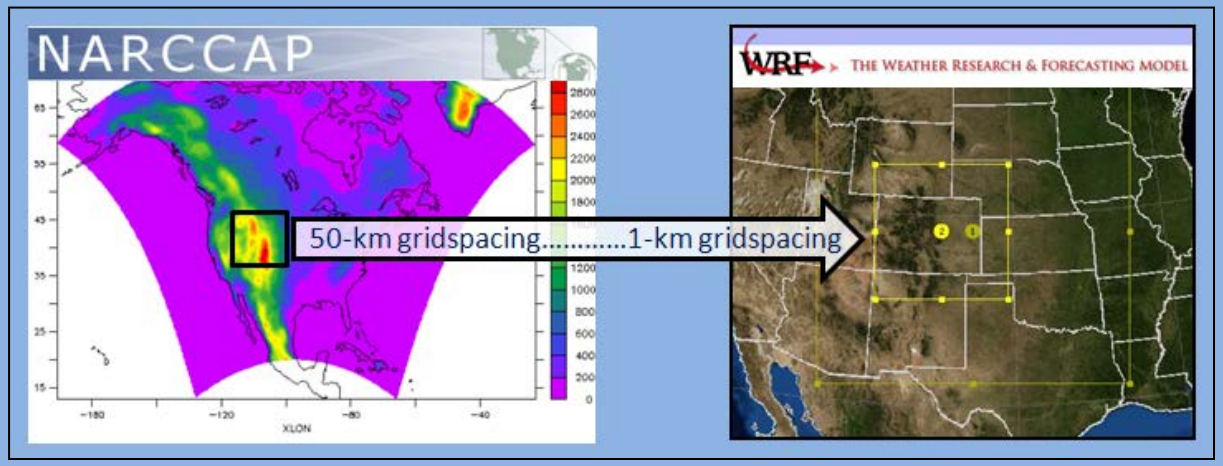
Improving extreme precipitation estimation and climate change projections using regional and high-resolution model simulations



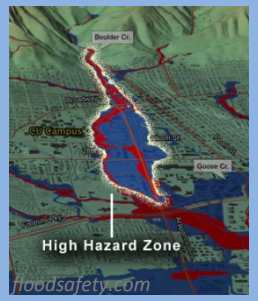
Annual Progress Meeting

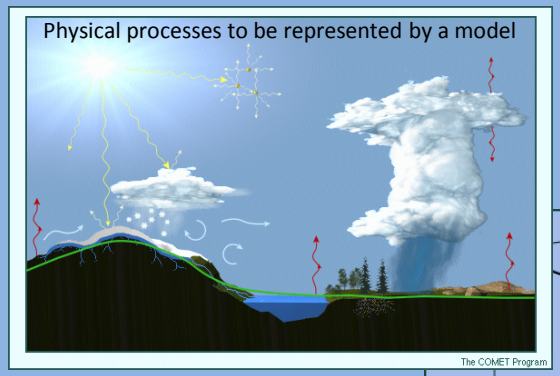
3 October 2012

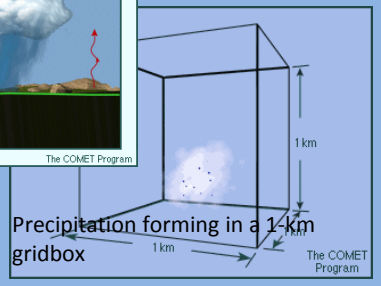
Kelly Mahoney, Mike Alexander, Jamie Scott, Joe Barsugli

Motivation: Extreme precipitation and climate change

- Extreme precipitation events predicted to change…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 to capture intensity of extreme events
- Extreme precipitation events and water resources management
  - Can elevation thresholds for storms, flooding, hail change in future scenarios? (Can/will extreme precip occur at high (7500-8000ft+) elevations?)
  - Do structural safety requirements, management practices need to change?





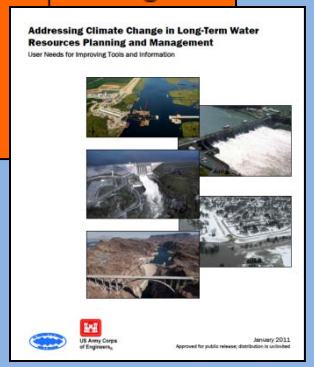


Background: Project history

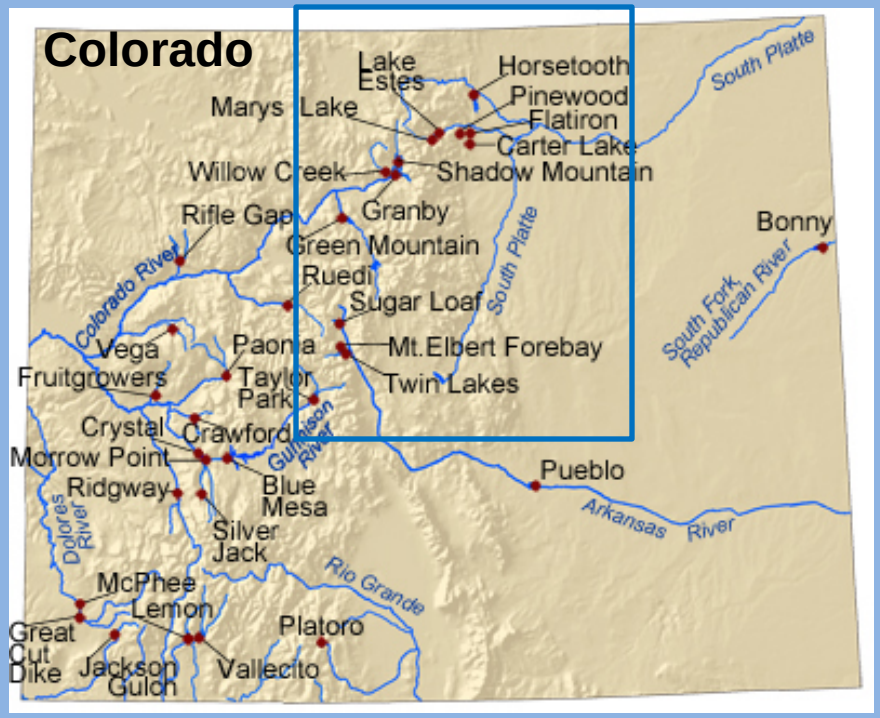
- High-resolution downscaling research started under UCAR PACE post-doc supported by USBR and NOAA
- Broadened study scope and added additional goals per user needs:
  - Information on finer space and time resolutions, strengths and weaknesses of downscaled data, extremes all ranked as high priority
- Year 1 (of 2) complete

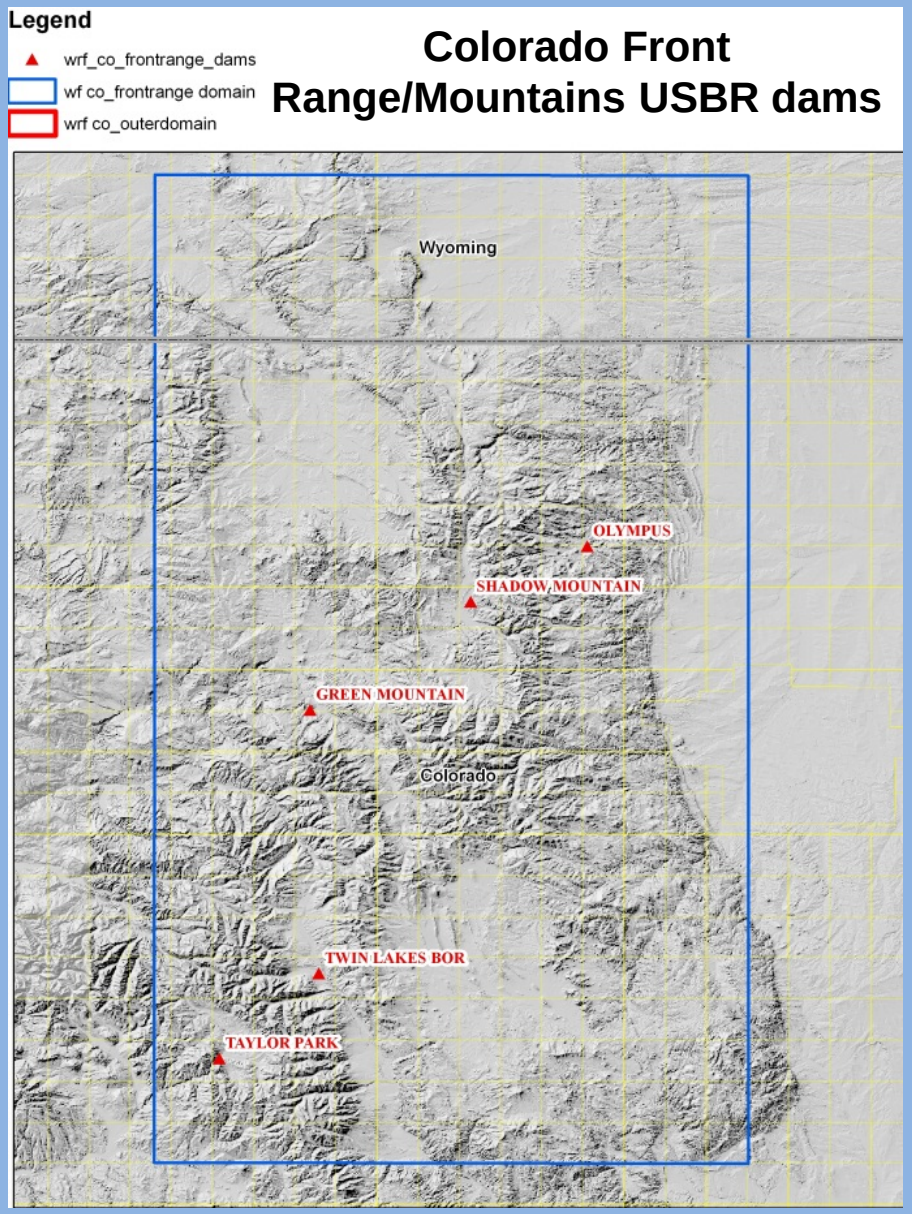
Table ES-1. Summary of gaps and relation to other needs assessments (continued)

Technical Planning Steps and Associated Gaps in Tools and Information	Priority Ranking[1]	
	Reclamation/ USACE	All Respondents
Step 2 – Obtaining Climate Change Information		
2.01 Improved skill in simulating long-term global to regional climate.	High	High
2.02 Downscaled data at finer space and time resolutions and for different variables.	High	High
2.03 Information on the strengths and weaknesses of downscaled data and the downscaling methodologies used to develop these data (including both statistical and dynamical methods and associated approaches for climate model bias-correction).	High	High
3.06 Method and basis for estimating extreme meteorological event possibilities, deterministically or probabilistically, in a changing climate.	High	High
Step 7 – Assess and Characterize Uncertainties		
7.01 Uncertainty information on global climate projections data, including uncertainties about climate system science, portrayal in climate models, emissions scenario development, and simulation methods.	High	High



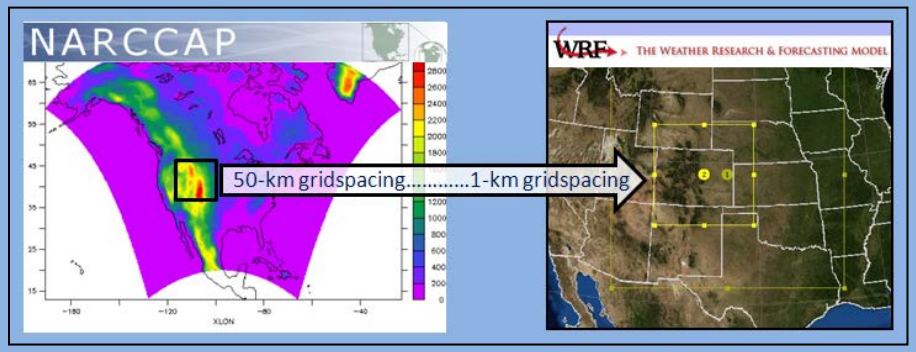
Front Range dam locations

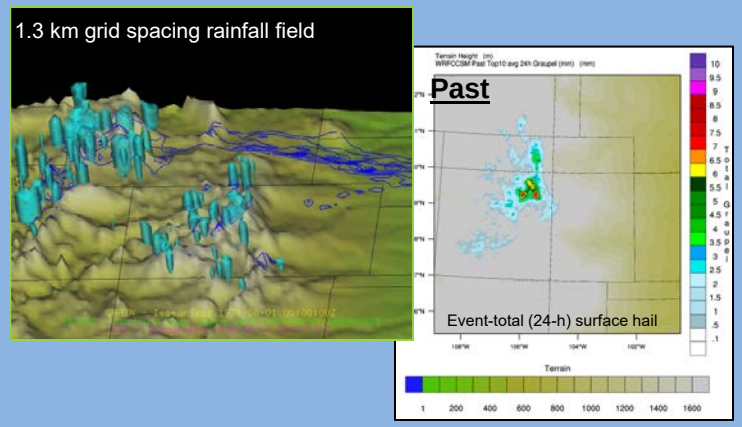




Project goals

1. Advance understanding of appropriate applications of extreme precipitation data from both climate model and reanalysis-based sources
2. Explore utility of high-resolution numerical modeling in understanding, anticipating, and preparing for extreme precipitation events in both present and future climates
3. Evaluate the potential for changes in intensity of extreme warm-season precipitation events in future climate scenarios in the Colorado Front Range
4. Consider potential for changes in elevation thresholds for storms, flooding, and hail
5. Understand potential and limitations of high-resolution modeling approach (and permutations thereof) in decision-making frameworks





Project approach

1. Analyze seasonal and extreme precipitation from regional climate model ensemble (NARCCAP)
2. Identify top extreme events in Colorado Front Range from regional models
3. Further downscale all individual events to high-resolution (1.3-km grid spacing); test various model initialization methods
4. Evaluate signal strength in projected changes in extremes and identify process-based explanations for changes

