Dynamical downscaling in Southwest U.S.: extreme weather study at convection-permitting scale

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THE UNIVERSITY OF ARIZONA

ATMOSPHERIC SCIENCES

UASCIENCE

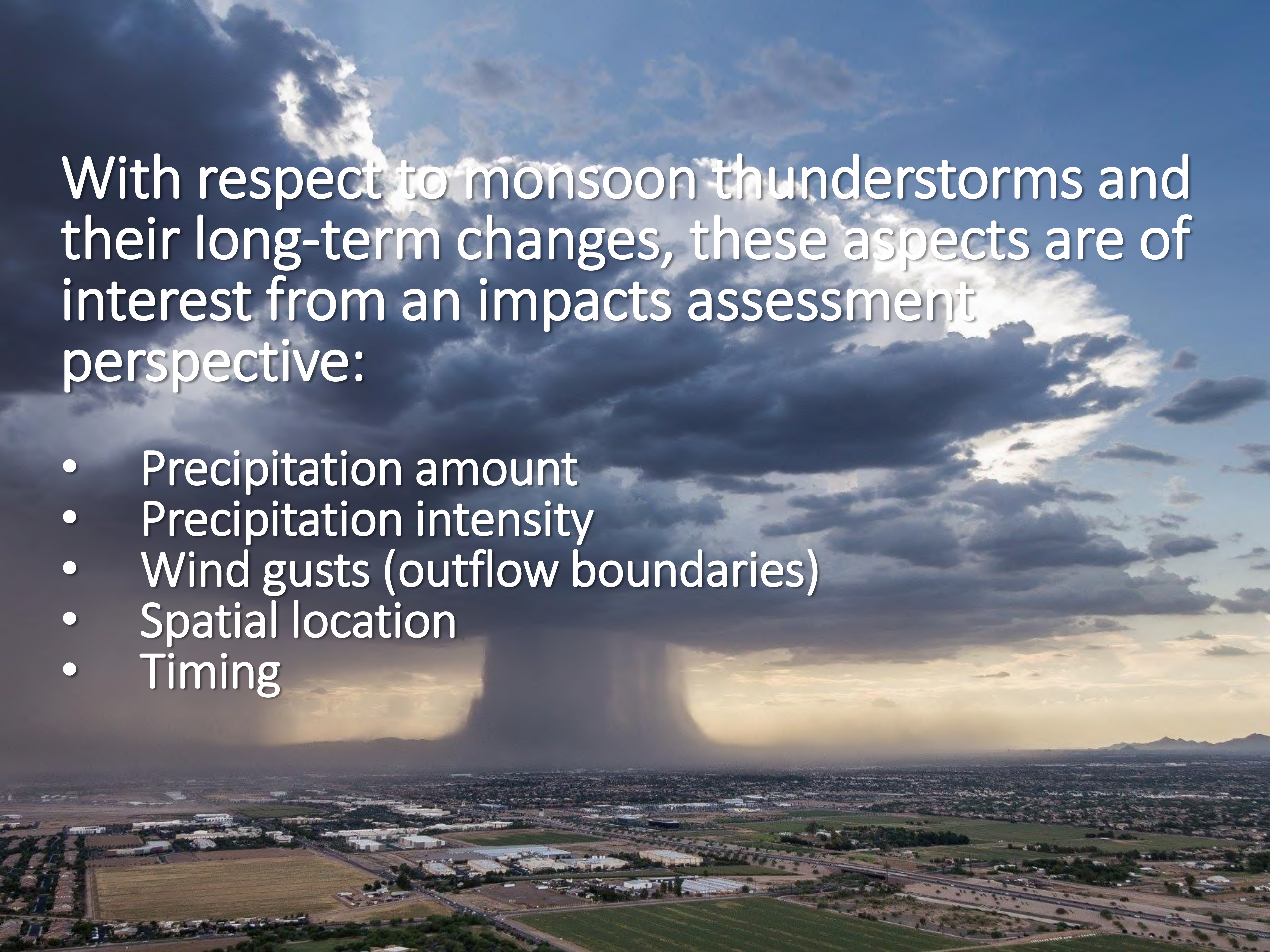
Typical extreme weather events in Southwest U.S. – related to North American monsoon

Monsoon Thunderstorms in Arizona

- Forced by the diurnal mountain valley circulation
- Form over the mountains during late morning to early afternoon
- Reach mature stage by about mid-afternoon.

