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

Courtesy Bill McCormick, Chief, CO Dam Safety


Oroville Dam, Feb 2017 (http://www.sacbee.com)

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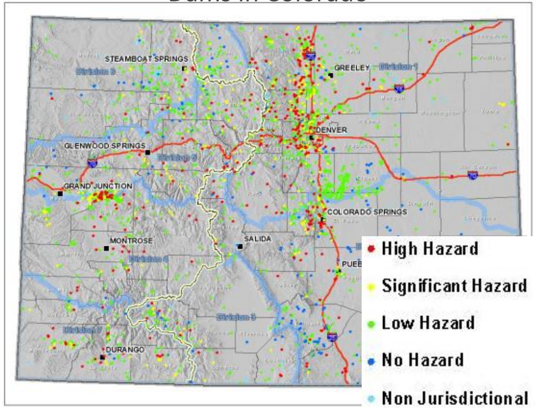
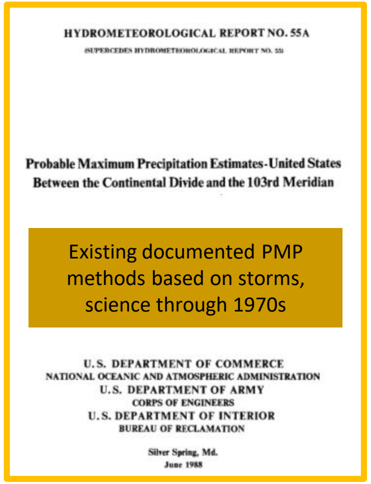
FIRO Science Task Group Workshop

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?

Dams in Colorado





HYDROMETEOROLOGICAL REPORT NO. 55A

(SUPERCEDES HYDROMETEOROLOGICAL REPORT NO. 55)

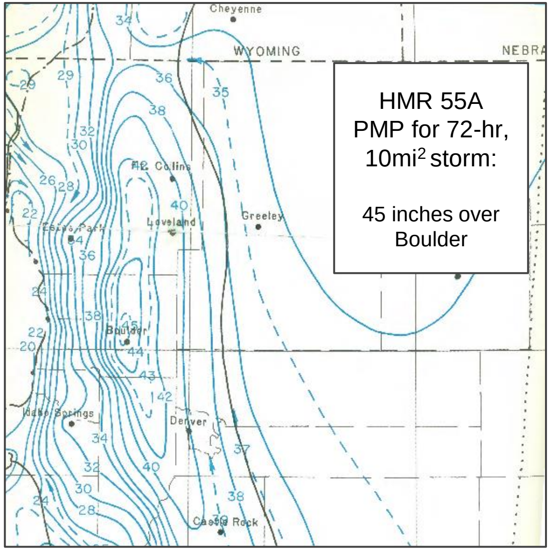
Probable Maximum Precipitation Estimates-United States Between the Continental Divide and the 103rd Meridian

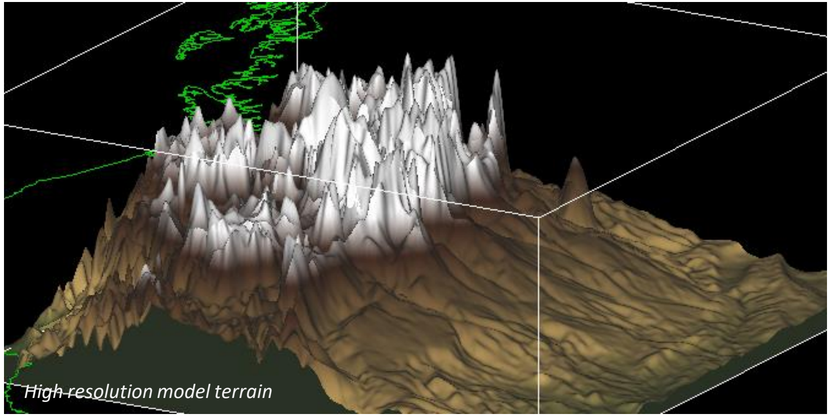
U.S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
U.S. DEPARTMENT OF ARMY
CORPS OF ENGINEERS
U.S. DEPARTMENT OF INTERIOR
BUREAU OF RECLAMATION

Silver Spring, Md.
June 1988

Existing documented PMP methods based on storms, science through 1970s

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?

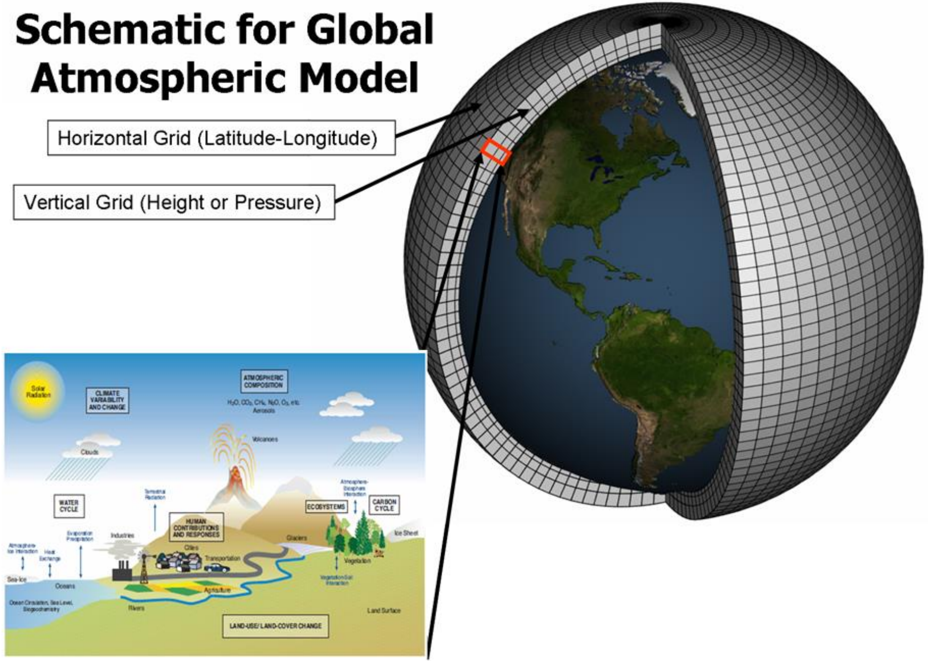
- Scientific understanding of physical processes responsible for extreme storms enhanced since NOAA HMRs (PMP "recipe books") created
- Dynamical models solve physical equations of atmosphere: generate precipitation according to "real-world" environment, with continuity in space and time
  - May alleviate 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

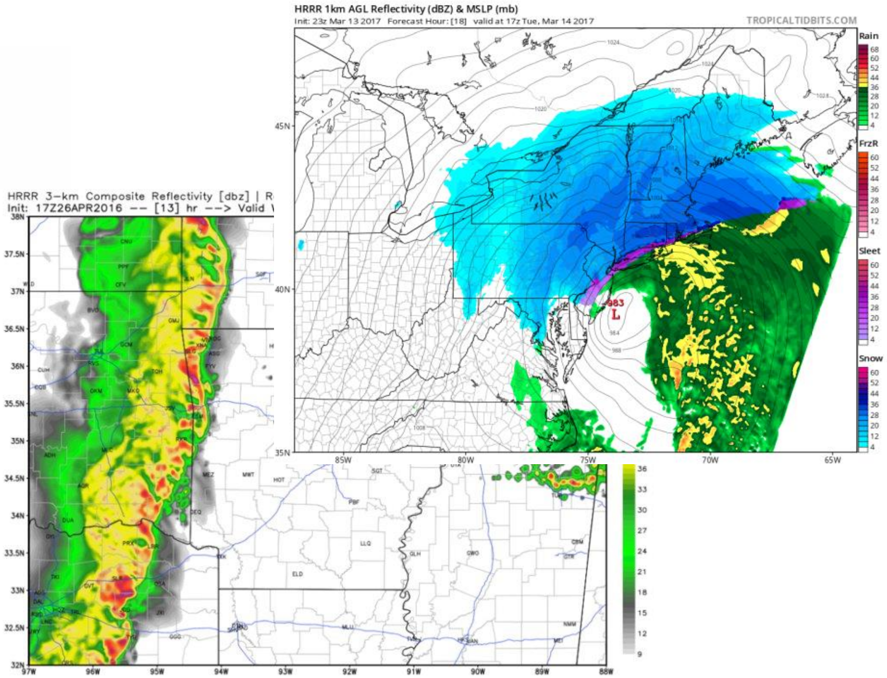
Processes and physical model elements that are represented in NWP models

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.