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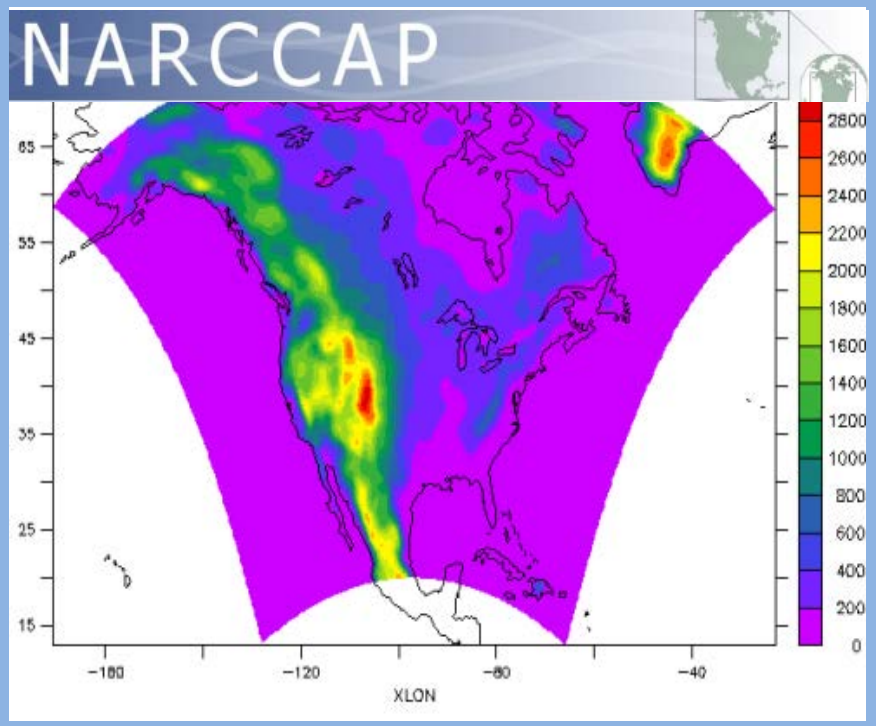
Regional climate model projections of warm-season precipitation in Colorado

- NARCCAP: North American Region Climate Change Assessment Program
  - Collection of regional climate model simulations (Δx = 50km)
  - Initial, boundary conditions from 20th, 21st century AOGCM experiments
  - http://www.narccap.ucar.edu/



NARCCAP AT A GLANCE

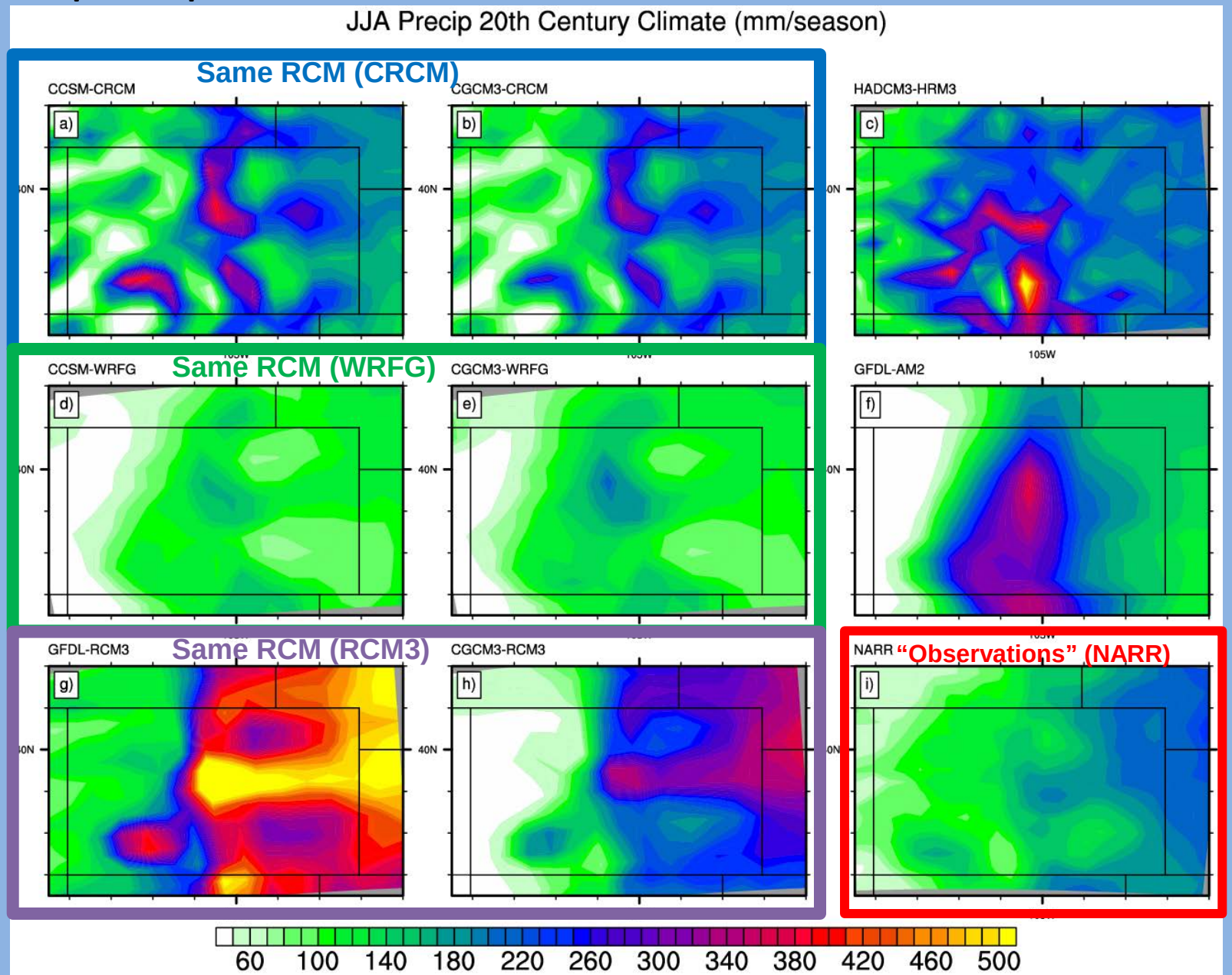
- 4 different AOGCMs driving 6 different RCMs
- 50 km spatial resolution
- 3 hourly temporal resolution
- 52 output variables
- 2 high-resolution AGCM timeslice experiments
- Future scenario: SRES A2

Phase I: RCMs are driven by historical (1979-2004) observed (NCEP2 Reanalysis) data

Phase II: Each RCM is driven by 2 GCMs for current (1971-2000) and future (2041-2070) scenarios. GCM/RCM pairings are chosen for maximum value in statistical analysis.

Timeslices: Atmospheric components of the GFDL & CCSM global models are run at 50 km resolution using observed SST data (offset in the future scenario) instead of a coupled ocean.

What does 20th century warm-seaon average precipitation look like in each NARCCAP model?



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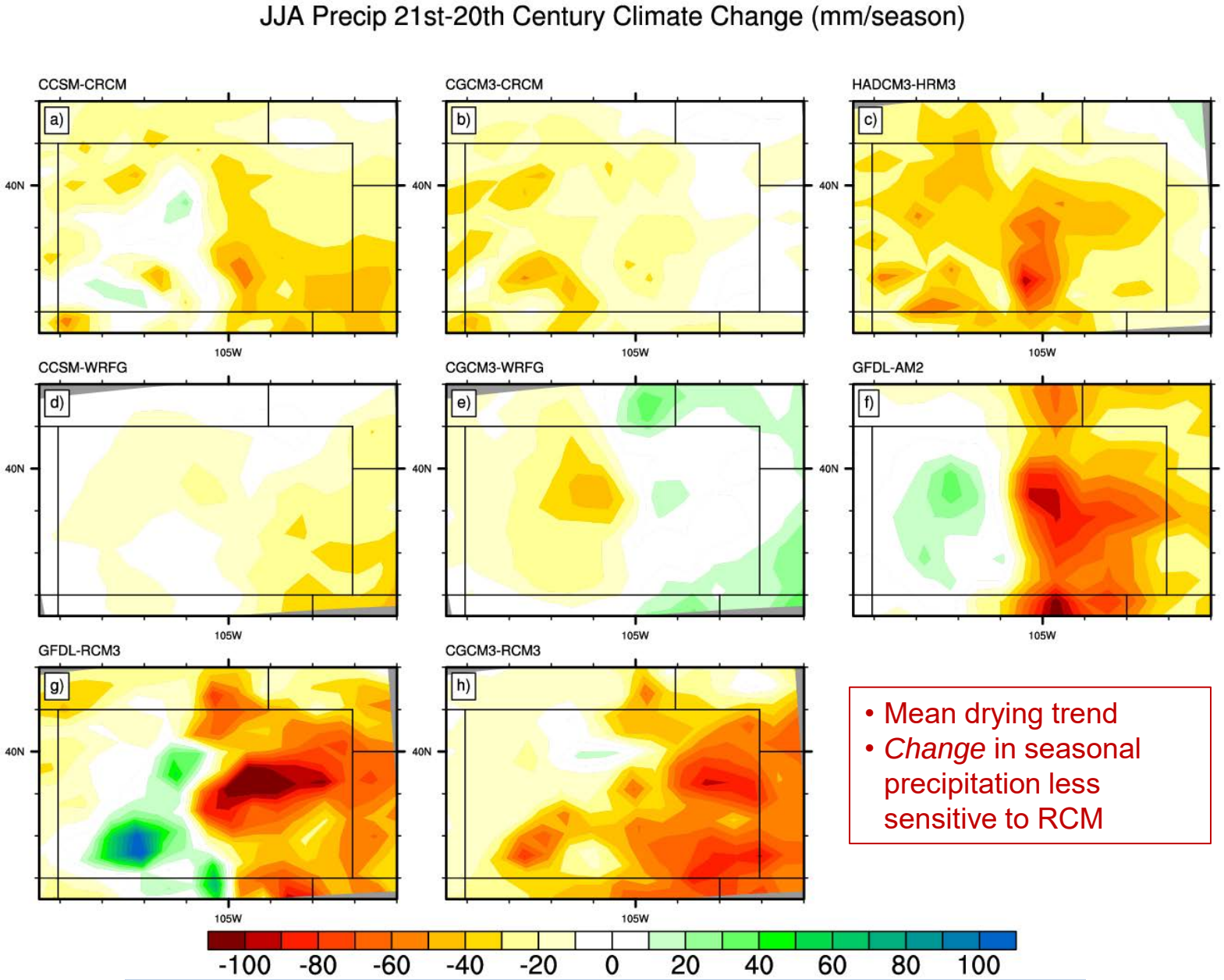
Changes in daily mean precipitation: NARCCAP 21st – 20th Century Change



- Mean drying trend
- *Change* in seasonal precipitation less sensitive to RCM

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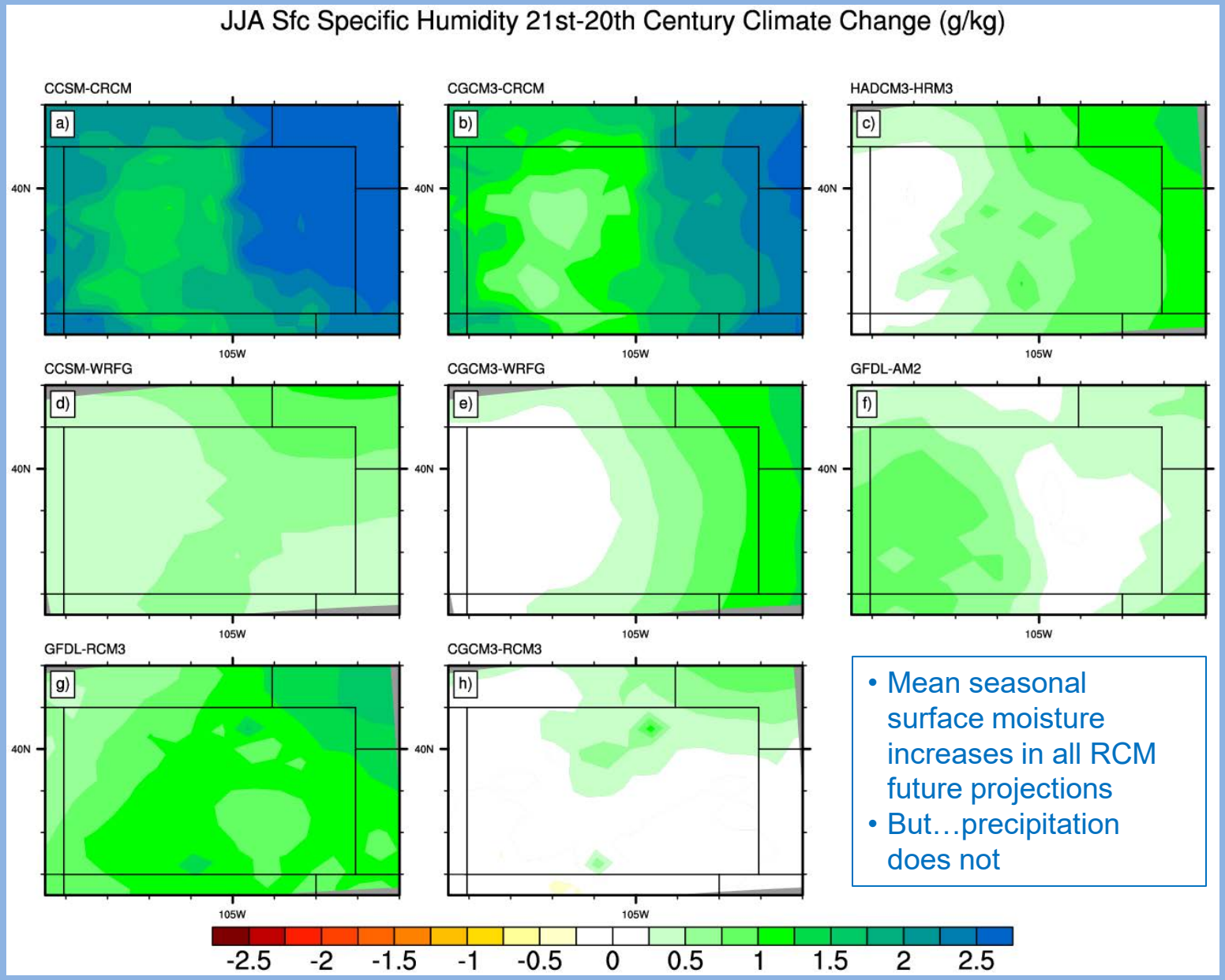
Changes in low-level humidity: NARCCAP 21st – 20th Century Change



- Mean seasonal surface moisture increases in all RCM future projections
- But…precipitation does not

