Newly Available High Resolution Data Dynamically Downscaled for the Colorado River Basin

Christopher Castro
Hsin-I Chang
Department of Hydrology and Atmospheric Sciences
University of Arizona
Uncertainty varies over time
Understanding uncertainties in climate and streamflow projections (BAMS, 2014)

- Sources of climate projection uncertainty for Colorado River:
  1. GCM and emission scenarios used
  2. Spatial scale and topography dependency
  3. How land surface hydrology represents precipitation and temperature change
  4. Downscaling methodologies

![Diagram showing the sources of climate projection uncertainty]
## Current global climate model (GCM) projection list

<table>
<thead>
<tr>
<th>Model</th>
<th>Center</th>
<th>Atmospheric Horizontal Resolution (lon. x lat.)</th>
<th>Number of model levels</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACCESS1-0</td>
<td>Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology, Australia</td>
<td>1.875 x 1.25</td>
<td>38</td>
<td>Bi et al. (2012)</td>
</tr>
<tr>
<td>BCC-CSM1.1*</td>
<td>Beijing Climate Center, China Meteorological Administration, China</td>
<td>2.8 x 2.8</td>
<td>26</td>
<td>Xin et al. (2012)</td>
</tr>
<tr>
<td>CanCM4</td>
<td>Canadian Centre for Climate Modelling and Analysis, Canada</td>
<td>2.8 x 2.8</td>
<td>35</td>
<td>Chylek et al. (2011)</td>
</tr>
<tr>
<td>CanESM2*</td>
<td>Canadian Center for Climate Modeling and Analysis, Canada</td>
<td>2.8 x 2.8</td>
<td>35</td>
<td>Arora et al. (2011)</td>
</tr>
<tr>
<td>CCSM4*</td>
<td>National Center for Atmospheric Research, USA</td>
<td>1.25 x 0.94</td>
<td>26</td>
<td>Gent et al. (2011)</td>
</tr>
<tr>
<td>CESM1-CAM5-1-FV2</td>
<td>Community Earth System Model Contributors (NSF-DOE-NCAR)</td>
<td>1.4 x 1.4</td>
<td>26</td>
<td>Gent et al. (2011)</td>
</tr>
<tr>
<td>CNRM-CM5.1*</td>
<td>National Centre for Meteorological Research, France</td>
<td>1.4 x 1.4</td>
<td>31</td>
<td>Voldoire et al. (2011)</td>
</tr>
<tr>
<td>CSIRO-MK3.6*</td>
<td>Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence, AUS</td>
<td>1.8 x 1.8</td>
<td>18</td>
<td>Roistayn et al. (2010)</td>
</tr>
<tr>
<td>EC-EARTH</td>
<td>EC-EARTH consortium</td>
<td>1.125 x 1.12</td>
<td>62</td>
<td>Hazeleger et al. (2010)</td>
</tr>
<tr>
<td>FGOALS-S2.0</td>
<td>LASG, Institute of Atmosphere Physical, Chinese Academy of Sciences</td>
<td>2.8 x 1.6</td>
<td>26</td>
<td>Bao et al. (2012)</td>
</tr>
<tr>