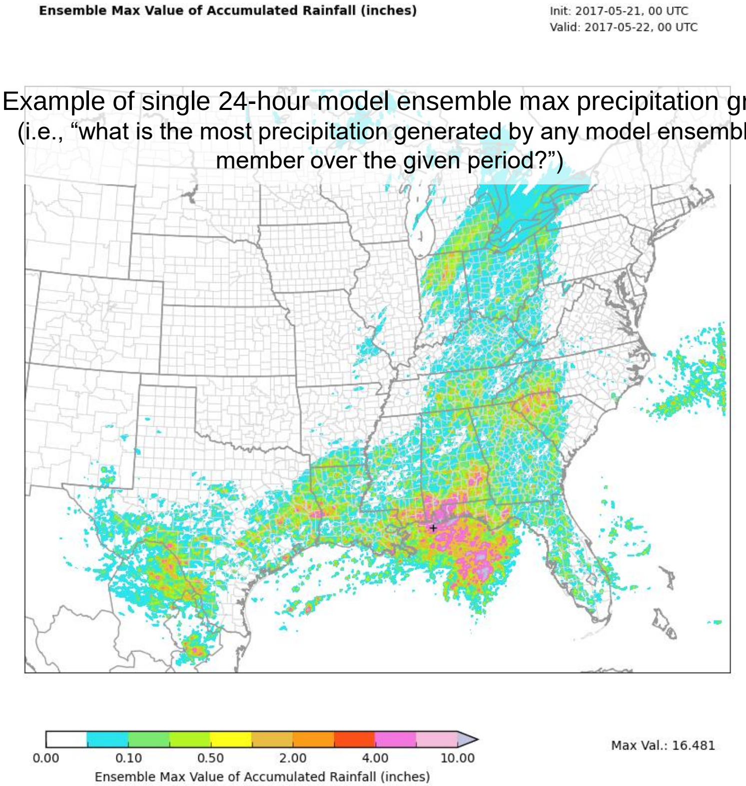




Why is dynamical modeling a potentially desirable approach to PMP estimation?

- 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

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?”)

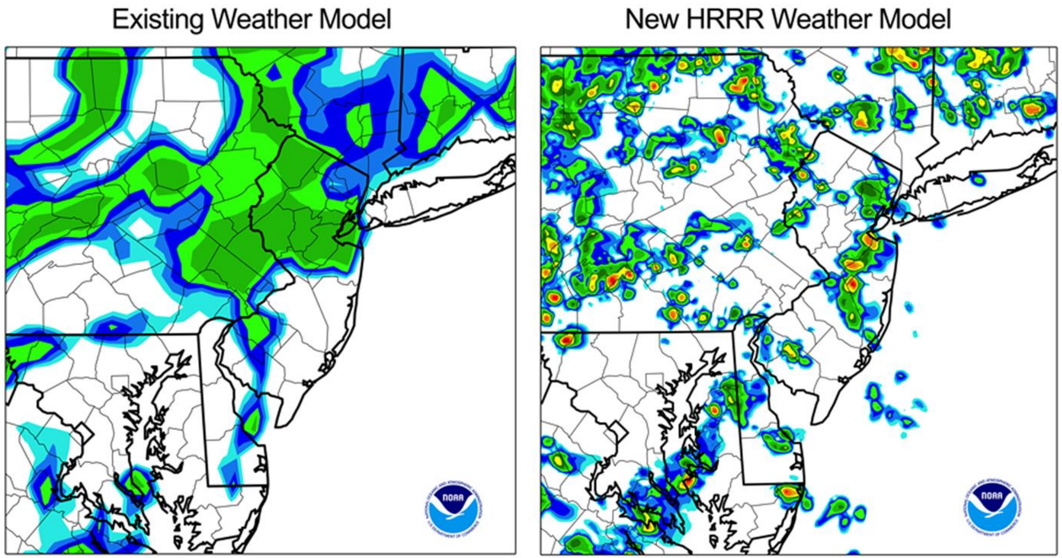


Max precip prototype: Integrate grids like this one to include many more forecasts: HRRR run every hour, every day, for 5+ years.

Is HRRR suitable for PMP estimation?

Strengths

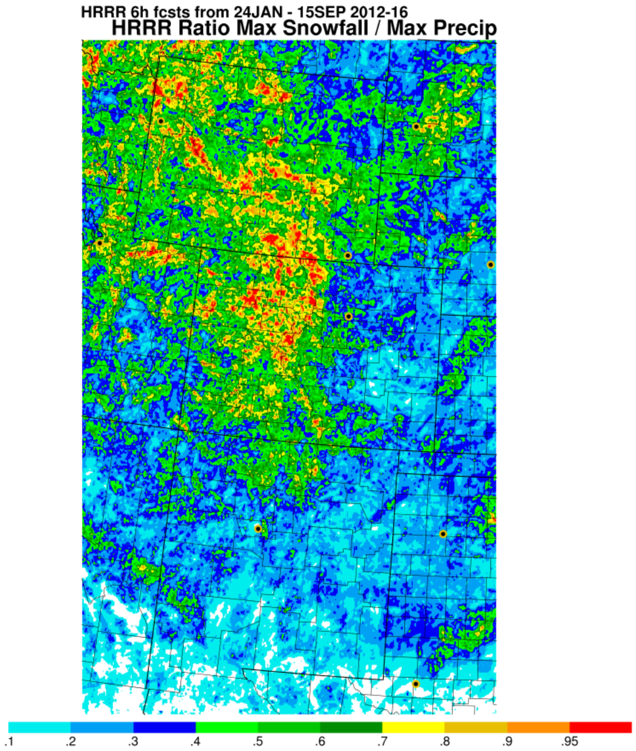
- High spatial resolution: 3-km grid allows for:
  - Mostly explicit physics (atmospheric processes are simulated directly, rather than through statistical relationships)
  - Realistic, physically-bounded estimates of heavy rainfall
- High temporal resolution: hourly forecasts over many years provide 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)



This is a comparison of two weather forecast models looking six hours ahead for the New Jersey area. Image on left shows the forecast which doesn't distinguish localized hazardous weather. Image on right shows the new HRRR (High-Resolution Rapid Refresh) model that clearly depicts where local thunderstorms (yellow and red coloring) are likely. (Credit: NOAA)

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?

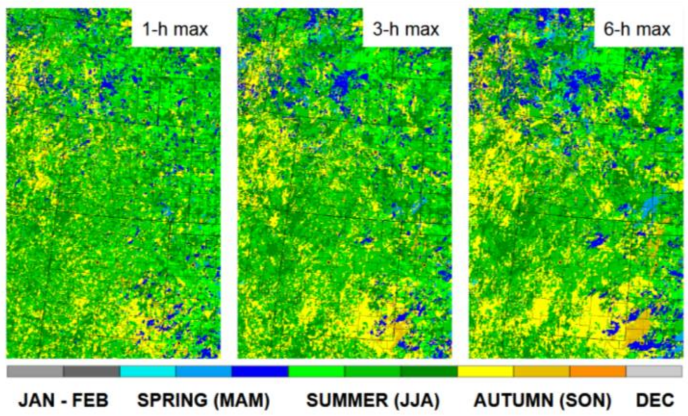


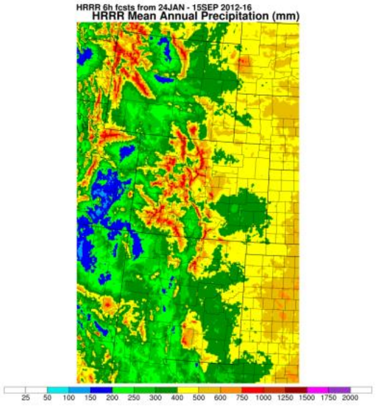
Example near-term dataset benefit:
Improved (model-derived) rain-vs-snow information

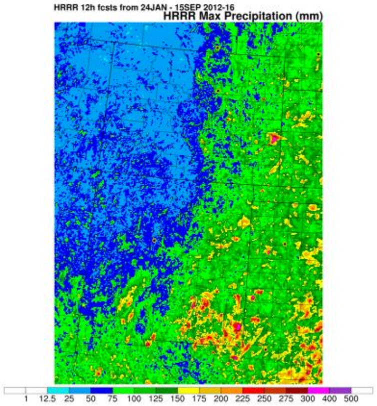
In progress & upcoming deliverables

- 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







For more information:
Colorado-New Mexico Regional Extreme Precipitation Study (REPS)

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 releasing stored water poses a risk to populations living downstream. Because of the potentially devastating consequences, all practical methods must be applied to prevent such failures and ensure public safety and maximize water storage.

