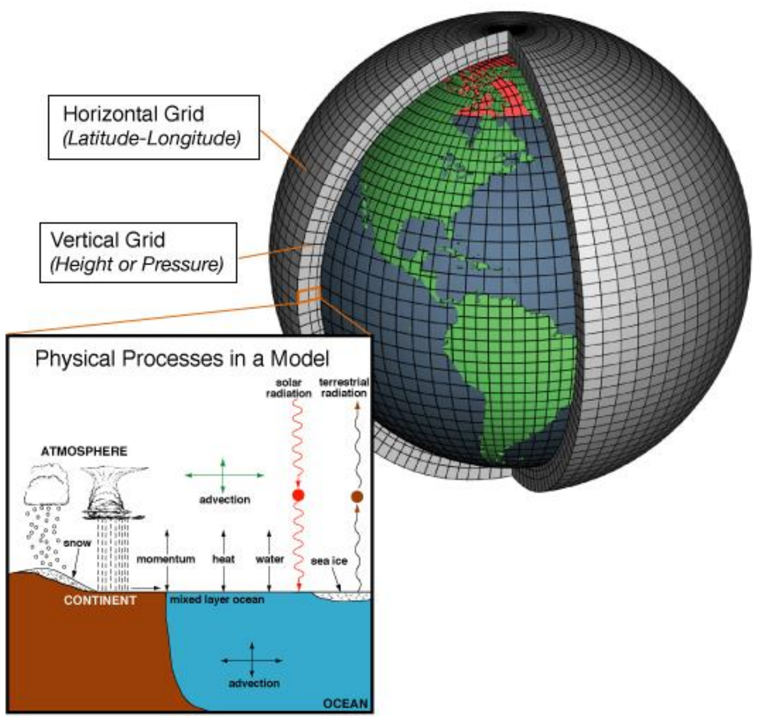


Tree rings from past

Tools for Understanding Future Change

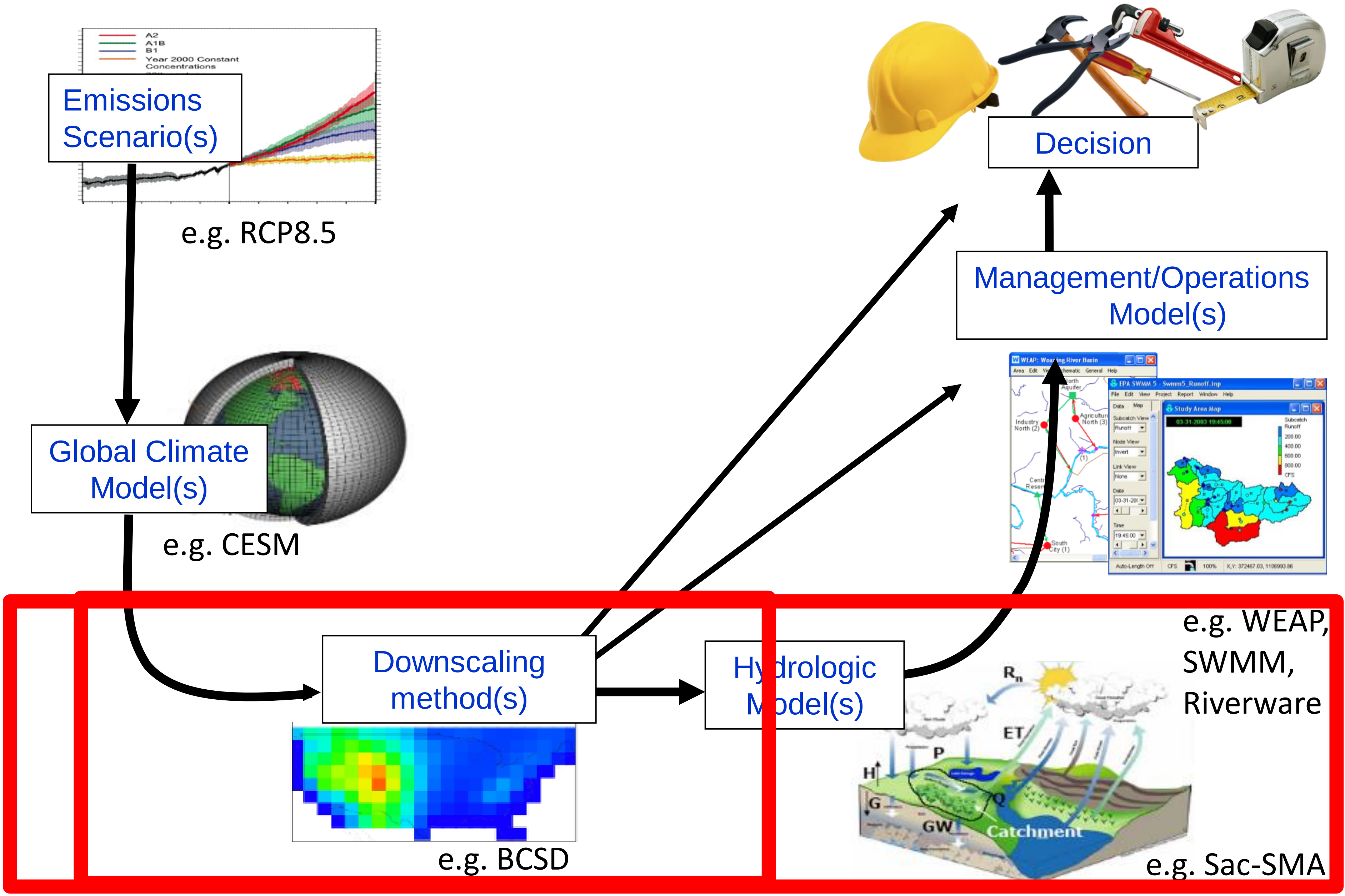






Model simulations of past, near-term seasonal prediction and future projections

Classic "Top-down" Impacts Modeling Chain



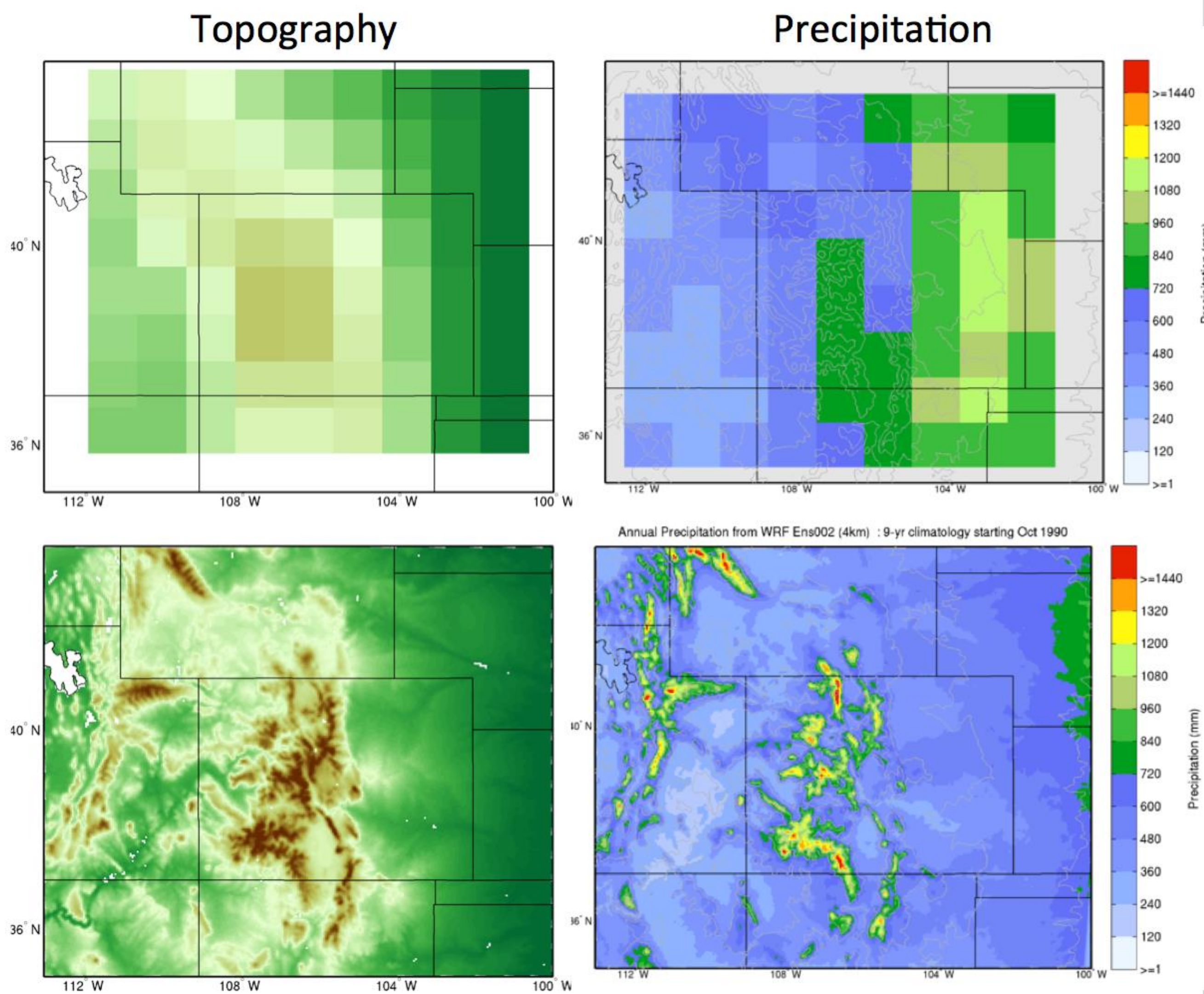
Why Downscale?

Global models:

- Coarse resolution of topography
- Inaccurate simulation of orographic precipitation, temperature gradients, cloud, snow, etc.

Regional models:

- High resolution of topography
- More accurate local physics and dynamics

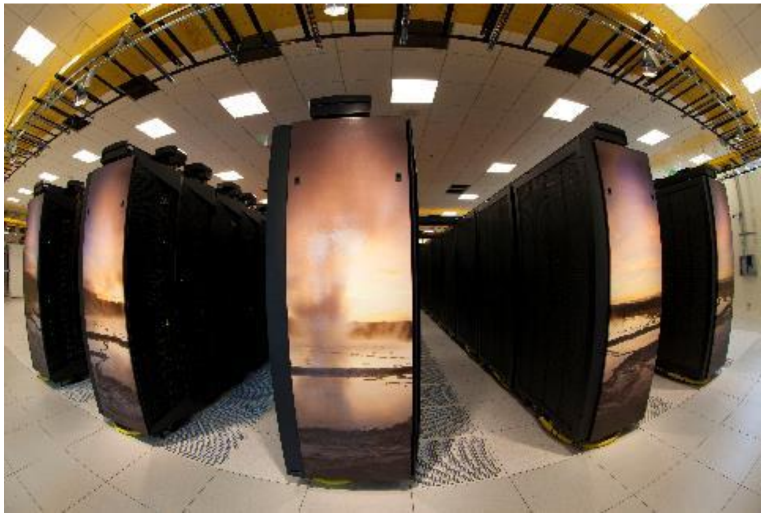


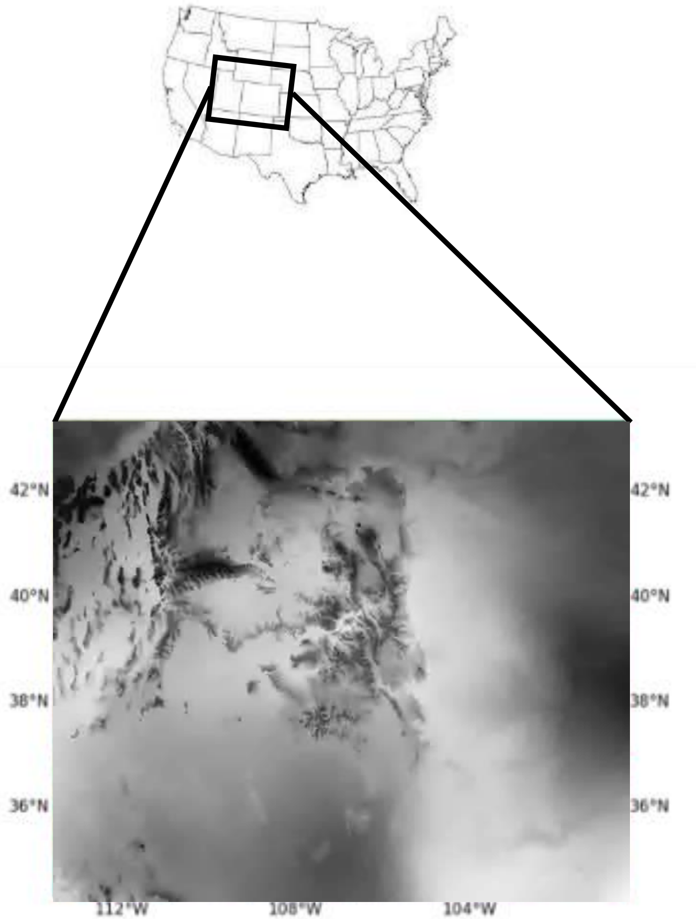
Benefits of Downscaling

- Downscaling provides **local-scale insight**
- Impacts models need **fine-scale and high-temporal resolution climate inputs** (e.g., precipitation, temperature, winds, radiation, moisture)
- Downscaling can **correct for certain biases** of global climate models