<td>GFDL-CM3*</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory, USA</td>
<td>2.5 x 2.0</td>
<td>48</td>
<td>Donner et al. (2011)</td>
</tr>
<tr>
<td>GFDL-ESM2G*</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory, USA</td>
<td>2.5 x 2.0</td>
<td>48</td>
<td>Donner et al. (2011)</td>
</tr>
<tr>
<td>GISS-E2-HR*</td>
<td>NASA Goddard Institute for Space Studies, USA</td>
<td>2.5 x 2.0</td>
<td>40</td>
<td>Kim et al. (2012)</td>
</tr>
<tr>
<td>HadCM3*</td>
<td>Met Office Hadley Centre, UK</td>
<td>3.75 x 2.5</td>
<td>19</td>
<td>Collins et al. (2001)</td>
</tr>
<tr>
<td>HadGEM2-CC (Chemistry coupled)</td>
<td>Met Office Hadley Centre, UK</td>
<td>1.875 x 1.25</td>
<td>60</td>
<td>Jones et al. (2011)</td>
</tr>
<tr>
<td>HadGEM2-ES*</td>
<td>Met Office Hadley Centre, UK</td>
<td>1.875 x 1.25</td>
<td>60</td>
<td>Jones et al. (2011)</td>
</tr>
<tr>
<td>INMCM4*</td>
<td>Institute for Numerical Mathematics, Russia</td>
<td>2 x 1.5</td>
<td>21</td>
<td>Volodin et al. (2010)</td>
</tr>
<tr>
<td>IPSL-CM5A-LR*</td>
<td>Institut Pierre Simon Laplace, France</td>
<td>3.75 x 1.8</td>
<td>39</td>
<td>Dufresne et al. (2012)</td>
</tr>
<tr>
<td>IPSL-CM5A-MR*</td>
<td>Institut Pierre Simon Laplace, France</td>
<td>2.5 x 1.25</td>
<td>39</td>
<td>Dufresne et al. (2012)</td>
</tr>
<tr>
<td>MIROC4h</td>
<td>Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan</td>
<td>0.56 x 0.56</td>
<td>56</td>
<td>Sakamoto et al. (2012)</td>
</tr>
<tr>
<td>MIROC5*</td>
<td>Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology, Japan</td>
<td>1.4 x 1.4</td>
<td>40</td>
<td>Watanabe et al. (2010)</td>
</tr>
<tr>
<td>MIROC-ESM*</td>
<td>Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies</td>
<td>2.8 x 2.8</td>
<td>80</td>
<td>Watanabe et al. (2010)</td>
</tr>
<tr>
<td>MIROC-ESM-CHEM</td>
<td>Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies</td>
<td>2.8 x 2.8</td>
<td>80</td>
<td>Watanabe et al. (2010)</td>
</tr>
<tr>
<td>MPI-ESM-LR*</td>
<td>Max Planck Institute for Meteorology, Germany</td>
<td>1.9 x 1.9</td>
<td>47</td>
<td>Zanchettid et al. (2012)</td>
</tr>
<tr>
<td>MRI-CGCM3*</td>
<td>Meteorological Research Institute, Japan</td>
<td>1.1 x 1.1</td>
<td>48</td>
<td>Yukimoto et al. (2011)</td>
</tr>
<tr>
<td>NorESM1-M*</td>
<td>Norwegian Climate Center, Norway</td>
<td>2.5 x 1.9</td>
<td>26</td>
<td>Zhang et al. (2012)</td>
</tr>
</tbody>
</table>
Not all GCM tells the same story
Southwest/Mexico precipitation (1980-1999)

