A 21st century HRRR-based approach to estimating probable maximum precipitation to enhance dam safety and community resilience

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Motivation

- Dams necessary to manage water in the West, but present risks
- Dam failures → fatalities, disasters (Johnstown PA 1889 2209 fatalities, 2017 Oroville Dam crisis)
- Probable Maximum Precipitation:
  - Theoretical calculated maximum possible precipitation
  - Important “upper limit” used for dam design, construction, operation
  - Current PMP estimates lack recent storms, updated precipitation process understanding, technology
  - HMR values often argued to be too high, especially in orographic areas
- In practice: subjective moving of storms, ad-hoc reductions: e.g., elevation-based decreases
- Can we do better with more modern data, tools, and methods?
Exploring Dynamical Rainfall Forecast Modeling for PMP Estimation

Goal: Perform a feasibility study to test and evaluate the potential benefits of adopting a high-resolution dynamical modeling-based framework for estimating the probable maximum precipitation (PMP) across Colorado and New Mexico.
Why is dynamical modeling a potentially desirable approach to PMP estimation?

- Scientific understanding of physical processes responsible for extreme storms enhanced since NOAA HMRs (PMP “recipe books”) created.
- Dynamical models solve physical equations of atmosphere: generate precipitation according to “real-world” environment, with continuity in space and time.
  - May alleviate need for many spatial, temporal, physical assumptions (e.g., storm transposition, storm templates, moisture maximization, etc.).
  - Especially important in data-sparse regions of complex (& high-elevation) topography.
What is the High-Resolution Rapid Refresh (HRRR) model?

The HRRR is a NOAA real-time 3-km resolution, hourly updated, cloud-resolving, convection-allowing atmospheric model, initialized by 3-km grids with 3-km radar assimilation. Radar data is assimilated in the HRRR every 15 min over a 1-h period adding further detail to that provided by the hourly data assimilation from the 13-km radar-enhanced Rapid Refresh.
Experimental proof-of-concept:

1. Treat all available HRRR simulations as an effective long-term, running “model ensemble”
   ➢~15-hour forecasts run each hour, every day, for 5+ years

2. Create a running “ensemble max” precipitation grid to keep track of the most precipitation forecast by the HRRR model over the 5-y period of record.

3. Develop gridded 1-hour, 6-hour, 12-hour precipitation maxima fields using all available HRRR model data

Why is dynamical modeling a potentially desirable approach to PMP estimation?

Example of single 24-hour model ensemble max precipitation grid:
(i.e., “what is the most precipitation generated by any model ensemble member over the given period?”)

Max precip prototype: Integrate grids like this one to include many more forecasts: HRRR run every hour, every day, for 5+ years.
Is HRRR suitable for PMP estimation?

Strengths

- High spatial resolution: 3-km grid allows for:
  - Mostly explicit physics (atmospheric processes are simulated directly, rather than through statistical relationships)
  - Realistic, physically-bounded estimates of heavy rainfall
- High temporal resolution: hourly forecasts over many years provide sample size of:
  - 15(+) hour/cycle * 24 cycles/day* 365 days/year * 5 years ~ 31,000+ model runs
- Large spatial coverage (CONUS)
- Already operational at NOAA NCEP (institutional acceptance/approval)
What are HRRR’s limitations?

- 5 years not long enough to sample all weather patterns that could occur at a given location
- No storm maximization taking place (also a strength)
- Biases relatively poorly understood at high elevations due to lack of verification data; work ongoing
- Proof of concept stage – next up:
  - How do patterns, qualitative findings compare to those of deterministic PMP estimation, precip/flood frequency analysis?
  - When and where does dynamical modeling approach offer immediate, unique, and/or complementary benefits?