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The Challenge

All dams have spillways to safely route flows from extreme runoff events around them and prevent overtopping. In the last 100 years, overtopping due to inadequate or improperly designed spillways is the leading cause of dam failure and resulting loss of life. In 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) have deficiencies.

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

The Need

Modern meteorological 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 Office of the State Engineer have identified and set as a priority the need to update their extreme precipitation estimates 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 states combining resources and working collaboratively toward a solution to the problem. The project began in June 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 annual exceedance probability (AEP) of the extreme rainfall amounts used for spillway design. This reality has lead to using an innovative ensemble approach and methods to update extreme precipitation estimates.

This study includes three technical tasks, which are conducted concurrently and in collaboration with each other. Task 1 consultants (Applied Weather Associates) are updating the conventional deterministic "storm-based" methods. Task 2 consultants (Extreme Precipitation Group - EPG - MetStat and other partners) are developing a risk-based regional precipitation frequency estimation tool to enable AEP estimates of the Task 1 results. Task 3 (NOAA Earth System Research Laboratory) includes a proof-of-concept scope utilizing NOAA's state-of-the-art High Resolution Rapid Refresh (HRRR) physically-based dynamical weather prediction model. A dedicated project manager (Acclivity Associates) has been hired to coordinate project activities.

NOAA Contributions

NOAA is working with REPS partners to provide innovative solutions to meet this project's unique challenges drawing on NOAA expertise in modeling and understanding of the physical processes that affect extreme precipitation. Experience from related stakeholder-driven research also allows NOAA scientists to critically consider limitations of past methods to estimate extreme precipitation and design updated alternative options. Research scientists in the Earth System Research Laboratory (ESRL) are leading this effort, with critical input 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 Physical 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 achievable by other states and/or 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 Arroyo Flood Control Authority, and the New Mexico Watershed and Dam Owners Coalition.

Project Goals

Creating updated, broadly accepted tools and procedures for estimating extreme precipitation depth, area, and duration relationships, as well as precipitation frequency estimates for individual basins within Colorado and New Mexico. This information will be used as part of new rules and regulations for determining spillway adequacy for dams in these states.

Developing a draft standard of practice guidance document for these studies suitable for use in the development of a national model for other states or regional groups of states to follow.

Evaluating the uncertainty of various components, elements, and variables as the project progresses. The project team will create a list of those issues that could benefit from further research or study to reduce or quantify their uncertainty, and help ensure the quality and longevity of the processes developed.

- https://www.esrl.noaa.gov/psd/outreach/resources/handouts/co-nm-precip-handout-psd.pdf
- kelly.mahoney@noaa.gov

Extra slides

Elevation-based precipitation reductions in practice

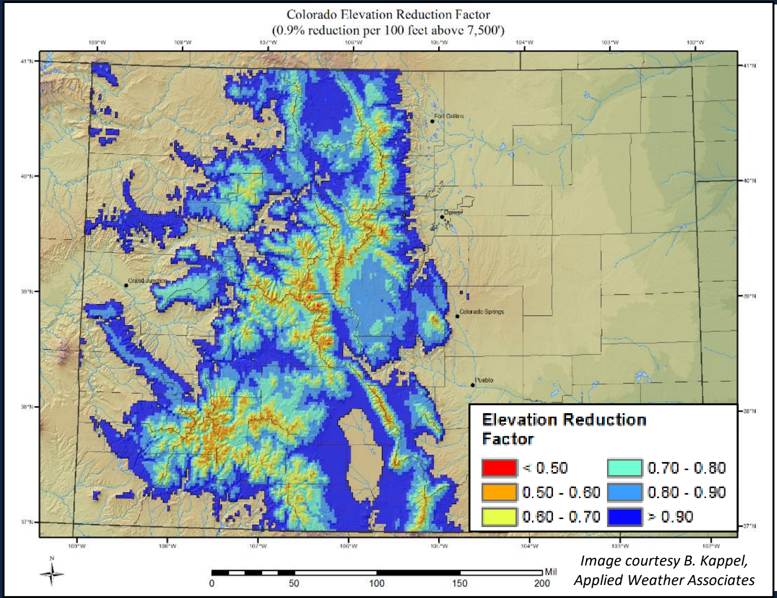


Image courtesy B. Kappel, Applied Weather Associates

TABLE 5.3

HMR PMP INFLOW DESIGN FLOOD REQUIREMENTS
REDUCED FOR ELEVATION

DAM SIZE	STORM TYPE	ELEVATION	HAZARD CLASSIFICATION	
			High	Significant
Large	General Storm East	6,000 - 12,000 ft MSL	0.80 PMP	0.60 PMP
		Above 12,000 ft MSL	0.70 PMP	0.53 PMP
	General Storm West	5,000 - 8,000 ft MSL	0.80 PMP	0.60 PMP
		Above 8,000 ft MSL	0.70 PMP	0.53 PMP
	Local Storm	10,000 - 11,500 ft MSL	0.80 PMP	0.60 PMP
		11,501 - 13,000 ft MSL	0.70 PMP	0.53 PMP
		Above 13,000 ft MSL	0.60 PMP	0.45 PMP
Small	General Storm East	6,000 - 12,000 ft MSL	0.80 PMP	0.40 PMP
		Above 12,000 ft MSL	0.70 PMP	0.35 PMP
	General Storm West	5,000 - 8,000 ft MSL	0.80 PMP	0.40 PMP
		Above 8,000 ft MSL	0.70 PMP	0.35 PMP
	Local Storm	10,000 - 11,500 ft MSL	0.80 PMP	0.40 PMP
		11,501 - 13,000 ft MSL	0.70 PMP	0.35 PMP
		Above 13,000 ft MSL	0.60 PMP	0.30 PMP
Minor	General Storm East	6,000 - 12,000 ft MSL	0.40 PMP	Not Applicable
		Above 12,000 ft MSL	0.35 PMP	Not Applicable
	General Storm West	5,000 - 8,000 ft MSL	0.40 PMP	Not Applicable
		Above 8,000 ft MSL	0.35 PMP	Not Applicable
	Local Storm	10,000 - 11,500 ft MSL	0.40 PMP	Not Applicable
		11,501 - 13,000 ft MSL	0.35 PMP	Not Applicable
		Above 13,000 ft MSL	0.30 PMP	Not Applicable

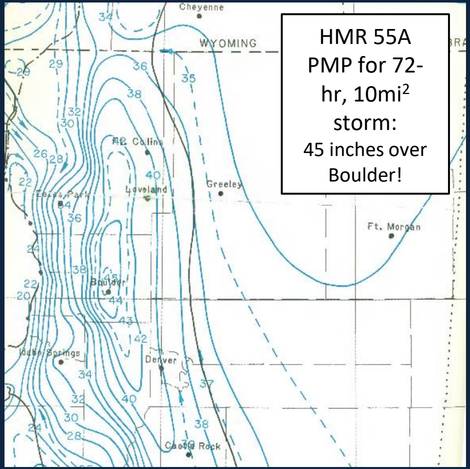
- Elevation-based precipitation reduction factors derived from HMRs
  - Concept: reduce moisture as elevation increases based on adiabatic lapse rate: ~9%/1000 ft

- State of CO rules: historically reduced even further

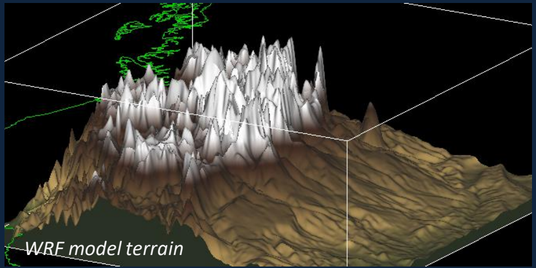
- Are these PMP methods physically-realistic?
- Can we do better with more modern data, tools, and methods?