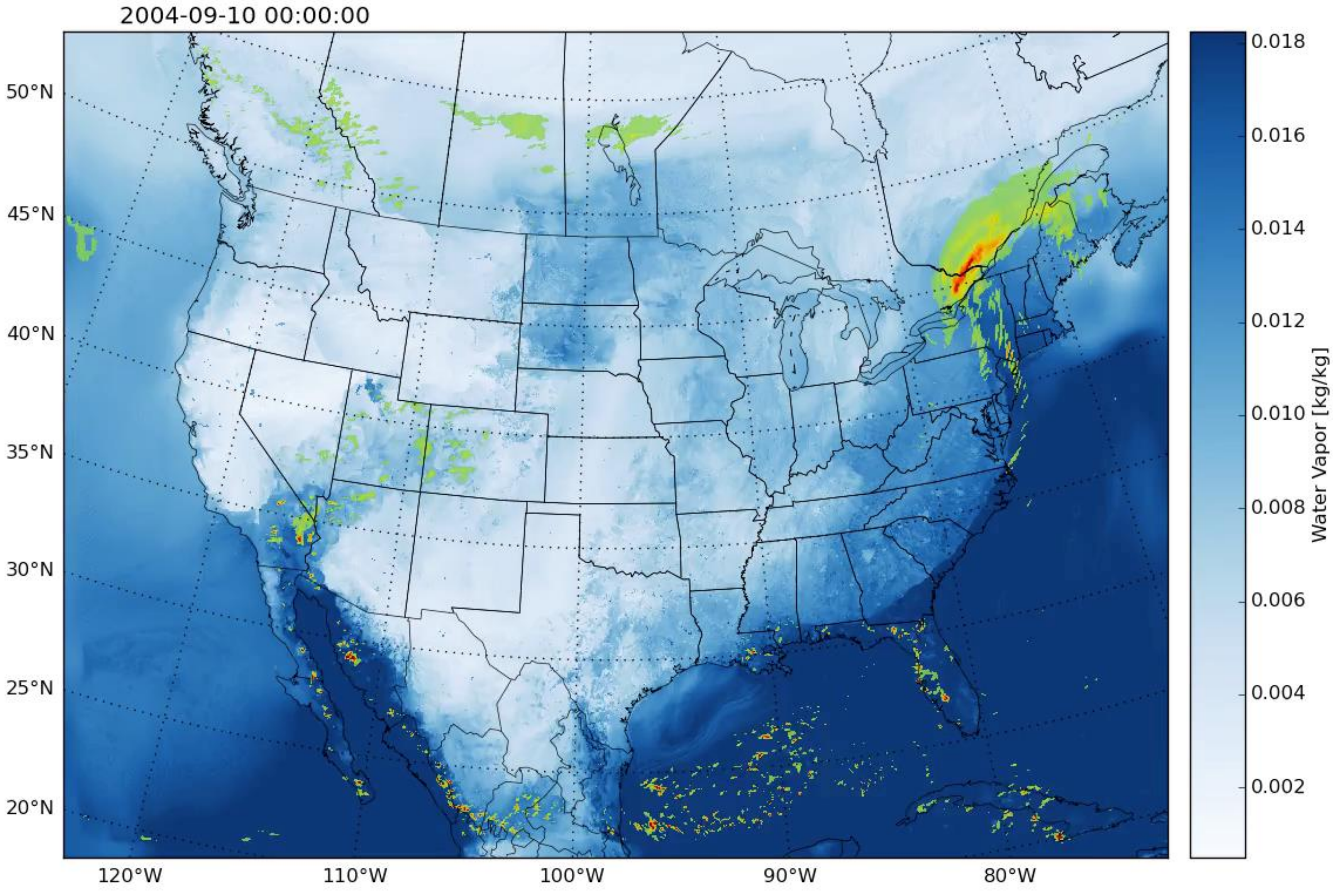
Types of Downscaling: Dynamical

- Uses a high-resolution regional climate model to simulate local dynamics over the area of interest
- Global model output applied along boundaries and as initial conditions
- Computationally expensive, time and supercomputers (usually) required

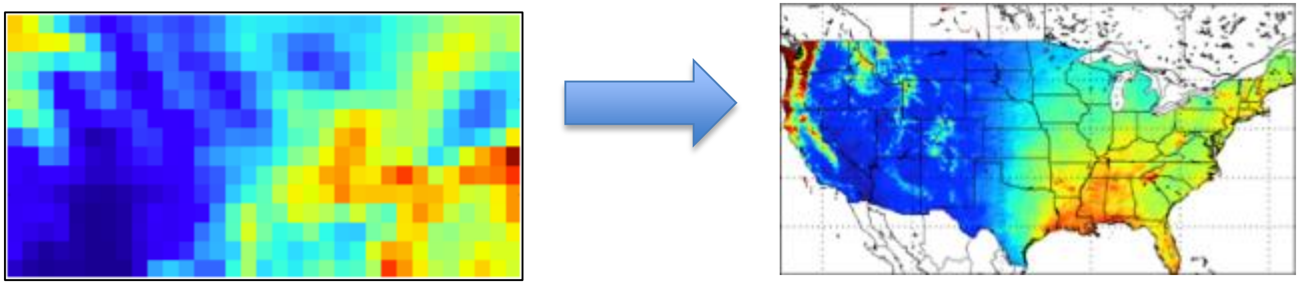




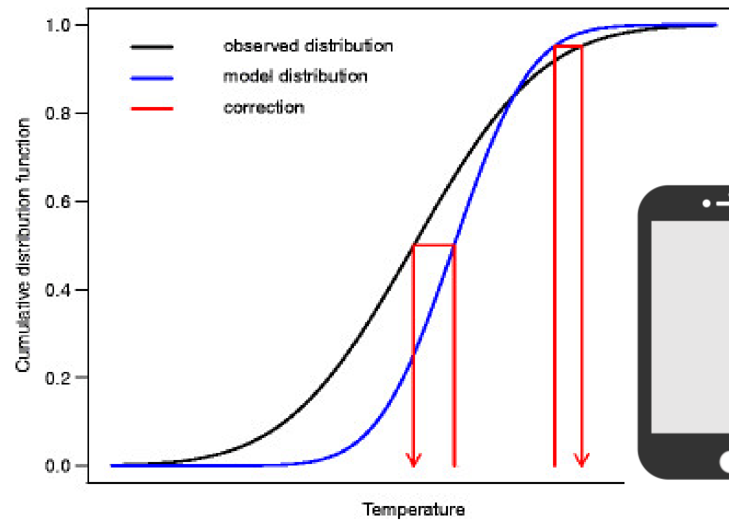
Dynamical Downscaling Output



Types of Downscaling: Statistical



- Uses statistical relationships that relate coarse to fine resolution from historical record
- Stationary statistical relationships then applied to future global model output
- Output usually for subset variables (temperature, precipitation)
- Computationally cheap, quick and can be done anywhere
- Statistical relationships do an excellent job reproducing historical data



Example: Bias correction with spatial disaggregation (BCSD)

Tradeoffs Between Dynamical and Statistical Downscaling

Dynamical

Pros

- **Represents physical processes**
- No stationarity assumptions
- Physically consistent across variables

Cons

- **Computationally expensive**
- Data set availability is limited
- Introduces need for additional ensembles
- Produces climate change signals that still must analyzed for credibility

Statistical

Pros

- **Computationally tractable for large GCM ensembles**
- Large high-resolution data sets publicly available
- Consistent with observations

Cons

- **May not represent climate change signal correctly** (often is effectively just interpolated GCM signal)
- Statistical nature often introduces artifacts

A Continuum of Downscaling Options

increasing physical representation

- Dynamical downscaling using state-of-the-art RCMs
  e.g., RSM-ROMS, Water Research and Forecasting (WRF) model,

- ”Hybrid” (dynamical + statistical) downscaling
  e.g., build statistical emulator using limited set of dynamical runs

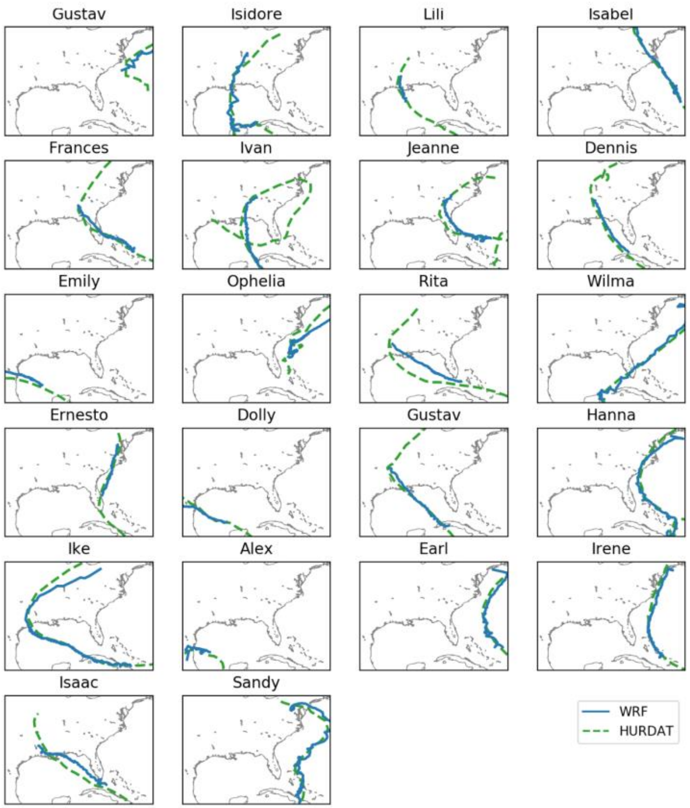
- Physically-based intermediate-complexity atmospheric models
  e.g., Linear Orographic Precipitation model

- Statistical downscaling based on GCM dynamics (water vapor, wind, convective potential, etc.)
  e.g., regression-based, analog, pattern scaling

- Methods to relate downscaled fields to synoptic scale atmospheric predictors
  e.g., self-organized maps, weather typing

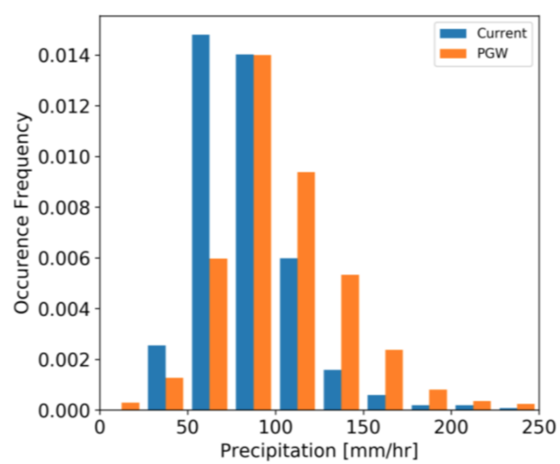
- Statistical downscaling based on rescaling GCM outputs
  e.g., BCSD, BCSA, LOCA, BCCA, linear regression, and more

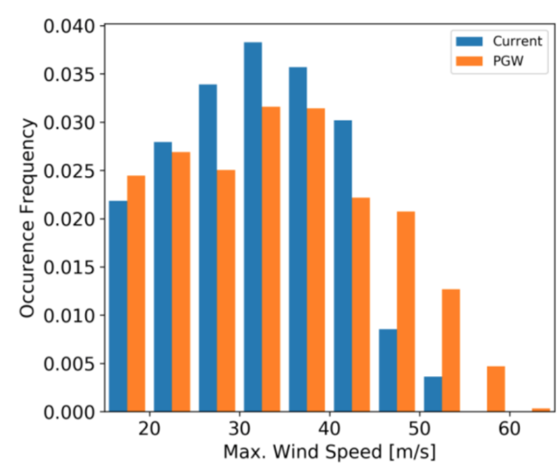
Hurricane Simulations



- Hurricanes in 2001-2013
- WRF model with a 4 km grid
- Pseudo-Global Warming Simulation, can compare modeled and observed characteristics
- higher precipitation rates (maximum rates by ~24%), faster maximum winds, slower storm translation speeds, and lower central pressures

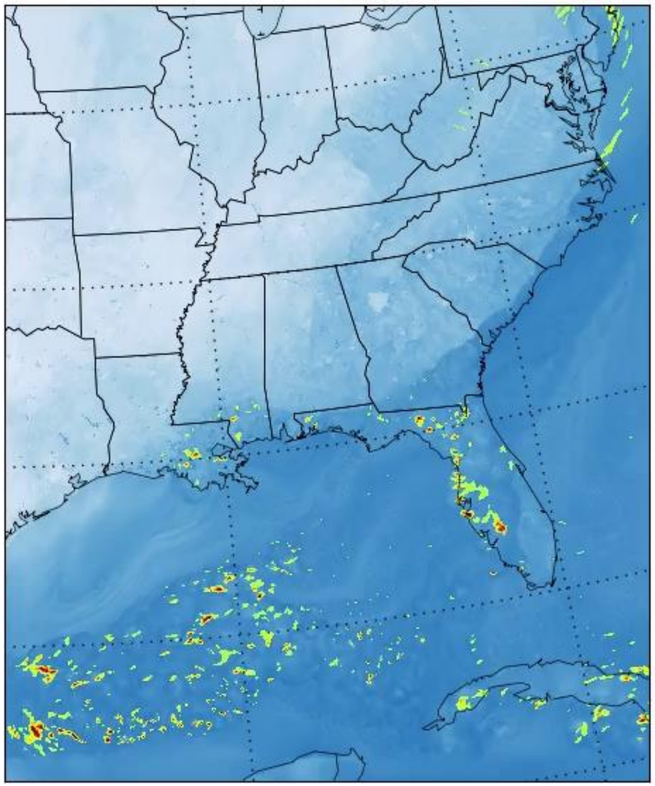
Gutmann et al. 2018
National Center for Atmospheric Research



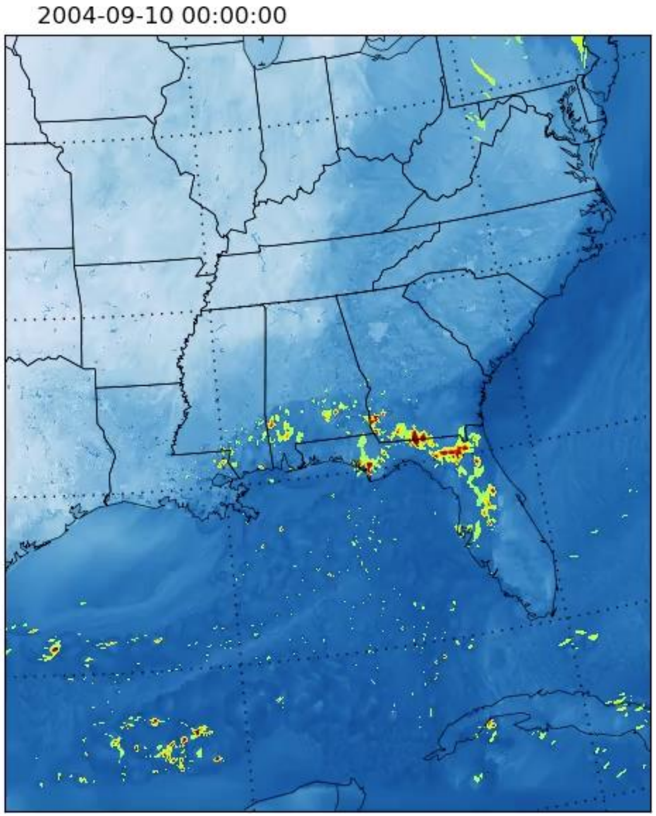


Changes in Hurricanes in a Warmer Climate

Hurricane Ivan (historical)
Current climate



Hurricane Ivan (future climate)
Pseudo Global Warming, warmer and moister

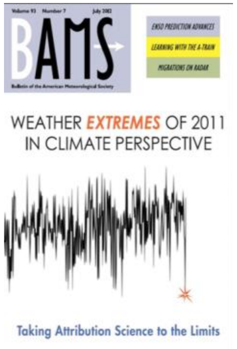


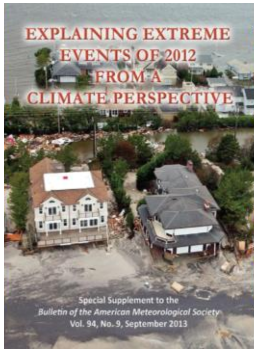
Water Vapor (Blues); Precipitation (Green to Red)

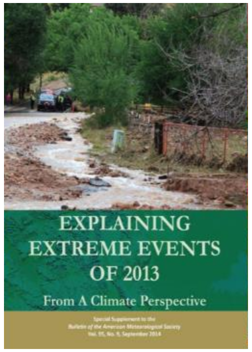
NCAR

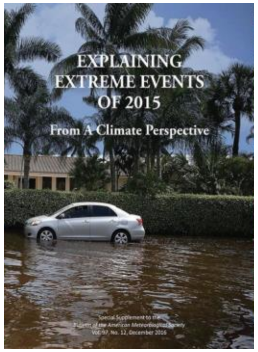
Changes in Hurricanes from a 13 Year Convection Permitting Pseudo-Global Warming Simulation, Gutmann et al., Journal of Climate, 2018, Ethan Gutmann, gutmann@ucar.edu
Analysis funded by Det Norske Veritas (DNV) and CONUS simulation by NSF under NCAR Water System Program

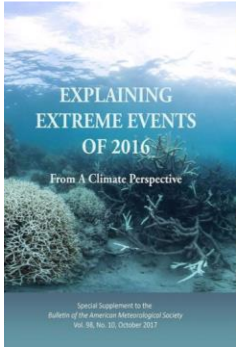
Climate Attribution Studies

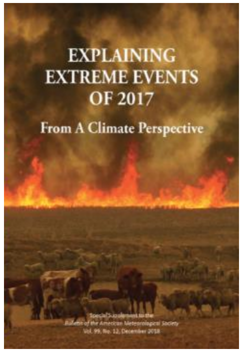












Using quantitative assessments of model ensembles to uncover whether and by how much climate change has influenced a particular event.

