Further dynamical downscaling of NARCCAP using WRF:

High-resolution simulations of extreme precipitation events in future NARCCAP climate scenarios

Kelly Mahoney (UCAR-PACE)
Michael Alexander, Jamie Scott, Joe Barsugli
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Motivation: Extreme precipitation and climate change

- Extreme precipitation events generally predicted to increase*...but why, when, where, and by how much?
- Global climate models not suited for simulation of extreme precipitation (resolution, parameterizations)
- Regional climate models often still too coarse, use CP schemes
- Projections, predictions most valuable at local, “weather” scales to users (public, planners) – especially in mountainous, complex terrain

* e.g., Frei et al. 1998; Meehl et al. 2005; IPCC 2007; Gutkowski et al. 2008; Karl et al. 2008
Research objectives

Across the Front Range of the Colorado Rocky Mountains...

1. Do elevation thresholds for storms, flooding, hail change in future scenarios?
2. Which storm-scale physical processes are most affected by changes in large-scale climate? (e.g., updraft strength, precipitation efficiency, entrainment?)

3. What are the strengths, limitations of various downscaling approaches?
   a. What is the “best” way to downscale climate extremes?
   b. Space, time scales required? Statistical vs. dynamical downscaling? Optimal approach to either?
   c. Research- and decision-making communities:
      
      Improved understanding of strengths, limitations of downscaling approaches → inform selection of most appropriate approach to specific problem
Methodology: Overview

1. Select extreme cases from regional climate model data
2. Create initial conditions for WRF simulations
3. Execute high-resolution simulations
4. Compare past, future high-resolution simulations
Methodology

- **NARCCAP**: North American Regional Climate Change Assessment Program
  - Initial, boundary conditions from 20\textsuperscript{th}, 21st century AOGCM experiments
  - GFDL-timeslice, WRF-CCSM used (so far)

- **Extreme event selection:**
  1. Target region: Colorado Front Range
  2. For past (1971-2000), future (2041-2070) simulations:
     1. Sort all warm-season (June-July-August) daily precipitation values in target region
     2. 30 largest precipitation values $\approx$ Top 1\% of events
Three different downscaling methodologies (Overview)

1. Individual simulations
2. Composite-initialized simulations
3. Delta method/“PGW”/climate-perturbed simulations of observed extreme event

1. Individual simulations: Comparison of top 10 past individual events vs. top 10 future individual events

2. Composite approach

3. Big Thompson Canyon Flood in “GFDL-TS Future”
WRF runs: Model set-up

- WRFV3.1
  - 4km outer domain: 450x450 gridpoints
  - 1.33 km inner domain: 574x601 gridpoints
  - Hourly output for 24-h
- Parameterizations:
  - WSM6 microphysics
  - YSU Planetary Boundary Layer scheme
  - RRTM, Dudhia LW/SW radiation physics
  - Noah land surface model (4-layers)
- Initial conditions for runs shown here:
  - Geophysical Fluid Dynamics Laboratory (GFDL) GCM – “Timeslice” simulations
  - GFDL AM2.1; 20C3M; SRES-A2 (Historical simulations not based on real events)
Examples of preliminary results*:

1. Individual simulations
2. Composite-initialized simulations
3. Delta method/“PGW”/climate-perturbed simulations of observed extreme event

*Main results shown are from one NARCCAP regional climate model dataset: the GFDL-timeslices experiment...brief comparison at end
As seen at 50-km regional climate scale:
Top 10 Past vs. Top 10 Future Events

Past Top 10

Future Top 10

Total precipitation/24h (mm, shaded), surface winds (vectors)
Top 10 Past vs. Top 10 future:

**WRF**

Past

Top 10

Future

Top 10

### Whole domain
(Average of all 10 cases)

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</tr>
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Total precipitation/24h (mm, shaded)
2. Extreme event composites as model initial conditions

Past Top 10

Create WRF initial, boundary conditions from composite fields

1km WRF simulation from PAST events composite

Future Top 10

Create WRF initial, boundary conditions from composite fields

1km WRF simulation from FUTURE events composite
2. Extreme event composites as model initial conditions

- Increase in future intensity, precipitation maxima; trends in composite results agree with averages of top 10 past, future individual events

- *For this particular region/driving model, 1 composite-initialized model run yields similar qualitative results as 10 individual model runs: implications for resource-limited user groups?*

- Caveat! Success of method largely dependent on signal strength in event composites (timing of extreme events, over-smoothing of initial fields may be problematic*)