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



2013: Big Thompson Canyon (~7500 ft) washed out US 34 in floods



2. What is the High-Resolution Rapid Refresh (HRRR) model?

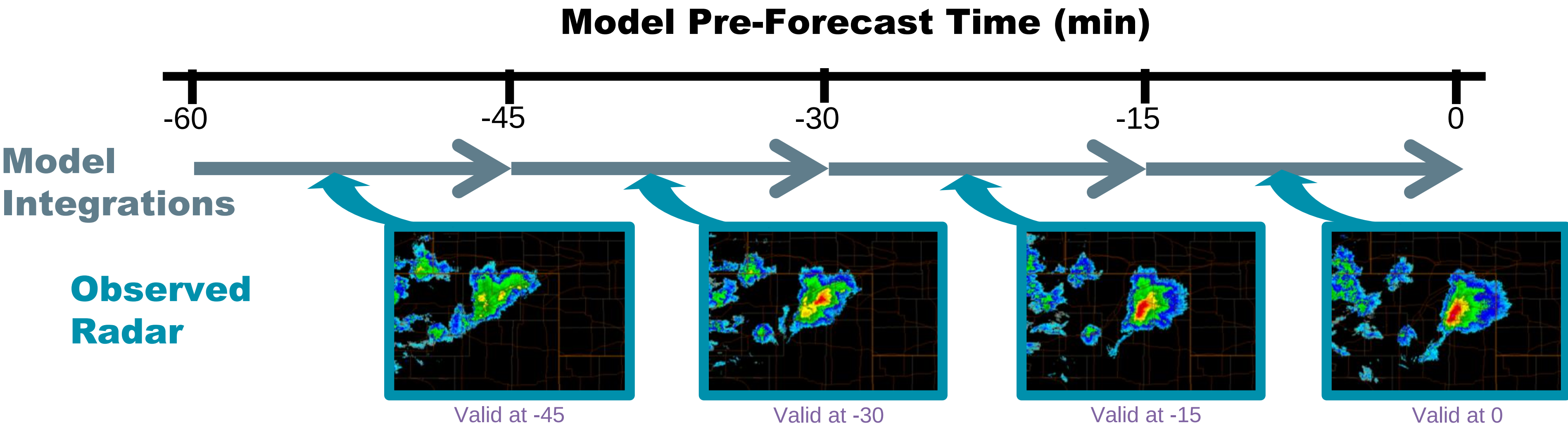
The RAP and HRRR models are run EVERY HOUR of every day to provide updated forecasts using the latest observations

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?

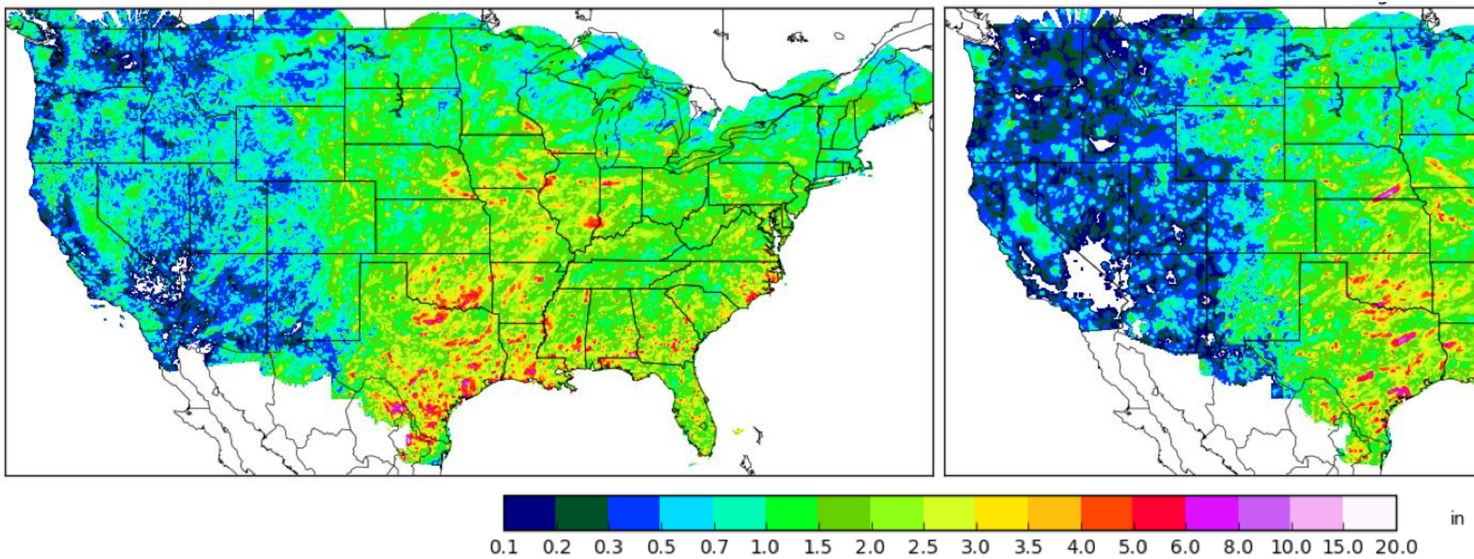
A HYDROMETEOR analysis is also carried out as part of the data assimilation step to ensure a realistic analysis:

Variables Updated	Add to model?	Remove from model?	Which observations are used?
cloud water, cloud ice, temperature, water vapor	Yes, below 1.2 km AGL	Yes	Satellite cloud top, Ceilometers
Rain water, snow water	Yes, If 2m T < 5°C: add to full column, Else: add at observed maximum reflectivity level and where obs 15-28 dBZ	Yes	Radar reflectivity

What are HRRR's limitations?

Spring 2015: Maximum HRRR 6-h QPF

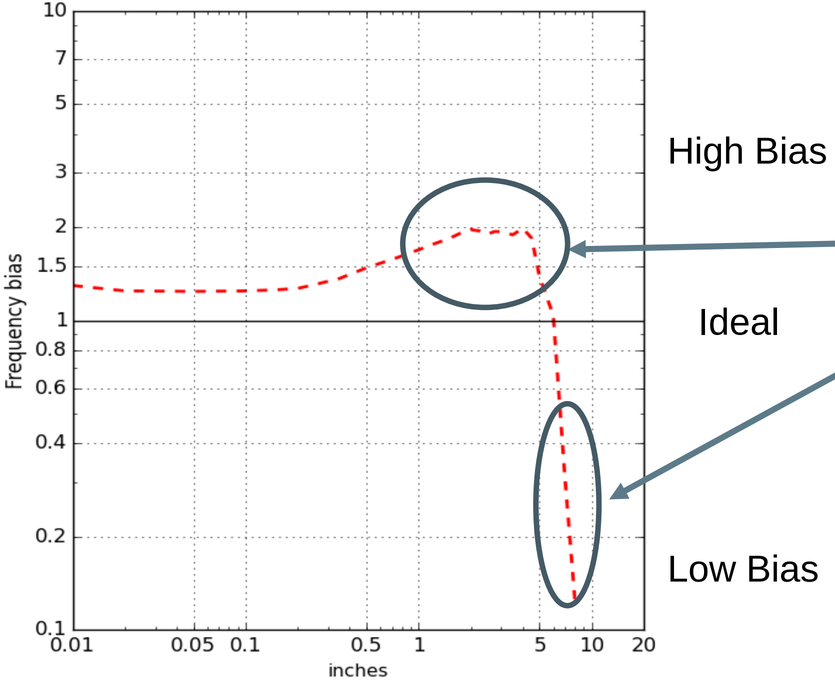
Spring 2015: Maximum 6-h Stage-IV QPE



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

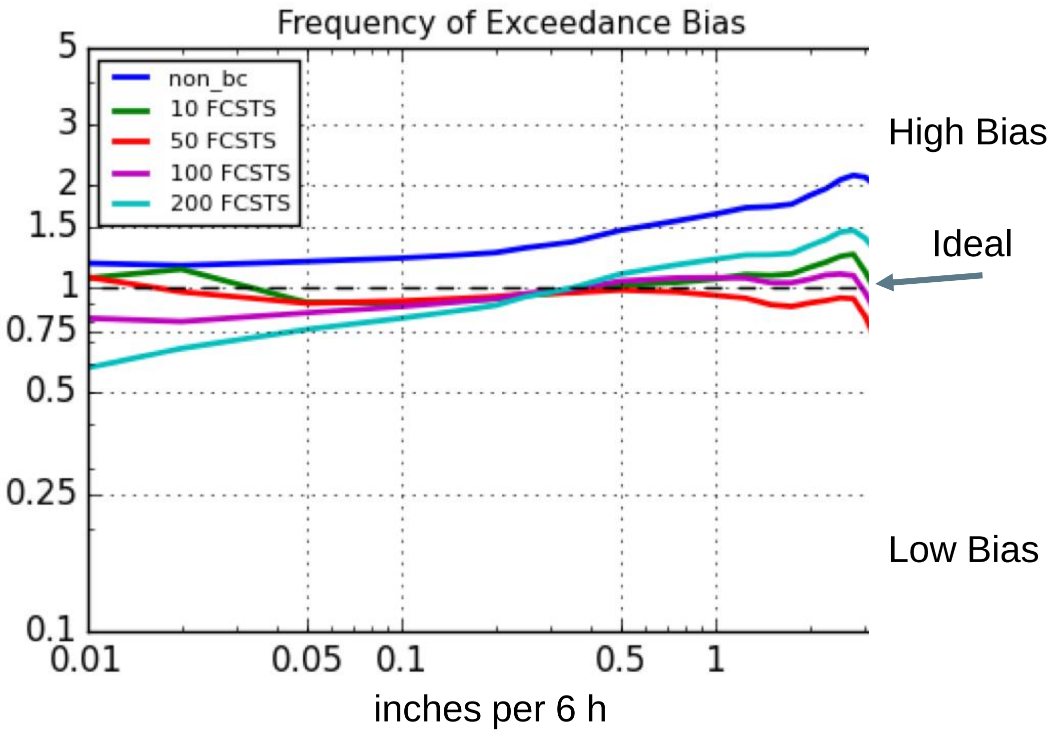
What are HRRR's limitations?