Example near-term dataset benefit:
Improved (model-derived) rain-vs-snow information
In progress & upcoming deliverables

- Using maximum precipitation prototype products, assess:
  - How do results from the temporally-short but spatially-high resolution HRRR analysis compare with/augment previous observations-based studies of extreme precipitation climatologies?
  - Do elevation-dependent precipitation thresholds exist?
  - How can observations-based, longer-record precipitation climatologies be best combined with HRRR’s high spatial, temporal resolution?
  - How feasible is it for dynamically-based modeling framework to address PMP as stakeholders presently require the information?

Example near-term dataset benefits: Improved understanding/data coverage related to (left to right)...
Seasonality of heavy precipitation; mean annual maximum precipitation; gridpoint max precip over 5-year record
Colorado–New Mexico Regional Extreme Precipitation Study (REPS)

Improving extreme precipitation estimates to enhance dam safety and community resilience.

Dams are essential for storing water for household use, irrigation, energy, and recreation. However, a dam failure can result in severe damage to infrastructure and community. Therefore, all practical methods must be applied to prevent such failures and ensure public safety and maximize water storage.

The Challenge

All dams have spillways to safely route flows from extreme rain events around them and prevent overtopping. In the last 150 years, overtopping due to inadequate or improperly designed spillways is the leading cause of dam failure and resulting loss of life. Colorado and New Mexico, some spillways at existing high and significant hazard dams (those most likely to result in loss of life if a failure occurs) are deficient.

Estimating extreme rainfall amounts is a critical component of building safe dams. However, the data and methods currently used to calculate these quantities are outdated and studies have shown current methods can both overestimate and underestimate rainfall, depending on location. A robust balance between the safety provided by conservatively designed spillways to protect dams against extreme events and the cost of the construction.

The Need

Modern methods to estimate probable maximum precipitation can reduce the likelihood of over- or under-estimating rainfall. New approaches aim to produce more realistic estimates of maximum precipitation to strike an appropriate balance between the protection of public health and safety and the required level of construction infrastructure. The Colorado Division of Water Resources and the New Mexico State Engineer have identified and set as a priority the need to update their extreme precipitation estimation for use in the evaluation of spillway adequacy for dams in these states, based on the most modern methods and scientific understanding available.

Innovation

Due to similarities in geography and meteorology between Colorado and New Mexico, a cooperative, regional study has been undertaken, the first instance of both states combining resources and working collaboratively toward a solution to the problem. The project began in January 2016 and is scheduled to be complete in June 2018. Of particular concern in both states are questions about the physical limits on high elevation rainfall amounts and the annually exceedance probability (AEP) of the extreme rainfall amounts used for spillway design. This study will test and implement an innovative approach to developing bias correction procedures for estimating extreme rainfall and the design of effective dam spillways.

NOAA Contributions

NOAA is working with REPS partners to provide innovative solutions to meet this project’s unique demands on NOAA expertise in modeling and understanding of the physical processes that affect extreme precipitation. Experience from related stakeholder-driven research allows NOAA scientists to critically consider limitations of past methods to estimate extreme precipitation design and develop alternative options. Research scientists in the Earth System Research Laboratory (ESRL) are leading this effort, with critical inputs from members of the Project Review Board, which includes NOAA representation from the National Weather Service, the Office of Water Prediction/National Water Center, and the ESRL Physics Sciences Division.

Potentially actionable science being developed by NOAA includes:

- Novel high-resolution datasets and post-processing techniques using a super ensemble of hourly forecasts from the HRRR model.
- Improved understanding of the limitations of older estimation methods and assumptions.
- Actionable recommendations based on improved physical process understanding, such as the relationship between elevation and heavy rainfall.
- Assessment of climate change implications for future estimation studies.

Outcomes

The regional collaborative effort of the two states, combined with an ensemble scope of work and Project Review Board project oversight will ensure the development of scientifically robust processes and procedures for the prediction of extreme rainfall and the design of effective dam spillways. The project sponsors will be able to develop policies and rules that minimize the risk of dam failures by overtopping and ensure public safety, while at the same time allow for the most efficient use of existing and new facilities to maximize water storage potential in their states. If all project goals are fulfilled, then similar benefits can be achieved by other states and regions across the nation.