(*Photo taken around 3pm)*

How are these monsoon related dangers in weather and climate time scale going to change in association with anthropogenic climate change?

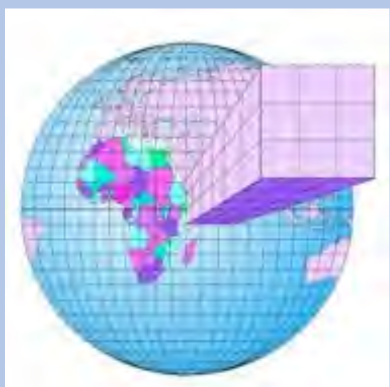


With respect to monsoon thunderstorms and their long-term changes, these aspects are of interest from an impacts assessment perspective:

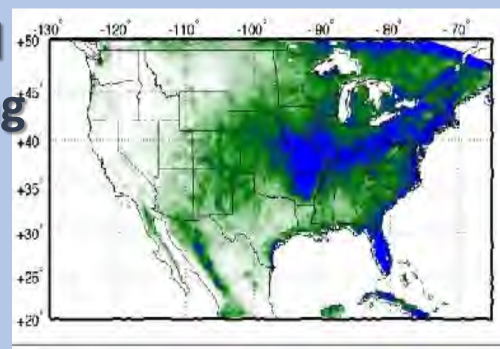
- Precipitation amount
- Precipitation intensity
- Wind gusts (outflow boundaries)
- Spatial location
- Timing

Physics-based fine resolution climate data:

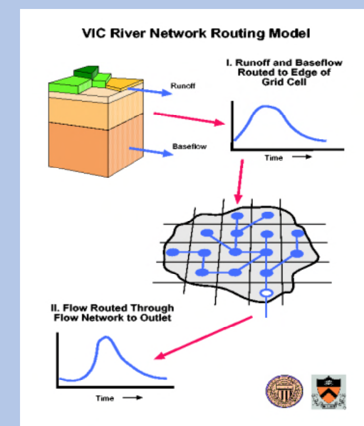
Translating IPCC climate signals to regional and local scale climate products



Dynamical downscaling



Bias correction



Global IPCC climate projections (1-2°)

Regional climate simulations (25 km to 3 km)

Basin-scale simulations

Statistical Downscaling

REPORT TYPE (ALL CAPS)

USE OF CLIMATE INFORMATION FOR DECISION-MAKING AND IMPACTS RESEARCH: STATE OF OUR UNDERSTANDING

SERDP Project RC-2242

MARCH 2016

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SERDP
DOD • EPA • DOE

One of the most debated tables by the authors in writing of the U.S. Department of Defense report…