Spring 2015: HRRR 6-h QPF vs Stage-IV QPE



- 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?



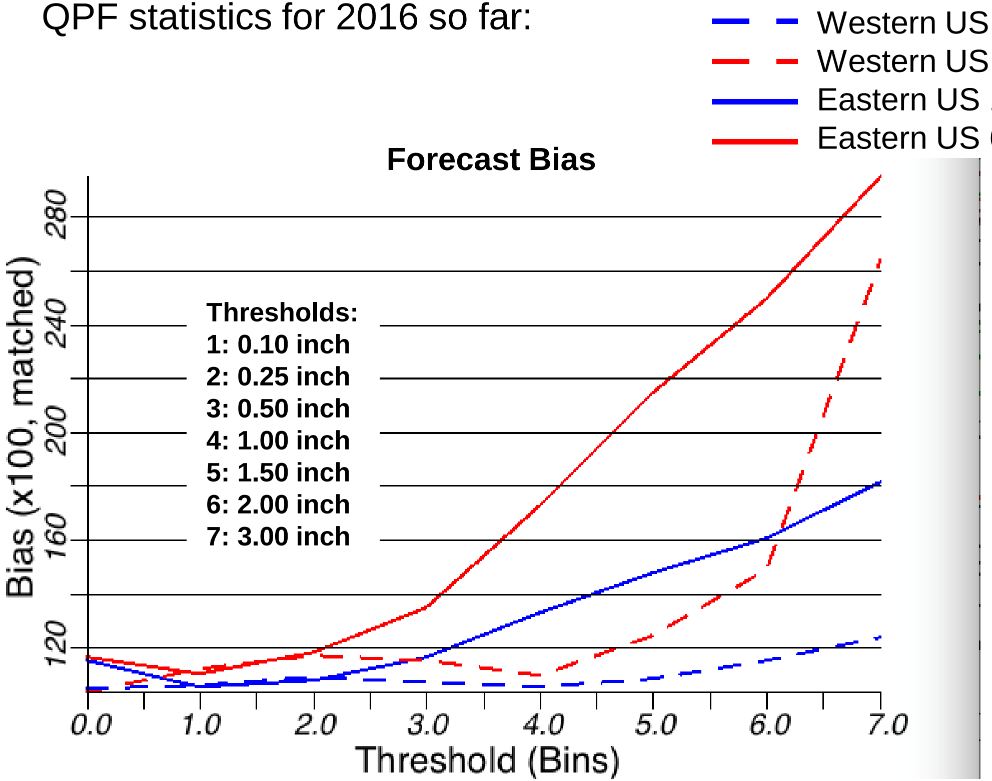
- Good news:
- Short term: both issues can be addressed ex post facto, through statistical bias correction, using a moving window of the most recent 50-100 forecasts (a few weeks of HRRR runs)
- Long term: planned improvements to HRRR model physics will reduce these biases in the model itself

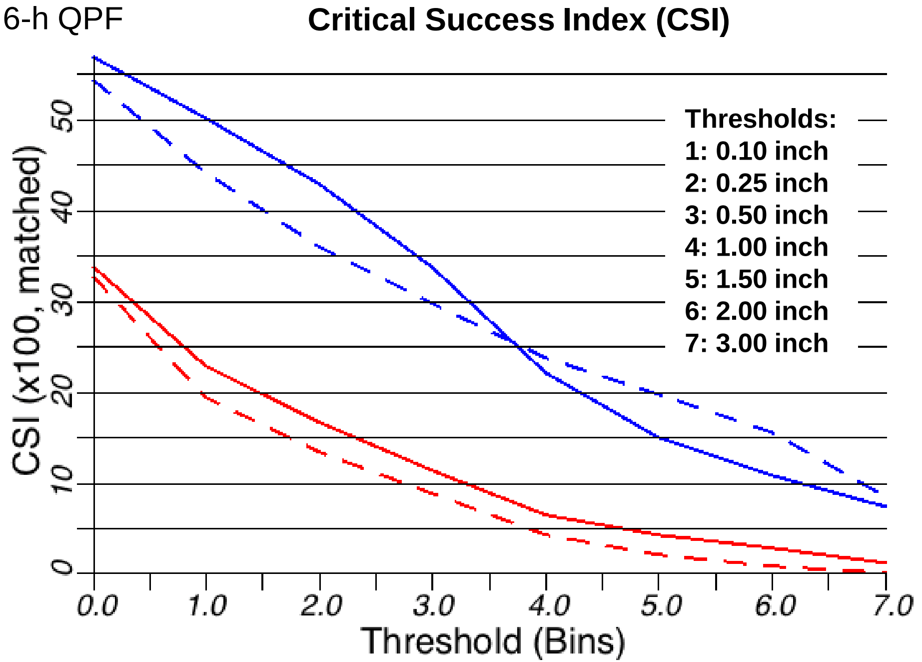
What are possible workarounds to HRRR's limitations?

- 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…

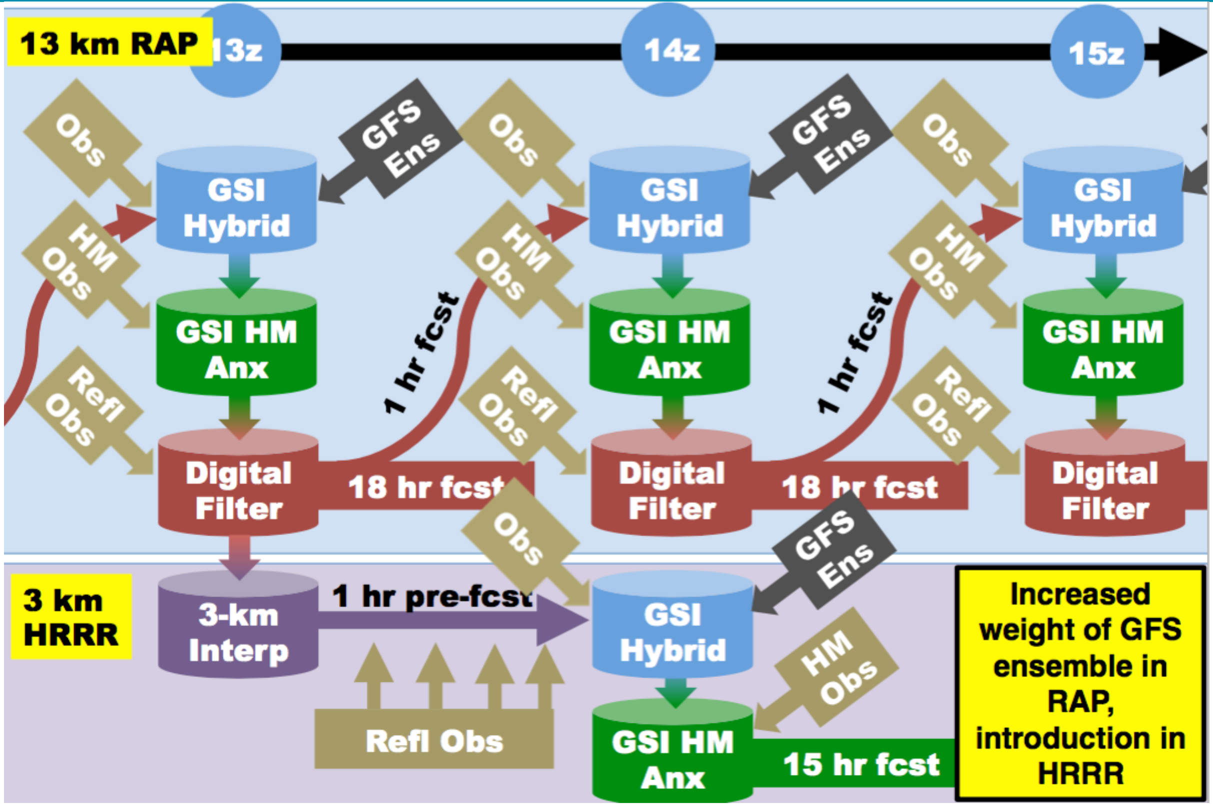
Is HRRR suitable for PMP estimation?