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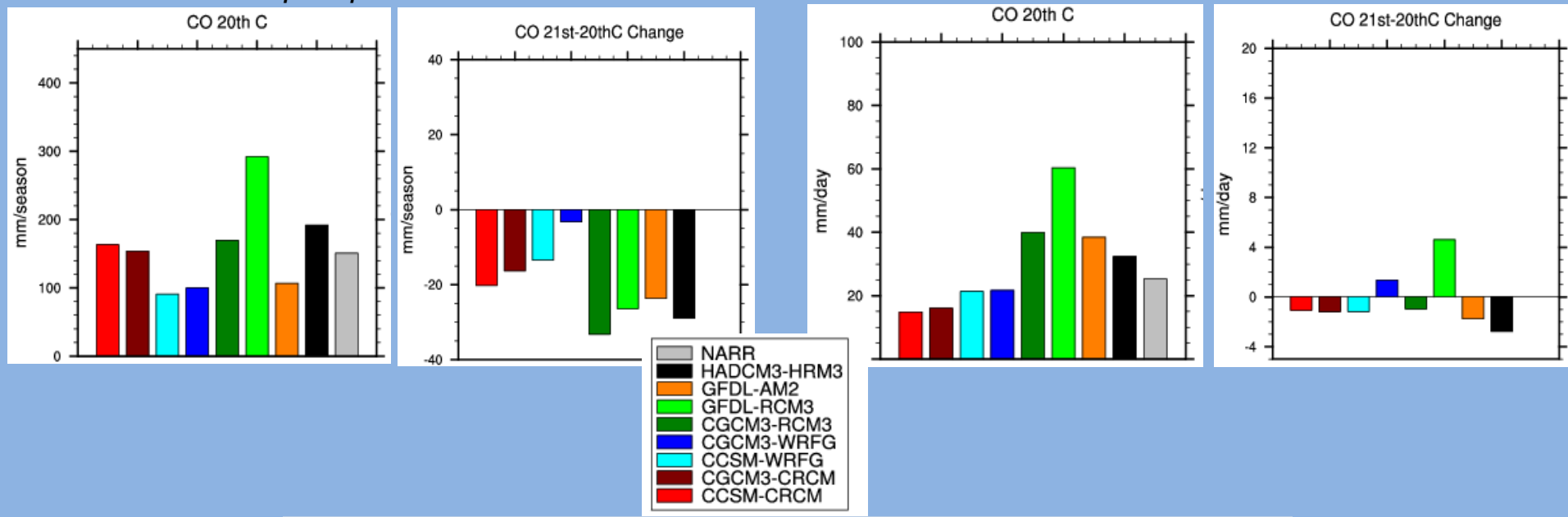
Regional climate model assessment summary

- Overall decreases in mean warm-season precipitation in Colorado
- Most (but not all) models also indicate drying in the extremes
- Decreased precipitation often occurs despite environmental humidity increasing
- Spatial distribution of precipitation sensitive to RCM used
- Precipitation amounts highly variable between models, both in mean and extremes

Mean warm season precipitation

"Extremes" (99th %-ile) warm season precipitation



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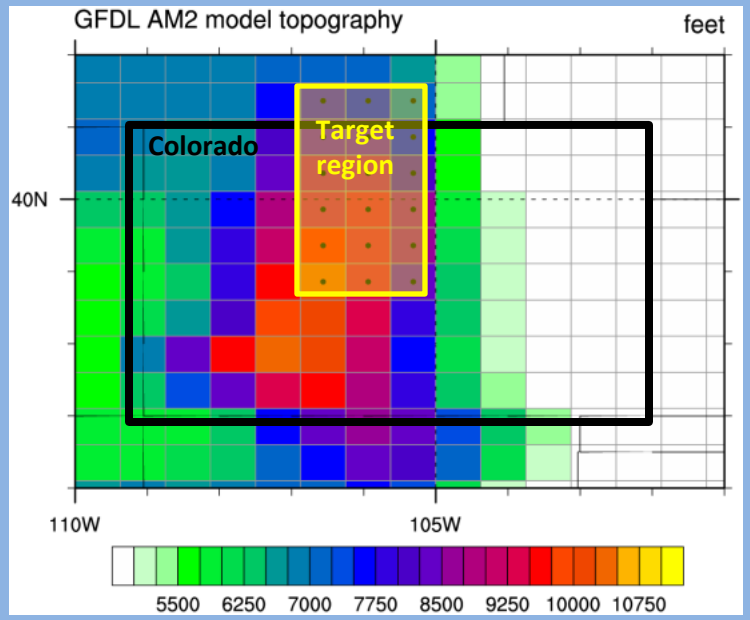
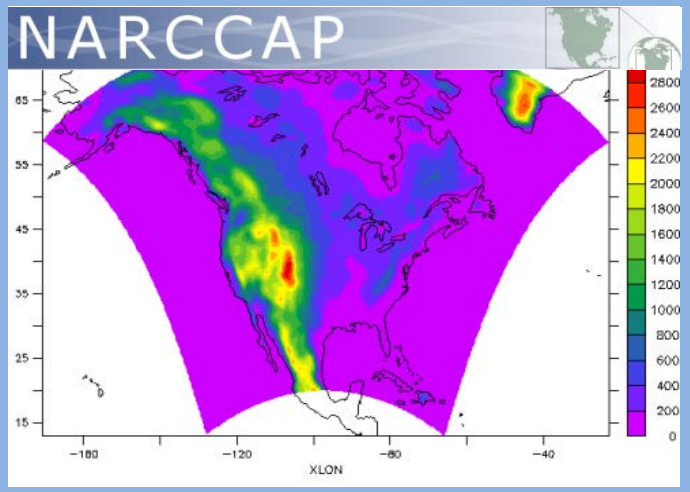
Regional climate model projections of warm-season precipitation in Colorado

- Extreme event selection from NARCCAP:
  - Target region: Colorado Front Range
  - For past (1971-2000), future (2041-2070) simulations:
    1. Sort all warm-season (June-July-August) daily precipitation values in target region
    2. 10 largest precipitation values ≈ Top 0.3% of events
- Initial conditions for downscaling from 3 RCMs:
  1. GFDL+ts (GT): Geophysical Fluid Dynamics Laboratory (GFDL) GCM – "Timeslice"
  2. WRF+CCSM (CW): WRF driven by Community Climate System Model (NCAR)
  3. CGCM3+RCM3 (CR): RegCM3 driven by 3rd Generation Coupled GCM (Canadian Centre)
  - All SRES-A2; Historical simulations *not* forced by observations; therefore, *not* based on actual past weather events





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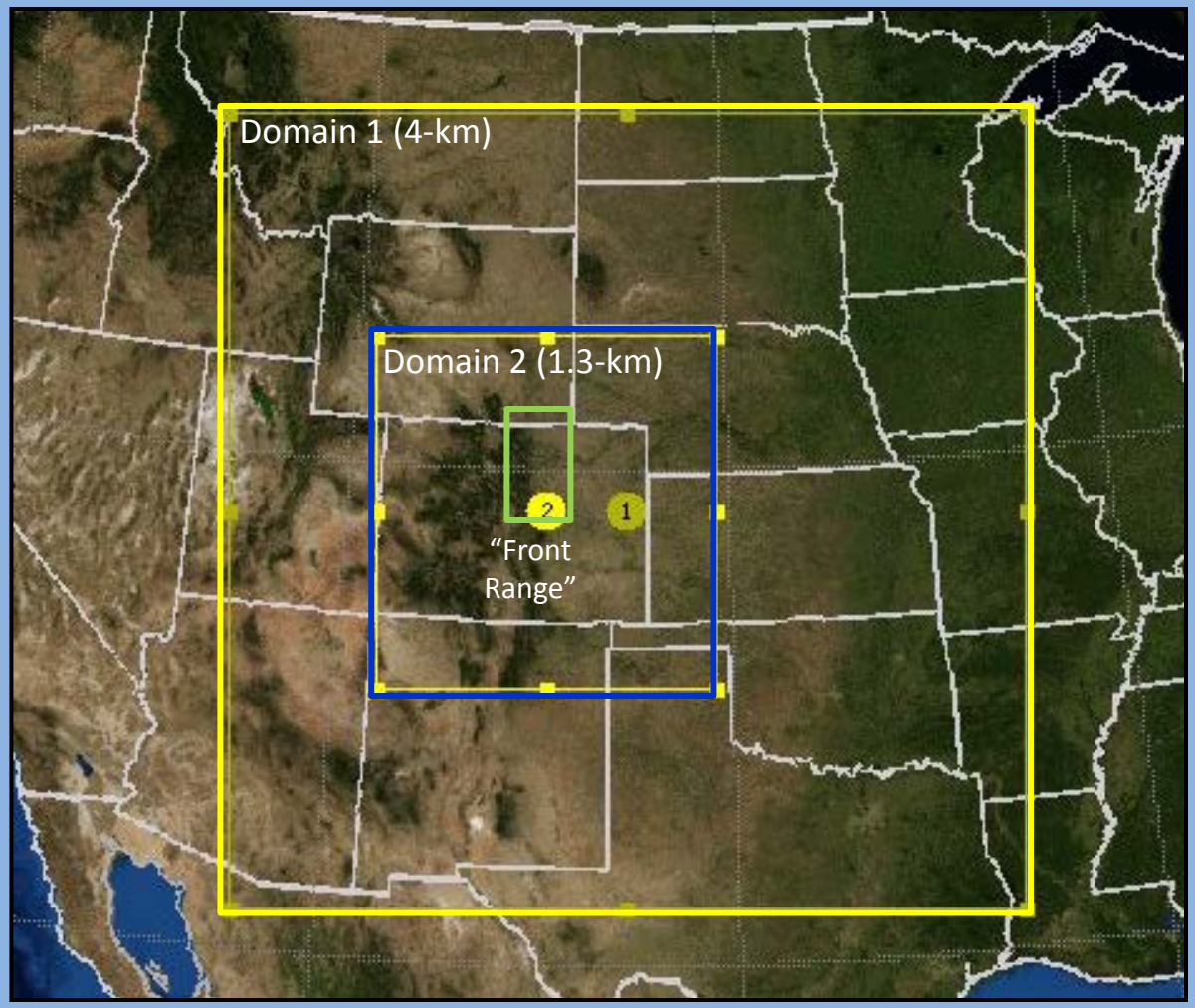
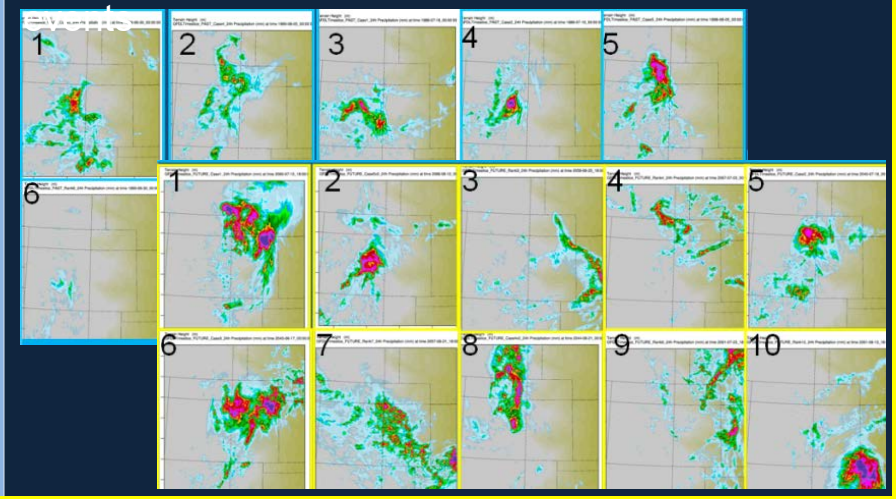
WRF model domain



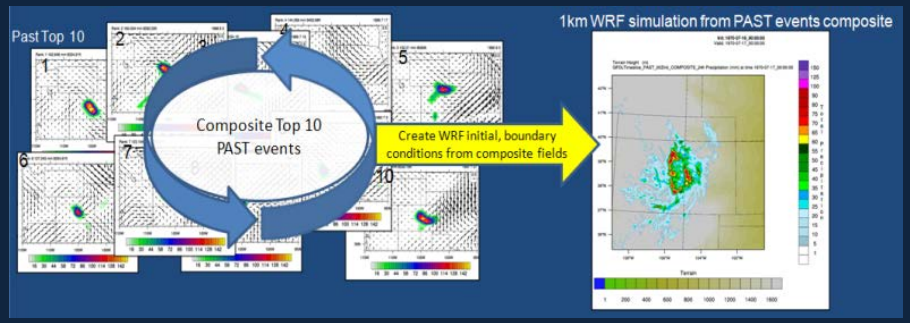
Three different downscaling methodologies (Overview)

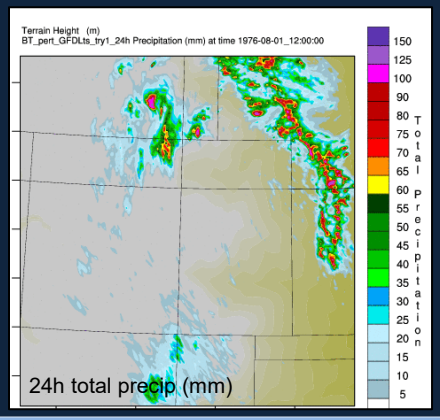
1. Individual simulations
2. Composite-initialized simulations
3. "Pseudo-global-warming/climate-perturbed simulations of historical (observed) extreme event

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



2. Composite approach



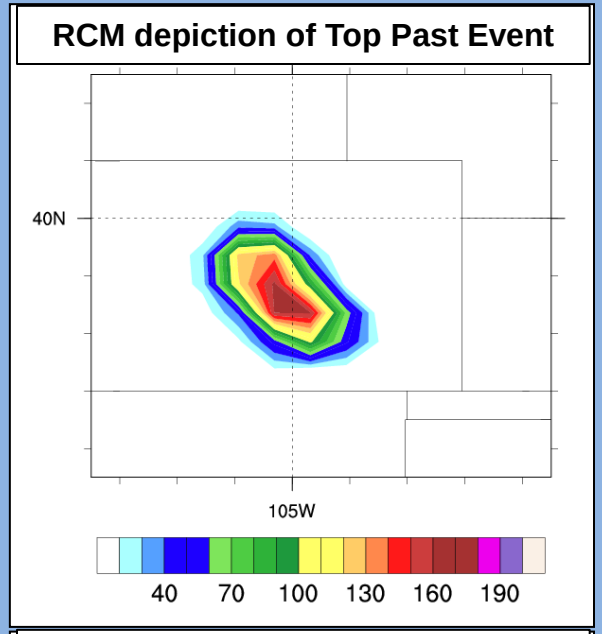


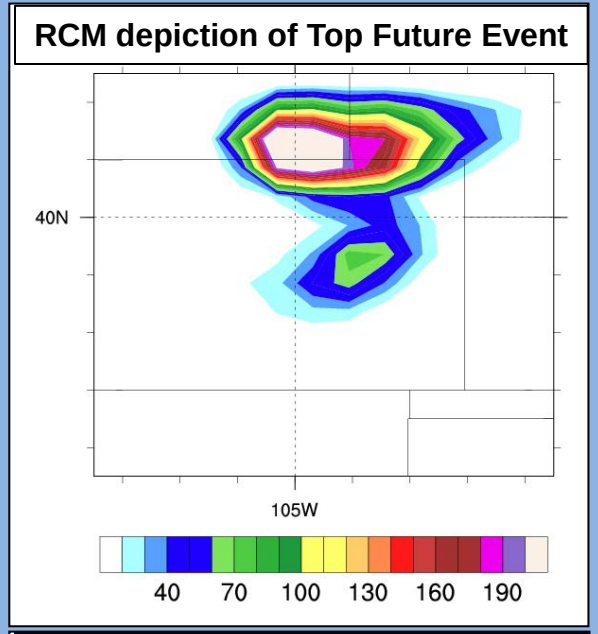
3. Example: Big Thompson Canyon Flood in "GFDL-TS Future"