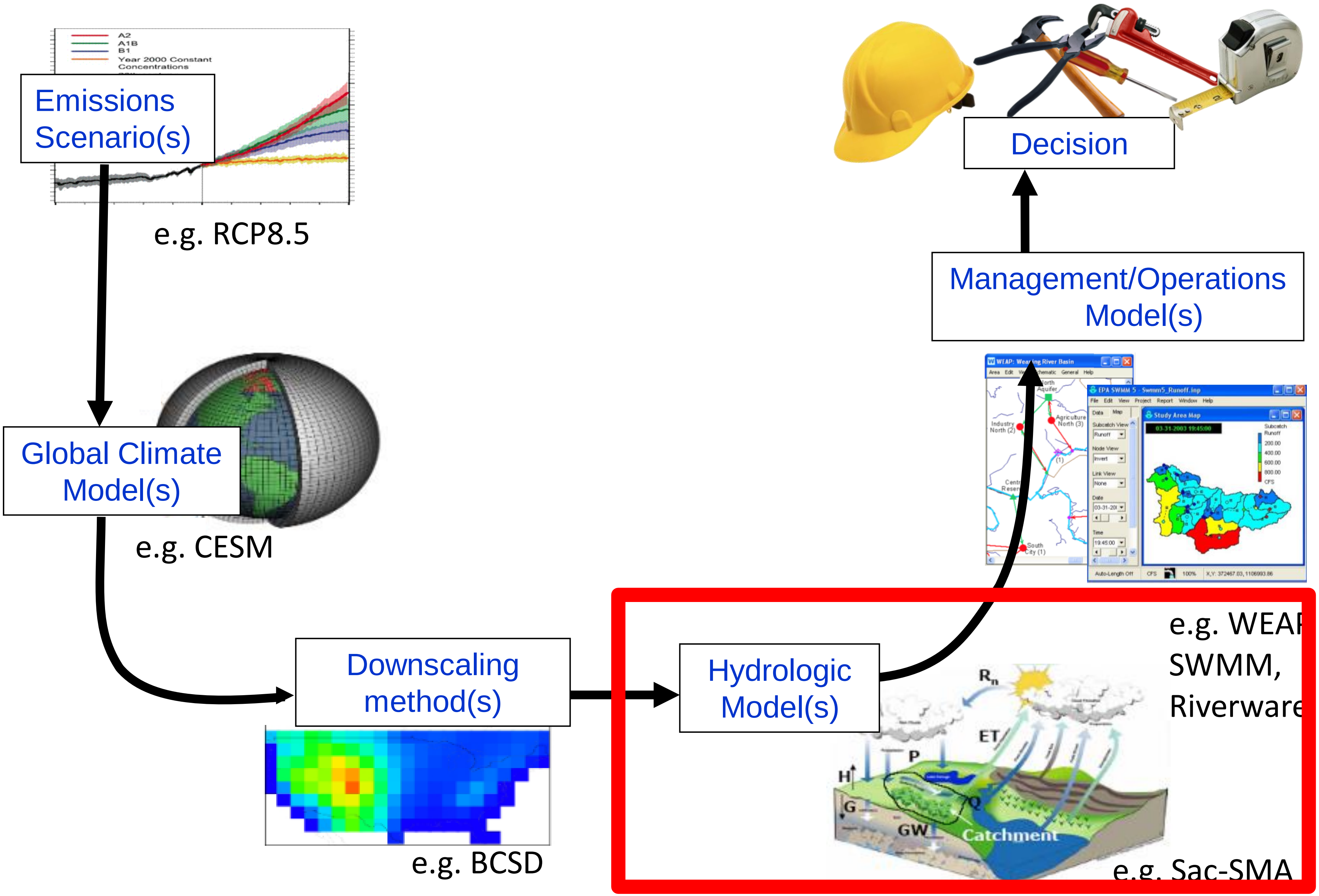
How much have we loaded the weather dice?

For example, Hurricane Harvey: 4 attribution studies to date indicate increased precipitation intensity; e.g., Emanuel (2017) found storms already increased 6% compared to late 20th century.

Questions to determine an appropriate downscaling technique

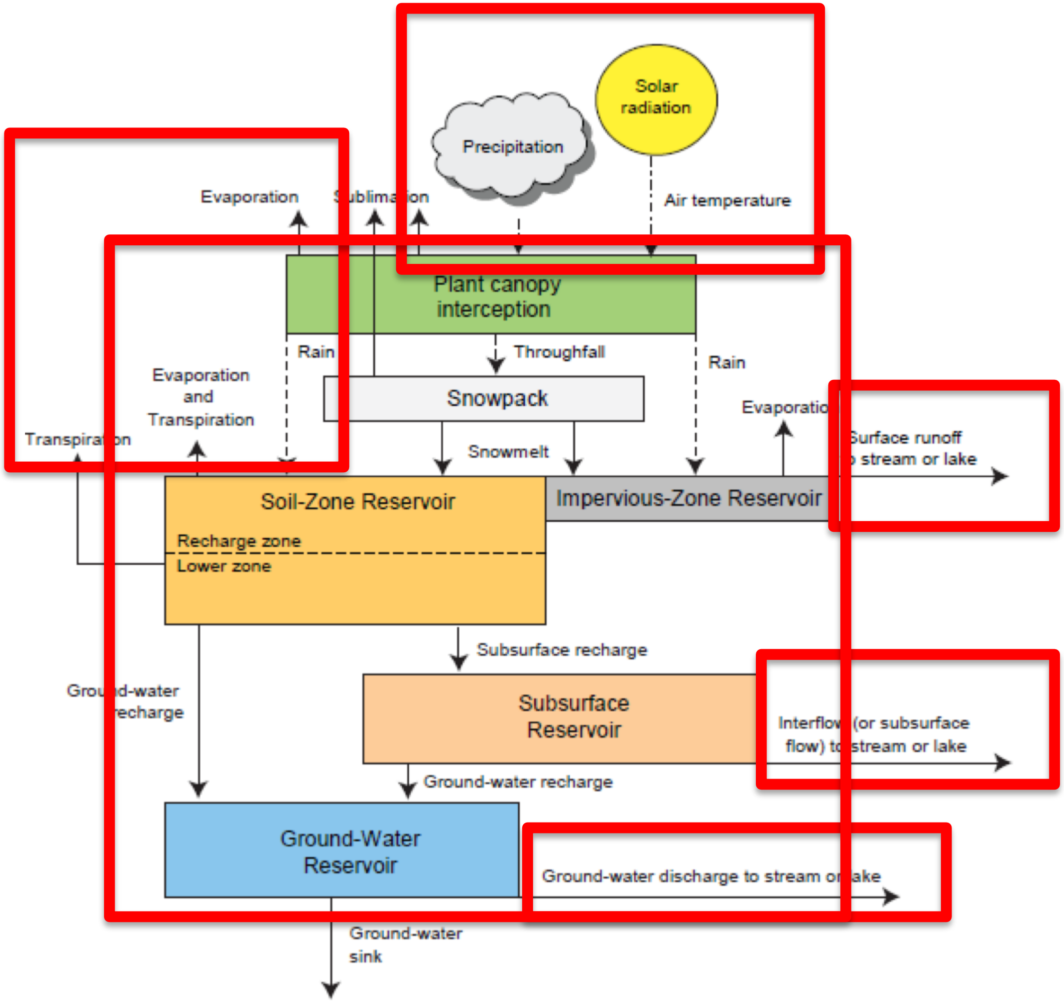
- Where is the area of interest?
- How large of an area?
- What is the impact of interest?
- When in the future?
- Does event sequencing matter?
- What type of climate uncertainty is important?
- What is available?

Classic "Top-down" Impacts Modeling Chain



What models do you use to track water in your system?

Why We Need Hydrology Models



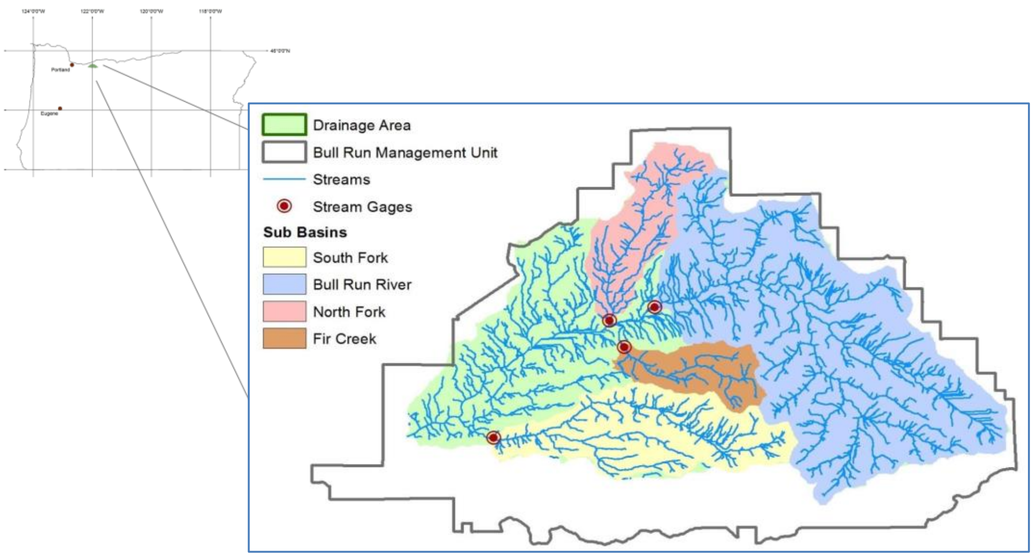
We have: precipitation, temperature, other atmospheric values

We want: streamflow (highs, lows), water demand from vegetation, water temperature

Hydrology models represent energy and water fluxes in watersheds, encapsulate our best understanding

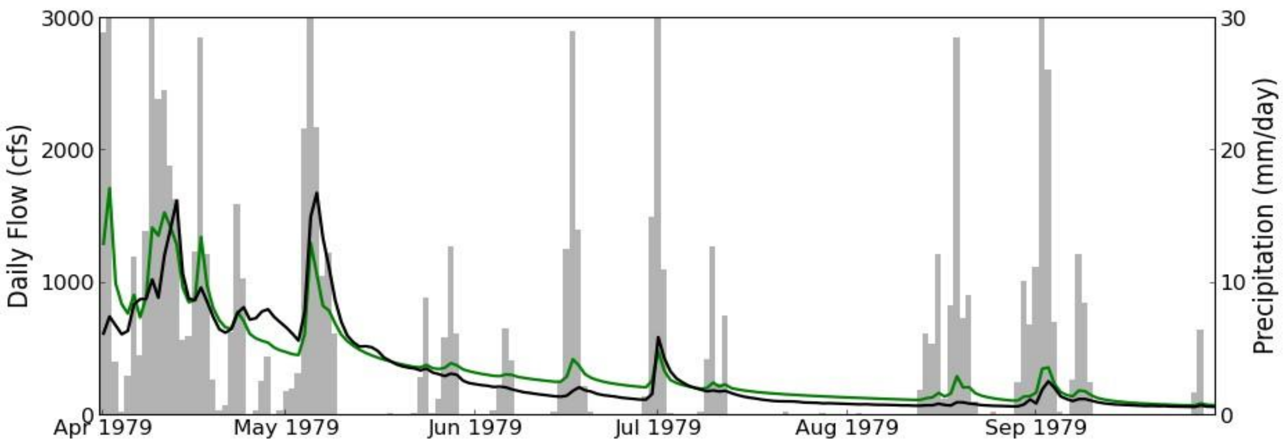
Fill gaps since measurements unavailable in most places

Benefits of Hydrology Modeling



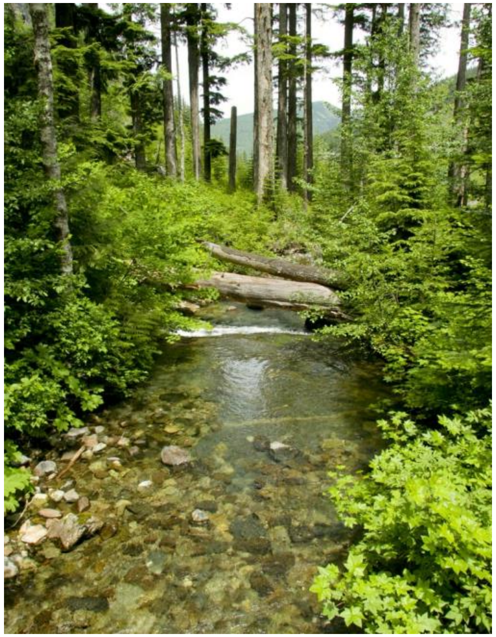
Portland Water Bureau

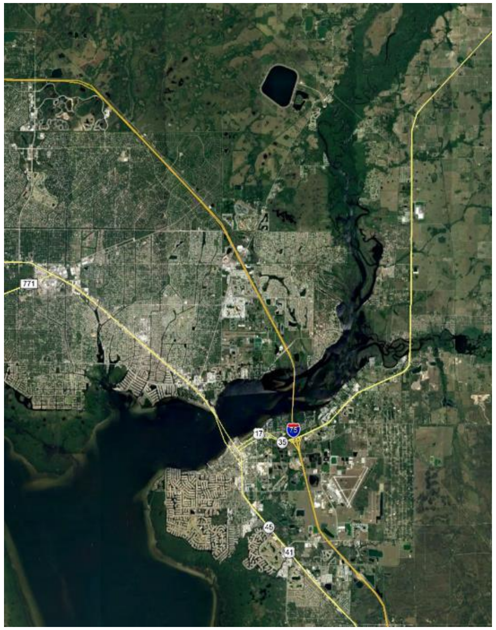
- Values from GCMs not helpful
- Worked with University of Washington to select and set up in-house hydrologic model
- Model helps understand how streamflow changes affect future supply conditions
- Included in Supply System Master Plan



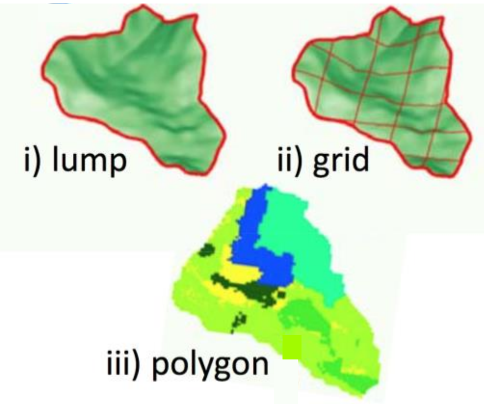
Modeling Cautions

- Models built to represent many landscapes, processes, spatial configurations+
- May miss key elements
  - Groundwater interactions
  - Salt water intrusion
- Important to be a savvy user