* WRF-CCSM composite runs not as successful
3. “Climate Perturbation”/ “Pseudo-Global-Warming”/ “Delta Method” Experiment*

- Assuming same synoptic forcing, what would an observed extreme event of the past look like with modified thermodynamics as specified by various future climate projections?
- Using extreme event composites, difference past and future files to define “future climate anomaly” for T, RH
- Add changes to original WRF input files; run model

*Methodology similar to Schär et al. (1996), Hara et al. (2008), Kawase et al. (2008), Hill and Lackmann (2011), and Rasmussen et al. (2011)
Big Thompson (1976) and Fort Collins (1997) Floods: Climate Perturbed Run

- Observed event location shifts north; magnitude of overall maxima similar
- Should “future” climate signal be derived from shifts in uniform seasonal averages, gridpoint-based shifts on “extreme-producing” days only, other?
- Proof of concept stage: value likely lies in ability to perturb environment across wide spectrum of climate change scenarios
Comparison of three approaches with 50-km NARCCAP data

Compare 3 approaches, NARCCAP:
- How do 50-km, 1.3-km simulations compare?
- What value is being added (if any?)
- Do we see the same qualitative trends?

1. Individual simulations
   - NARCCAP (50km)
   - Future (red)
   - Past (black)

2. Composite approach
   - Domain-wide averages of top 10 vs. top 10 runs

3. Climate perturbation method
   - CTRL (black)
   - Future (red)

NARCCAP (GFDL-ts) Top events composite: PAST
- Intensity decrease

NARCCAP (GFDL-ts) Top events composite: FUTURE
- Intensity increase

1. Top 10 Individual Event WRF Simulation Average: PAST
2. WRF's PAST events composite
3. WRF's Future events composite

Intensity increase
“Surprise” findings?

• What happens to surface hail?

Example of average accumulated surface graupel/hail fields in Top 10 past vs. Top 10 future individual cases

Event-total (24-h) hail at the surface:
Past
(Average of “top 10” 1-km simulations from WRF-CCSM)

Trend persists across *all* simulations: individual top events, composite-based, delta-method, *and* with GFDL-ts and WRF-CCSM...

• Until you change the microphysics scheme...

• Importance of model microphysics with increased downscaling!
Comparison of GFDL-ts, WRF-CCSM results

**GFDS-Timeslices**

Avg difference (Future – Past) of Top 10 events: **GFDS-Timeslices**
(red/orange = drier in future; blue/green = wetter in future)

<table>
<thead>
<tr>
<th>Target Region Only (Average of all 10 cases)</th>
<th>Whole domain (Average of all 10 cases)</th>
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<tbody>
<tr>
<td><strong>PAST</strong></td>
<td>16.3</td>
</tr>
<tr>
<td><strong>FUT</strong></td>
<td>18.0</td>
</tr>
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**WRF-CCSM**

Avg difference (Future – Past) of Top 10 events: **WRF-CCSM**
(red/orange = drier in future; blue/green = wetter in future)

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<td>13.3</td>
</tr>
<tr>
<td><strong>FUT</strong></td>
<td>10.1</td>
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Summary by region:
- **WRF 1-km Top 10 events** from GFDL-ts:
- **WRF 1-km Top 10 events** from WRF-CCSM:
- Elevation analysis: **Max** Precip (Top 10 event averages)

Elevation analysis: **Max** Precip (Top 10 event averages)
Preliminary conclusions

1. High-resolution simulations offer insight into past, future extreme events: spatial/temporal detail, assessment of storm-scale physical processes

2. Preliminary results (GFDL-timeslices, WRF-CCSM) suggest:
   - more intense precipitation extremes in future, particularly ~5000 – 9000ft (both models)
   - changes in hail amount at surface due to sub-cloud melting (both models)
   - GFDL-ts wetter overall (past and future) than WRF-CCSM
   - WRF-CCSM may have diurnal precip, QC issues: has several days with $10^{20}$ mm of precip reported, composites problematic

3. Value over RCM likely depends on objective (and geographic region, computing capabilities...)
   - Over whole domain, average precip amounts may be similar but spatial pattern of changes reversed in high-res vs. RCM
   - Ongoing work to establish why pattern reversal results; also differences in high- vs. low-elevation locations

4. Comparison of model methodologies underway: Composite approach may offer shortcut around individual simulations in some cases; strengths, weaknesses of all approaches to be analyzed further