Green: good
Yellow: maybe
Red: bad

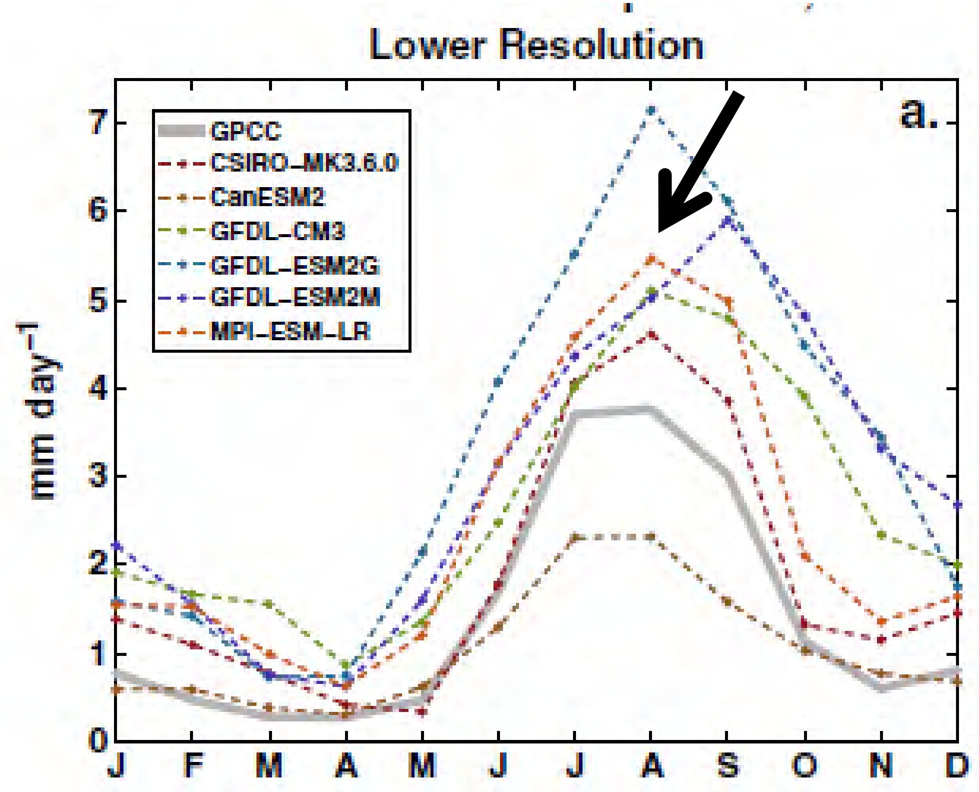
TABLE 4 Recommendation Table on the Use of Climate Datasets based on Regional Features[a]

Scale		Statistical Downscaling Methods					Dynamic Downscaling		GCM
	Delta Correction	Empirical Quantile Mapping	Bias correction	Parametric Quantile Mapping	Constructed Analogues	Wx generator	NARCCAP, CORDEX	Convective-permitting	CMIP5
Global scale: ~3,000 km or more, weeks to months (general circulation structure, jet stream position)	Green	Green	Green	Green	Green	Green	Green	Green	Green
Synoptic scale: 100–3,000 km, days to weeks (highs and lows, midlatitude cyclones, monsoons, atmospheric teleconnections)	Green	Green	Green	Green	Green	Green	Green	Green	Green
Course mesoscale-α, β: 10–100 km, hours to days (katabatic winds, weather fronts, mesoscale convective systems, tropical cyclones, sea breeze circulations)	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Yellow	Green	Yellow
Fine mesoscale-γ: 1–10 km, hours to minutes (supercell thunderstorms, tornadoes, gust fronts, air mass thunderstorms, mountain-valley winds, mountain snowfall)	Red	Red	Red	Red	Red	Red	Yellow	Green	Red

Spatial and temporal resolution suited for basin-scale hydroclimate studies

Not all GCM tells the same story

Southwest/Mexico precipitation (1980-1999)