This project is funded by grants from the Colorado Water Conservation Board, the New Mexico Office of the State Engineer, the Albuquerque Metropolitan Area Flood Control Authority, and the New Mexico Water Ski and Dam Owners Coalition.

For more information:
- Colorado-New Mexico Regional Extreme Precipitation Study (REPS)
- Colorado-New Mexico Regional Extreme Precipitation Study (REPS)
- Contact: Madeline Solis-Burke (Phone: 303.420.3667) or (Email: Madeline.SolisBurke@noaa.gov)
- Project Goals:
  - Creating a high-resolution dataset to support extreme precipitation predictions
  - Developing an innovative approach to developing bias correction procedures
  - Evaluating the uncertainty of various components of the modeling chain

Resources:
- kelly.mahoney@noaa.gov
Elevation-based precipitation reductions in practice

- Elevation-based precipitation reduction factors derived from HMRs
  - Concept: reduce moisture as elevation increases based on adiabatic lapse rate: ~9%/1000 ft
- State of CO rules: historically reduced even further

- Are these PMP methods physically-realistic?
- Can we do better with more modern data, tools, and methods?
Study objectives

➢ Examine approximations and assumptions currently used in PMP elevation adjustment factors
➢ Investigate role of elevation in 2013 Colorado Front Range floods
➢ Using a high-resolution numerical modeling framework, investigate:
   ➢ Model terrain sensitivities
   ➢ Storm environment effect on maximum elevations affected
➢ Evaluate potential benefit of state-of-the-art climate and weather modeling capabilities in PMP-based risk-assessment methods
2. What is the High-Resolution Rapid Refresh (HRRR) model?

The RAP and HRRR models are run EVERY HOUR of every day to provide updated forecasts using the latest observations.

DATA ASSIMILATION is the science of bringing in all the available weather observations (from radars, satellites, aircraft, surface weather stations, etc) to create an initial condition for the forecast.

The RAP is an hourly CYCLED system, meaning the 1-h forecast is used to provide a background for the data assimilation at the next hour; this allows us to cycle a physically-realistic atmospheric state.
2. What is the High-Resolution Rapid Refresh (HRRR) model?

Part of the data assimilation step is a “pre-forecast” model integration bringing in radar reflectivity data every 15 min

GOAL: To create a starting point that is as realistic as possible, and allow for a good forecast
2. What is the High-Resolution Rapid Refresh (HRRR) model?

During the 1-hour pre-forecast, radar reflectivity observations are used to specify latent heating rates (atmospheric heat release due to precipitation formation) in each previous 15-min period:

- **Observed Reflectivity ≤ 0 dBZ**: Zero heating rate to suppress spurious model precipitation.
- **0 dBZ < Observed Reflectivity < 28 dBZ**: Model microphysics heating rate preserved.
- **Observed Reflectivity ≥ 28 dBZ**: Positive heating rate to promote convective development.
- **No radar coverage**: Model microphysics heating rate preserved.

This allows us to force the model to have realistic precipitation-related vertical motion at the starting point.
2. What is the High-Resolution Rapid Refresh (HRRR) model?

A HYDROMETEOR analysis is also carried out as part of the data assimilation step to ensure a realistic analysis:

<table>
<thead>
<tr>
<th>Variables Updated</th>
<th>Add to model?</th>
<th>Remove from model?</th>
<th>Which observations are used?</th>
</tr>
</thead>
<tbody>
<tr>
<td>cloud water, cloud ice, temperature, water vapor</td>
<td>Yes, below 1.2 km AGL</td>
<td>Yes</td>
<td>Satellite cloud top, Ceilometers</td>
</tr>
<tr>
<td>Rain water, snow water</td>
<td>Yes, If 2m T &lt; 5°C: add to full column, Else: add at observed maximum reflectivity level and where obs 15-28 dBZ</td>
<td>Yes</td>
<td>Radar reflectivity</td>
</tr>
</tbody>
</table>
What are HRRR’s limitations?