5. Need (at least) one more set of NARCCAP simulations for downscaling (all methods)
Acknowledgments


• UCAR/CLIVAR/PACE program

• NARCCAP Project (NCAR)

• NCAR, National Science Foundation for WRF, NCL, wrfhelp

• Unidata (UCAR) for IDV, GEMPAK

• NOAA ESRL High-Performance Computing System

• Western Water Assessment (WWA)

Contact:

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Extra slides
Case selection: Comparing NARCCAP extreme cases to extreme precipitation climatology

- Case selection quality control:
  
  NARR Analysis
  (composites of observed extreme events from 1979 - 2008)

- Compare RCM’s extreme event characteristics to observed extreme events (NARR)

- Moist, easterly (upslope) flow dominant weather pattern in both observations and models; large scale weather matches overall
Preliminary Results: Analysis of Top 10 past events vs. Top 10 future individual events

*Does elevation of heaviest precipitation change from past to future?*

- Intense precip in future simulations increases up to 9000ft (~2700m)
- More cases, regions to be examined
- Shifts in this elevation range relevant to water resource management concerns, flood/dam safety!
Comparison of three approaches with 50-km NARCCAP data

Compare 3 approaches, NARCCAP:

– How do 50-km, 1.3-km simulations compare?
– What value is being added (if any?)
– Do we see the same qualitative trends?
“Surprise” findings?

- What happens to surface hail?
  Example of average accumulated surface graupel/hail fields in Top 10 past vs. Top 10 future individual cases

Event-total (24-h) hail at the surface:
  - Past
  - Future
(Average of “top 10” 1-km simulations from WRF-CCSM)

Average freezing level height:
  - Past
  - Future

Event-avg freezing level height: GFDL-Compos-Past (WSM6)
  (Height is above sea level) Time 24

Event-avg freezing level height: GFDL-Compos-Future (WSM6)
  (Height is above sea level) Time 24
Comparison of GFDL-ts, WRF-CCSM results

**GFDTimeslices**

Avg difference (Future – Past) of Top 10 events: GFDL-Timeslices (red/orange = drier in future; blue/green = wetter in future)

<table>
<thead>
<tr>
<th>NARCCAP (50 km) GFDL-Timeslice</th>
<th>WRF-1km (from GFDL-Timeslice)</th>
</tr>
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<tr>
<td>WRF 1-km Target Region Only</td>
<td>WRF 1-km from GFDL-Timeslice</td>
</tr>
<tr>
<td>(Average of all 10 cases)</td>
<td></td>
</tr>
<tr>
<td><strong>Past</strong></td>
<td></td>
</tr>
<tr>
<td>Average precip (mm/24h)</td>
<td>16.3</td>
</tr>
<tr>
<td>Max precip (mm/24h)</td>
<td>117</td>
</tr>
<tr>
<td><strong>Fut</strong></td>
<td></td>
</tr>
<tr>
<td>Average precip (mm/24h)</td>
<td>18.0</td>
</tr>
<tr>
<td>Max precip (mm/24h)</td>
<td>131</td>
</tr>
</tbody>
</table>

Summary by region:
- WRF 1-km Top 10 events from GFDL-ts:
  - Future (red)
  - Past (black)

**WRF-CCSM**

Avg difference (Future – Past) of Top 10 events: WRF-CCSM (red/orange = drier in future; blue/green = wetter in future)

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<td>Average precip (mm/24h)</td>
<td>13.3</td>
</tr>
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<td>Max precip (mm/24h)</td>
<td>74</td>
</tr>
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<td></td>
</tr>
<tr>
<td>Average precip (mm/24h)</td>
<td>10.1</td>
</tr>
<tr>
<td>Max precip (mm/24h)</td>
<td>79</td>
</tr>
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Summary by region:
- WRF 1-km Top 10 events from WRF-CCSM:
  - Future (red)
  - Past (black)

**Elevation analysis**
- Top 10 event averages
Comparison of three approaches with one another

### 1. Individual simulations: Top 10 past vs. top 10 future

<table>
<thead>
<tr>
<th>Top 10 vs. Top 10 avgs</th>
<th><strong>Whole domain</strong> (Average of all 10 cases)</th>
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### 2. Composite approach

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<th>GFDL-ts COMPOSITES</th>
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<td><strong>Maximum gridpoint precipitation (mm/24h)</strong></td>
</tr>
<tr>
<td>PAST</td>
<td>4.7</td>
<td>109</td>
</tr>
<tr>
<td>FUTURE</td>
<td>10.0</td>
<td>165</td>
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### 3. Climate perturbation/delta method

