Extreme precipitation in an ensemble of regional climate simulations

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Frequency of heavy precipitation has increased greatly over the central U.S.

“One of the clearest trends in the United States observational record is an increasing frequency and intensity of heavy precipitation events... Over the last century there was a 50% increase in the frequency of days with precipitation over 101.6 mm (four inches) in the upper midwestern U.S.; this trend is statistically significant.”

Karl et al. 2008: Synthesis and Assessment Product 3.3. Report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research
Why does heavy precipitation matter?

Flooding:
- loss of life, damage to public and private property, failure of transportation systems

Agriculture
- soil erosion, nutrient runoff, excessive soil moisture, interference with field operations
Experiment design

Construct a **systematic ensemble** of AOGCM-driven simulations over the CORDEX-North America domain for 1950-2099 using RegCM4.

- Compare statistics of heavy precipitation simulated for current climate (1971-2000) to observations over the central U.S.
- Evaluate changes to heavy precipitation in future climate (2041-2070).

Observations:

- U.S. Historical Climate Network daily precipitation measurements.
- About 1300 stations used.
Model configurations

Choices of horizontal resolution, convection scheme, and driving AOGCM were used to build a 2x2x2 ensemble of RegCM4 simulations.

This produces a three-dimensional parameter space:

- Horizontal grid: 50 km and 25 km.
- Two options for convection: Emanuel (1991), and "mixed" with Emanuel over oceans and Grell (1993) over land.
- Two global models: HadGEM2-ES (high climate sensitivity) and GFDL-ESM2M (low sensitivity), both RCP8.5.
Precipitation intensity spectra: Model versus observations

- Light events are more frequent than observed.
- Moderate and heavy events are less frequent than observed.
Frequency of heavy precipitation in contemporary climate does not show a clear dependence on the global model.
Slight tendency for 50 km grid spacing to produce more frequent heavy precipitation than 25 km
Emanuel scheme produces more frequent heavy precipitation in current climate

Mixed scheme = orange/filled
Emanuel = open/black
Model ranking by tendency to produce heavy precipitation events

Emanuel scheme tends to produce more frequent heavy precipitation.

50 km grid spacing often produces more frequent heavy precipitation though the trend is not consistent.
Future Projections


Same periods as used in NARCCAP
Future vs current: 50 km

The heavier the amount, the greater the fractional increase.

Current = open symbols
Future = filled symbols

The graph compares current and future frequency distributions of precipitation amounts for 50 km. The heavier the amount of precipitation, the greater the fractional increase in the future compared to the current conditions.
Future vs current: 25 km

Fractional increase is overall similar to 50 km.

Current = open symbols
Future = filled symbols
Increase in frequency of heavy precipitation (> 100 mm/day) for future climate is smallest with the Emanuel scheme.
Clausius-Clapeyron scaling

Clausius-Clapeyron scaling is often proposed as a control on extreme precipitation.

Compare predicted changes in 99th percentile and 99.9 percentile amounts to Clausius-Clapeyron scaling.

Based on projected regional mean warming between current and future climates.
## Clausius-Clapeyron scaling

<table>
<thead>
<tr>
<th></th>
<th>99 percentile</th>
<th>99.9 percentile</th>
<th>1971-2000 T (°C)</th>
<th>ΔT (°C)</th>
<th>CC Scaling</th>
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<tbody>
<tr>
<td></td>
<td>1971-2000 (mm/day)</td>
<td>Percent Change</td>
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<tr>
<td><strong>50 / GFDL</strong></td>
<td><strong>37.8</strong></td>
<td><strong>7.9%</strong></td>
<td><strong>73.6</strong></td>
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<td><strong>50 / GFDL</strong></td>
<td><strong>37.0</strong></td>
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<td><strong>77.4</strong></td>
<td><strong>10.3%</strong></td>
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<td>Emanuel</td>
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<tr>
<td><strong>50 / Had</strong></td>
<td><strong>37.7</strong></td>
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<td>Average</td>
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<tr>
<td><strong>25 km Average</strong></td>
<td><strong>35.6</strong></td>
<td><strong>9.2%</strong></td>
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HadGEM2 (higher ECS, more warming) produces a greater increase

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<td><strong>16.2%</strong></td>
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<tr>
<td><strong>HadGEM2 Average</strong></td>
<td><strong>35.7</strong></td>
<td><strong>10.9%</strong></td>
<td><strong>75.2</strong></td>
<td><strong>17.8%</strong></td>
<td><strong>19.8%</strong></td>
</tr>
</tbody>
</table>
Summary

• AOGCM did not affect frequency of heavy precipitation for current climate but influenced changes for future climate.
  – Presumably reflects differing climate sensitivity of the two AOGCMs (runs with third AOGCM are in progress).