QPF statistics for 2016 so far:





RAP/HRRR "wiring diagram"



Current RAP/HRRR configuration

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

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

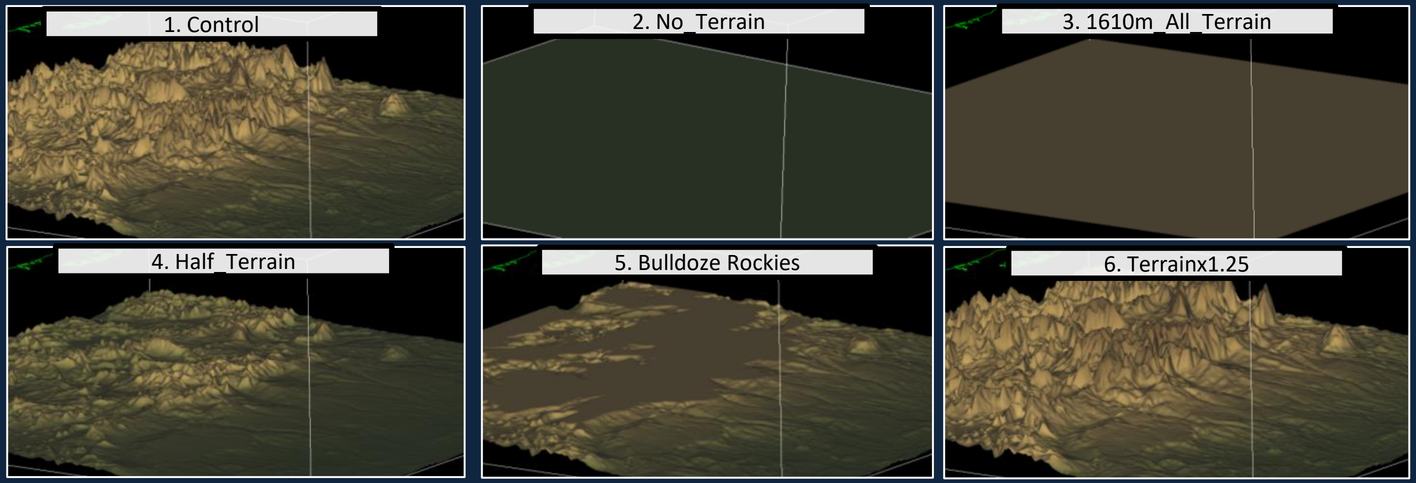
Model	Horiz/Vert Advection	Scalar Advection	Upper-Level Damping	6^{th} Order Diffusion	SW Radiation Update	Land Use	MP Tend Limit	Time-Step
RAP	$5^{th}/5^{th}$	Positive-Definite	w-Rayleigh 0.2	Yes 0.12	20 min	MODIS Fractional	0.01 K/s	60 s
HRRR	$5^{th}/5^{th}$	Positive-Definite	w-Rayleigh 0.2	Yes 0.25 (flat terr)	15 min with SW-dt (Ruiz-Arias)	MODIS Fractional	0.07 K/s	20 s

Observations used in the data assimilation

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

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

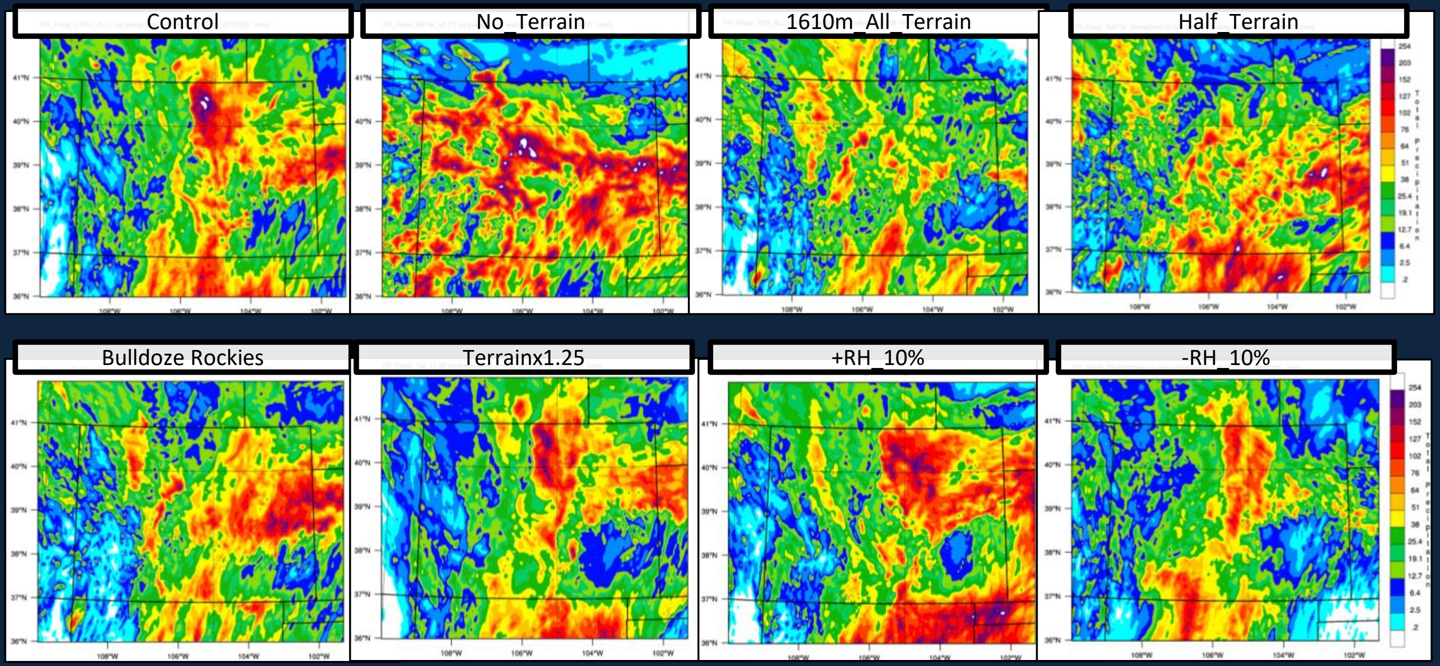
Terrain modifications:

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:

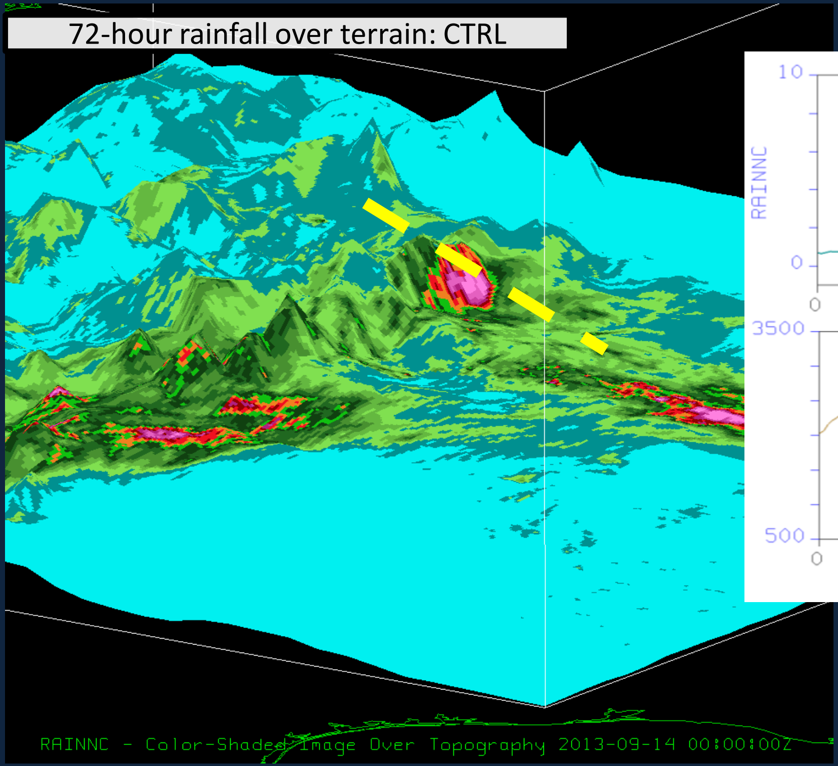
7. +RH_10%: Increase initial, lateral boundary environmental humidity by 10%
8. -RH_10%: Decrease initial, lateral boundary environmental humidity by 10%
9. +RH_50%: Increase initial, lateral boundary environmental humidity by 50%
10. +RH_100%: Increase initial, lateral boundary environmental humidity to 100%