<table>
<thead>
<tr>
<th>Big Thompson experiment</th>
<th><strong>Whole domain</strong></th>
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<tr>
<td>PAST(CTRL)</td>
<td>6.9</td>
<td>209</td>
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<tr>
<td>FUTURE</td>
<td>7.0</td>
<td>187</td>
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#### Domain-wide averages of top 10 vs. top 10 runs

- **Future (red)** vs. **Past (black)**

#### Domain-wide averages of composite runs

- **Future (red)** vs. **Past (black)**

#### Domain-wide averages of Big Thompson runs

- **CTRL (black)** vs. **Perturbed “Future” (red)**
Comparison of three approaches with 50-km NARCCAP data

1. **Individual simulations**

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2. **Composite approach**

<table>
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<th>BT run</th>
<th>Whole domain</th>
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<tr>
<td>GFDL ts COMPOSITES</td>
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3. **Climate perturbation/ delta method**

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<td>7.8</td>
</tr>
<tr>
<td></td>
<td>139</td>
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<tr>
<td>FUTURE</td>
<td>9.6</td>
</tr>
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<td></td>
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- **Compare 3 approaches NARCCAP:**
  - How does 50-km data compare to high-res WRF simulations?
  - What value is being added (if any?) in the detail?
  - Do we see the same qualitative trends?
Data details

• NARCCAP: North American Region Climate Change Assessment Program
  – Uses large scale forcing from 20th century and 21st century climate change (SRES A2) AOGCM experiments to force high resolution regional climate models.
  – http://www.narccap.ucar.edu/

• GFDL-AM2 (timeslice)
  – Observed SST/Sea-ice/GHG forcing for 20thC
  – Anomalous SST/Sea-ice/GHG from SRES A2 in 21stC run
  – Run atmosphere-only model at high res with prescribed BC (no regional model used)

• WRF-CCSM

• Examine daily average (12UTC-12UTC) Precipitation from NARCCAP:
  – 21st century (2038-2070)
  – Warm season (June-July-August)
GFDL-ts vs. WRF-CCSM (top 10 case average): 2m-Temp

Past

Future

Difference (ΔT)
Plot using narccap instead – make sure this isn’t a WRF interpolation thing!

GFDL-ts vs. WRF-CCSM (top 10 case average at F00): 2m-MIXR

Past

Future

Difference (ΔT)
GFDL-ts vs. WRF-CCSM (top 10 case average at F00): 2m-MIXR

These are top 30 – do top 10 w/ same color scale as with wrf
GFDL-ts vs. WRF-CCSM (top 10 case average): Precip (from WRF)
GFDL-ts vs. WRF-CCSM (top 10 case average): Precip (from NARCCAP)

These are top 30 – do top 10 w/ same color scale as with wrf
GFDL-ts vs. WRF-CCSM (top 10 case average): Precipitable Water

Add same thing for PW, CAPE
Targeted Composite Technique

• Target region (TR): Colorado Front Range
• 38.5N-41.5N, 106.5W-105W
• Identify model grid points in TR
• Sort all Daily Prec values from JJA in TR
• Find top 30 Prec values from unique events
• Average prec, sfc hum, sfc winds and other fields (when avail) from each event
Mean Summer (JJA) Precip 1968-2000

- **GFDL-AM2**: Map showing precipitation with color gradients.
- **HADCM3-HRM3**: Another map with similar color gradients.
- **GFDL-RCM3**: Map with precipitation details.
- **CGCM3-RCM3**: Map with precipitation data.

Maps display precipitation in millimeters per season with color scales ranging from 50 to 500.
WRF vs. GFDL Topography
To delete
Big Thompson Climate Perturbed Run

Big Thompson “Control”
BT_CTRL 1km D02

Simulated radar reflectivity (dBZ)

Big Thompson “GFDLts Future”
BT_Fut_GFDL1mSI 1km D02

Simulated radar reflectivity (dBZ)
How can Reclamation use these results?

• Feedback from USBR water resources managers:
  – Want to understand elevation threshold of extreme precipitation:
    • Present precipitation-elevation thresholds?
    • Future changes?
  – Help generate future-climate scenarios for emergency preparedness exercises
  – Incorporate results into dam safety evaluations, USBR Early Warning System operations, community/risk analysis, floodplain re-mapping

• Challenges:
  – Adapting findings from atmospheric science/WRF framework to hydrologic/water management framework
  – Language/jargon, units, technology, time