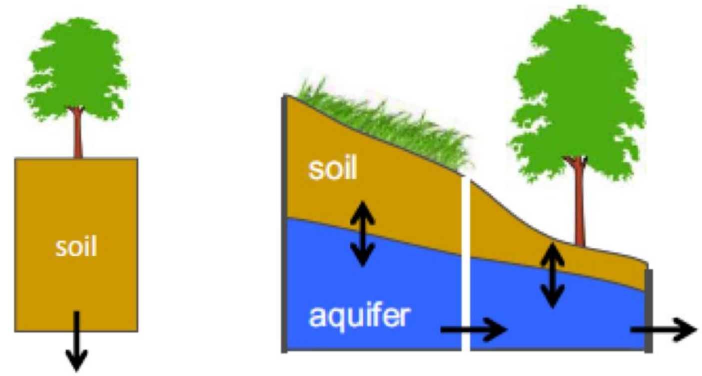


Model Spatial Structures



Lumped, gridded or hydrologically similar areas

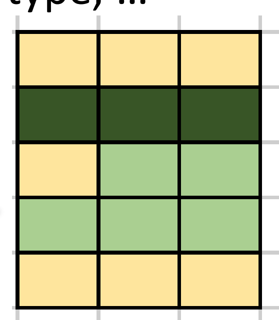
Figures from Clark et al., WRR, 2015



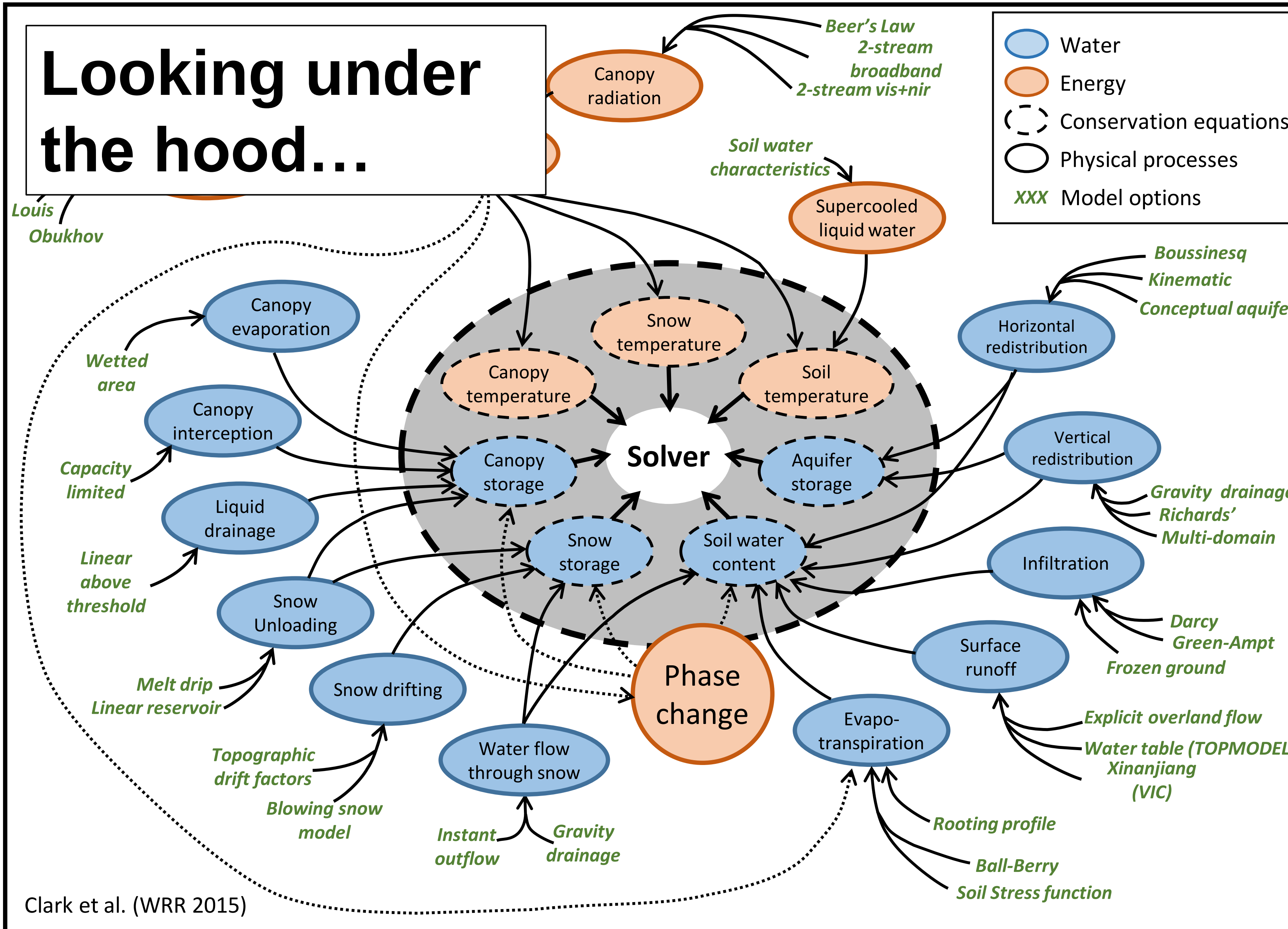
Connections between soil and aquifer

Model Parameters

Vegetation, Soil type, …

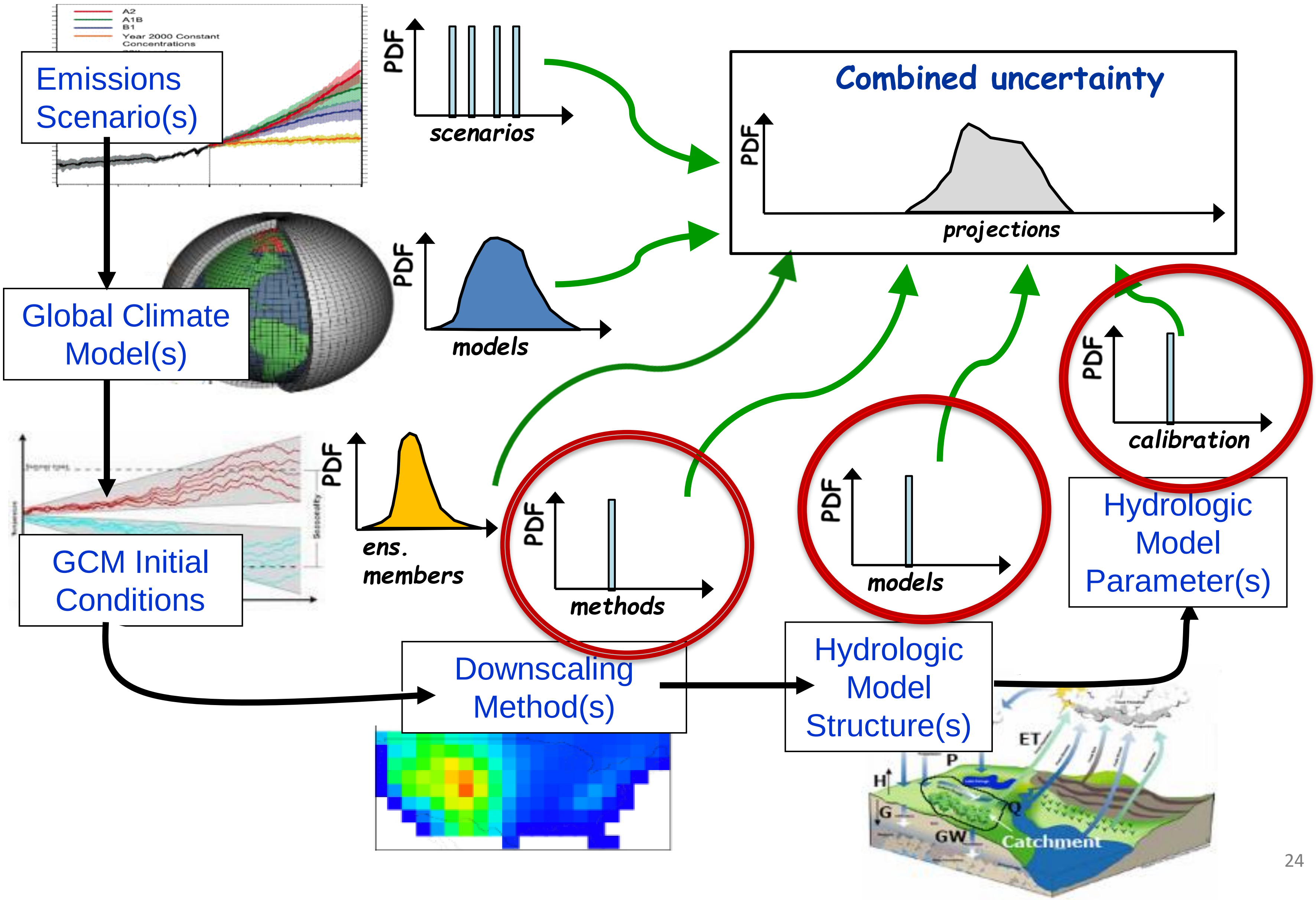


Hydrologic Model Processes

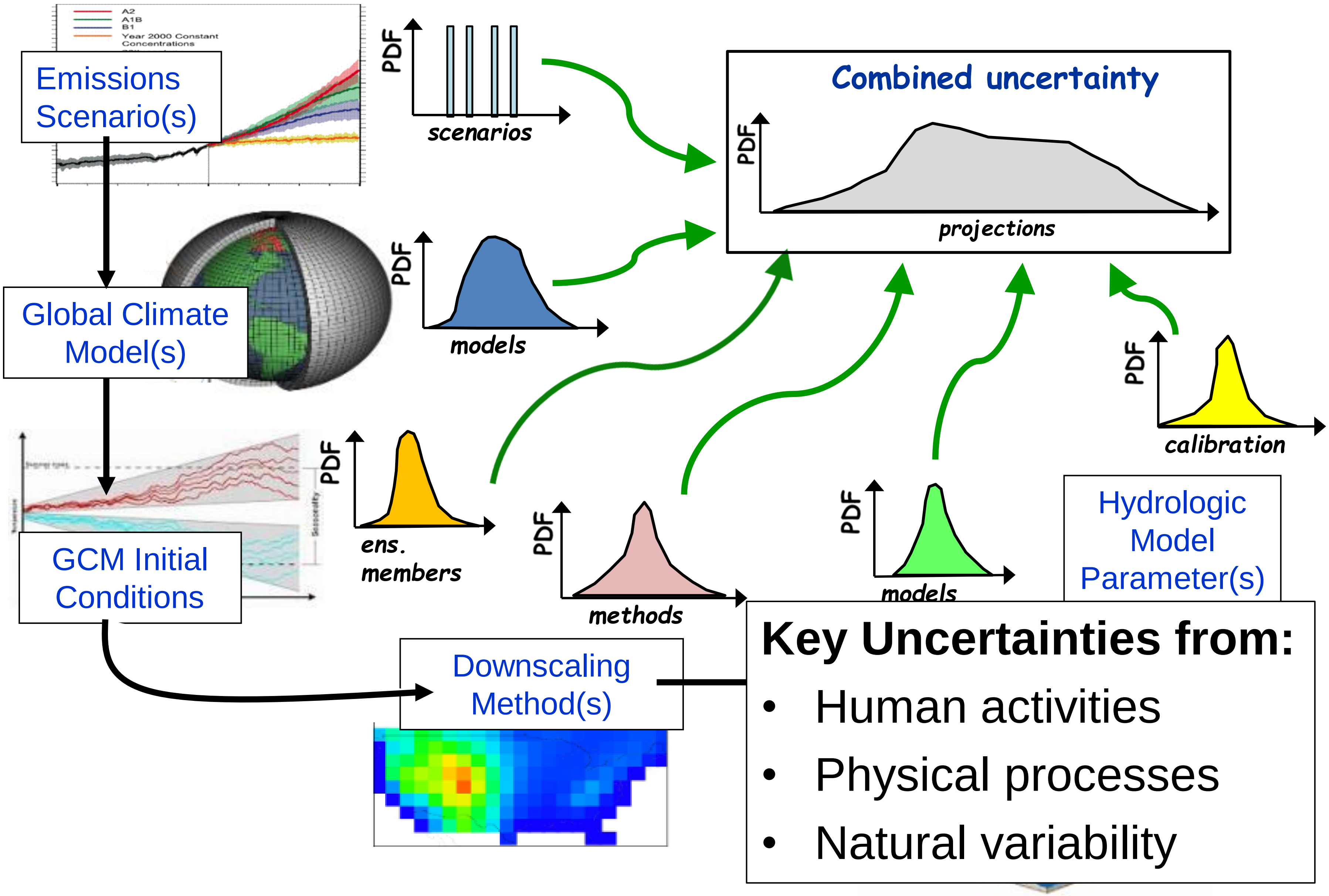


Clark et al. (WRR 2015)