• Effect of grid spacing was not consistent for either current climate or future changes.

• Influences of convective parameterization are complex:
  – Emanuel scheme produced the largest frequency of heavy precipitation in current climate.
  – Emanuel scheme produced the smallest increase of heavy precipitation in future climate.

• Changes in the most extreme events (99.9 percentile) approach Clausius-Clapeyron scaling.
Future Work

• Look at skill in reproducing past trends of extreme precipitation, not just (static) climatology.

• Understand why the parameterizations produce different changes in frequency of heavy precipitation.

• Investigate circulation patterns and weather systems causing the changes.

• Why did finer grid spacing not consistently produce higher frequencies of heavy events?
Thank You!

**Acknowledgment:** This research was sponsored in part by the U.S. Department of Agriculture (USDA) under the Earth System Modeling program, Award 2013-67003-20642. This research also is part of a regional collaborative project supported by the USDA-NIFA, Award No. 2011-68002-3019.
Construction of regional observed statistics

**Problem**: Observing locations are non-uniformly spaced.

This means a simple average over all stations within a region can produce non-representative results.

Interpolation of measurements will smooth out extremes.
Approach for regional comparisons

Superimpose lat/lon grid on the irregular distribution of stations

Compute aggregate statistics over the observations within each grid cell.

Average the statistics over all grid cells to produce regional frequencies

Precipitation, mm/day

0,2 2 4 6 8 10 12 14 16 18 20
Increase in frequency of heavy precipitation for future climate is smallest with the Emanuel scheme.
Historical Climate Network Data

- U.S. Cooperative Summary of the Day
- U.S. First Order Summary of the Day
- 1769 total stations in the region of interest
- Only used stations with less than 20% of data records missing (around 1300 stations used).
Model ranking by tendency to produce heavy precipitation events

50 km grid spacing may produce more frequent heavy precipitation but trend is not consistent.
Model ranking by tendency to produce heavy precipitation events

Emanuel scheme tends to produce more frequent heavy precipitation.

50 km grid spacing often produces more frequent heavy precipitation though the trend is not consistent.
Increase in frequency of heavy precipitation for future climate is smallest with the Emanuel scheme.
## Clausius-Clapeyron Scaling

<table>
<thead>
<tr>
<th>Model Simulations</th>
<th>1971-2000 Avg</th>
<th>2041-2071 Avg</th>
<th>Temperature Change (°C)</th>
<th>CC-Scaling Increase (6.5%/degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temperature</td>
<td>Temperature</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(°C)</td>
<td>(°C)</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>50 km GFDL Mixed</strong></td>
<td>10.5729</td>
<td>12.9534</td>
<td>2.3804</td>
<td>15.47%</td>
</tr>
<tr>
<td><strong>50 km GFDL Emanuel</strong></td>
<td>11.5366</td>
<td>14.1542</td>
<td>2.6176</td>
<td>17.01%</td>
</tr>
<tr>
<td><strong>50 km Had Mixed</strong></td>
<td>13.0646</td>
<td>16.1873</td>
<td>3.1227</td>
<td>20.30%</td>
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<tr>
<td><strong>50 km Had Emanuel</strong></td>
<td>14.0029</td>
<td>17.1114</td>
<td>3.1084</td>
<td>20.20%</td>
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<tr>
<td><strong>25 km GFDL Mixed</strong></td>
<td>10.3867</td>
<td>12.9123</td>
<td>2.5256</td>
<td>16.42%</td>
</tr>
<tr>
<td><strong>25 km GFDL Emanuel</strong></td>
<td>11.4302</td>
<td>13.8684</td>
<td>2.4382</td>
<td>15.85%</td>
</tr>
<tr>
<td><strong>25 km Had Mixed</strong></td>
<td>12.9717</td>
<td>16.1026</td>
<td>3.1309</td>
<td>20.35%</td>
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<tr>
<td><strong>25 km Had Emanuel</strong></td>
<td>14.0096</td>
<td>16.8309</td>
<td>2.8213</td>
<td>18.34%</td>
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<tr>
<td><strong>50 km Model Average</strong></td>
<td>12.2943</td>
<td>15.1015</td>
<td>2.8073</td>
<td>18.25%</td>
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<tr>
<td><strong>25 km Model Average</strong></td>
<td>12.1996</td>
<td>14.9286</td>
<td>2.7290</td>
<td>17.74%</td>
</tr>
</tbody>
</table>
Future Projections of Moderate Events