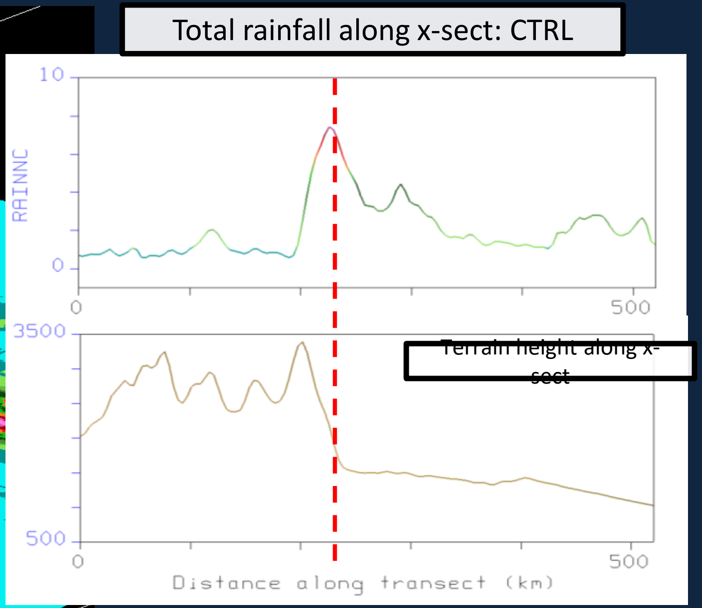
Results: 72-hour precipitation



- 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

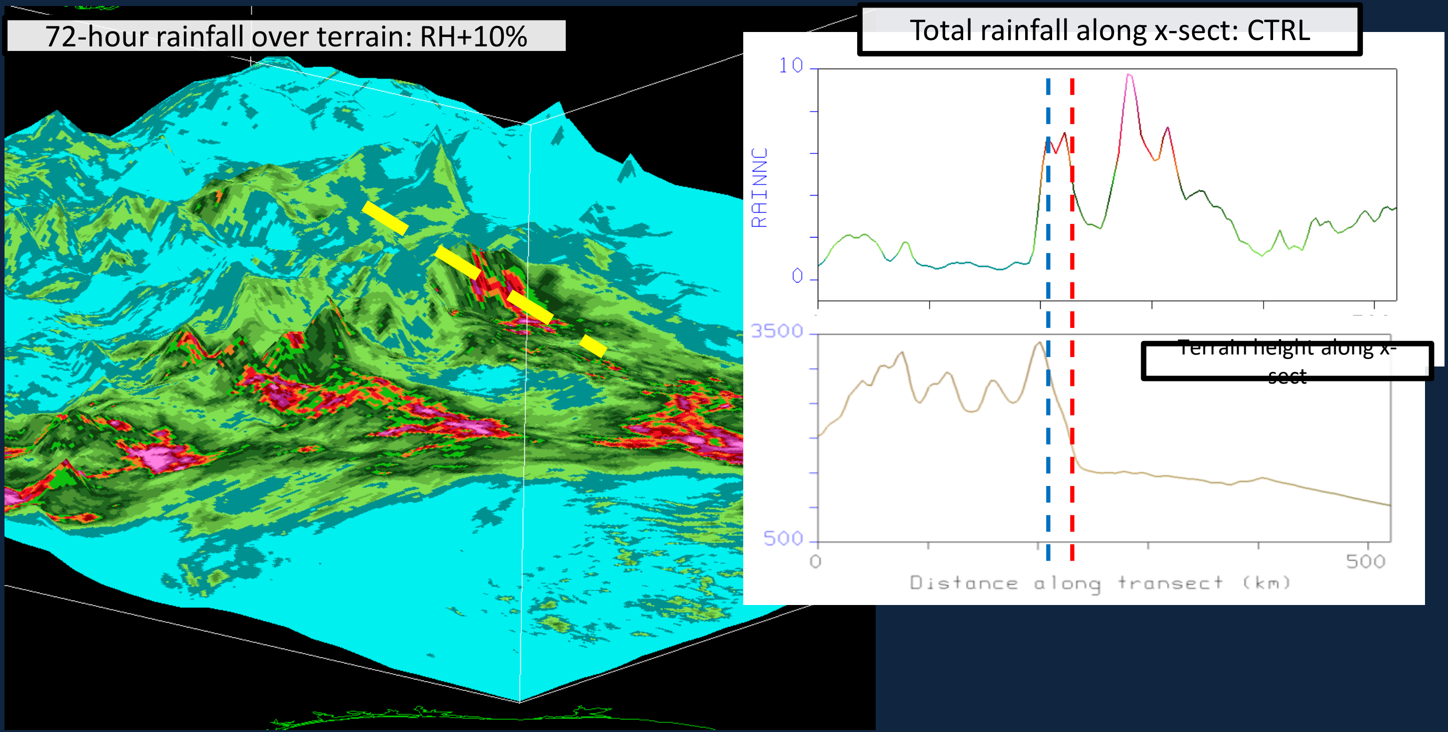
Precipitation vs. elevation: Max precip cross-section example





- CTRL simulation elevation vs. precipitation: rainfall max 2000 – 2500 m (6500 - ~8000 feet)

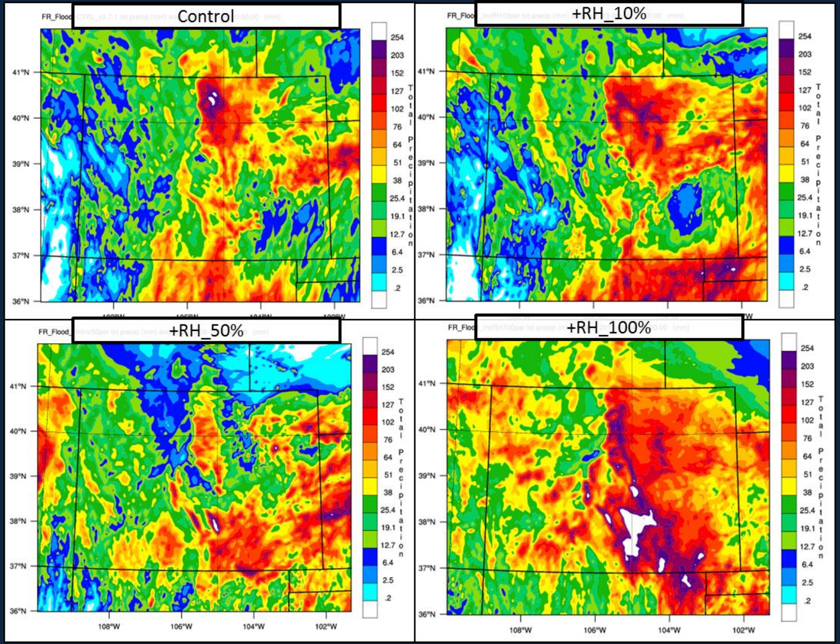
Precipitation vs. elevation: Max precip cross-section example



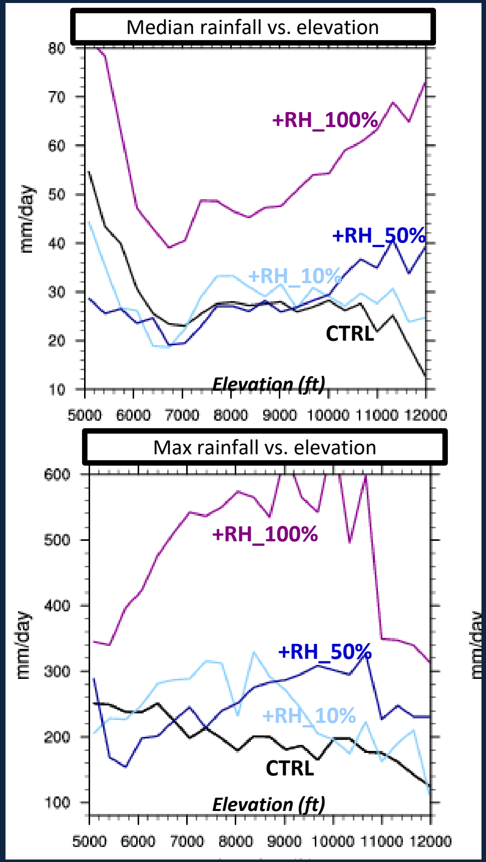
- CTRL simulation elevation vs. precipitation: precip max ~8500 ft (2590m)
- +RH_10%: max precip: amount less, but location moves over higher Front Range terrain (~3000m)
- What about over the whole domain?