Revealing Uncertainties



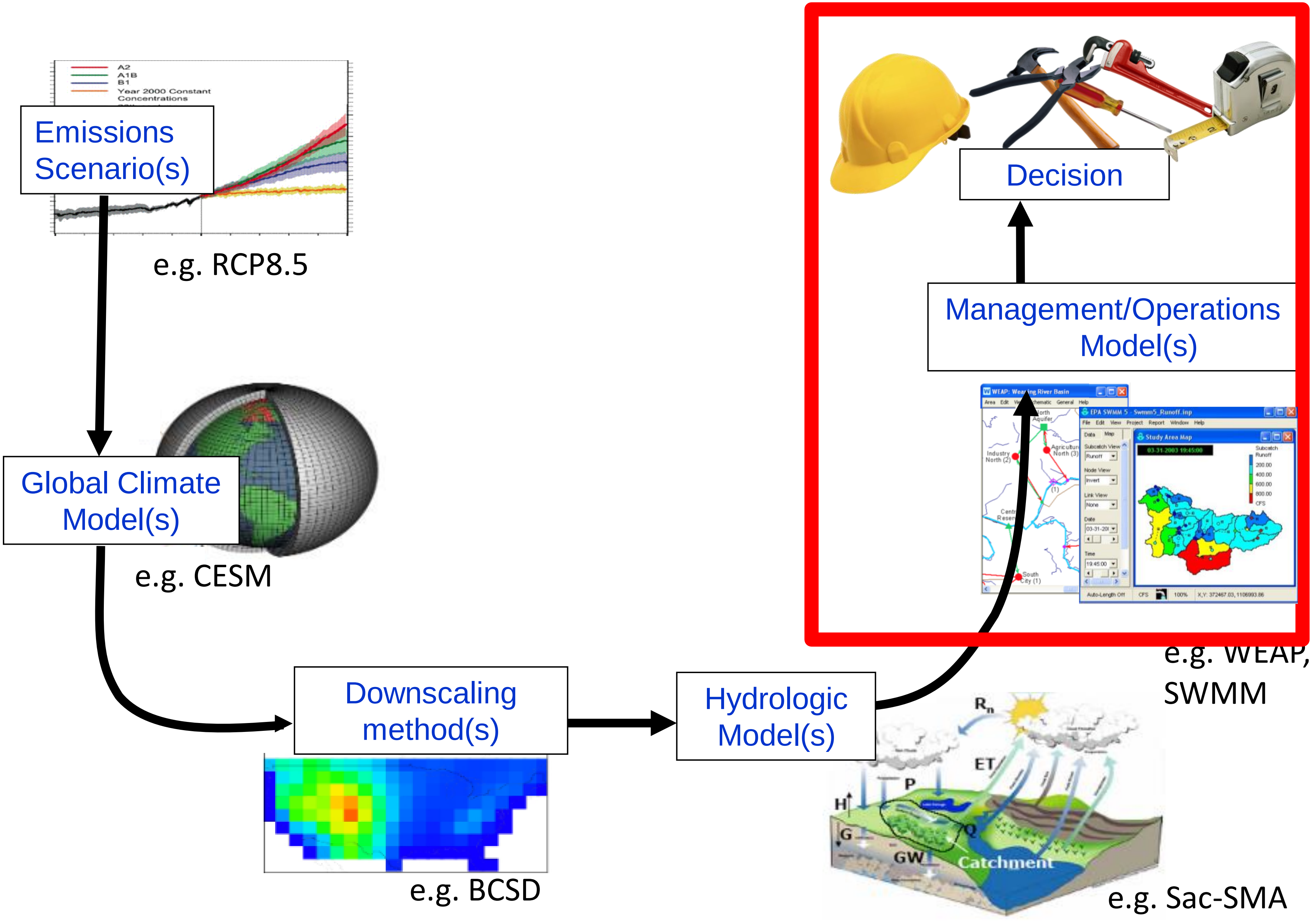
Revealing Uncertainties



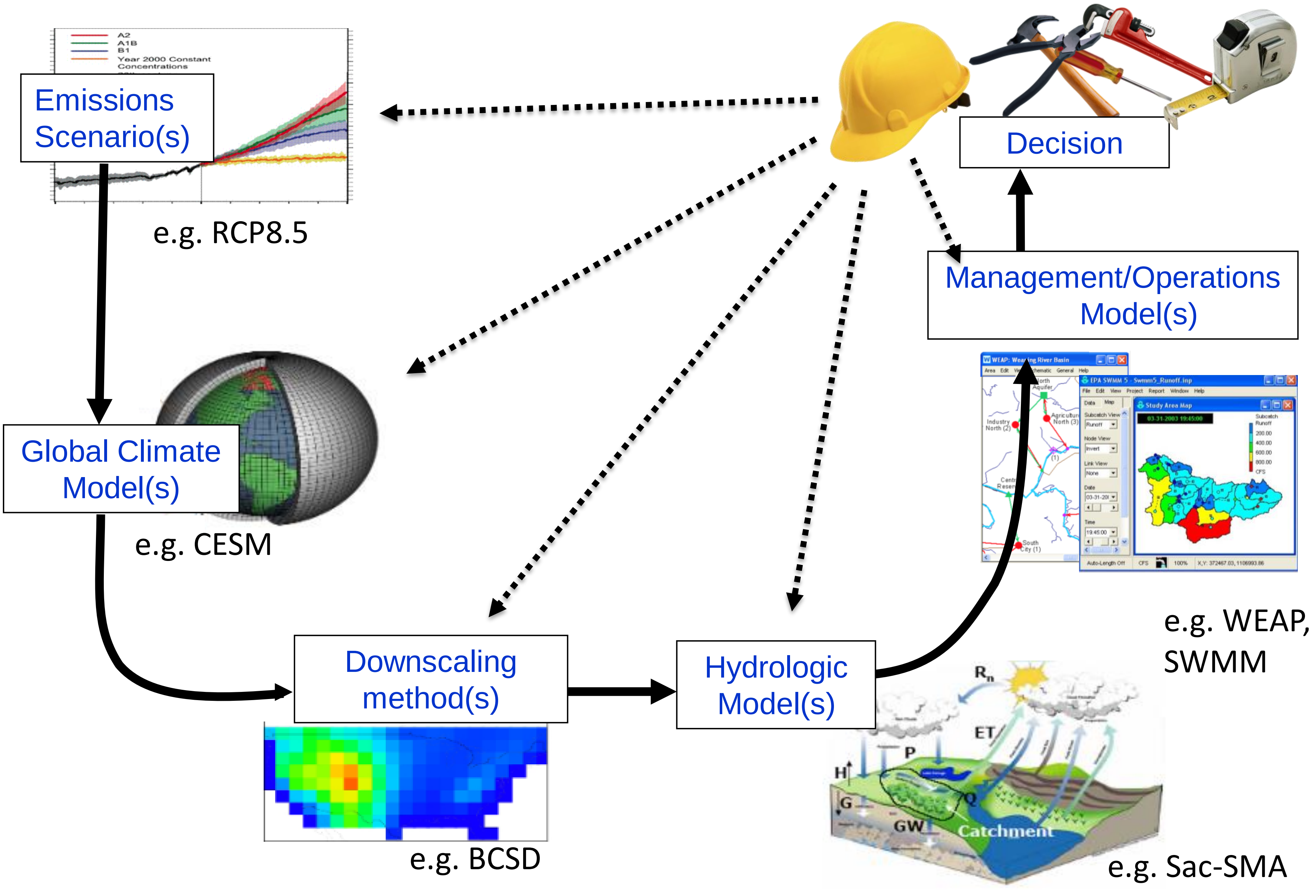
Key Uncertainties from:

- Human activities
- Physical processes
- Natural variability

Classic "Top-down" Impacts Modeling Chain

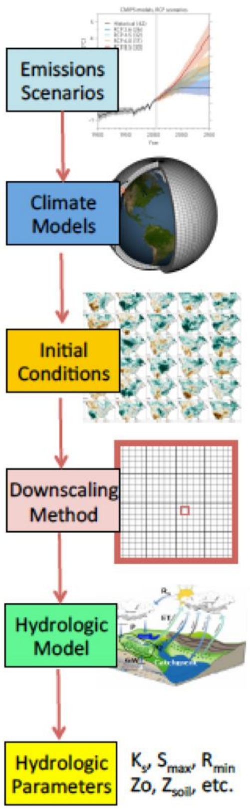


Revised "Top-down" Impacts Modeling Chain



Do Be Aware of Multiple Ways to Evaluate Future Changes

Scenario studies



Clark et al. 2016; connect models in a chain

Stochastic hydrology

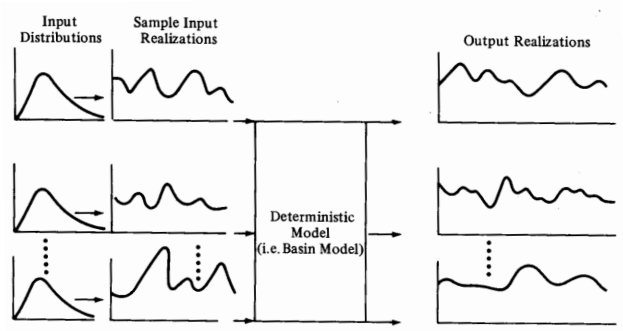
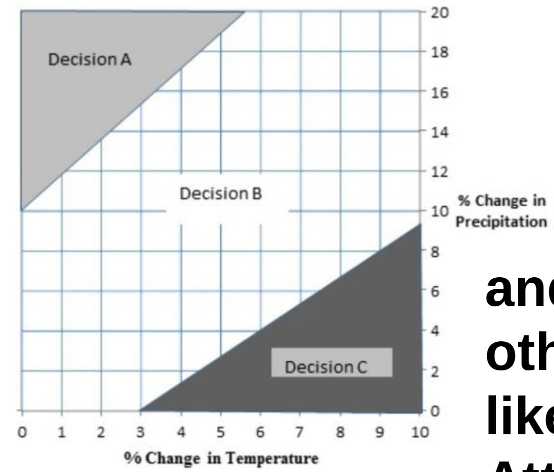


Figure 1.3 Concept of Monte Carlo experiments.

Bras and Rodriguez-Iturbe, 1985; generate synthetic timeseries using statics from the past

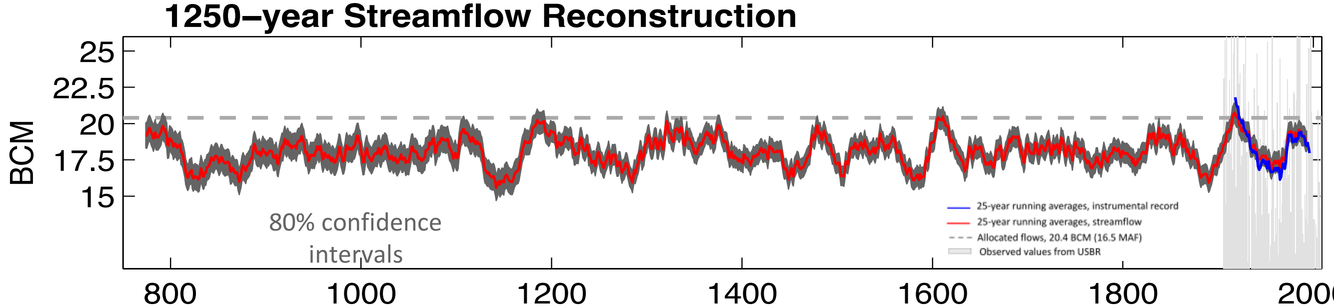
Climate-informed vulnerability analysis



Brown et al., WRR, 2016; explore sy vulnerabilities with perturbations

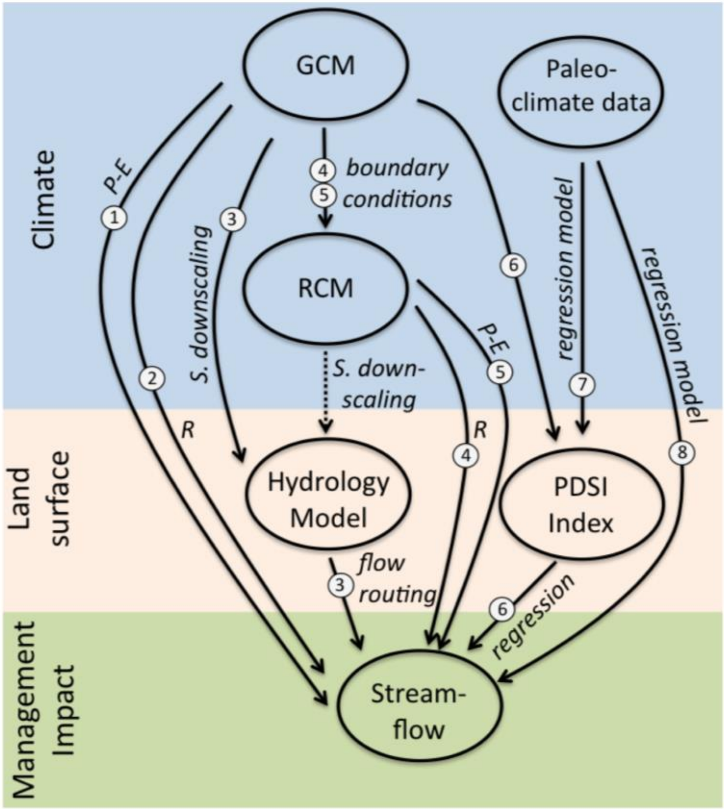
and others… like Attribution Science

Paleoclimate studies



Vano et al., BAMS, 2016; generate timeseries using reconstructions of the distant past

Don't Treat All Future Projections or Methods Equally



Different: GCMs, emission scenarios, spatial resolution, hydrology, +

- Certain models and methods are more appropriate
- Certain spatial and temporal scales are more appropriate for certain questions
- Realize some questions may not be possible to answer with current knowledge
- Finer resolution in space and time is not necessarily better
  - Higher Resolution ≠ Higher Accuracy

Be a savvy consumer and remember…

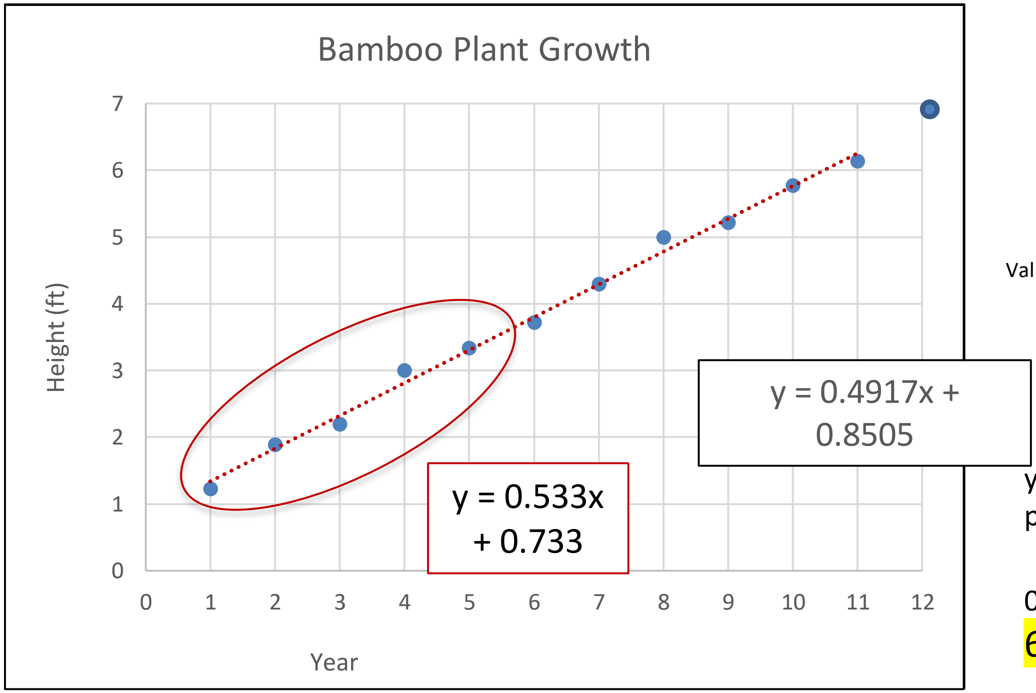
Figure from Vano et al., BAMS, January 2014

No Model is Perfect

“The accuracy of streamflow simulations in natural catchments will always be limited by simplified model representations of the real world as well as the availability and quality of hydrologic measurements.” (Clark et al., WRR, 2008)

- **Don’t expect perfect results,**
  - Not prediction, but a tool to test how system responds (what if scenarios)
- **BUT we can make better choices…**
  - Seek simple yet defensible (don’t need a Cadillac)
  - Be aware of models shortcomings

Year	height (ft)
1	1.23
2	1.89
3	2.2
4	3
5	3.34
6	3.72
7	4.3
8	5
9	5.22
10	5.77
11	6.14



$y = mx + b$

- y: Value we want
- m: Slope
- x: X axis value
- b: Y axis intercept

y = height of bamboo plant in year 12

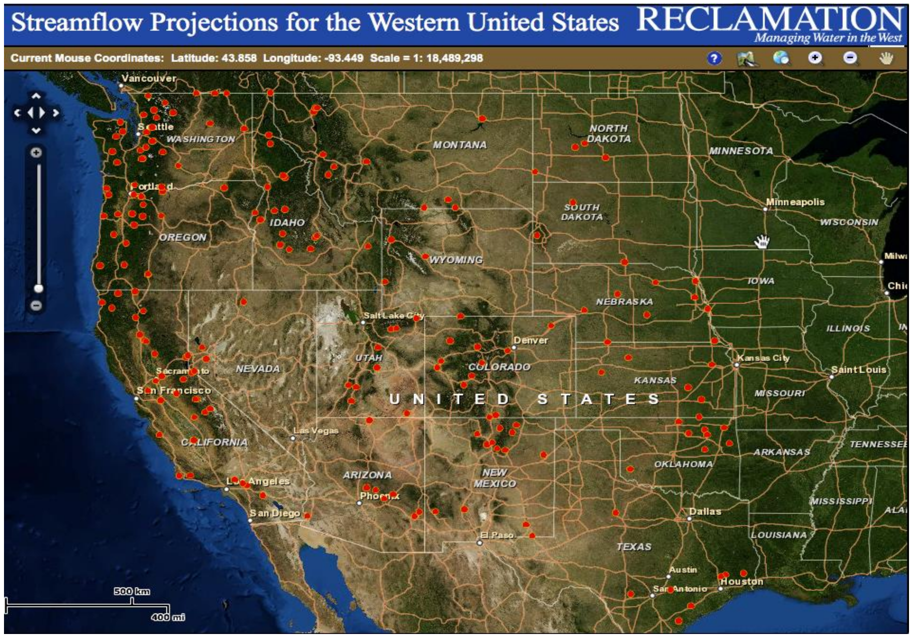
0.4917 x 12 + 0.8505 = **6.7509**

Ways to test your model

- Does the model adequately represent the variable(s) of interest?
- Is the model cross-validated?

