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

80% confidence intervals

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

- **Emissions Scenario(s)**
  - e.g. RCP8.5

- **Global Climate Model(s)**
  - e.g. CESM

- **Downscaling method(s)**
  - e.g. BCSD

- **Hydrologic Model(s)**
  - e.g. WEAP, SWMM, Riverware

- **Management/Operations Model(s)**
  - e.g. Sac-SMA

- **Decision**
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

<table>
<thead>
<tr>
<th>Pros</th>
<th>Cons</th>
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<tbody>
<tr>
<td><strong>Dynamical</strong></td>
<td><strong>Statistical</strong></td>
</tr>
<tr>
<td>Represents physical processes</td>
<td>Computationally tractable for large GCM ensembles</td>
</tr>
<tr>
<td>No stationarity assumptions</td>
<td>Large high-resolution data sets publicly available</td>
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<tr>
<td>Physically consistent across variables</td>
<td>Consistent with observations</td>
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<tr>
<td>Computationally expensive</td>
<td>May not represent climate change signal correctly (often is effectively just interpolated GCM signal)</td>
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<tr>
<td>Data set availability is limited</td>
<td>Statistical nature often introduces artifacts</td>
</tr>
<tr>
<td>Introduces need for additional ensembles</td>
<td>Produces climate change signals that still must analyzed for credibility</td>
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A Continuum of Downscaling Options

- 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)

2004-09-10 00:00:00

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

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

Connections between soil and aquifer

Model Parameters

Vegetation, Soil type, ...

Figures from Clark et al., WRR, 2015
Hydrologic Model Processes

Looking under the hood...

- Canopy radiation
- Conservation equations
- Physical processes
- Model options

Water
- Evapotranspiration
- Infiltration
- Surface runoff
- Aquifer storage
- Snow storage
- Soil water content
- Snow temperature
- Canopy temperature
- Canopy storage
- Canopy interception
- Infiltration
- Surface runoff
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- Beer's Law 2-stream broadband 2-stream vis+nir
- Soil water characteristics
- Supercooled liquid water

- Horizontal redistribution
- Vertical redistribution
- Gravity drainage
- Richards’ Multi-domain
- Boussinesq Kinematic Conceptual aquifer

- Water table (TOPMODEL)
- Xinanjiang (VIC)
- Rooting profile
- Ball-Berry
- Soil Stress function

- Capacity limited
- Liquid drainage
- Linear above threshold
- Wetted area
- Melt drip
- Linear reservoir
- Topographic drift factors
- Blowing snow model
- Instant outflow
- Gravity drainage

- Clark et al. (WRR 2015)
Revealing Uncertainties

Emissions Scenario(s)

Global Climate Model(s)

GCM Initial Conditions

Combined uncertainty

Downscaling Method(s)

Hydrologic Model Structure(s)

Hydrologic Model Parameter(s)

Combined uncertainty projections

PDF

PDF

PDF
calibration

ens. members

models

methods

PDF

PDF
Revealing Uncertainties

Key Uncertainties from:
- Human activities
- Physical processes
- Natural variability
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Decision

Management/Operations Model(s)

- e.g. WEAP, SWMM
- e.g. Sac-SMA
Revised “Top-down” Impacts Modeling Chain

- Emissions Scenario(s)
  - e.g. RCP8.5
- Global Climate Model(s)
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- Decision
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Do Be Aware of Multiple Ways to Evaluate Future Changes

Scenario studies

Stochastic hydrology

Climate-informed vulnerability analysis

Paleoclimate studies

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

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

Clark et al. 2016; connect models in a chain

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

Vano et al., BAMS, 2016; generate timeseries using reconstructions of the distant past
Don’t Treat All Future Projections or Methods Equally

- 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 $\neq$ Higher Accuracy

Be a savvy consumer and remember...

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

Figure from Vano et al., BAMS, January 2014
“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
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](http://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](http://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):
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
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?
Model Set Up

GIS data = soil, vegetation, elevation maps

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NRCS STATSGO2 and SSURGO²,³
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
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
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

Historical

Temperature perturbations

Precipitation perturbations

mm/day

P

ET

Q
Hydrologic Modeling in the Colorado River

**Historical**

**Precipitation perturbation**

**Temperature increase**

P | ET | Q

VIC | Catchment | CLM | Noah 2.7 | Noah 2.8 | Sac
Hydrologic Model Choice

Flows at Lees Ferry using six different Hydrologic Models

• Hydrologic models provide a range of results
Hydrologic Model Choice

- 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

\[
\text{Temperature Sensitivity} = \frac{Q_{\text{ref}+0.1 ^\circ C} - Q_{\text{ref}}}{Q_{\text{ref}}} / 0.1 ^\circ C
\]
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
Conservation equations, the order they are solved and time step matter

Clark et al. (WRR 2015)
Equations to calculate model fluxes (e.g., evapotranspiration)