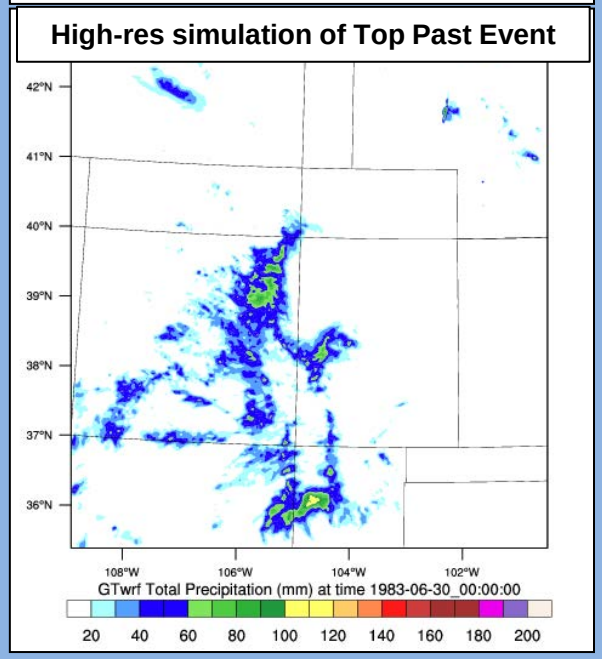
- Multiple approaches → add info regarding confidence, uncertainty
- Here, will focus on Approach #1…

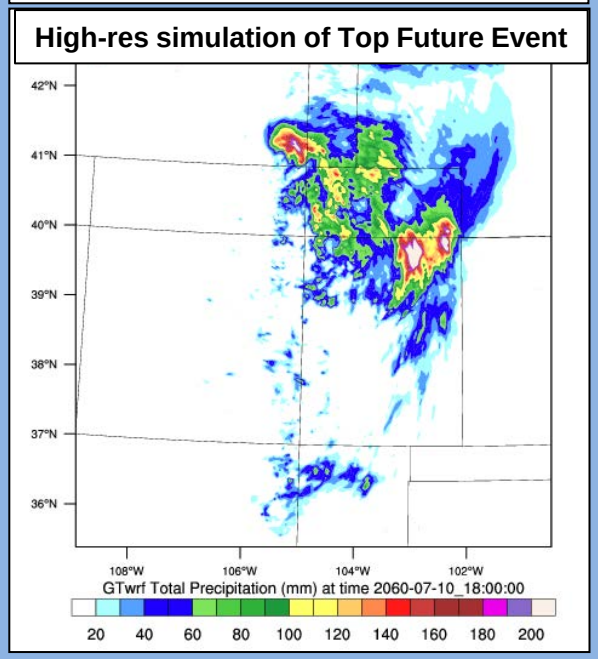
Example: Individual case downscaling approach

Compare difference in precipitation character (spatial distribution, amounts) from 50-km (top) to 1.3km (bottom)









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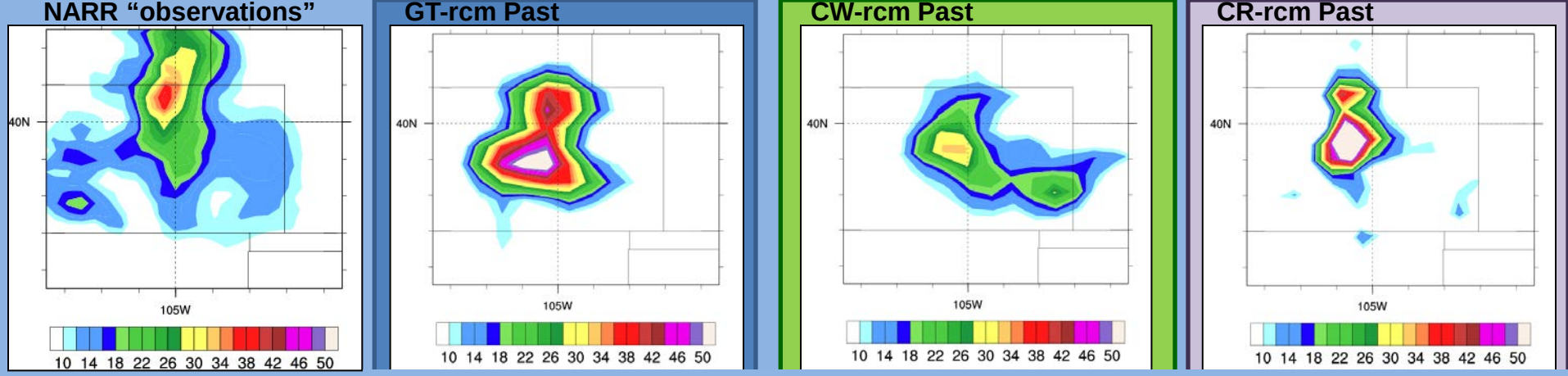

Average 24-h precipitation for top 10 past, future events for 3 NARCCAP models

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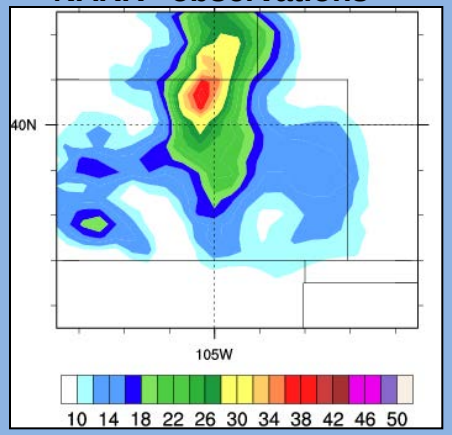
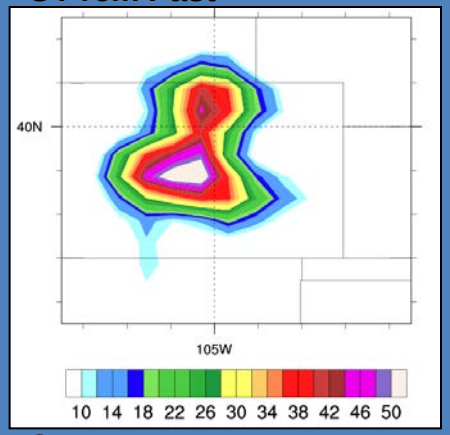
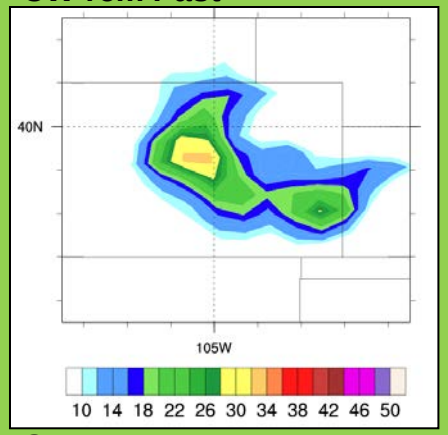
NARR "observations"



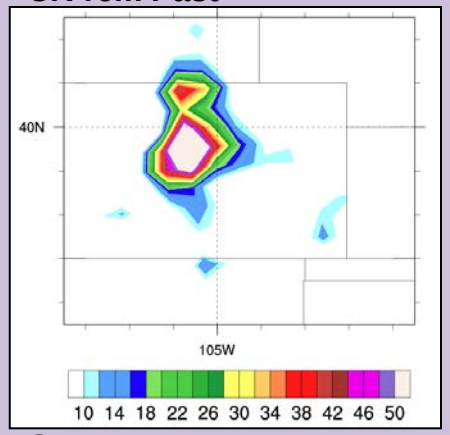
GT-rcm Past



CW-rcm Past

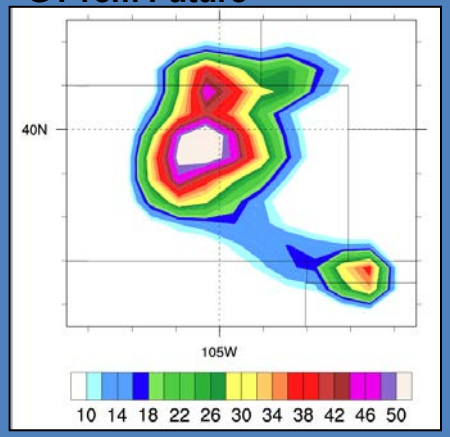


CR-rcm Past

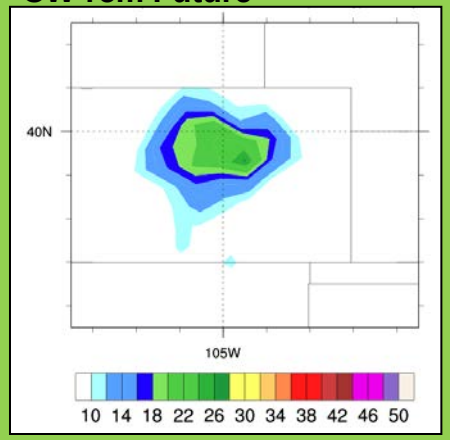


Average 24-h precipitation for top 10 past, future events for 3 NARCCAP models

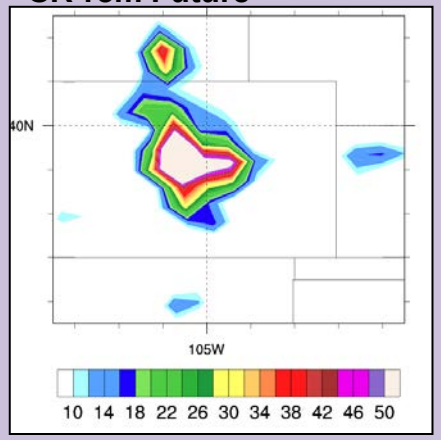
GT-rcm Future



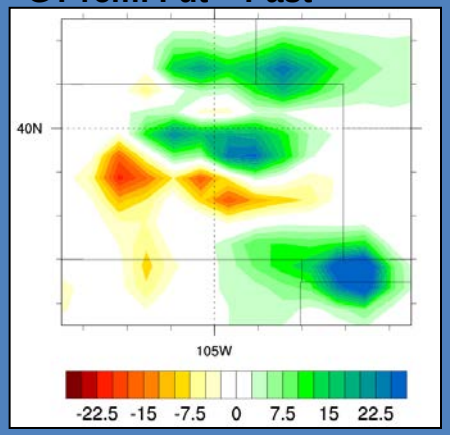
CW-rcm Future



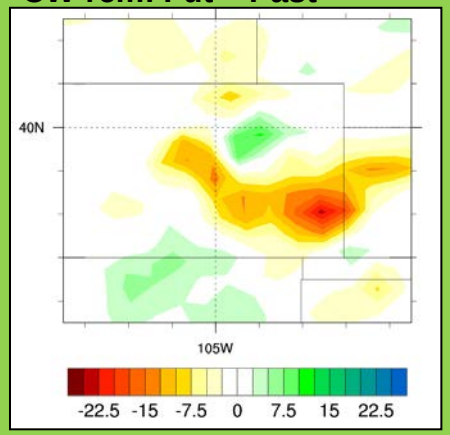
CR-rcm Future



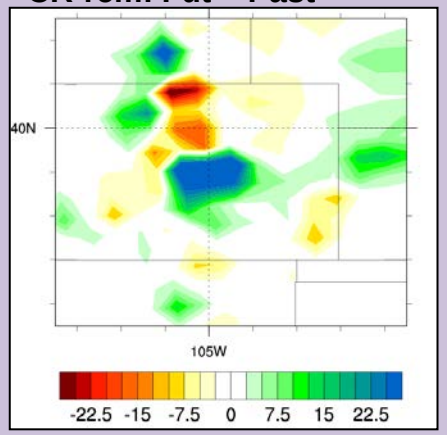
GT-rcm: Fut – Past



CW-rcm: Fut – Past



CR-rcm: Fut – Past



Δ Precip (mm)
(Future – Past)

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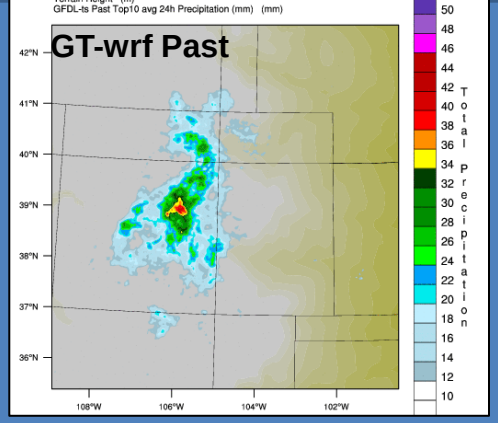
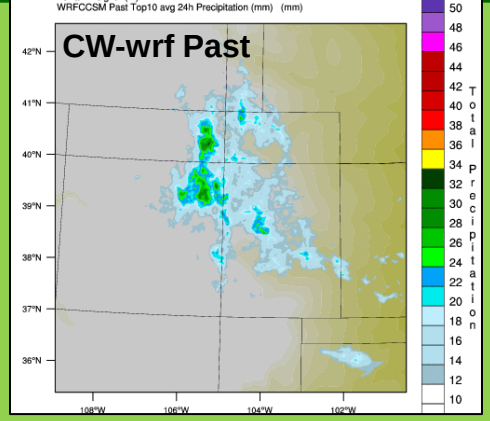
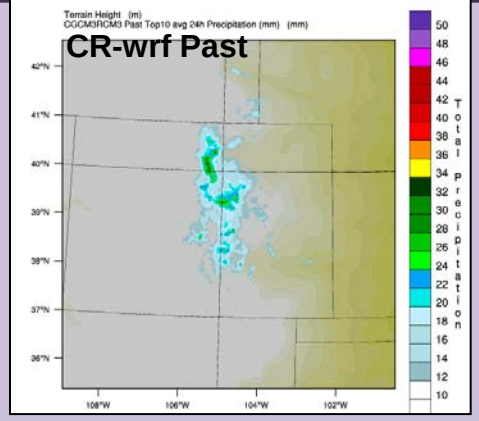
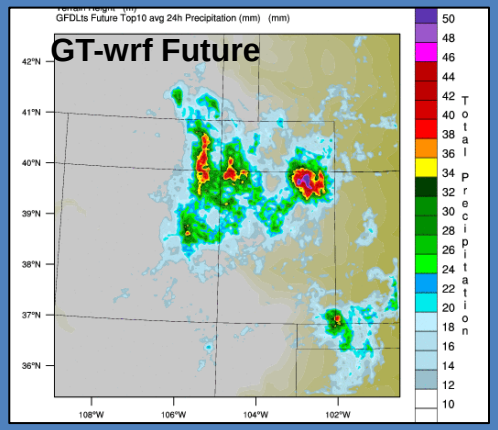
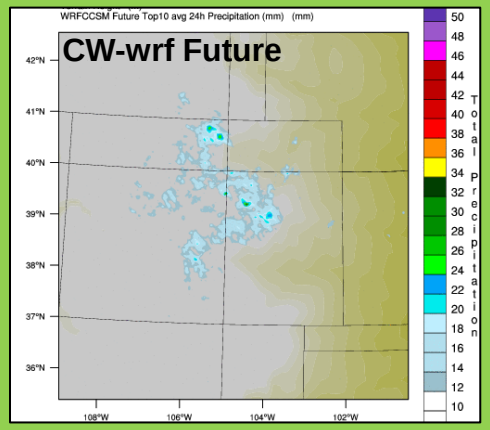
Average 24-h precipitation for top 10 past, future events for high-resolution WRF downscaled experiments from 3 NARCCAP models