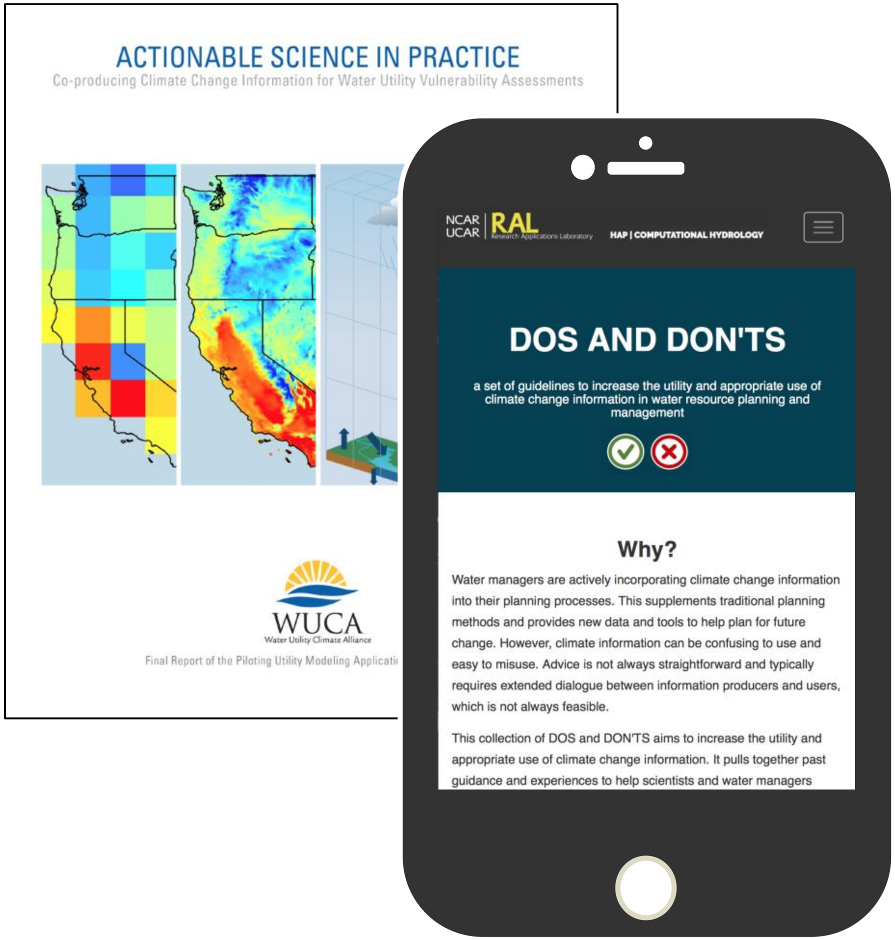
Available Data

- Hydrology on Green Data Oasis portal
  - BCSD (12km), LOCA (6km)
  - VIC streamflow
- Dynamical
  - NARCCAP (50km),
  - CORDEX (limited 25km)
  - Others over regional domains or limited time periods
- USGS GeoDataPortal
  - Collection of different archives
- Many others (NASA NEX, ARRM)

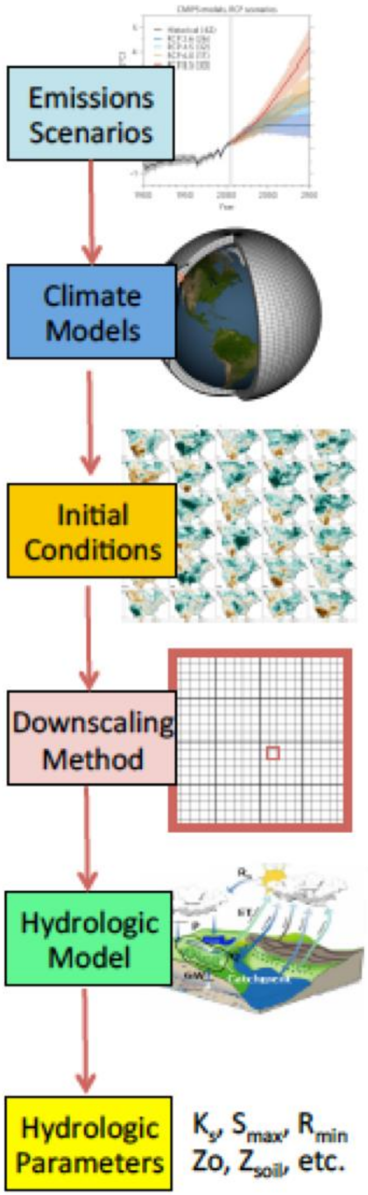


Available Resources

- WUCA products
  - PUMA project examples
  - www.wucaonline.org
- Federal Agency Guidance
  - Bureau of Reclamation
  - U.S. Army Corps of Engineers
  - Environmental Protection Agency
  - U.S. Climate Resilience Toolkit
- Professional Societies
  - American Society of Civil Engineers
- Dos and Don'ts Guidelines
  - Reviews other guidance
  - www.ncar.github.io/dos_and_donts
- Many others, including each other



Guide to Climate Study Choices



- Approach type (e.g. scenarios, paleo, vulnerability analysis):
- Emission scenarios used:
- GCMs used:
- Number of initial conditions for each GCM used:
- Downscaling methods used:
- Hydrologic models and parameter sets used:
- Time period of interest (transient or delta):
- Project timeline:
- Impacts evaluated:
- Results reported (ensembles, individual simulations):

Clark et al. 2016

Key Takeaways

- Models can be used in a variety of ways to better understand the past and think about the future.
- Downscaling and hydrology modeling provide **local-scale insights** of global scale information.
- Downscaling exist on a continuum of tradeoffs between computational efficiency and method complexity.
- Model uncertainty is unavoidable.
  - Representation of uncertainties is hard but necessary.
  - Uncertainties are always there; just understanding them now.
  - Previous studies may be over-confident.

Key Takeaways

- Be extra careful not to confuse high resolution with increased accuracy.
- It is critical to understand important processes and uncertainties in **your** system.
- Models are tools that can be useful, if used appropriately. **Be a savvy consumer.**
- Consult local experts and national resources, e.g., https://global-change.github.io/dos_and_donts

EXTRA SLIDES

Do Understand How the Decision Being Evaluated is Important to Model Selection

What are the questions we are trying to answer?

How will flows in April-September change in the future?

How should facilities be sized to prevent sewer overflows?

How will the magnitude, duration, and frequency of drought change?

How much warmer will streams be in 20 years?

water supply, streamflow timing, drought, stormwater, wastewater

FIT FOR PURPOSE

Do Start by Determining the Level of Details that Fits Your Need and Resources

Additional Considerations:

- How much will it cost?
- How long will it take?
- To what extent will the analysis improve the decision?
- Can appropriate data and information be obtained?
- Who will undertake the analysis?
- How much information can you manage?

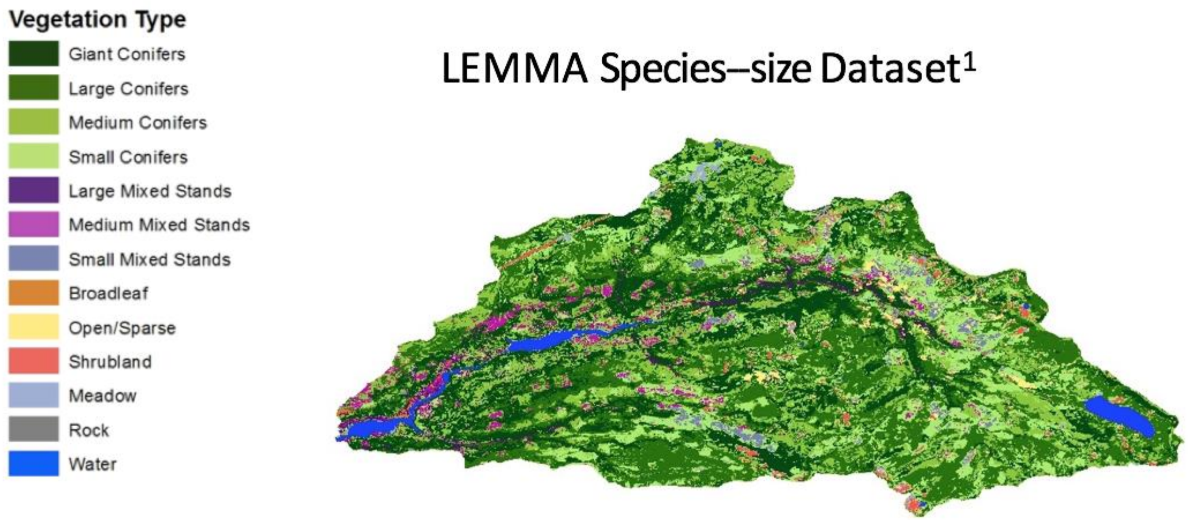



List from UK Climate Impacts Programme's report Climate adaptation: Risk, uncertainty and decision-making (+ one from WUCA)

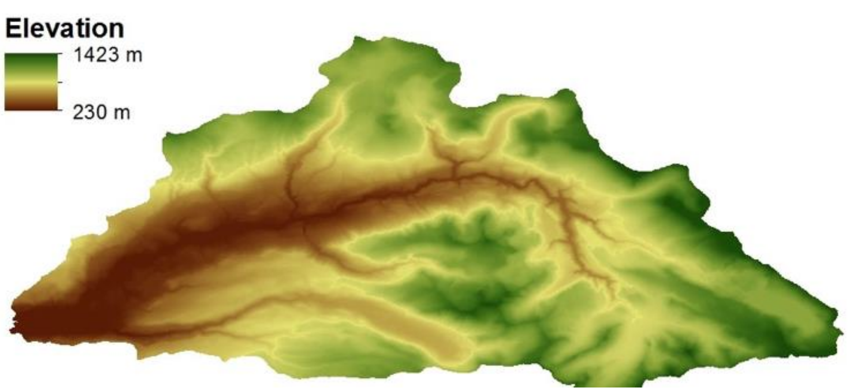
Model Set Up

GIS data = soil, vegetation, elevation maps

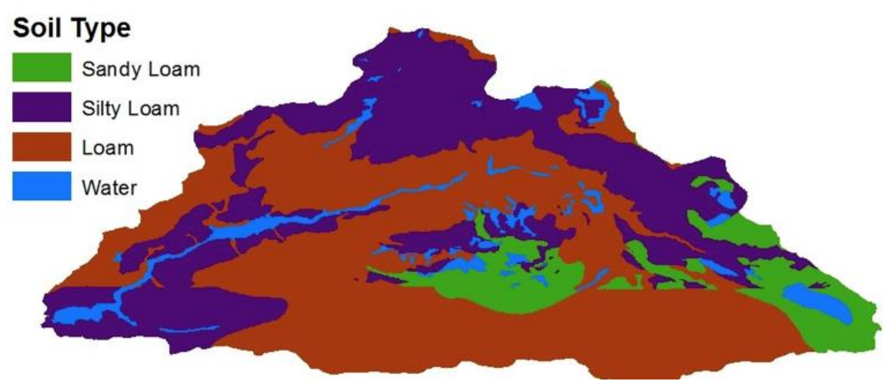
LEMMA Species–size Dataset[1]



Portland Water Bureau



NRCS STATSGO2 and SSURGO[2,3]