Introduction – Data and Methods – Results – Conclusions/Future Work
Top 10% of Events

Precipitation 90\textsuperscript{th} Percentile

- 25km GFDL Emanuel
- 25km Had Mixed
- 25km Had Emanuel
- 25km GFDL Mixed
- 50km GFDL Emanuel
- 50km Had Mixed
- 50km GFDL Mixed
- 50km Had Emanuel
- Station Data Observed Precipitation

mm/day

90.00% 92.00% 94.00% 96.00% 98.00% 100.00%
Approach

Generate a systematic set of model configurations to test generality of findings and sensitivity to model configuration.

Perform reanalysis-driven simulations for CORDEX-North America domain using RegCM4 with 50 km grid spacing.

- Test combinations of convective parameterization and land surface physics.
- Evaluate based on annual cycle of the spatial correlation with observed precipitation.
- Eliminate configurations that perform poorly.
Top 1% of Events
Finer resolution gives modest improvement for all convection schemes

Comparison of region-mean precipitation with observed annual cycle

<table>
<thead>
<tr>
<th></th>
<th>Mixed</th>
<th>Emanuel</th>
<th>Grell</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 km</td>
<td>0.92</td>
<td>0.93</td>
<td>0.89</td>
</tr>
<tr>
<td>25 km</td>
<td>0.95</td>
<td>0.95</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Correlation with observed annual cycle
There are noticeable GCM x resolution interactions

Comparison of region-mean precipitation with observed annual cycle

<table>
<thead>
<tr>
<th></th>
<th>GFDL</th>
<th>HadGEM</th>
<th>ERAI</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 km</td>
<td>0.95</td>
<td>0.78</td>
<td>0.66</td>
</tr>
<tr>
<td>25 km</td>
<td>0.96</td>
<td>0.86</td>
<td>0.72</td>
</tr>
</tbody>
</table>
Emanuel is the wettest scheme, but when driven by HadGEM2 it produces the **smallest increase**.
Replication of observed change, 1981-2010 versus 1951-1981

GFDL-ESM2M driven

When driven by the GFDL GCM the Emanuel scheme produces the largest increase.
Seasonal aspects of trends in RegCM4 are vaguely consistent with recent observed trends.

1981-2010 versus 1951-1980

Observed

RegCM4, 50 km ensemble

RegCM4, 25 km ensemble
Projected seasonal changes in precipitation differ from recent trends

RegCM4, 50 km ensemble

RegCM4, 25 km ensemble
Next step: Look at changes in extreme precipitation

Observed change in frequency for daily thresholds, 1981-2010 versus 1951-1980
Summary and comments

Resolution, physical parameterizations and GCM all interact in complex ways.

- We have to take these interactions into account when using climate simulations to assess possible futures.
  - Intuitive suppositions may not hold.

Finer resolution tends to produce better results

- But improvement depends on convection scheme and even the driving GCM.

Replication of observed trends by the regional model should be compared to those in the GCMs.

- Does better ability to reproduce observed trends imply more confidence in future projections?
Global models project wetter winters and drier summers

Winter (DJF)  
Summer (JJA)

Change in mean precipitation rate (mm/day), 2070-99 relative to 1961-90, average for 17 models.

Maloney et al. (2014) J. Climate
This is opposite of recent observed trends

1981-2010 versus 1951-1980

Observed

RegCM4, 25 km ensemble

RegCM4, 25 km ensemble
Differences between convection schemes can depend on driving GCM

<table>
<thead>
<tr>
<th>Correlation with observed annual cycle</th>
<th>GFDL</th>
<th>Emanuel</th>
<th>Grell</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mixed</td>
<td>0.94</td>
<td>0.96</td>
<td>0.94</td>
</tr>
<tr>
<td>HadGEM</td>
<td>0.78</td>
<td>0.84</td>
<td>0.83</td>
</tr>
</tbody>
</table>
Configuration

at 25 and 50 km.
HadGEM2-ES driven
GFDL-ESM2M driven
Overview

Where have we been?
  ✦ Recent climate change

Where are we going?
  ✦ Climate change projections

Why does it matter?
  ✦ Potential implications for crop yield, nutrient runoff and soil carbon.
Warming? What warming?

Observed change in annual mean surface temperature, 1901-2012

Central and southeast U.S. has warmed less than any other land area on the planet

IPCC Fifth Assessment Report, Summary for Policymakers
Most of the region's warming has been in the cool half of the year.