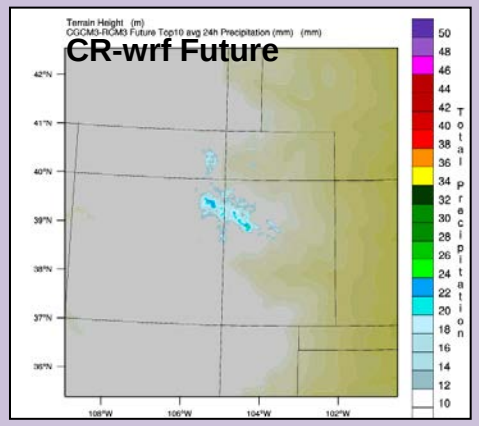




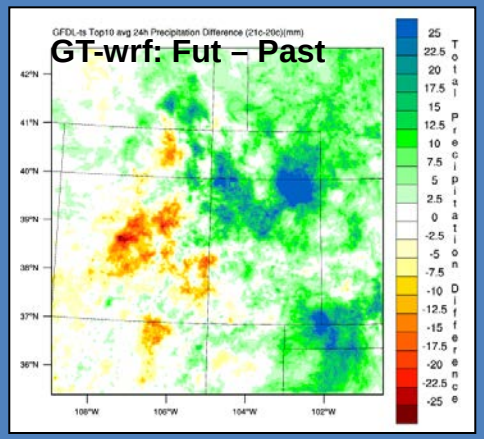


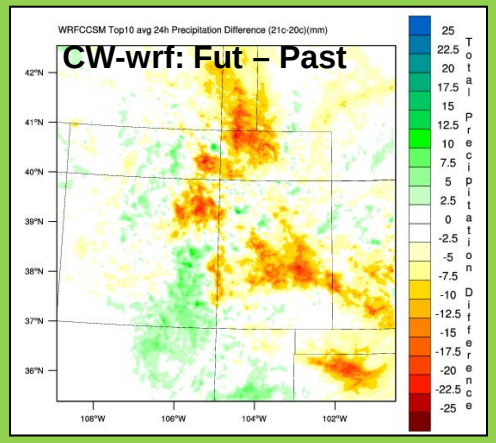


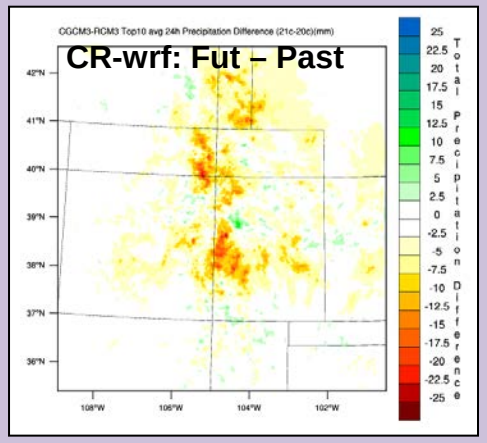




Δ Precip (mm) (Future – Past)







More intense events in Front Range

Less intense events in Front Range

Weak signal in Front Range

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Comparing the numbers

Average of top 10 events:
Maximum 24-h precipitation value

	Past: Average Maximum 24-h precip (mm)	Future: Average Maximum 24-h precip (mm)	% change
NARR	62.7	n/a	n/a
GT-rcm	144	189	**131.3**
CW-rcm	86.7	60.4	**69.7**
CR-rcm	204.7	271.2	**132.5**
GT-wrf	125	207	**165.6**
CW-wrf	101	103	**102.0**
CR-wrf	100.7	80.1	**79.5**

Average of top 10 events:
Domain-average 24-h precipitation value

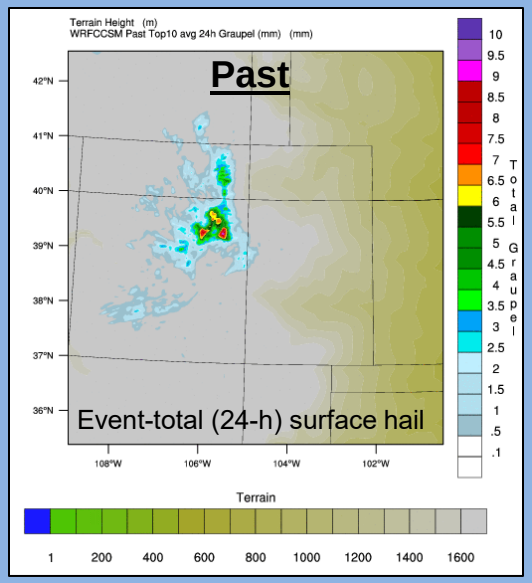
	Past: Average domain-average 24-h precip (mm)	Future: Average domain-average 24-h precip (mm)	% change
NARR	10.4	n/a	n/a
GT-rcm	8.3	11.2	**134.9**
CW-rcm	7.0	5.5	**78.6**
CR-rcm	5.4	6.3	**116.7**
GT-wrf	5.1	9.3	**182.4**
CW-wrf	6.1	4.0	**65.6**
CR-wrf	3.9	2.1	**53.8**

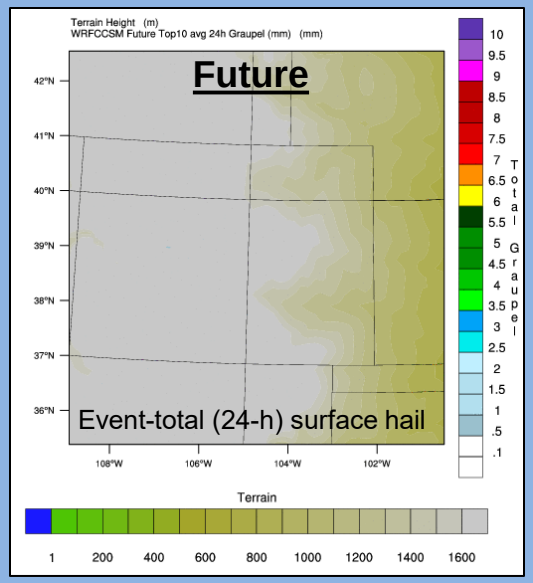
- Strong local maxima increase/persist even in average drying signal
- Averaging of bulk numbers can mask real utility of high-resolution approach (i.e., average numbers don't provide clear consensus on extreme precipitation projections)
- What about other fields, details available from high-resolution framework?

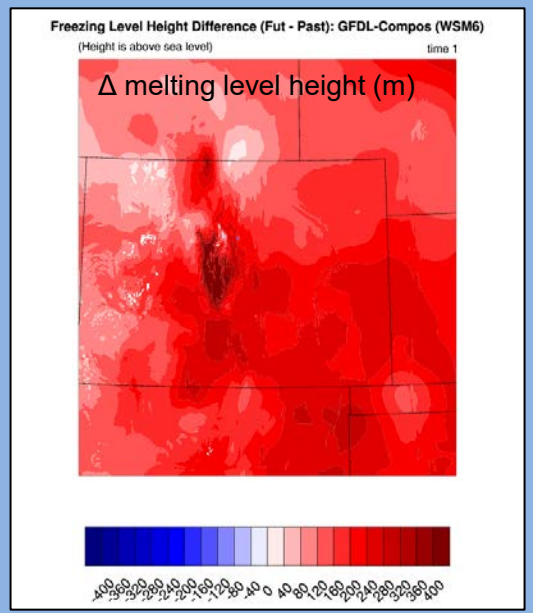
Changes in hail?

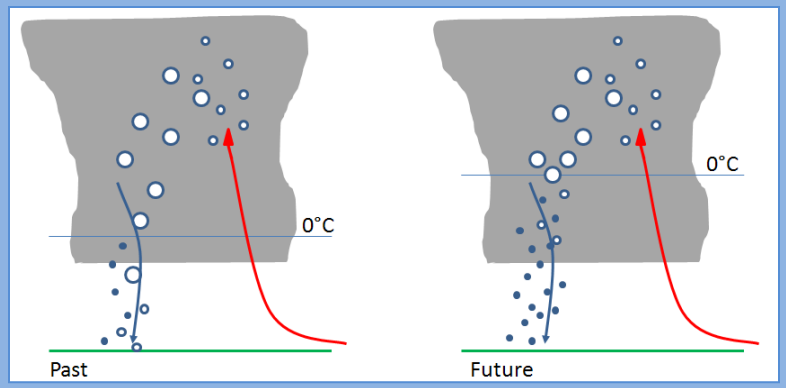
- What happens to surface hail?

Average accumulated surface graupel/hail fields in Top 10 past vs. Top 10 future individual cases







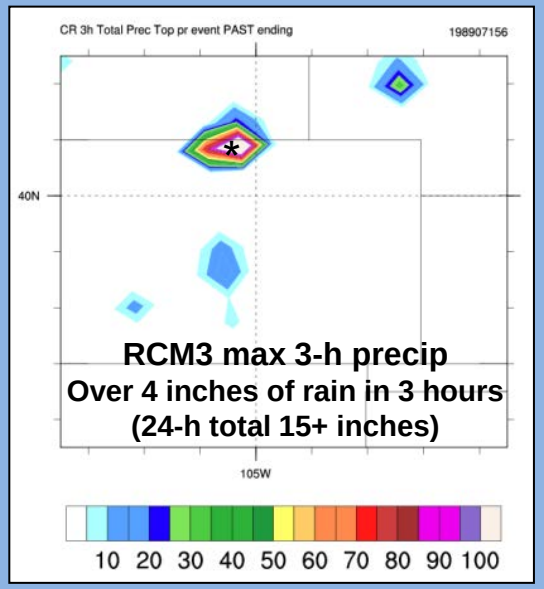


- Height of freezing level increases in future (~400 m difference) → decreases hail found at surface
- Absolute answer is sensitive to model cloud physics parameterization choice and size of hail resolved
- Findings across <u>all</u> simulations show decrease in small hail high-elevation locations

Mahoney, K. M., M. A. Alexander, G. Thompson, J. Barsugli, and J. Scott, 2012: Changes in hail and flood risk in high-resolution simulations over the Colorado Mountains. *Nature Clim. Ch.*, DOI: doi:10.1038/nclimate1344.

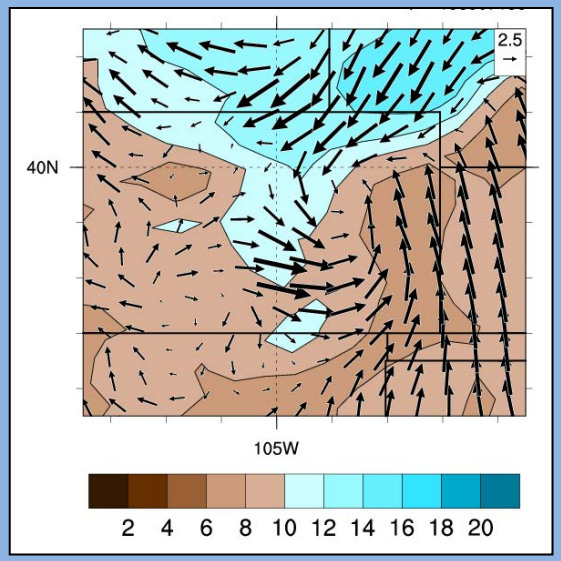
Exposure of RCM errors

(Example of spurious gridpoint storms)

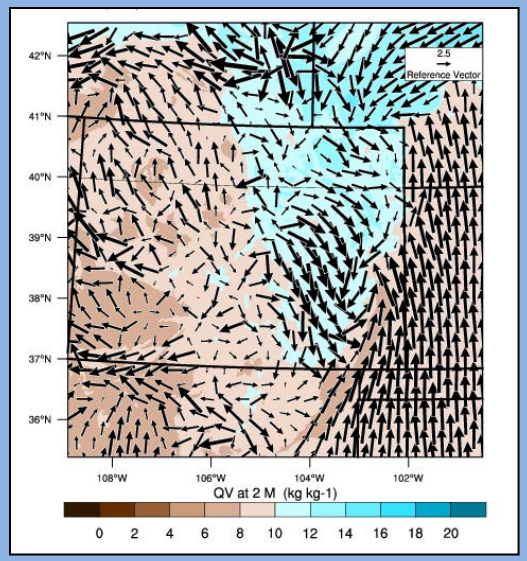


RCM3 max 3-h precip
Over 4 inches of rain in 3 hours
(24-h total 15+ inches)

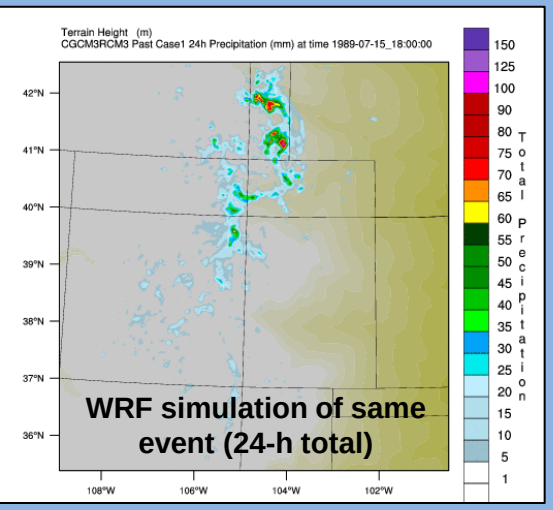
RCM3 2-m humidity and 10-m winds (6Z 7/15)



WRF 2-m humidity and 10-m winds (6Z 7/15)

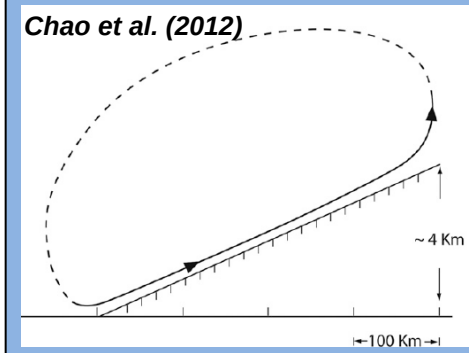


RCM3 has persistent low-level easterly/upslope flow; WRF shifts winds to westerly