Models are improving

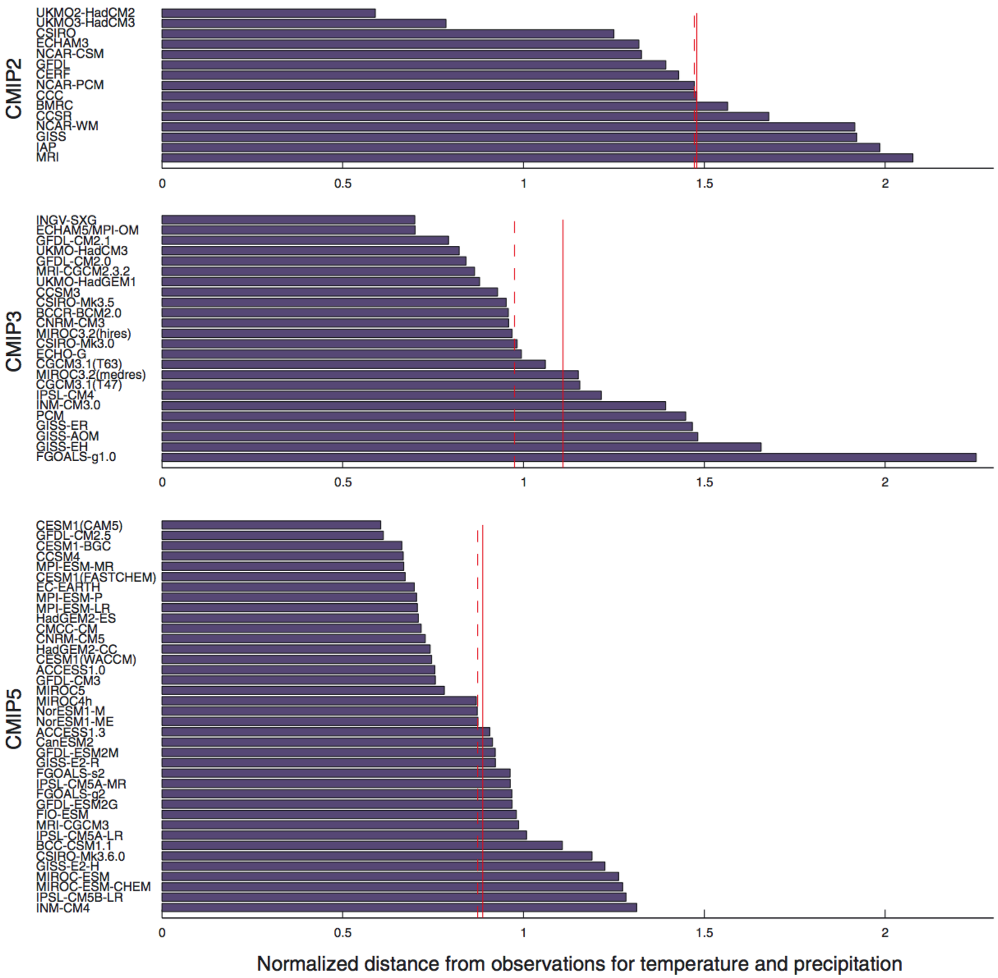


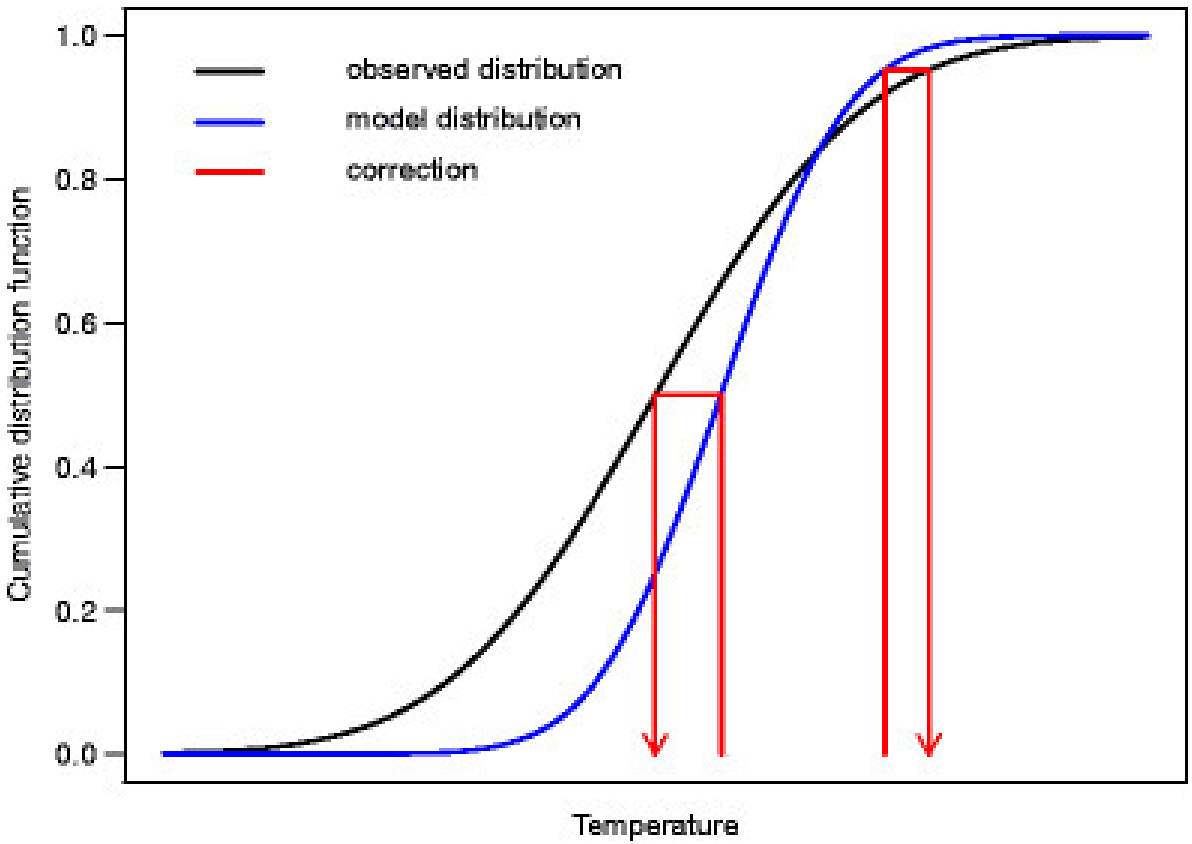
Figure 3. Normalized distance from observations in the CMIP2, CMIP3, and CMIP5 models. The distance metric is calculated as the root mean square of the surface temperature and precipitation distance as in Figure 1 but relative to observations (NCEP, ERA40, and MERRA for temperature; GPCP and CMAP for precipitation, see MK11). Mean and medians for the different ensembles are indicated by red solid and dashed lines, respectively. Note that most models in CMIP2 (including HadCM2, but not HadCM3) used flux corrections.

Knutti et al., Geophysical Research Letters 2013

Common Statistical Downscaling Methods

1. Bias correction with spatial disaggregation (BCSD)

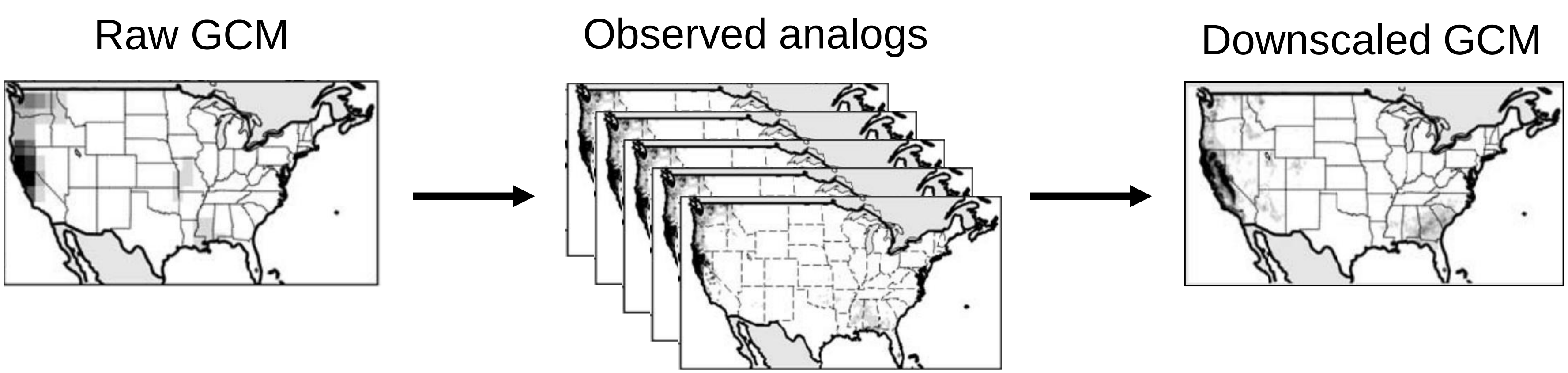
- Used on CMIP3 and CMIP5 GCMs
- Point-by-point quantile mapping on monthly data (temp/precip distributions are bias corrected and transformed from the coarse resolution data to finer resolutions)
- Spatial patterns may not be dynamically consistent



Common Statistical Downscaling Methods

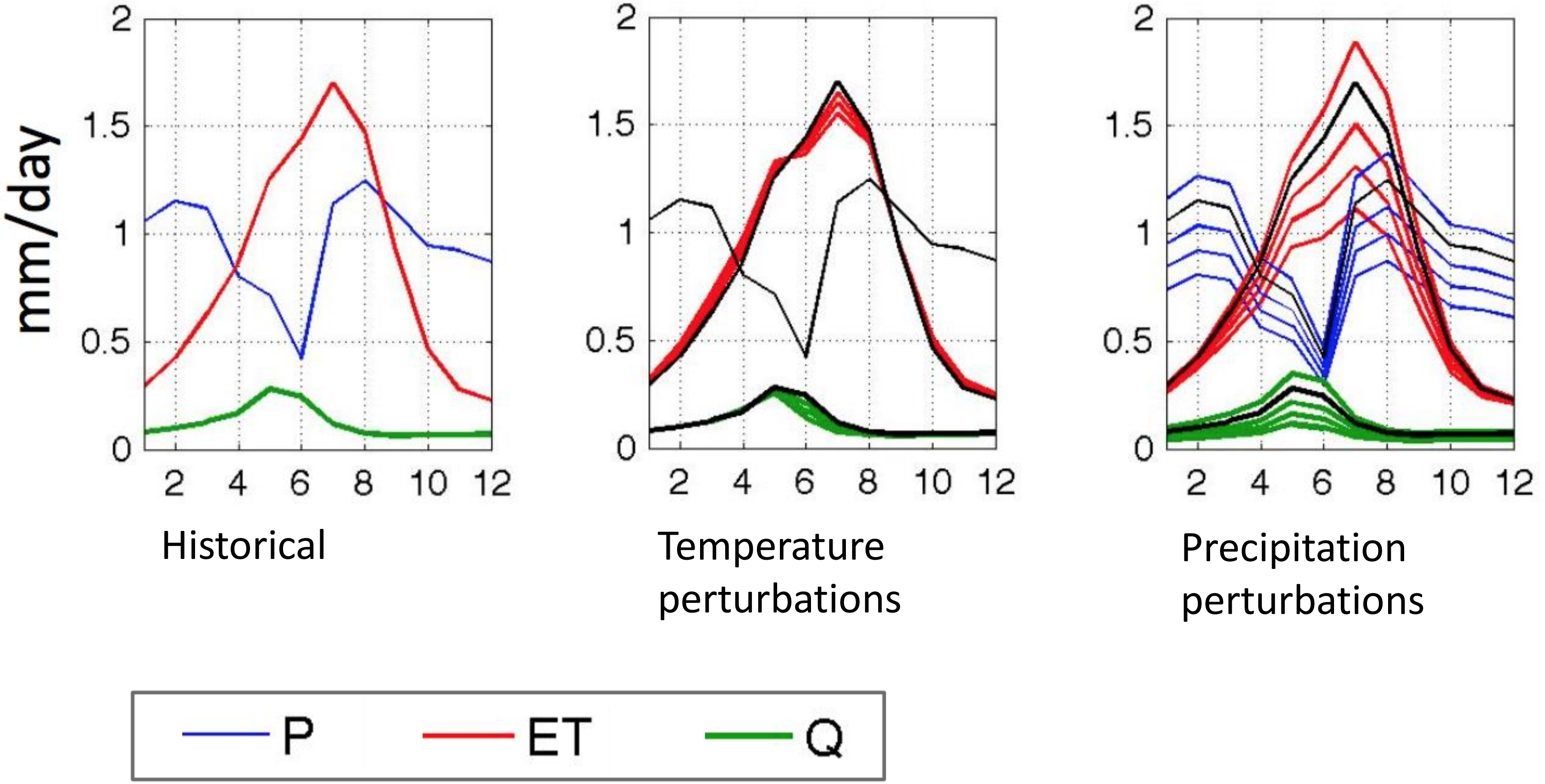
2. Localized Constructed Analogs (LOCA)

- Used on CMIP5 GCMs (and in the 4th National Climate Assessment)
- Given coarse resolution data, find analogous days in the historical period and uses the associated fine-resolution historical data to produce fine-resolution output
- Statistical corrections to frequency and quantiles
- Improved representation of extremes and spatial patterns

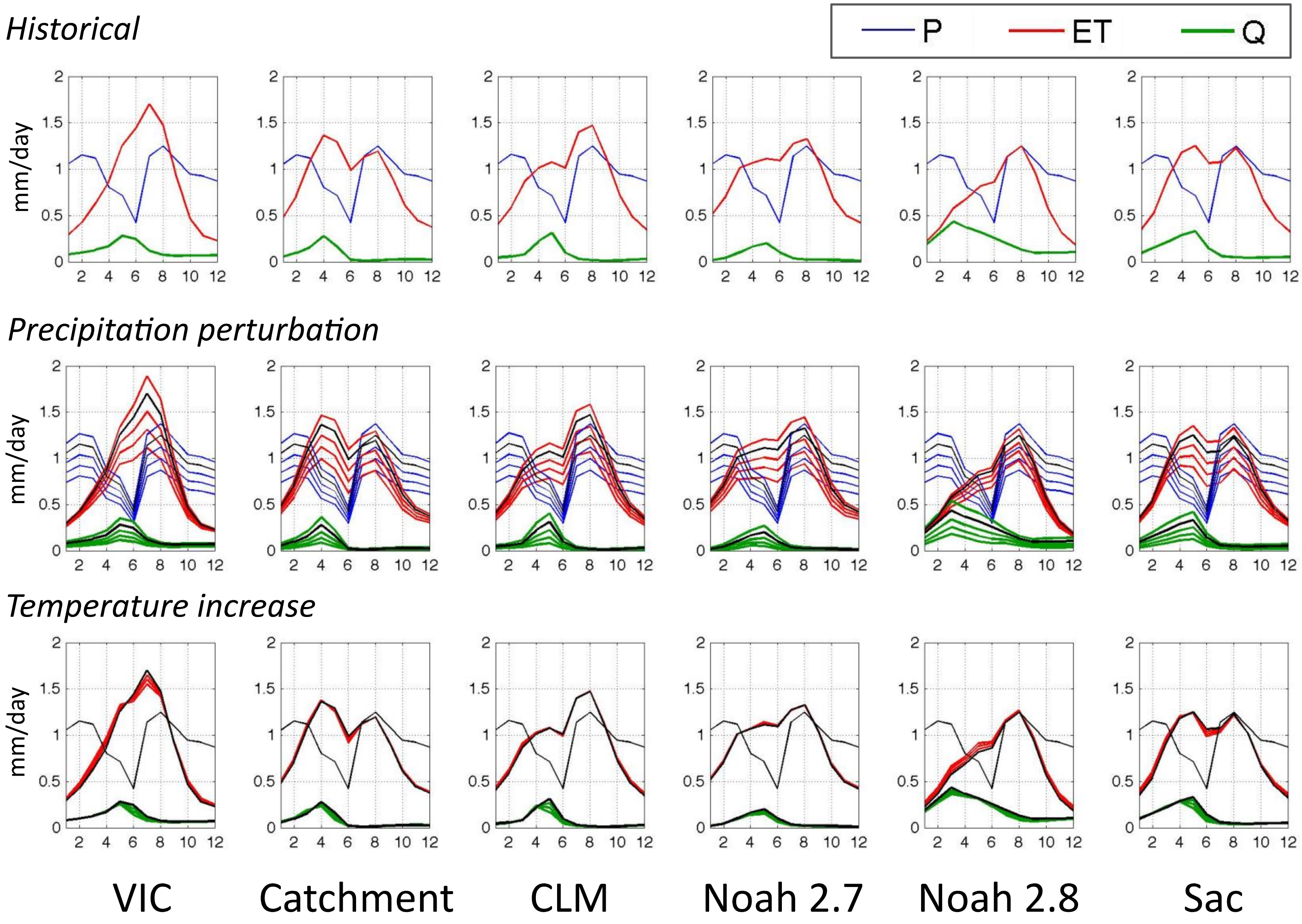


Hydrologic Modeling in the Colorado River

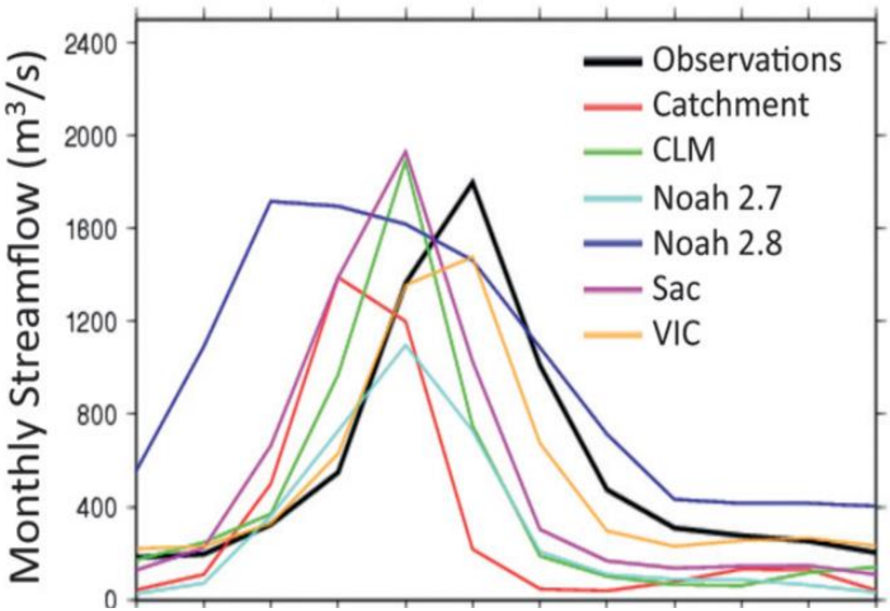
Variable Infiltration Capacity (VIC) model