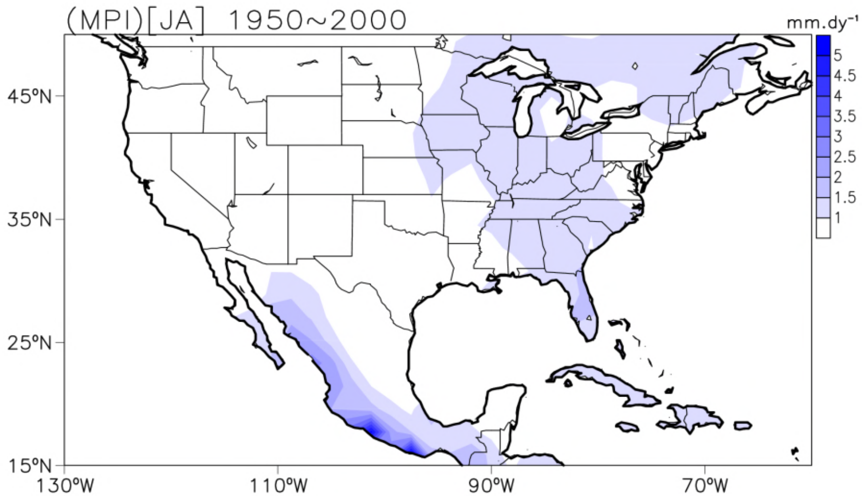


CPM-type simulation uses GCMs that has good historic climate results for the Southwest and Mexico

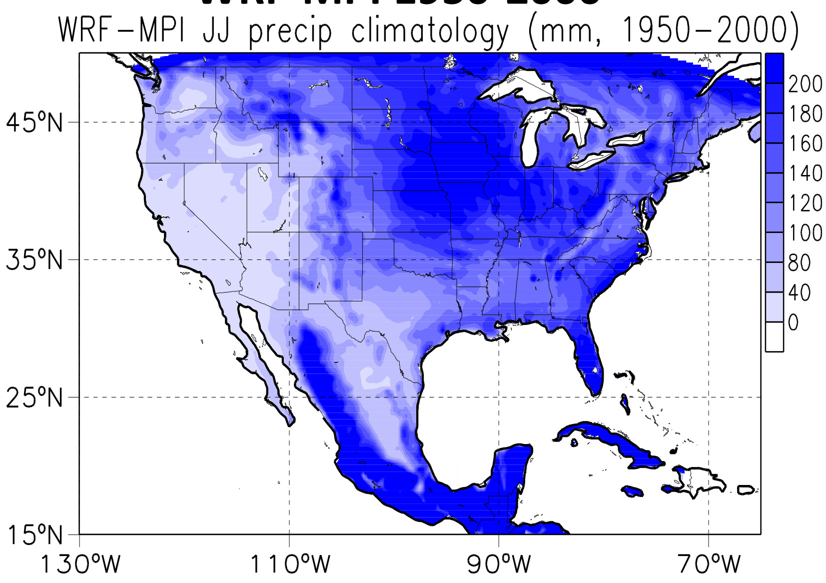
Cook and Seager (2013, *J. Geophys. Res.*)