We selected GCMs that has good historic climate results for the Southwest and Mexico

Cook and Seager (2013, J. Geophys. Res.)
Multi-model schematic: Translating IPCC climate signals to basin-scale hydroclimate projections

Global IPCC climate projections (1-2°) → Regional climate simulations (25-35 km) → Basin-scale simulations (12.5km resolution)

Dynamical downscaling

Bias correction

Statistical Downscaling
One of the most debated tables by the authors in writing of the DOD report...

**TABLE 4 Recommendation Table on the Use of Climate Datasets based on Regional Features**

<table>
<thead>
<tr>
<th>Scale</th>
<th>Statistical Downscaling Methods</th>
<th>Dynamic Downscaling</th>
<th>GCM</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Data correction</td>
<td>Empirical quantile mapping</td>
<td>Bias correction</td>
</tr>
<tr>
<td>Global scale: ~3,000 km or more, weeks to months (general circulation structure, jet stream position)</td>
<td>G</td>
<td>G</td>
<td>B</td>
</tr>
<tr>
<td>Synoptic scale: 100–3,000 km, days to weeks (highs and lows, midlatitude cyclones, monsoons, atmospheric teleconnections)</td>
<td>G</td>
<td>G</td>
<td>B</td>
</tr>
<tr>
<td>Course mesoscale-α, β: 10–100 km, hours to days (katabatic winds, weather fronts, mesoscale convective systems, tropical cyclones, sea breeze circulations)</td>
<td>G</td>
<td>G</td>
<td>B</td>
</tr>
<tr>
<td>Fine mesoscale-γ: 1–10 km, hours to minutes (supercell thunderstorms, tornadoes, gust fronts, air mass thunderstorms, mountain-valley winds, mountain snowfall)</td>
<td>R</td>
<td>R</td>
<td>B</td>
</tr>
</tbody>
</table>

**Legend:**
- Green: good
- Yellow: maybe
- Red: bad

Spatial and temporal resolution suited for basin-scale hydroclimate studies
Regional Climate Modeling with Dynamical Downscaling
From Global scale to Regional Scale: Monsoon vs. No Monsoon for the Southwest

Observation

Global Climate Model

Dynamical Downscaling
Performance of Regional Climate Model:
60-year Winter Precipitation

Observation

Dynamical Downscaling
Performance of Regional Climate Modeling: 60-year Summer Precipitation

Observation

Dynamical Downscaling
Mean and extreme precipitation difference:

 Trends of future extreme precipitation do not follow the mean precipitation ([2011-2040] - [1950-2010]).

**Mean Precipitation Difference**

Monsoon season: Mean precipitation decreasing in Southwest, increasing in Mexico

**Extreme Precipitation Difference**

Monsoon season: More intense rainfall in Southwest, opposite in Mexico
Downscaled Regional Climate to Streamflow Projections over Colorado River Basins
Study Region: Upper and Lower Colorado River Basins

Harding et al. (HESSD, 2012)
Current operational streamflow projection products:
Upper Colorado River basin at Lees Ferry gauge
Full 112-Member BCSD CMIP3 Ensemble Projection

Assumptions
Greater reduction in uncertainty with more ensemble members, or the “bigger cloud”

Mean of the multi-model ensemble is our most confident metric because of cancellation of model error

But what should Bureau of Reclamation do if dynamical downscaling would yield a different result than BCSD, but with far fewer members??

Harding et al. (2012, HESSD)
Multi-model schematic: Translating IPCC climate signals to basin-scale hydroclimate projections

Global IPCC climate projections (1-2°) → Regional climate simulations (25-35 km) → Bias correction → Basin-scale simulations (12.5km resolution)
Monthly precipitation and streamflow at Upper Colorado Basin (Lees Ferry): 1971-2000

Precipitation

Streamflow

Blue: Statistical Downscaling
Red: Dynamical Downscaling
Black: Observation
Upper Colorado Streamflow Bias at Lees Ferry: 1971-2000

Dynamical downscaling leads to reduced bias in representation of historical streamflow, generally independent of high and low flows. The regional modeling component is main reason why, not choice of bias correction technique.

- **Precipitation**: Blue: Statistical Downscaling, Red: Dynamical Downscaling, Black: Observation

- **Streamflow**: Blue: Statistical Downscaling, Red: Dynamical Downscaling, Black: Observation
Upper Colorado River Streamflow Percentage Change: (2041-2070) minus (1971-2000)

Greatest difference between a statistically vs. dynamically downscaled streamflow projection occurs for highest flows. On order of 10-20% lower streamflow during peak flows with dynamical downscaling!
Salt and Verde Basin Streamflow Percentage Change: (2041-2070) minus (1971-2000)

The potential decreases on the smaller rivers that are the lifeblood of the SRP system may be even more dramatic than for the Upper Basin!