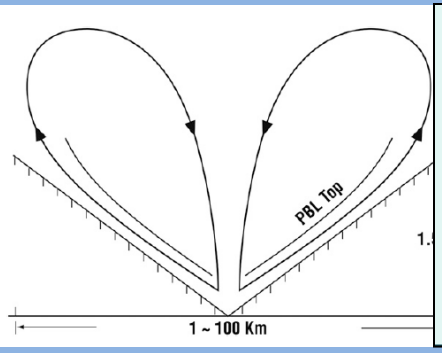


WRF simulation of same event (24-h total)

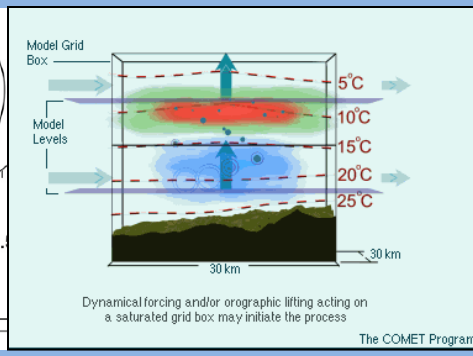
Chao et al. (2012)



What a 50-km RCM resolves in response to surface heating on steep terrain gradient



Motions that should actually happen within a model gridbox (parameterized effects)



Continual orographic lifting of moist gridbox produces convective feedback: unphysical precipitation bullseyes

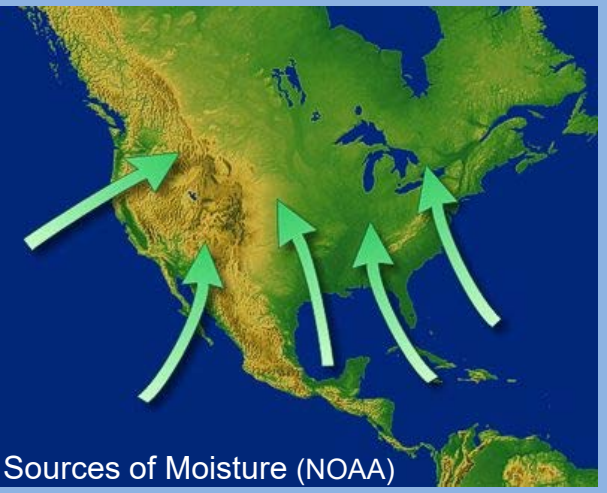
Project approach

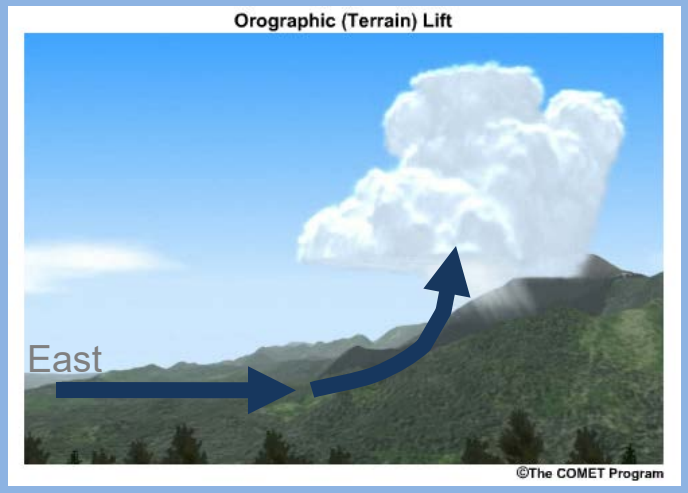
1. Analyze seasonal and extreme precipitation from regional climate model ensemble (NARCCAP)
2. Identify top extreme events in Colorado Front Range from regional models
3. Further downscale all individual events to high-resolution (1.3-km grid spacing); test various model initialization methods
4. **Evaluate signal strength in projected changes in extremes and identify process-based explanations for changes**

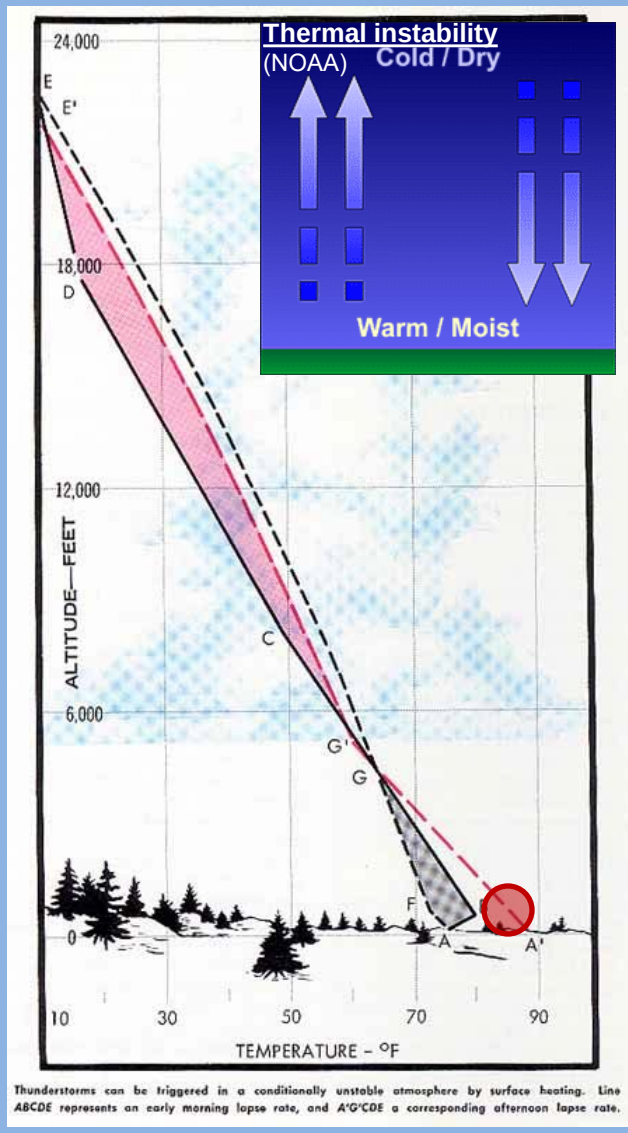
Motivation: Extreme precipitation in the Colorado Front Range

Ingredients for extreme summertime precipitation in Front Range:

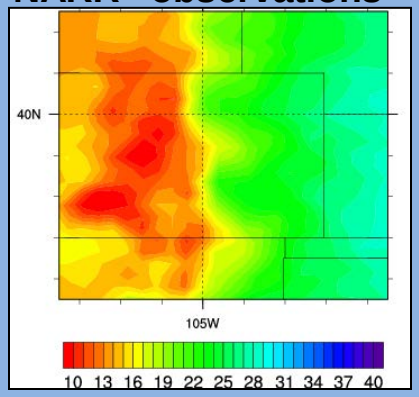
1. **Moisture**
   - Dewpoint > 55°F, precipitable water > 1 inch
2. **Lift**
   - easterly winds
3. **Instability**
   - buoyancy-driven potential energy
   - …or enough forcing to lift air parcels above any stable layers in atmosphere



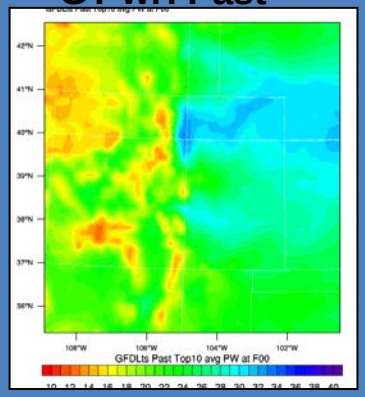




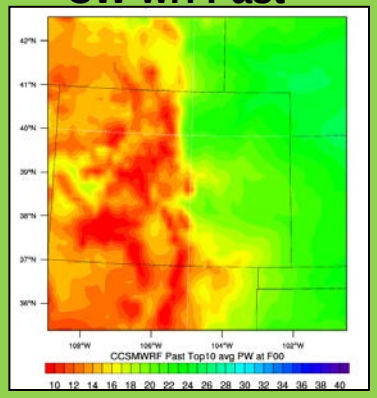
NARR "observations"



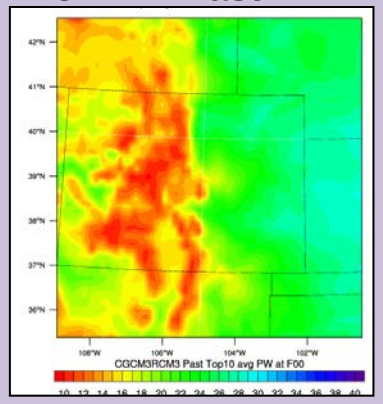
GT-wrf Past



CW-wrf Past



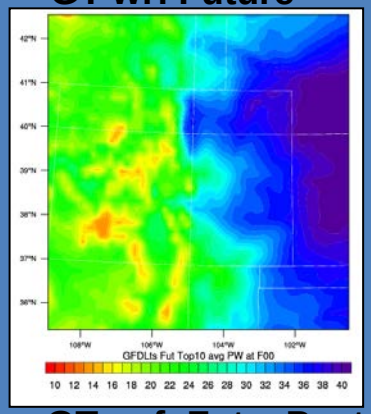
CR-wrf Past



Moisture:

All runs show larger future (column-deep) moisture in the Front Range

GT-wrf Future



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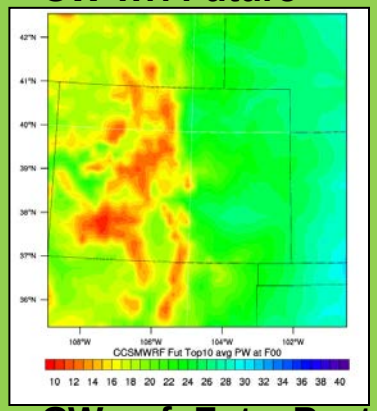
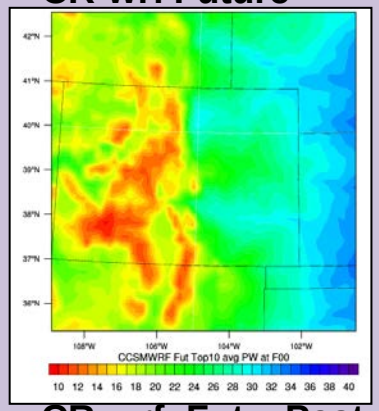
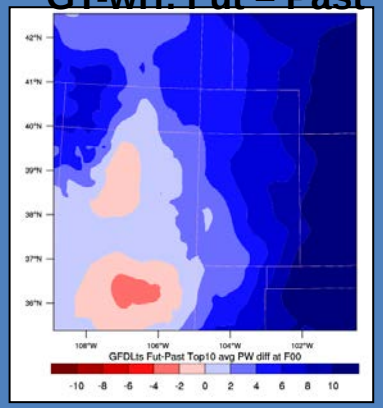


CR-wrf Future



GT-wrf: Fut – Past



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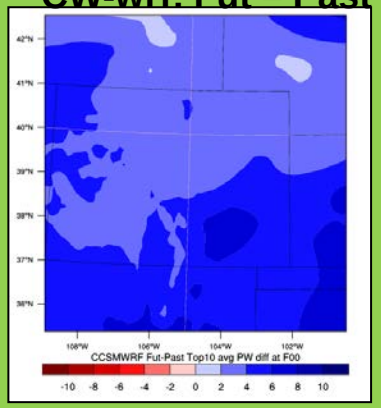

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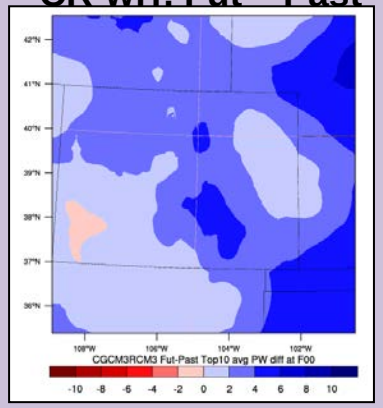

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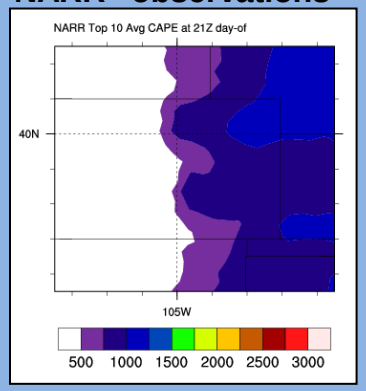
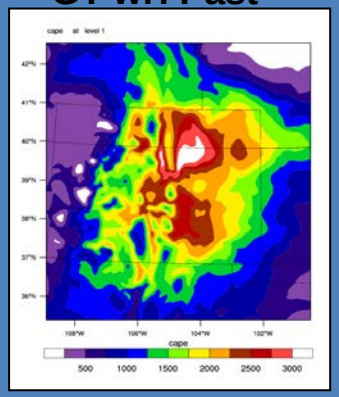
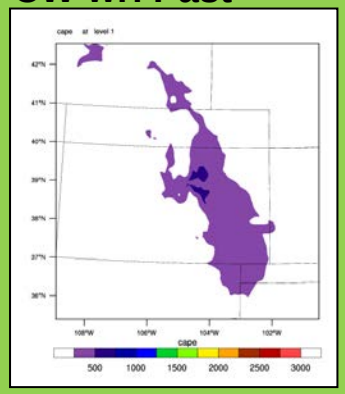
NARR "observations"



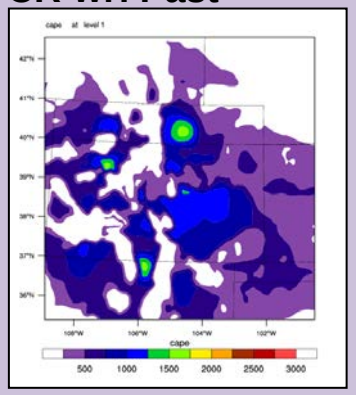
GT-wrf Past



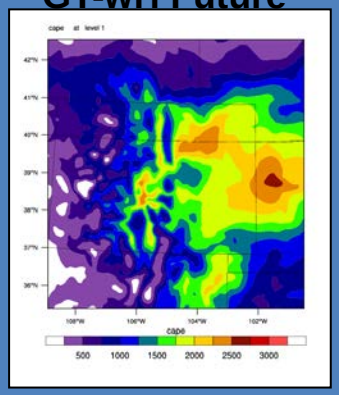
CW-wrf Past



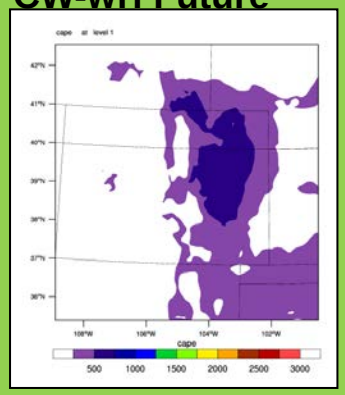
CR-wrf Past



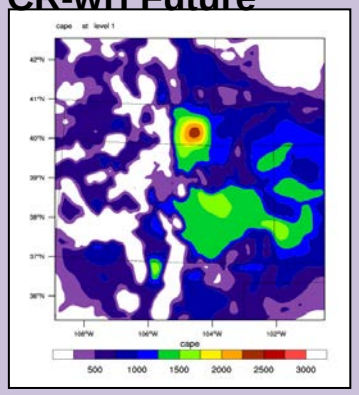
GT-wrf Future



CW-wrf Future



CR-wrf Future



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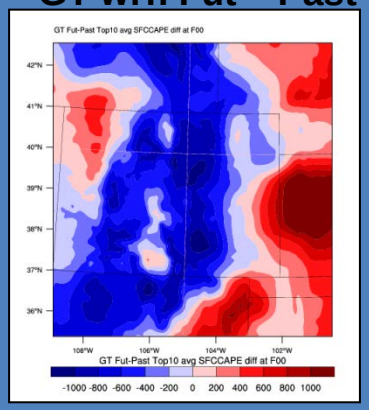