RCM Dynamic Downscaling Motivation

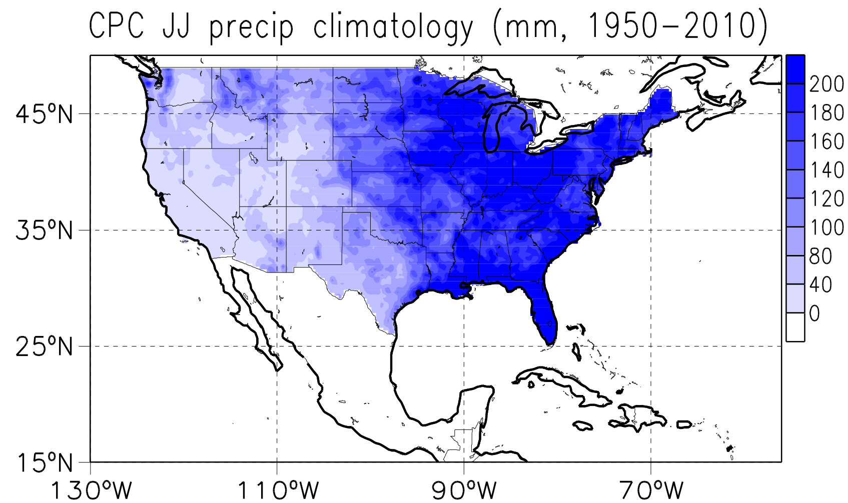
MPI 1950-2000



WRF-MPI 1950-2000



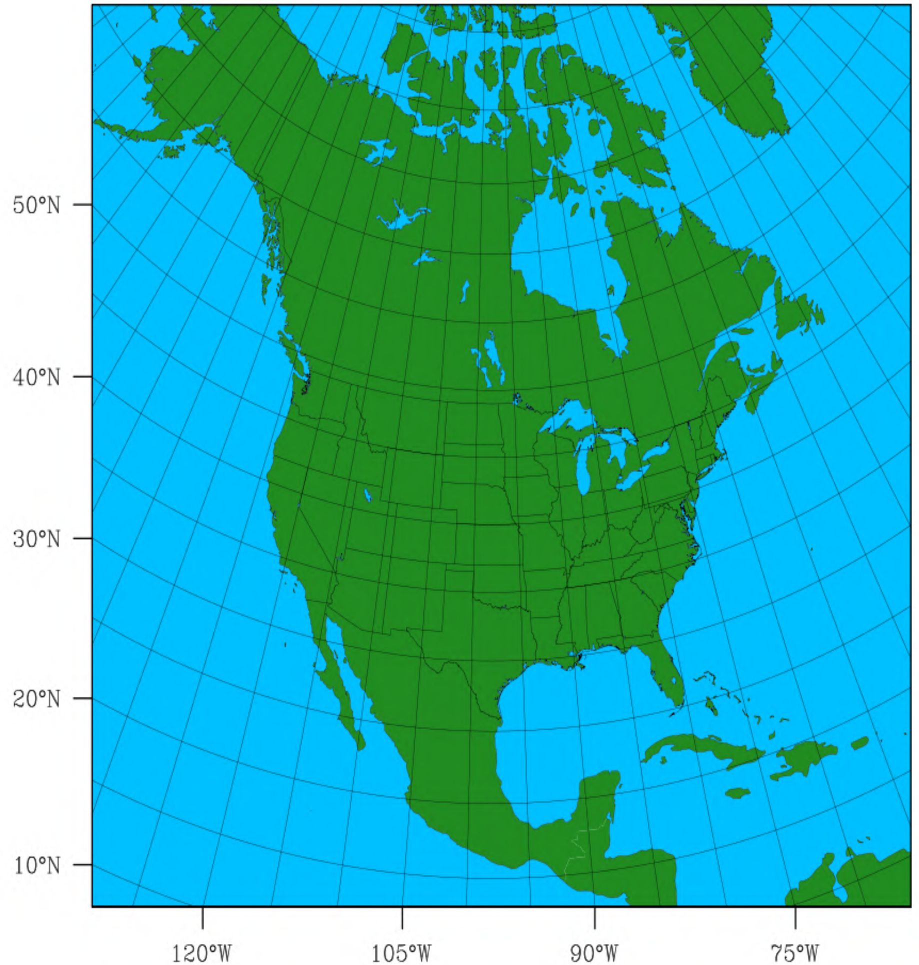
Obs: CPC 1950-2010



RCM simulations have good representation in SW summer monsoon precipitation that are not well-represented in the GCM.

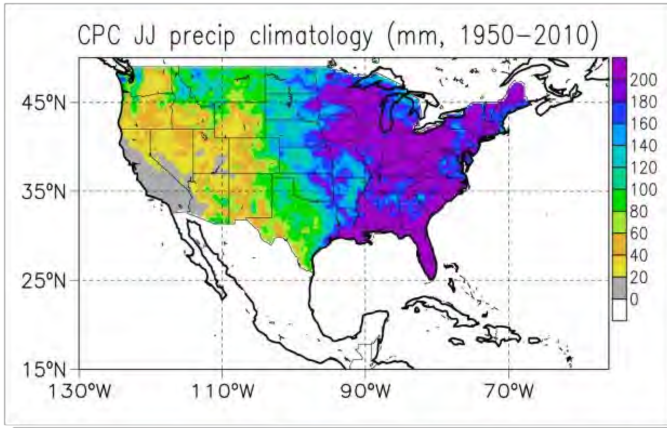
RCM simulaitons:
WRF Dynamical Downscaling using IPCC climate projection data