Blue: Statistical Downscaling
Red: Dynamical Downscaling
Black: Observation
Summary for Upper Colorado Basin Streamflow

• Dynamically downscaled streamflow has comparatively less bias in the historical period.

• Both statistical and dynamical downscaling show a shift of the hydrograph to an earlier period of peak flow.

• Dynamical downscaling projects lower peak streamflow than statistical downscaling, on the order of 10-20% additional decline in the mid 21st century.

• The range of simulated streamflow with dynamical downscaling is outside the range of statistical downscaling ensembles with BCSD challenging the paradigm of the cloud of points.
Supplemental slides
Climate projection products under different greenhouse gas emission scenarios:
Why are projections uncertain?

- **HUMAN** We don’t know what future emissions from human activities will be.

- **SCIENTIFIC** We don’t know how sensitive the planet is, and our ability to simulate the climate system is limited and incomplete, particularly at the local to regional scale.

- **NATURAL** Continuous natural variations in climate make it difficult to predict conditions over shorter time scales.
Improved North American monsoon precipitation in CMIP5 models: SW only

- Some has lagged peak monsoon season
- Many don’t capture the monsoon retreat
- Large spread in model results from summer to early fall

Geil et al (2013, J. Climate)
NARCCAP (CMIP3) Winter precipitation (1979-1999):

Observation  NARR  Multi-Model Ensemble Mean

Dominguez et al. (2012, JGR)
Figure 4. Comparison of model-derived snowfall for the period 1981–2005 winter (December–March) to observed snowfall for three different latitudinal bands and seven altitudinal bands. Each period is averaged in space, and shows total snowfall for the winter (December–March) season.

Wi et al.. 2012
Sometimes, driving GCM is not the problem.

Bukovsky et al. (2014, *J. Climate*)

NARCCAP (CMIP3)
July/Aug Precipitation for Southwest

Figure 3: JA average precipitation change (%) from the baseline period. Hatching indicates where the change is statistically significant at the 0.1 level.
Which is “right” way to go?

<table>
<thead>
<tr>
<th>Pros</th>
<th>Statistical Downscaling</th>
<th>Dynamical Downscaling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Simple and inexpensive</td>
<td>Represents physical processes</td>
</tr>
<tr>
<td></td>
<td>Many realizations</td>
<td>Lots of variables available</td>
</tr>
<tr>
<td></td>
<td>Relatively easy to apply</td>
<td>Characterize extremes</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cons</th>
<th>Statistical Downscaling</th>
<th>Dynamical Downscaling</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stationarity problem</td>
<td>Lesser scenario simulations</td>
</tr>
<tr>
<td></td>
<td>Underestimates extremes</td>
<td>Computationally expensive</td>
</tr>
<tr>
<td></td>
<td>No physical process basis</td>
<td>Requires training, experience</td>
</tr>
</tbody>
</table>

**Reduce statistical uncertainty**

**Reduce physical process uncertainty**
North American Regional Climate Assessment Program (NARCCAP, dynamically downscaling IPCC CMIP3 products)

NARCCAP PLAN – Phase II

A2 Emissions Scenario

GFDL
CGCM3
HADCM3
CCSM

GF DL
Time slice
50 km

CM3
Time slice
50 km

Provide boundary conditions

1971-2000 current

2041-2070 future

MM5
Iowa State/ PNNL

RegCM3
UC Santa Cruz
ICTP

CRCM
Quebec, Ouranos

HADRM3
Hadley Centre

RSM
Scripps

WRF
NCAR/ PNNL

Courtesy Dr. Linda Mearns, National Center for Atmospheric Research
## North America Coordinated Regional Downscaling Experiment (NA CORDEX, dynamically downscaling IPCC CMIP5 products)

