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

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Classic “Top-down” Impacts Modeling Chain

- Emissions Scenario(s)
  - e.g. RCP8.5
- Global Climate Model(s)
  - e.g. CESM
- Decision
  - Management/Operations Model(s)
  - e.g. WEAP, SWMM
- Downscaling method(s)
  - e.g. BCSD
- Hydrologic Model(s)
  - e.g. Sac-SMA
Why Do We Need to Downscale?

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

Regional climate models:
- High resolution of topography
- More accurate simulation of 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 (e.g., WRF) to simulate local dynamics over the area of interest
- Global model output is applied along the boundaries and as initial conditions
- Computationally expensive, time and supercomputers (usually) required
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>Dynamical</th>
<th>Statistical</th>
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<tbody>
<tr>
<td><strong>Pros</strong></td>
<td><strong>Pros</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>
</tr>
<tr>
<td>Physically consistent across variables</td>
<td>Consistent with observations</td>
</tr>
<tr>
<td><strong>Cons</strong></td>
<td><strong>Cons</strong></td>
</tr>
<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 be 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
Simulations in the Southeast

- 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)

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

Demonstrating a climate change signal 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 Help Determine an Appropriate Downscaling Technique

• How large is the area of interest?
• Where is it?
• What is the impact of interest?
• When in the future?
• Does the sequencing of events matter?
• What type of climate change uncertainty is important?
• What is available?
Classic “Top-down” Impacts Modeling Chain

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Decision

Hydrologic Model(s)
What type of models do you use to track water in your system?
Why Do We Need Hydrology Models?

What we have: precipitation, temperature, other atmospheric values

What we would like: streamflow (highs, lows), water demand from vegetation, water temperature

Hydrology models represent energy and water fluxes in watersheds, combine measurements and physical processes to encapsulate our understanding.

Important in filling gaps since measurements are not available in most places.
Portland Water Bureau

- Land surface values from GCMs measures not helpful
- Worked with University of Washington to select and set up in-house hydrologic model
- Model allows PWB to understand how changes in streamflow 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 Process Structure

Looking under the hood...

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

Solver

Canopy radiation

Conservation equations

Physical processes

XXX Model options

Beer's Law
2-stream broadband
2-stream vis+nir

Soil water characteristics

Evapotranspiration
Infiltration
Surface runoff
Evapotranspiration

Canopy storage
Aquifer storage
Soil storage
Snow storage

Canopy temperature
Snow temperature
Soil temperature

Canopy interception
Liquid drainage
Snow Unloading
Snow drifting
Water flow through snow

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

Louis
Obukhov

Horizontal redistribution
Vertical redistribution
Gravity drainage
Richards’ Multi-domain
Darcy
Green-Ampt
Frozen ground
Explicit overland flow

Phase change

Water flow through snow

Clark et al. (WRR 2015)
Hydrologic Model Construction

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

Clark et al. (WRR 2015)
Clark et al. (WRR 2015)

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

Hydrologic Model Construction

Conservation equations

- Water
- Energy
- Physical processes

Canopy turbulence

Atmospheric stability

Net energy fluxes

Canopy radiation

Supercooled liquid water

Horizontal redistribution

Vertical redistribution

Infiltration

Surface runoff

Evapotranspiration

Soil water content

Snow temperature

Canopy temperature

Aquifer storage

Canopy storage

Snow storage

Canopy evaporation

Canopy interception

Liquid drainage

Snow Unloading

Snow drifting

Water flow through snow

Snow drifting

Soil temperature

Phase change

Clark et al. (WRR 2015)
Revealing Uncertainties

Emissions Scenario(s)

Global Climate Model(s)

GCM Initial Conditions

Combined uncertainty

PDF

scenarios

models

ens. members

methods

PDF

models

PDF

hydrologic model

PDF

hydrologic model parameter(s)

PDF

calibration

Hydrologic Model Structure(s)

Hydrologic Model Structure(s)

Combined uncertainty
Revealing Uncertainties

Key Uncertainties from:
- Human activities
- Physical processes
- Natural variability
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Revised “Top-down” Impacts Modeling Chain

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Do Be Aware of Multiple Ways to Evaluate Future Changes

Scenario studies

Stochastic hydrology

Climate-informed vulnerability analysis

Paleoclimate studies

Clark et al. 2016; connect models in a chain

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

Brown et al., WRR, 2016; explore syvulnerabilities with perturbations

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

Figure 1.3 Concept of Monte Carlo experiments.

80% confidence intervals

1250–year Streamflow Reconstruction

Grey areas represent 80% confidence intervals.
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 ≠ Higher Accuracy

Be a savvy consumer and remember...

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

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 (know the warts)
What Data are Available Now?

- Hydrology focused Green Data Oasis (GDO) 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)
What Resources are Available?

• 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

• Regional Boundary Organizations
  – Florida Water & Climate Alliance

• Dos and Don’ts Guidelines from NCAR
  – Reviews other guidance
  – www.ncar.github.io/dos_and_donts

• Many others, including each other
Climate Change 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

• Downscaling and hydrology modeling provide local-scale insights into possibilities projected by GCMs.

• There is a continuum of downscaling approaches that span tradeoffs between computational efficiency and methodological complexity.

• Some change signals are more certain than others.

• Some uncertainty is unavoidable.
  – Representation of uncertainties is hard but necessary.
  – Uncertainties have always been there; just understanding them now.
  – Previous studies may be over-confident.
Key Takeaways

• Research underway to develop ways to select representative set of scenarios useful for water resources planning.

• 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., Florida Water & Climate Alliance, NCAR https://ncar.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

Portland Water Bureau

NRCS STATSGO2 and SSURGO\textsuperscript{2,3}

![Vegetation Type legend](Image)

![Elevation](Image)

![Soil Type](Image)
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.
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

Historical

Temperature perturbations

Precipitation perturbations

mm/day

P  ET  Q
Hydrologic Modeling in the Colorado River

**Historical**

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<td>1</td>
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<td>0.5</td>
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Historical data for different models:

- **VIC**
- **Catchment**
- **CLM**
- **Noah 2.7**
- **Noah 2.8**
- **Sac**

**Precipitation perturbation**

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**Temperature increase**

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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
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