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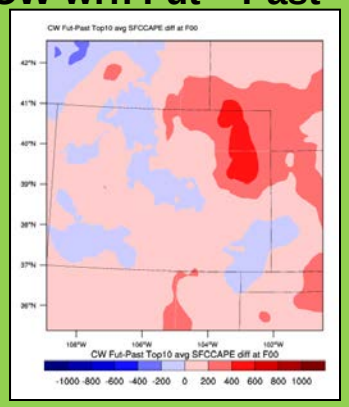

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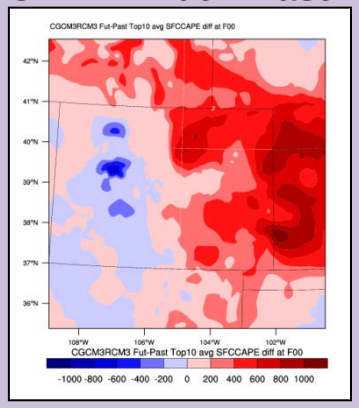

Instability:

CAPE is variable

The model environment with the most CAPE (GT) shows a future *decrease* in CAPE but a future *increase* in precipitation

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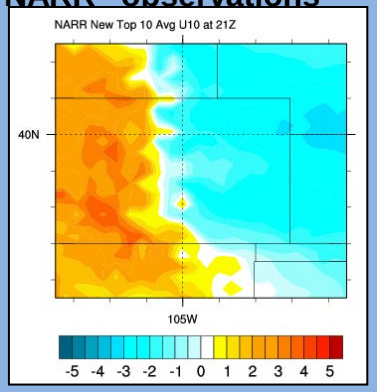
NARR "observations"



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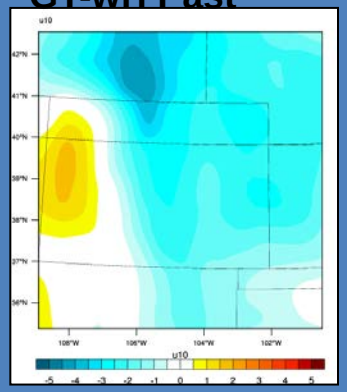

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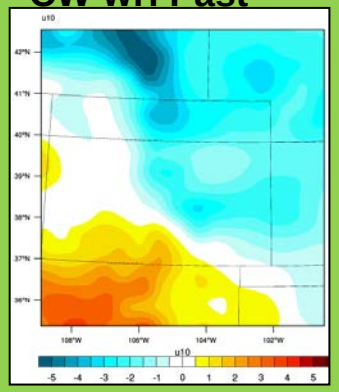

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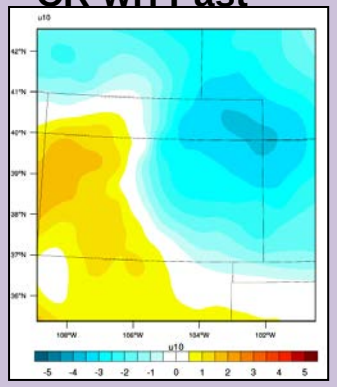
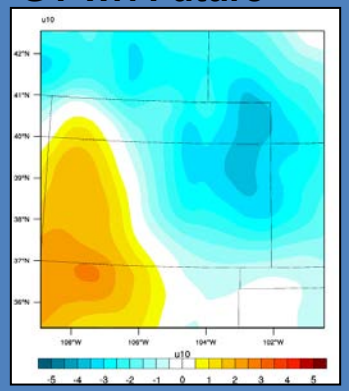


GT-wrf Future



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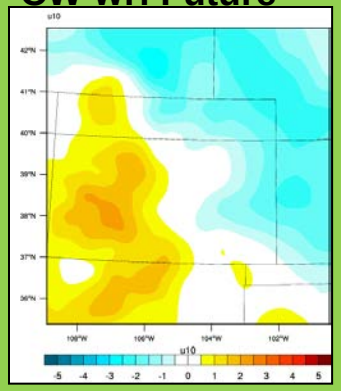

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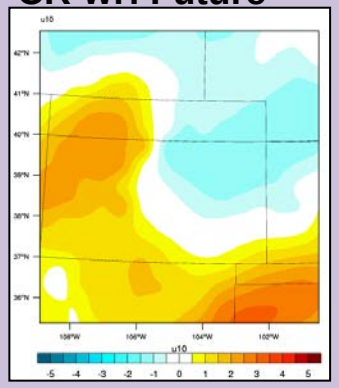

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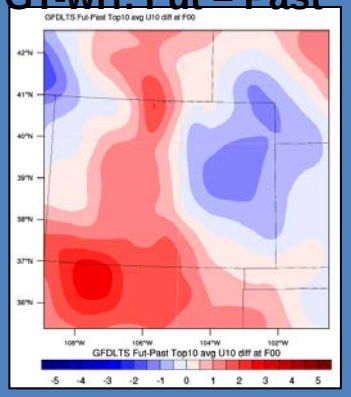

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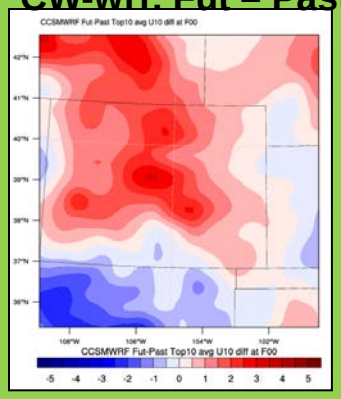

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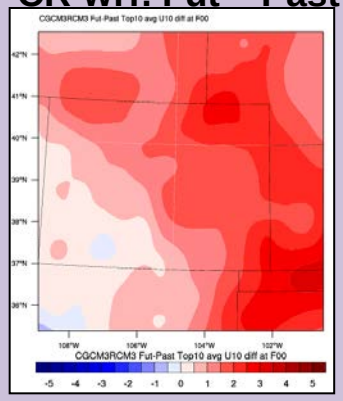

Lift:

A decreasing easterly surface flow trend is seen in the two experiments *not* showing a significant increase in future precipitation

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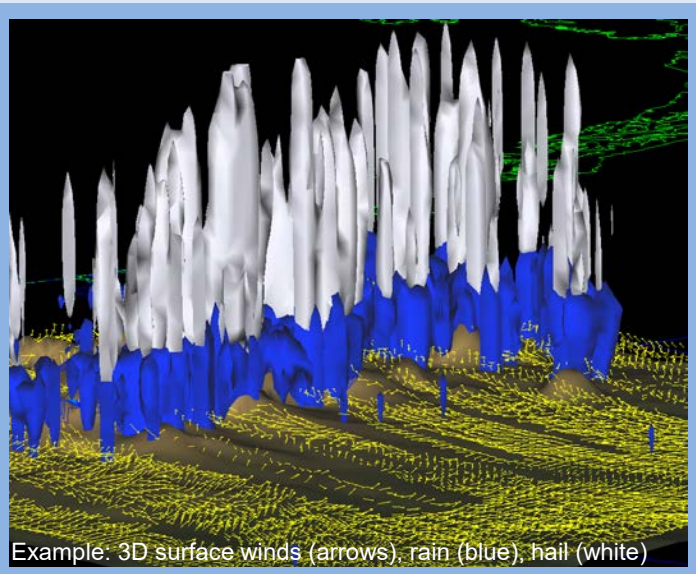
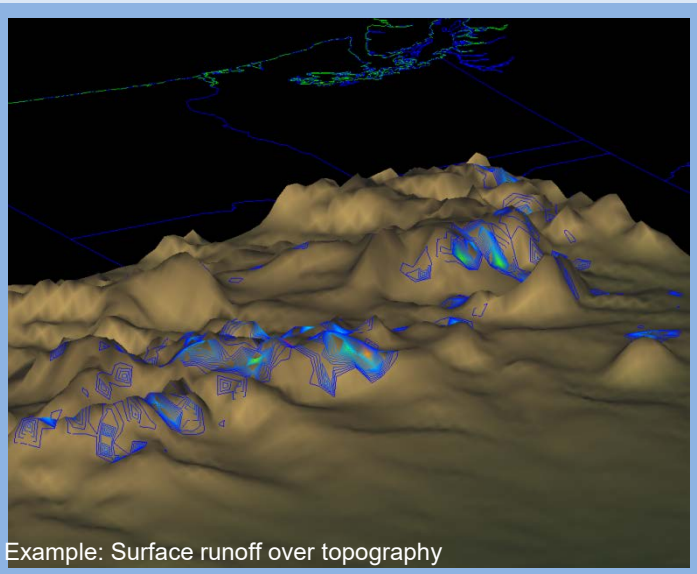
What does it mean?
Where do we go from here?

What does it mean?

- Extreme warm-season precipitation changes in the CO Front Range: remains a complex signal
- Regional models suggest decreased mean warm-season rainfall; extremes less agreement
- High-resolution (storm-scale) downscaling suggests approximately equal chances of extreme events increasing or decreasing overall – but that local maxima will increase or remain large
- The high-resolution framework also provides:
  - **Insight into *how* changes in large-scale climate parameters may affect small-scale storms**
  - **Resolution of multi-scale interactions not well-represented by model parameterizations (e.g., dry air entrainment).**
  - **Advantages over proxy-based approaches (e.g., instances of increased CAPE, moisture, but decreased precipitation)**
  - **Allows for assessment of fields such as hydrometeor concentrations (e.g., hail), cloud-scale motions, and some hydrologic routing information that are not resolved on regional and global scales.**
- These results motivate further questions, specific hypotheses that can be tested
- Method presented does not capture very localized storms that often cause flash flooding (e.g., Ft. Collins 1997). Additional methods to be evaluated toward this goal in year 2.



Example: 3D surface winds (arrows), rain (blue), hail (white)

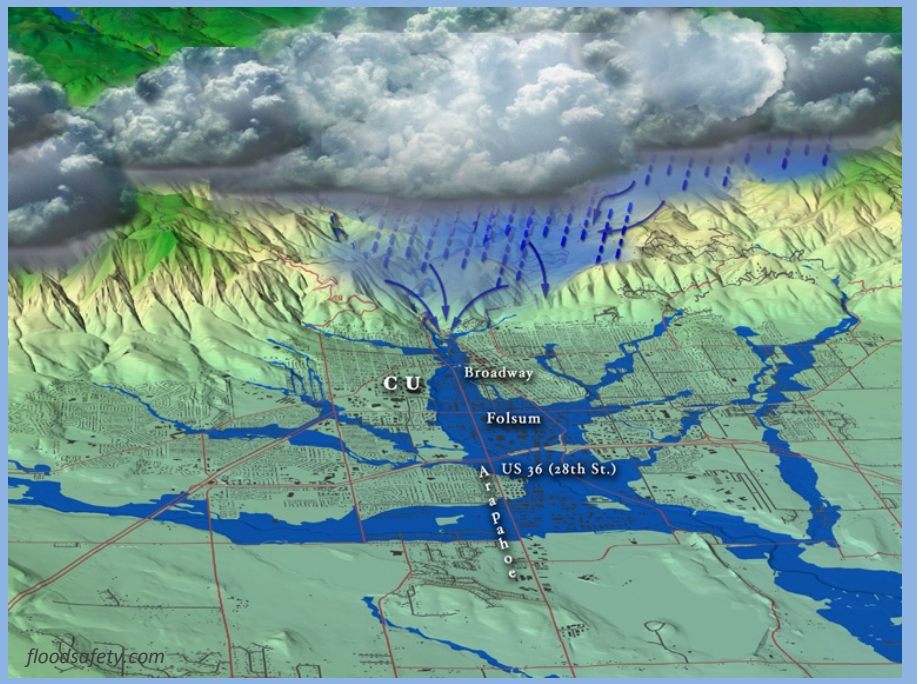


Example: Surface runoff over topography

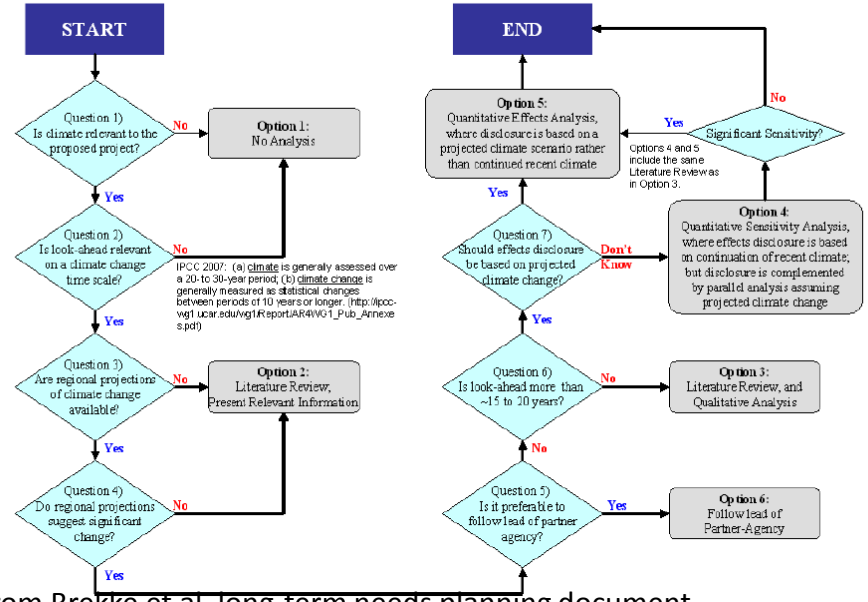
Where do we go from here?