Precipitation vs. elevation: Moisture-increased experiments

- Moisture-modified runs show variable precip-elevation relationships



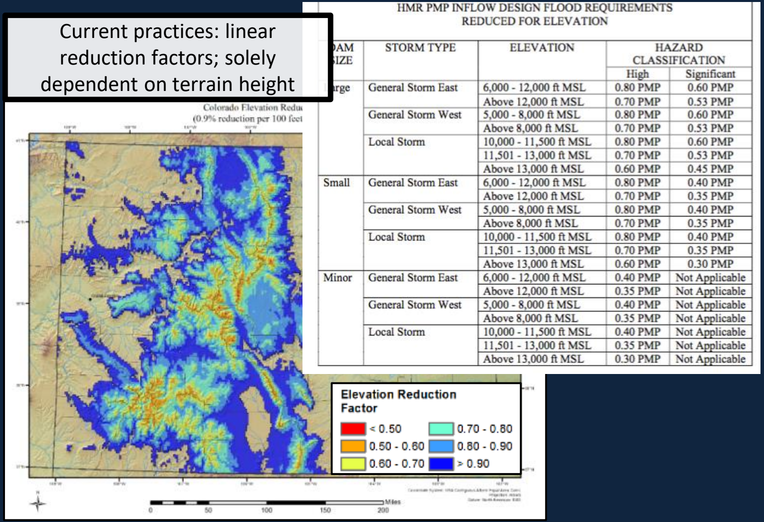
Domain-wide analysis (all gridpoints)



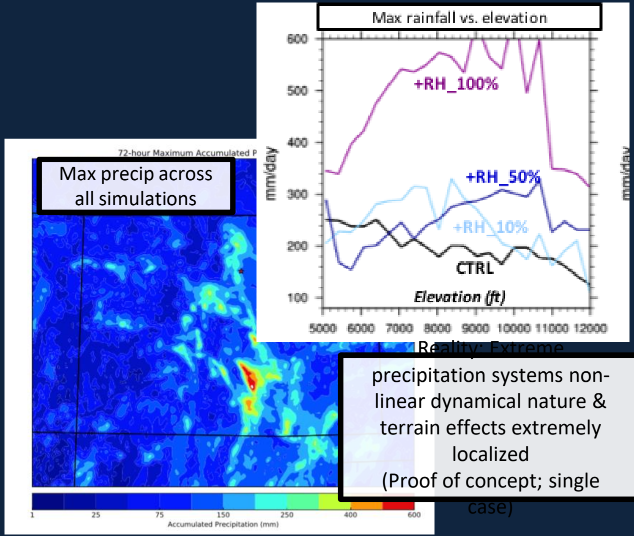
- Distribution of median, max precip shifts as moisture increases
  - Generally upward trend in 50%, 100% increases, but not consistently
- Variability indicates localized nature of terrain effects, case-specific dynamical details
- More cases needed for systematic relationships; proof-of-concept demonstrates potential benefit to extreme precipitation estimation in complex terrain

Precipitation vs. elevation: Comparison to reduction factors

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


HMR PMP INFLOW DESIGN FLOOD REQUIREMENTS
REDUCED FOR ELEVATION

AM IZE	STORM TYPE	ELEVATION	HAZARD CLASSIFICATION	
			High	Significant
rge	General Storm East	6,000 - 12,000 ft MSL	0.80 PMP	0.60 PMP
		Above 12,000 ft MSL	0.70 PMP	0.53 PMP
	General Storm West	5,000 - 8,000 ft MSL	0.80 PMP	0.60 PMP
		Above 8,000 ft MSL	0.70 PMP	0.53 PMP
	Local Storm	10,000 - 11,500 ft MSL	0.80 PMP	0.60 PMP
		11,501 - 13,000 ft MSL	0.70 PMP	0.53 PMP
		Above 13,000 ft MSL	0.60 PMP	0.45 PMP
Small	General Storm East	6,000 - 12,000 ft MSL	0.80 PMP	0.40 PMP
		Above 12,000 ft MSL	0.70 PMP	0.35 PMP
	General Storm West	5,000 - 8,000 ft MSL	0.80 PMP	0.40 PMP
		Above 8,000 ft MSL	0.70 PMP	0.35 PMP
	Local Storm	10,000 - 11,500 ft MSL	0.80 PMP	0.40 PMP
		11,501 - 13,000 ft MSL	0.70 PMP	0.35 PMP
		Above 13,000 ft MSL	0.60 PMP	0.30 PMP
Minor	General Storm East	6,000 - 12,000 ft MSL	0.40 PMP	Not Applicable
		Above 12,000 ft MSL	0.35 PMP	Not Applicable
	General Storm West	5,000 - 8,000 ft MSL	0.40 PMP	Not Applicable
		Above 8,000 ft MSL	0.35 PMP	Not Applicable
	Local Storm	10,000 - 11,500 ft MSL	0.40 PMP	Not Applicable
		11,501 - 13,000 ft MSL	0.35 PMP	Not Applicable
		Above 13,000 ft MSL	0.30 PMP	Not Applicable



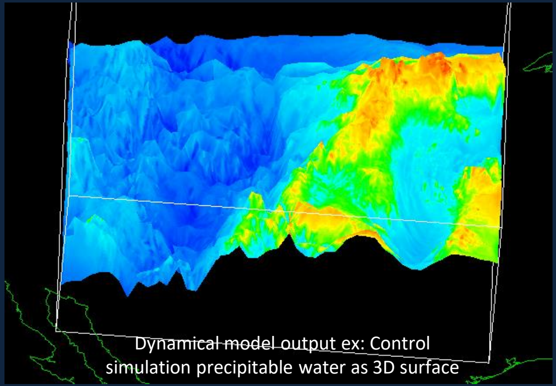
Reality: Extreme precipitation systems non-linear dynamical nature & terrain effects extremely localized
(Proof of concept; single case)

- High variability across model realizations of <u>this event</u>
  - 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

Summary and future work

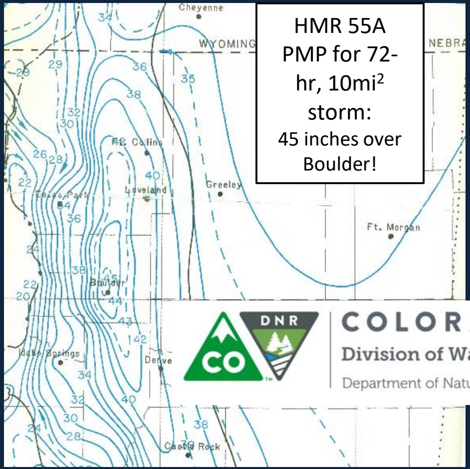
- 2013 Colorado floods exceeded 7500-foot terrain "limit" for flood potential
  - Some dams stressed but no major failures. PMP is "conservatively safe" but inefficient
- Modeling case study: model terrain, storm environment experiments emphasize sensitivity of amount and distribution of heavy precipitation
- 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)

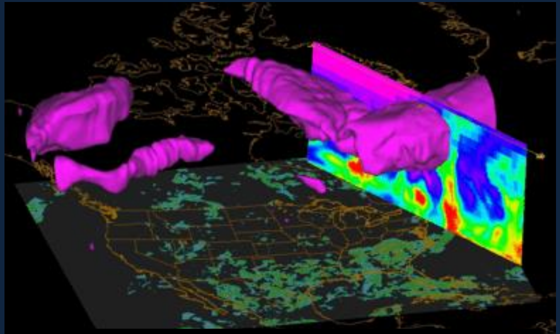

Dynamical model output ex: Control simulation precipitable water as 3D surface

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



COLORADO
Division of Water Resources
Department of Natural Resources



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