Average for 1981-2010 versus 1951-1980, °F

Growing season temperature change (April - Sept)

Cool season temperature change (Oct - March)

Data source: Univ. of Delaware Precipitation and Air Temperature gridded analysis, v3.01
Mean precipitation has increased slightly, with regional and seasonal variations.

<table>
<thead>
<tr>
<th>Season</th>
<th>Change for 1981-2010 versus 1951-1980, mm/day</th>
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</thead>
<tbody>
<tr>
<td>Winter</td>
<td></td>
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<tr>
<td>Spring</td>
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<tr>
<td>Summer</td>
<td></td>
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<tr>
<td>Fall</td>
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Data source: Univ. of Delaware Precipitation and Air Temperature gridded analysis, v3.01
Heavy rainfall happens more often

“One of the clearest trends in the United States observational record is an increasing frequency and intensity of heavy precipitation events... Over the last century there was a 50% increase in the frequency of days with precipitation over 101.6 mm (four inches) in the upper midwestern U.S.; this trend is statistically significant.”

Ames, 1993

Ames, 2010

Heavy rainfall has become much more frequent despite total rainfall increasing only slightly.

Ratio of mean frequency in 1981-2010 versus frequency in 1951-1980 for each threshold.

Data source: NWS Cooperative Observer Program
More summer humidity in most of the region

Average for June-July-August of each year, 1950-2014.
Green bars indicate years that are above the mean.

Rapid City, SD

Ames, IA

Columbus, OH

D. Herzmann, Iowa Environmental Mesonet
Growing season is projected to become much longer (based on global models) for the period 2071-2100 versus 1971-2000. Colored shading represents the change in length (days), while contours indicate the standard deviation (days). Maloney et al. (2014) J. Climate
A problem

Global climate models are too coarse to include the most important precipitation processes for our region. Use a finer-resolution regional dynamical model to "downscale" some global model results. Vary the methodology to see if results are robust:

- Two global models are downscaled.
- Downscaling grid: 50 km, 25 km.
- Two options for modeling deep convective clouds.

This produces a 2 x 2 x 2 matrix of downscaled simulations (8 simulations total).
Downscaled precipitation trends are more consistent with observed trends

Observed change in summer (JJA) precipitation, 1981-2010 versus 1951-1980 (rate in mm/day)

Global model changes are 2070-2099 versus present. Downscaled model changes are 2041-2070 versus present.
Heavy precipitation is projected to increase regardless of the modeling approach used.

Average over central U.S.

Note logarithmic scale.

blue = present (1971-2000)
red = future (2041-2070)
Why does it matter?

- What are the potential implications of climate change for crop yield, nutrient runoff and soil carbon?
- Simulate the effects of several global climate scenarios using SALUS.
Summary

• Mean temperature and precipitation in the Corn Belt have both changed over the past 60 years:
  ✷ Cool-season warming in the north has allowed corn to be grown there. Most of the region has seen 5-10% increase in yearly precipitation.

• In the Corn Belt one of the clearest changes has been more frequent occurrence of heavy precipitation.

• The trend of heavy precipitation occurring more often is predicted to continue and strengthen. This appears to be a robust finding.
  ✷ More agreement on changes in heavy precipitation (global and regional models both +) than on changes in mean precipitation (global models -, regional models +).
Summary

- Based on global climate model scenarios, corn yields are expected to decrease with climate change by -17% (mean value for Midwest using RCP 2.6 scenario) to -40% (mean value for Midwest using RCP 6).
  - Decrease is steady across management scenarios.

- N-NO3 leaching is expected to increase with climate change.
  - The increase in leaching under climate change is reduced when CC or extended rotation are implemented.

- SOC is expected to decrease with climate change.
  - The decrease under climate change is reduced when CC or extended rotation are implemented.
Recommendations

• Increased frequency of heavy rainfall in past decades is not a natural fluctuation but is the "new normal" and is very likely to intensify.
  ✧ Producers need to be prepared for impacts of more frequent heavy rainfall. Adaptation could include drainage water management, cover crops to reduce erosion, etc.

• Increasing summer humidity may lead to increased disease pressure. Development of new cultivars or improved disease management approaches can help.
Recommendations

• Addition of manure, CC, extended rotation, using N-split application or no-till reduce the yield decline due to increased temperature, but it is not sufficient to reverse the effects. New cultivars along with best management practices (varying planting dates) need to be introduced to adapt to climate change.

• The effects vary from one site/state to another.

• All these practices, considered alone or in combination, have a great impacts on mitigating and reducing N-NO3-leaching and SOC losses, but not sufficient to reverse the effects.