Year 2 tasks and timeline

1. Finalize NARCCAP/RCM Colorado warm-season analysis; submit manuscript (Oct – Dec 2012)
2. Complete analysis on case study collections; submit manuscript (Oct – Dec 2012)
3. Further investigate utility of other high-resolution approaches (composite-based methods, pseudo-global warming approaches applied to specific cases) (Jan – March 2012)
4. Expand Green Mountain Dam site-specific study results (to be discussed at 10:30)
5. **Synthesize findings with USBR needs and interests; determine additional work needed to fit findings within existing decision-making strategies; identify most desirable future directions**



Example of decision tree for guiding incorporation of climate information in longer-term project planning



From Brekke et al. long-term needs planning document

Questions? Discussion?

Contact: Kelly Mahoney

kelly.mahoney@noaa.gov

Extra slides

Mid-term (End of Year 1) progress

Tasks listed in project description

Task 1: Complete high-resolution extreme event simulations begun under PACE post-doctoral study; address additional climate change scenarios and quantify uncertainty information

Task 2: Compare three different dynamical downscaling methods to identify strengths and weaknesses of each

Task 3: Compare findings to regional, global models, statistical downscaling using extreme value theory

Task 4: Green Mountain extension proof-of-concept

Task 5: Broader elevation dependency questions

Task 6: Focused education and outreach efforts within wider USBR community

Progress/Accomplishments

→ Manuscript draft completed (in internal review) on high-resolution, event-based downscaling of Front Range extreme precip

→ Manuscript in development on RCM/NARCCAP handling of Colorado warm-season precipitation

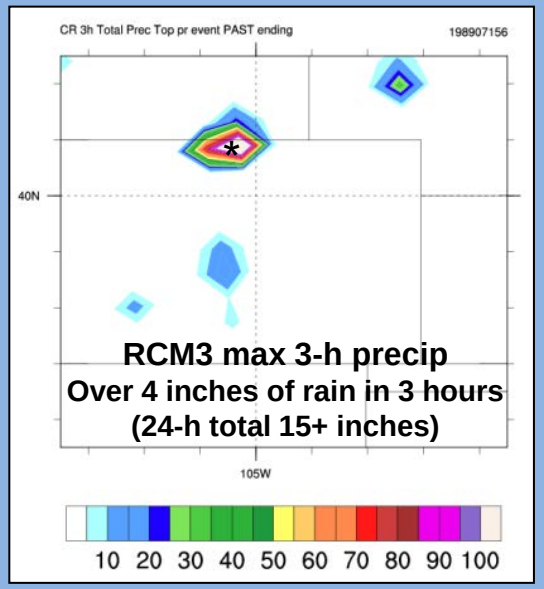
→ Publication on hail decrease in *Nature Climate Change*, Jan 2012.

→ Green Mountain Dam Case Study report submitted to Dam Safety office

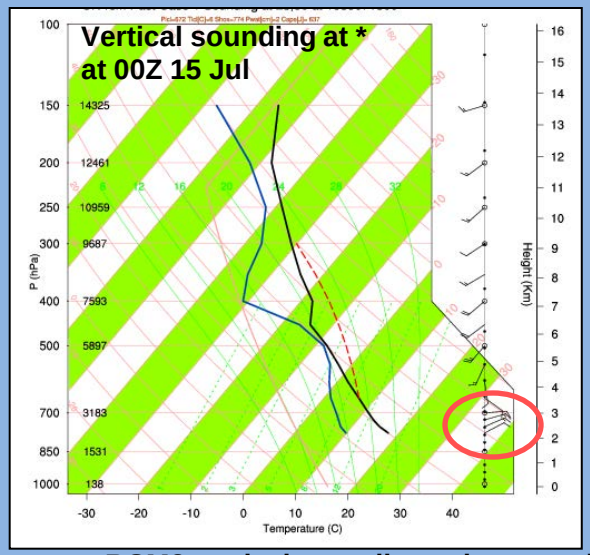
→ Project has been presented at AGU and AMS annual meetings, the 2012 Weather and Forecasting/Numerical Weather prediction meeting, and as an invited seminar at the Center for Science and Technology Policy Research at CU-Boulder.

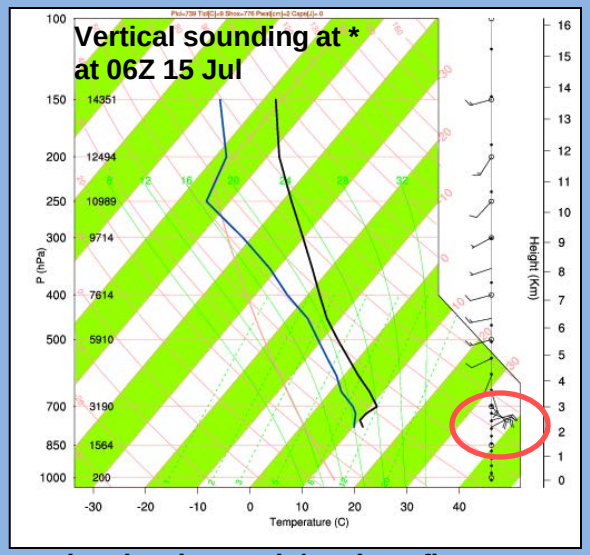
Exposure of RCM errors

(Example of spurious gridpoint storms)

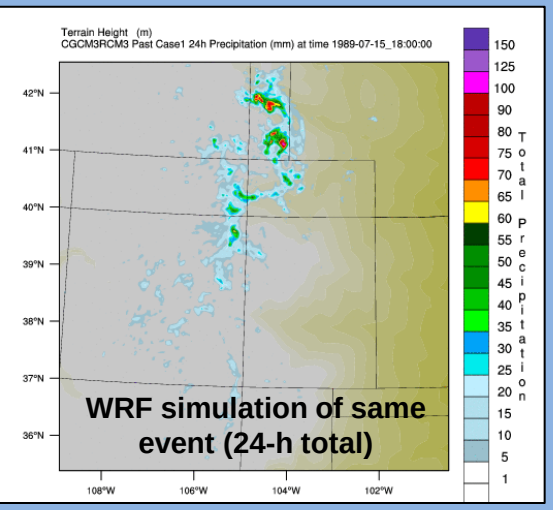


RCM3 max 3-h precip
Over 4 inches of rain in 3 hours
(24-h total 15+ inches)

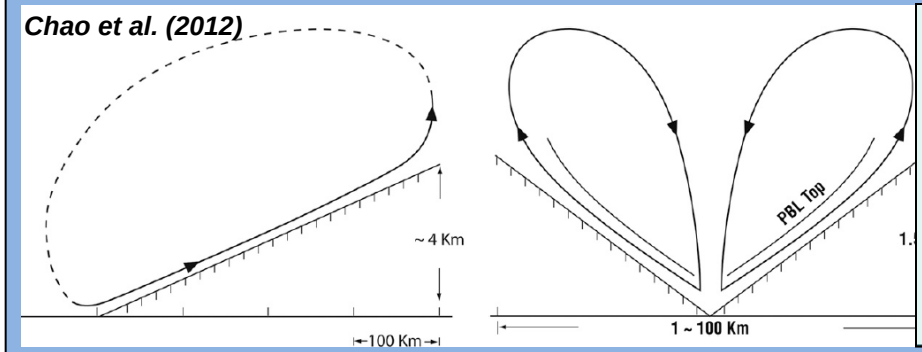




RCM3 vertical soundings show persistent low-level easterly/upslope flow
(WRF quickly shifts winds to westerly)

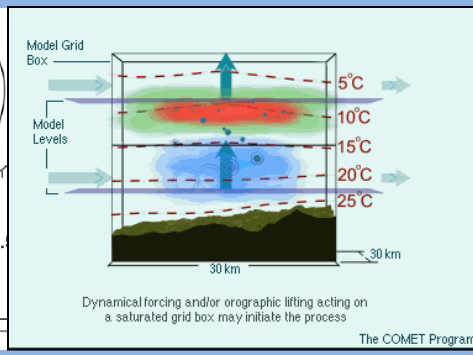


WRF simulation of same event (24-h total)



What a 50-km RCM resolves in response to surface heating on steep terrain gradient

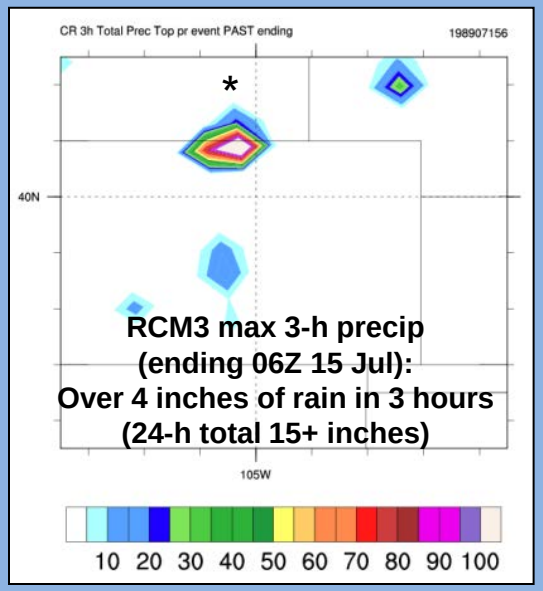
Motions that should actually happen within a model gridbox (parameterized effects)



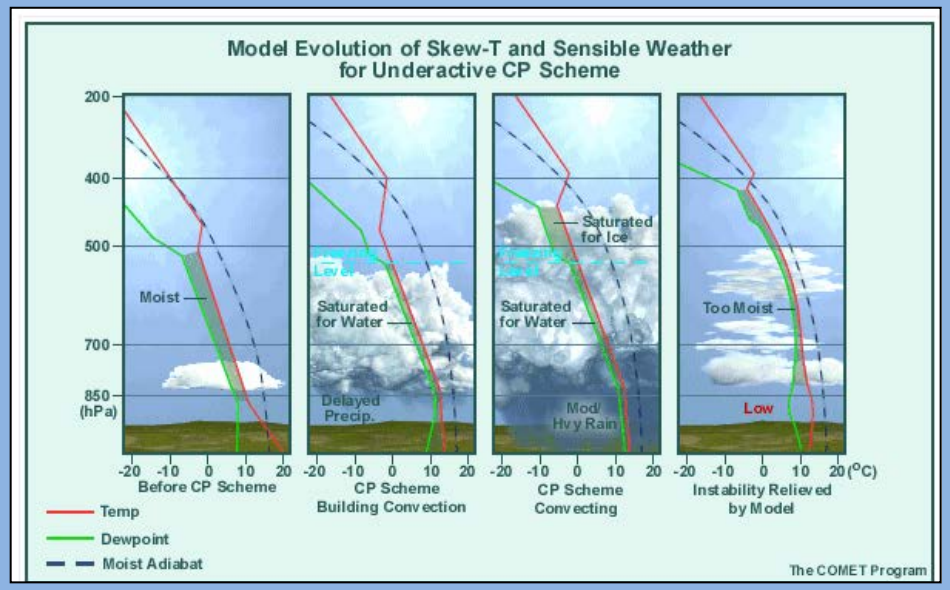
Continual orographic lifting of moist gridbox produces convective feedback: unphysical precipitation bullseyes

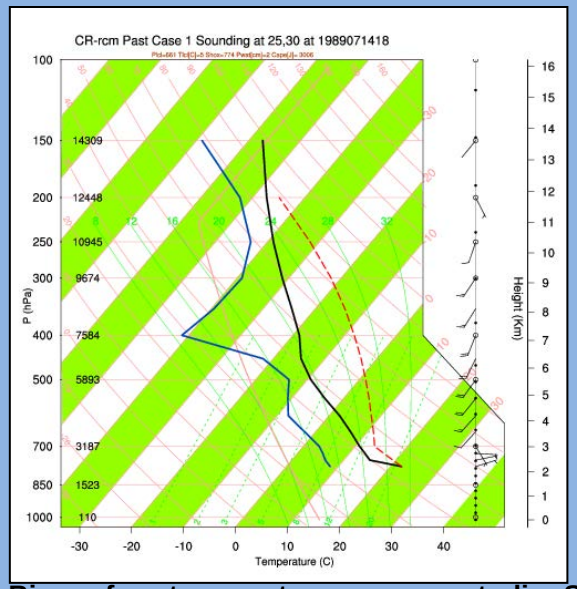
Exposure of RCM errors

(Example of spurious gridpoint storms)

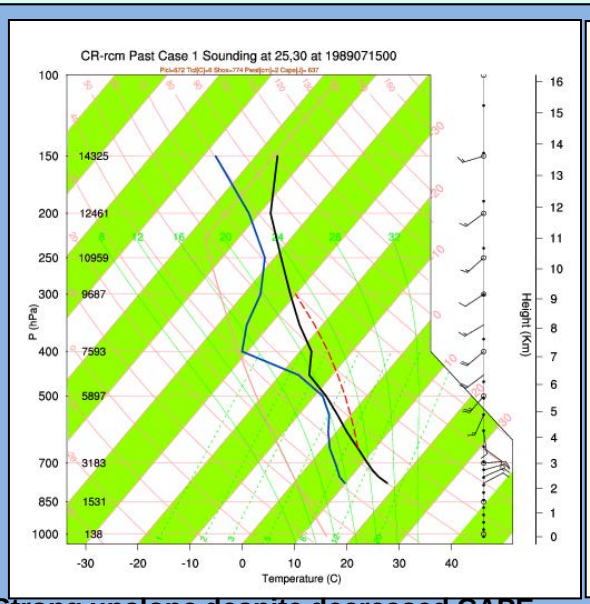


RCM3 max 3-h precip (ending 06Z 15 Jul): Over 4 inches of rain in 3 hours (24-h total 15+ inches)

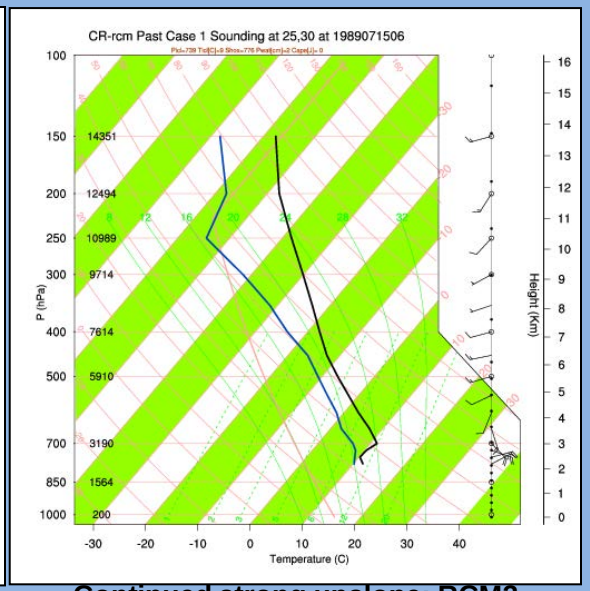




Big surface temperature surge, easterlies set up: RCM3 sounding at * at 18Z 14 Jul)



Strong upslope despite decreased CAPE RCM3 sounding at * at 00Z 15 Jul)



Continued strong upslope: RCM3 sounding at * at 06Z 15 Jul)