- Overall physical representation of precipitation is good, but biases are evident
- Observations (QPE) have obvious limitations too (radar coverage) over Western US complex terrain
What are HRRR’s limitations?

- We can examine the frequency of occurrence of different precipitation amount in the HRRR to a QPE analysis.

- Based on 6-h forecasts, HRRR produces:
  - (1) too many *heavy* rainfall events
  - (2) too few *extreme* events

- (1) is related to the initial “push” from radar data being a bit too strong
- (2) is related to resolution. The strongest storms on a 3-km grid still aren’t quite strong enough
What are HRRR’s limitations?

- Good news:
  - Short term: both issues can be addressed ex post facto, through statistical bias correction, using a moving window of the most recent 50-100 forecasts (a few weeks of HRRR runs)
  - Long term: planned improvements to HRRR model physics will reduce these biases in the model itself
What are possible workarounds to HRRR’s limitations?

• Bias correction using trusted QPE analyses and/or point observations
• Group together grid points with similar overall climatologies, but different 5-year maximum values; i.e., an “intelligent” neighborhood technique
• Combine multiple HRRR runs with overlapping valid times into an ensemble to place error bars on predicted rainfall
• Many other ideas to explore along the way...
Is HRRR suitable for PMP estimation?

QPF statistics for 2016 so far:

- **Forecast Bias**
  - Thresholds:
    - 1: 0.10 inch
    - 2: 0.25 inch
    - 3: 0.50 inch
    - 4: 1.00 inch
    - 5: 1.50 inch
    - 6: 2.00 inch
    - 7: 3.00 inch

- **Critical Success Index (CSI)**
  - Thresholds:
    - 1: 0.10 inch
    - 2: 0.25 inch
    - 3: 0.50 inch
    - 4: 1.00 inch
    - 5: 1.50 inch
    - 6: 2.00 inch
    - 7: 3.00 inch
RAP/HRRR “wiring diagram”
### Current RAP/HRRR configuration

<table>
<thead>
<tr>
<th>Model</th>
<th>Run at:</th>
<th>Domain</th>
<th>Grid Points</th>
<th>Grid Spacing</th>
<th>Vertical Levels</th>
<th>Pressure Top</th>
<th>Boundary Conditions</th>
<th>Initialized</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP</td>
<td>GSD, NCEP</td>
<td>North America</td>
<td>953 x 834</td>
<td>13 km</td>
<td>50</td>
<td>10 mb</td>
<td>GFS</td>
<td>Hourly (cycled)</td>
</tr>
<tr>
<td>HRRR</td>
<td>GSD, NCEP</td>
<td>CONUS</td>
<td>1799 x 1059</td>
<td>3 km</td>
<td>50</td>
<td>20 mb</td>
<td>RAP</td>
<td>Hourly (pre-forecast hour cycle, LSM full)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Version</th>
<th>Assimilation</th>
<th>Radar DA</th>
<th>Radiation LW/SW</th>
<th>Microphysics</th>
<th>Cumulus Param</th>
<th>PBL</th>
<th>LSM</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP</td>
<td>WRF-ARW v3.6+</td>
<td>GSI Hybrid 3D-VAR/Ensemble to 0.75</td>
<td>13-km DFI + low reflect</td>
<td>RRTMG/RRTMG</td>
<td>Thompson – aerosol v3.6.1</td>
<td>GFO v3.6+</td>
<td>MYNN v3.6+</td>
<td>RUC v3.6+</td>
</tr>
<tr>
<td>HRRR</td>
<td>WRF-ARW v3.6+</td>
<td>3km: GSI Hybrid 3D-VAR/Ensemble to 0.75</td>
<td>3-km 15-min LH + low reflect</td>
<td>RRTMG/RRTMG</td>
<td>Thompson – aerosol v3.6.1</td>
<td>MYNN PBL Clouds</td>
<td>MYNN v3.6+</td>
<td>RUC v3.6+</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Model</th>
<th>Horiz/Vert Advection</th>
<th>Scalar Advection</th>
<th>Upper-Level Damping</th>
<th>6th Order Diffusion</th>
<th>SW Radiation Update</th>
<th>Land Use</th>
<th>MP Tend Limit</th>
<th>Time-Step</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAP</td>
<td>5th/5th</td>
<td>Positive-Definite</td>
<td>w-Rayleigh 0.2</td>
<td>Yes 0.12</td>
<td>20 min</td>
<td>MODIS Fractional</td>
<td>0.01 K/s</td>
<td>60 s</td>
</tr>
<tr>
<td>HRRR</td>
<td>5th/5th</td>
<td>Positive-Definite</td>
<td>w-Rayleigh 0.2</td>
<td>Yes 0.25 (flat terr)</td>
<td>15 min with SW-dt (Ruiz-Arias)</td>
<td>MODIS Fractional</td>
<td>0.07 K/s</td>
<td>20 s</td>
</tr>
</tbody>
</table>
# Observations used in the data assimilation