### Point of Contact (PoC)

<table>
<thead>
<tr>
<th>Model</th>
<th>Runs done</th>
<th>Time period</th>
<th>Resolution</th>
<th>Domain</th>
<th>Accessibility of output</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRCM5</td>
<td>3</td>
<td>ERA40</td>
<td>ERA - Int</td>
<td>CanESM2</td>
<td>4.5 - 8.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MPI - ESM</td>
<td>LR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>MPI - ESM</td>
<td>MR</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1958 - 2013</td>
<td>2061 - 2105</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2006 - 2100</td>
<td>2006 - 2100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2006 - 2100</td>
<td>2006 - 2100</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>44, 22, 11</td>
<td>same three?</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>44</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

58 - 78

### Email Point of Contact (PoC)

1) Katja Winger
   - Email: winger.katja@uqam.ca

2) Kevin Sieck
   - Email: kevin.sieck@mpimet.mpg.de

3) Grigory Nikulin
   - Email: grigory.nikulin@smhi.se

4) Ph. Lucas-Picher
   - Email: plp@sca.uqam.ca

5) Ray Arritt
   - Email: rwarritt@bruce.agron.iastate.edu

6) Hsin-I Chang
   - Email: chang@atmo.arizona.edu
   - Email: castro@atmo.arizona.edu

7) Wilfran or who?
   - Email: HadGEM3RA

8) John Scinocca
   - Email: John.scinocca@ec.gc.ca

9) Ole Christensen
   - Email: obc@dmi

### Map

- CORDEX_NAMEERICA
  - Resolution: 0.44° (50 km)
  - nx: 171, ny: 146
  - You have the HadRM3P model and the MOSES2 land surface scheme selected.
  - New soil and land use overrides are incompatible with MOSES2.2 and have been disabled.
  - Existing soil and land use overrides will be ignored in this experiment.

- Domain: Lambert conformal
  - A bit larger than NARCCAP

**Contact PoC**
Extreme precipitation rate (top 10%): June/July vs Aug/Sep (WRF-CMIP5)

June/July (1950-2010)

WRF–ECHAM6 JJ extreme precip rate (mm/day, 1950–2010, 50km)

Aug/Sep (1950-2010)

WRF–ECHAM6 AS extreme precip rate (mm/day, 1950–2010, 50km)

June/July (2011-2040)

WRF–ECHAM6 JJ extreme precip rate (mm/day, 2011–2040, 50km)

Aug/Sep (2011-2040)

WRF–ECHAM6 AS extreme precip rate (mm/day, 2011–2040, 50km)
Summary for Regional Climate Modeling:

- **Value added using dynamical downscaling technique:** Precipitation distribution better represented in WRF regional climate model, as compared to raw IPCC global climate datasets.

- **Performance in seasonal mean climatology:** WRF simulations using IPCC climate projections have reasonable 20th century precipitation climatology for both summer and winter seasons.

- **Regional climatology from different generation of IPCC projections:** improvements in mean precipitation climatology are found in downscaled WRF-CMIP5 simulations, as compared to the WRF-CMIP3 runs.
Fig. 6. Comparison of BCSD downscaling from C&L with a delta-method downscaling approach for Lees Ferry in the 2040–69 future period for A2 emission scenarios. On average, the BCSD approach has a decline in streamflow of 7% (average values of 93%), whereas with the delta method, declines are 13% (average values of 87%). Differences are the BCSD approach minus the delta-method approach.
Bias Correction and Spatial Disaggregation (BCSD)

CMIP3 A2 Scenario
NARCCAP GCMs
UA: MPI-ECHAM5 and HadCM3

Dynamical Downscaling
Regional Climate Model
NARCCAP
UA-WRF: MPI, HadCM3

Statistical Downscaling

New Parametric Bias Correction (BC-UA)

BOR Calibrated VIC hydrologic model

Statistically Downscaled Streamflow using BCSD

Non Parametric Bias Correction (NP-BC) of BCSD

BOR Calibrated VIC hydrologic model

Dynamically Downscaled Streamflow using BC-UA

BOR Calibrated VIC hydrologic model

Dynamically Downscaled Streamflow using NP-BC