Hydrologic Modeling in the Colorado River



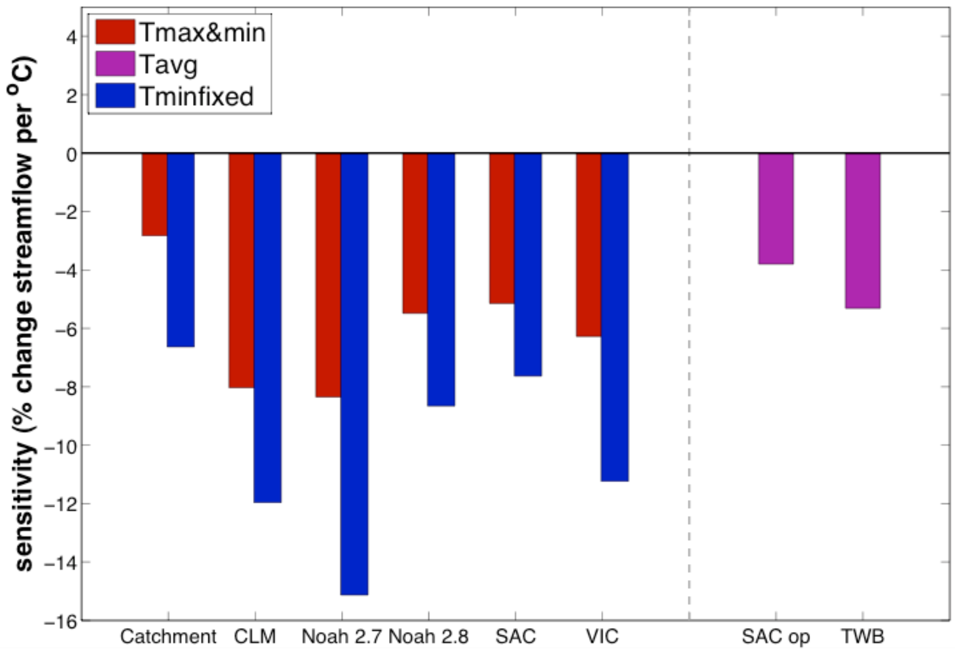
Hydrologic Model Choice



Flows at Lees Ferry using six different Hydrologic Models

- Hydrologic models provide a range of results

Hydrologic Model Choice



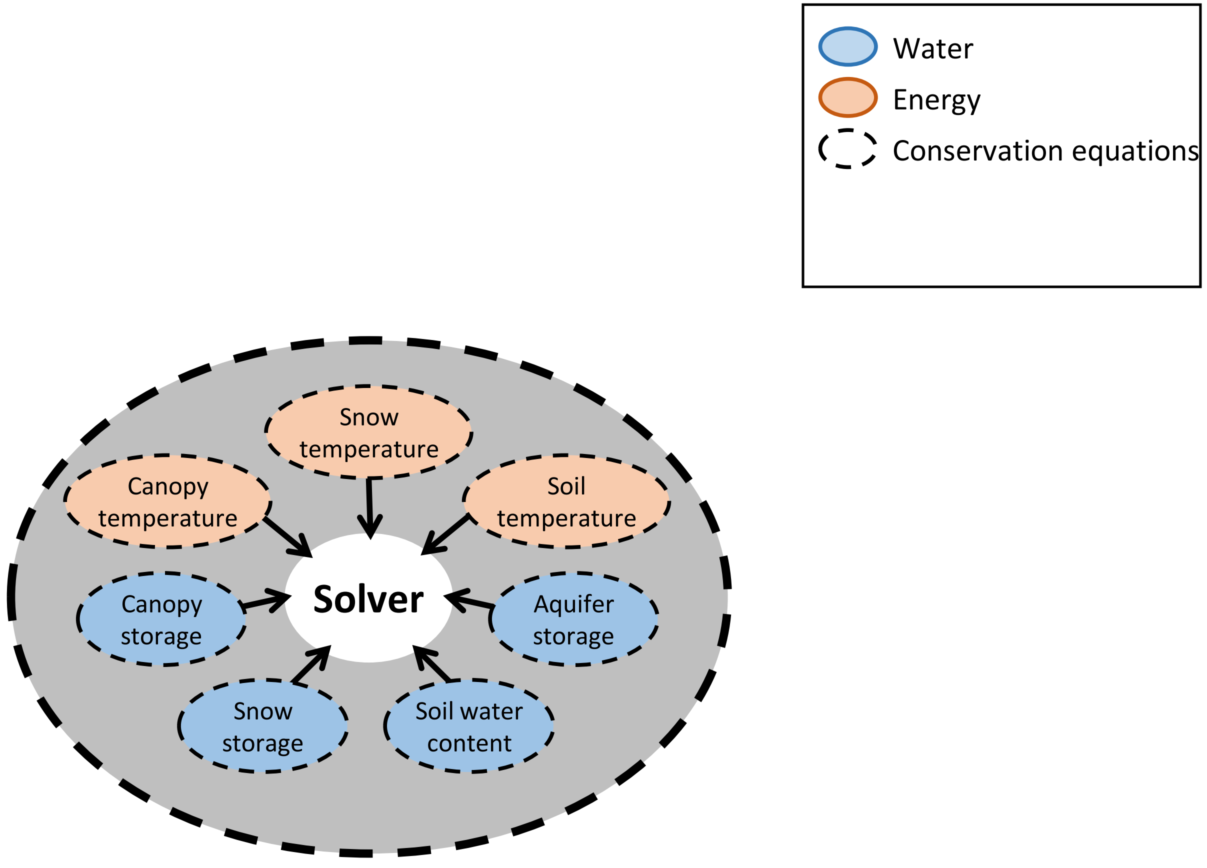
$$\textbf{Temperature Sensitivity} = \frac{\dfrac{Q_{ref+0.1°C} - Q_{ref}}{Q_{ref}}}{0.1\ °C}$$

- Hydrologic models provide a range of results
- Change signal across hydrologic models also differs
- How sensitive a model is depends on hydrologic model choice!
- Some signals are less sensitive to model choice than others

What Do Models Tell Us?

- Many responses to climate change are “obvious” but some are not
- Hydrology-climate interactions not always linear
  - Rain-on-snow events
  - Slower snow melt in a warmer world
- Tipping points can be hard to detect
- Models encapsulate our understanding of the system, but far from perfect

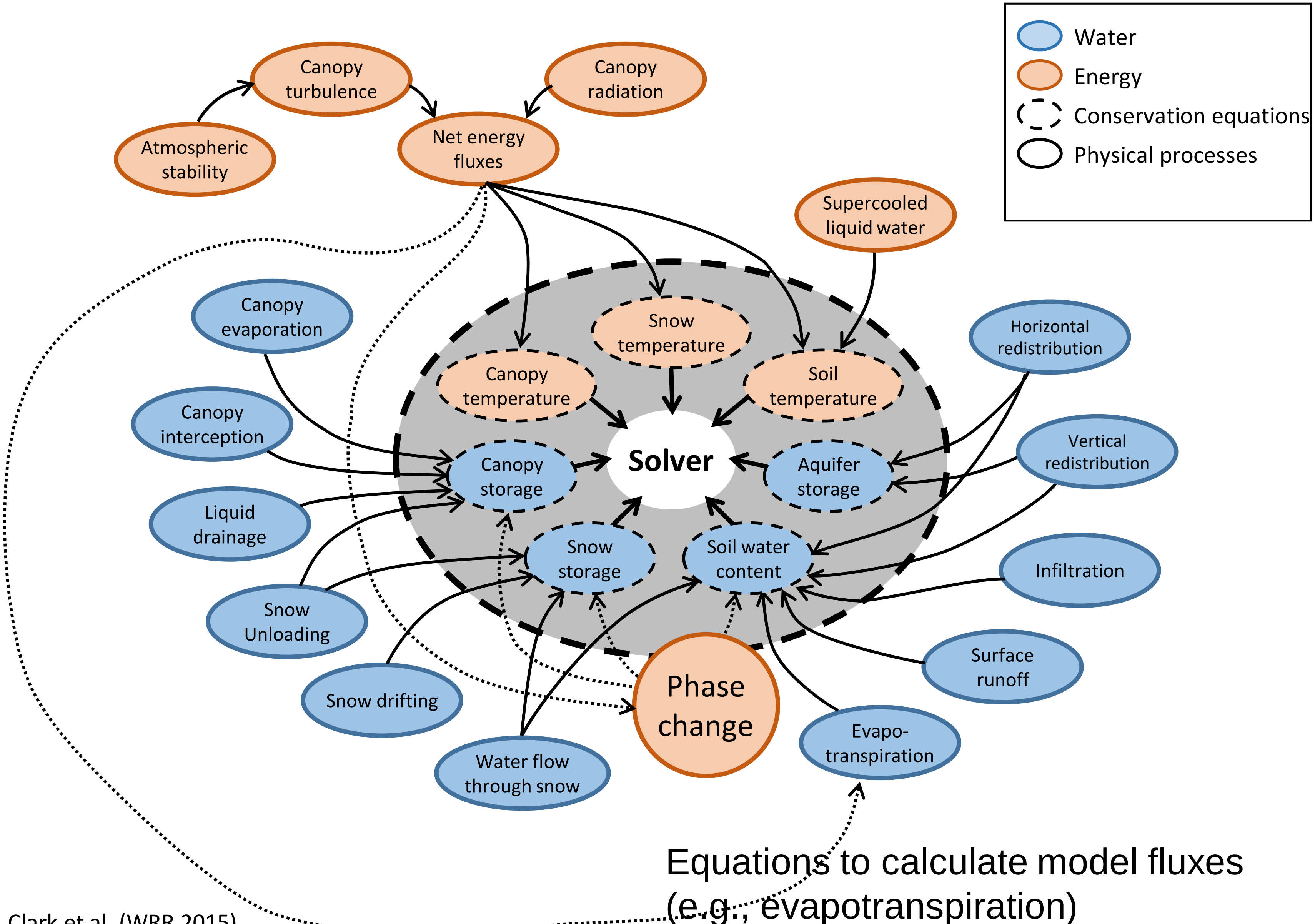
Hydrologic Model Construction



Conservation equations, the order they are solved and time step matter

Clark et al. (WRR 2015)

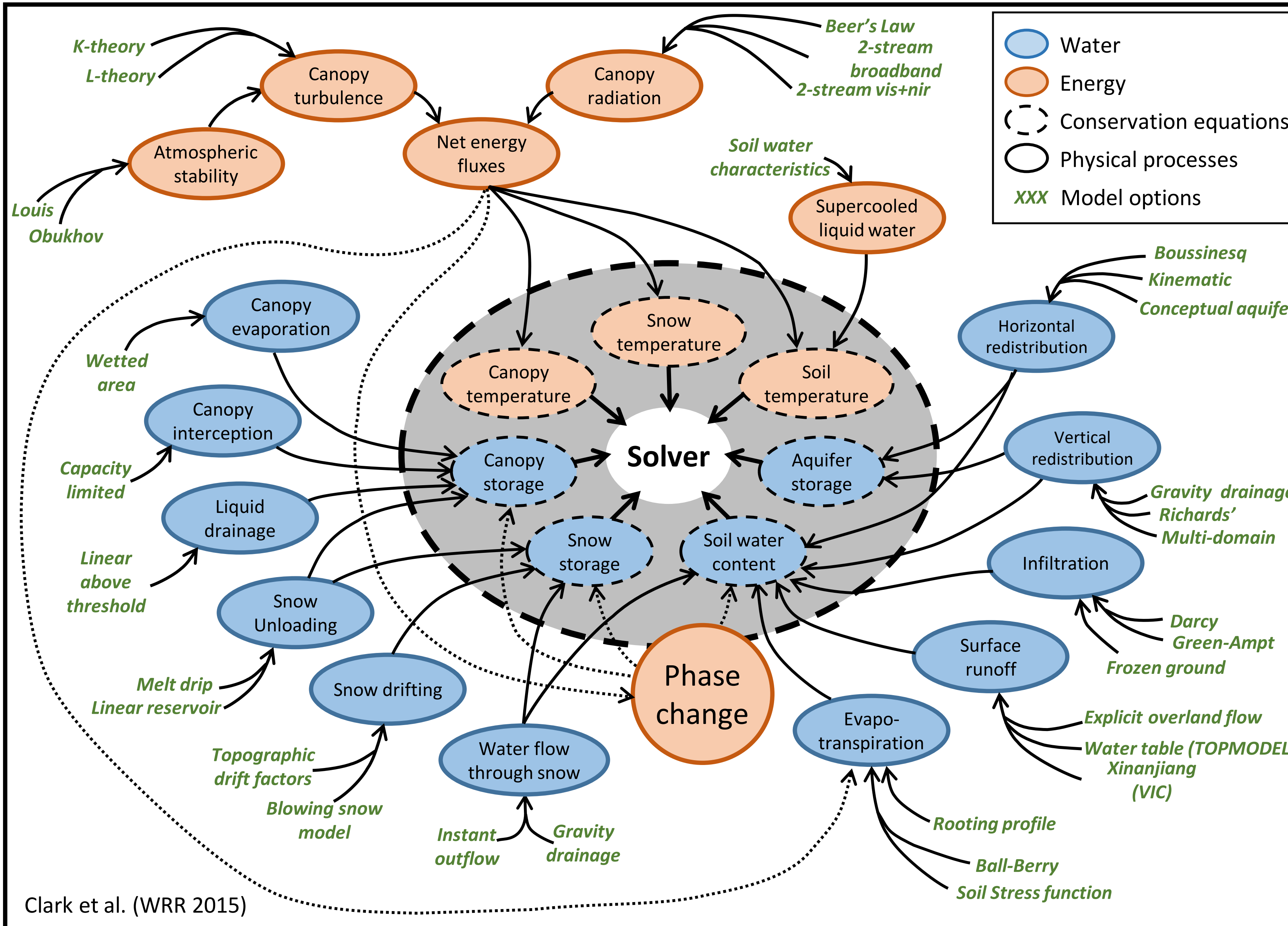
Hydrologic Model Construction



Equations to calculate model fluxes (e.g., evapotranspiration)

Clark et al. (WRR 2015)

Hydrologic Process Selection



Clark et al. (WRR 2015)