<table>
<thead>
<tr>
<th>Hourly Observation Type</th>
<th>Variables Observed</th>
<th>Observation Count</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rawinsonde</td>
<td>Temperature, Humidity, Wind, Pressure</td>
<td>120</td>
</tr>
<tr>
<td>Profiler – 915 MHz</td>
<td>Wind, Virtual Temperature</td>
<td>20-30</td>
</tr>
<tr>
<td>Radar – VAD</td>
<td>Wind</td>
<td>125</td>
</tr>
<tr>
<td>Radar</td>
<td>Radial Velocity</td>
<td>125 radars</td>
</tr>
<tr>
<td>Radar reflectivity – CONUS</td>
<td>3-d refl → Rain, Snow, Graupel</td>
<td>1,500,000</td>
</tr>
<tr>
<td>Lightning (proxy reflectivity)</td>
<td></td>
<td>NLDN</td>
</tr>
<tr>
<td>Aircraft</td>
<td>Wind, Temperature</td>
<td>2,000 - 15,000</td>
</tr>
<tr>
<td>Aircraft - WVSS</td>
<td>Humidity</td>
<td>0 - 800</td>
</tr>
<tr>
<td>Surface/METAR</td>
<td>Temperature, Moisture, Wind, Pressure, Clouds, Visibility, Weather</td>
<td>2200 - 2500</td>
</tr>
<tr>
<td>Surface/Mesonet</td>
<td>Temperature, Moisture, Wind</td>
<td>~5K-12K</td>
</tr>
<tr>
<td>Buoys/ships</td>
<td>Wind, Pressure</td>
<td>200 - 400</td>
</tr>
<tr>
<td>GOES AMVs</td>
<td>Wind</td>
<td>2000 - 4000</td>
</tr>
<tr>
<td>AMSU/HIRS/MHS (RARS)</td>
<td>Radiances</td>
<td>1K-10K</td>
</tr>
<tr>
<td>GOES</td>
<td>Radiances</td>
<td>large</td>
</tr>
<tr>
<td>GOES cloud-top press/tem</td>
<td>Cloud Top Height</td>
<td>100,000</td>
</tr>
<tr>
<td>GPS – Precipitable water</td>
<td>Humidity</td>
<td>260</td>
</tr>
<tr>
<td>WindSat Scatterometer</td>
<td>Winds</td>
<td>2,000 – 10,000</td>
</tr>
</tbody>
</table>
WRF Model experiments

- What is the precipitation sensitivity to terrain elevation?
- How sensitive to storm environment are maximum elevations affected by heavy precipitation?

**Experiments:**
1. Control
2. No_Terrain
3. 1610m_All_Terrain
4. Half_Terrain
5. Bulldoze Rockies
6. Terrainx1.25

**Terrain modifications:**
2. No-Terrain (Domain flattened, terrain HGT=0)
3. Terrain-All-1610m (Domain flattened, terrain HGT=1610 m)
4. Terrain-1/2-height (Domain terrain HGT=HGT\_orig/2)
5. Terrain-Bulldoze-Rockies (Domain terrain capped at 1610 m)
6. Terrainx1.25 (Domain terrain HGT increased by 25%)

**Environment modifications:**
7. +RH\_10\%: Increase initial, lateral boundary environmental humidity by 10%
8. -RH\_10\%: Decrease initial, lateral boundary environmental humidity by 10%
9. +RH\_50\%: Increase initial, lateral boundary environmental humidity by 50%
10. +RH\_100\%: Increase initial, lateral boundary environmental humidity to 100%
Results: 72-hour precipitation

- Flat terrain simulations show impact of dynamics-only
- Increasing terrain height by 25% decreases max precip by ~10 – 20%; similar max location
- Increasing RH diffuses maxima, increases average precipitation
• CTRL simulation elevation vs. precipitation: rainfall max 2000 – 2500 m (6500 - ~8000 feet)
CTRL simulation elevation vs. precipitation: precip max ~8500 ft (2590m)
+RH_10%: max precip: amount less, but location moves over higher Front Range terrain (~3000m)
What about over the whole domain?
Precipitation vs. elevation: Moisture-increased experiments

- Moisture-modified runs show variable precip-elevation relationships
  - Distribution of median, max precip shifts as moisture increases
    - Generally upward trend in 50%, 100% increases, but not consistently
  - Variability indicates localized nature of terrain effects, case-specific dynamical details
  - More cases needed for systematic relationships; proof-of-concept demonstrates potential benefit to extreme precipitation estimation in complex terrain
Precipitation vs. elevation: Comparison to reduction factors

- High variability across model realizations of this event
  - Many cases, more perturbed realizations, post-processing techniques needed to see systematic extreme precipitation/elevation relationships

- Dynamics, weather climatology still dictate that precipitation changes will not vary with elevation alone; dynamical model results over sufficiently long period can highlight relative controls of local dynamics vs. elevation

Current practices: linear reduction factors; solely dependent on terrain height

- Reality: Extreme precipitation systems non-linear dynamical nature & terrain effects extremely localized (Proof of concept; single case)
Summary and future work

➢ 2013 Colorado floods exceeded 7500-foot terrain “limit” for flood potential
  ➢ Some dams stressed but no major failures. PMP is “conservatively safe” but inefficient
➢ Modeling case study: model terrain, storm environment experiments emphasize sensitivity of amount and distribution of heavy precipitation
➢ Role of terrain in CO floods complex:
  ➢ Terrain focused/enhanced precipitation in Front Range
  ➢ Dynamics produced considerable precipitation - even in absence of terrain
  ➢ “Terrain” role complex: Rockies vs. Front Range vs. Palmer Divide (Morales et al. 2015))
➢ Elevation adjustment factors used today draw on overly-simplified, average conditions and do not account for real-world dynamics; new data and tools are available and should be considered for application

Estes Park, CO flooding 13 Sept 2013: Elevation 7820 ft
(Walt Hester)”

Dynamical-model output ex: Control simulation precipitable water as 3D surface
Summary and future work

- **Future Work**
  - Participate in 2016 – 2017 multi-agency CO/NM PMP study to assess new PMP methods including dynamical modeling
  - Connect state-of-the-art climate and weather modeling capabilities with currently-used risk-assessment approaches
  - Work toward ideal long-term solution: long-running model ensembles using perturbations that allow confidence in improved PMP and elimination of adjustment factors

Evaluate use of state-of-the-art modeling datasets in PMP estimation (e.g., HRRR)
(Image RAP model – NCEI)