- Dynamical downscaling with spectral nudging
- Weather Research and Forecasting model (WRF)
- IPCC CMIP3 data: MPI-ECHAM5, HadCM3
  - North American Regional Climate Change Assessment Program
  - NARCCAP domain (CONUS U.S. and Mexico)
- IPCC CMIP5 data: MPI-ECHAM6, HadGEM2
  - North American Coordinated Regional Climate Downscaling Experiment
  - Extended NA CORDEX domain (CONUS U.S., Mexico and Canada)
- Time period: >100 year

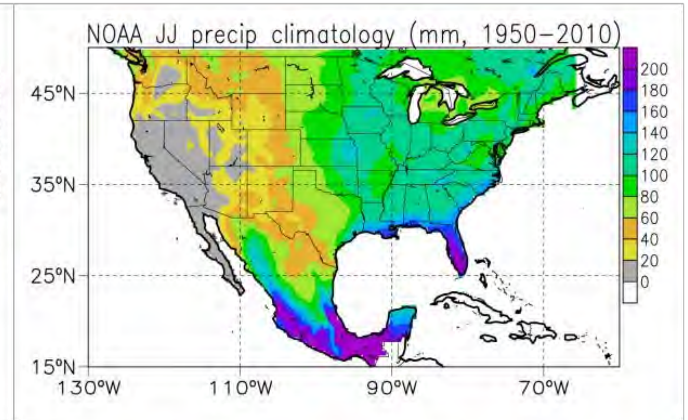


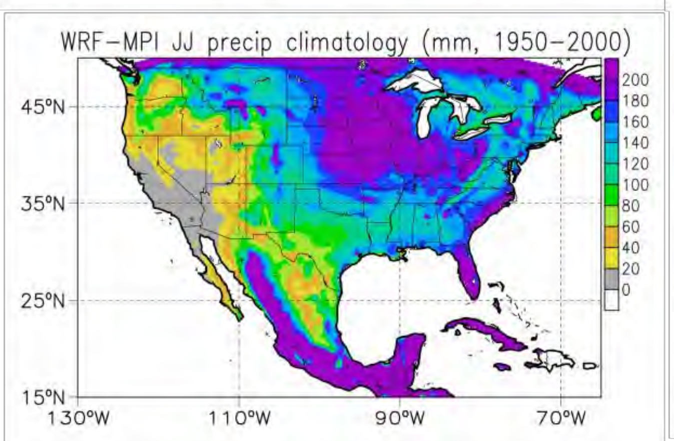
Precipitation June/July Climatology: Observations vs WRF-CMIP3

Climate Prediction Center

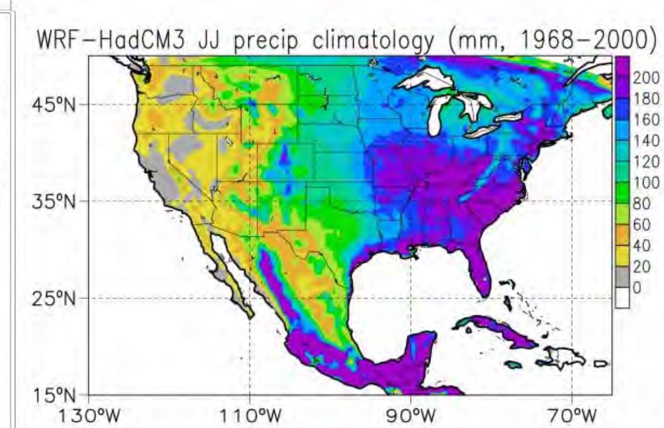


NOAA





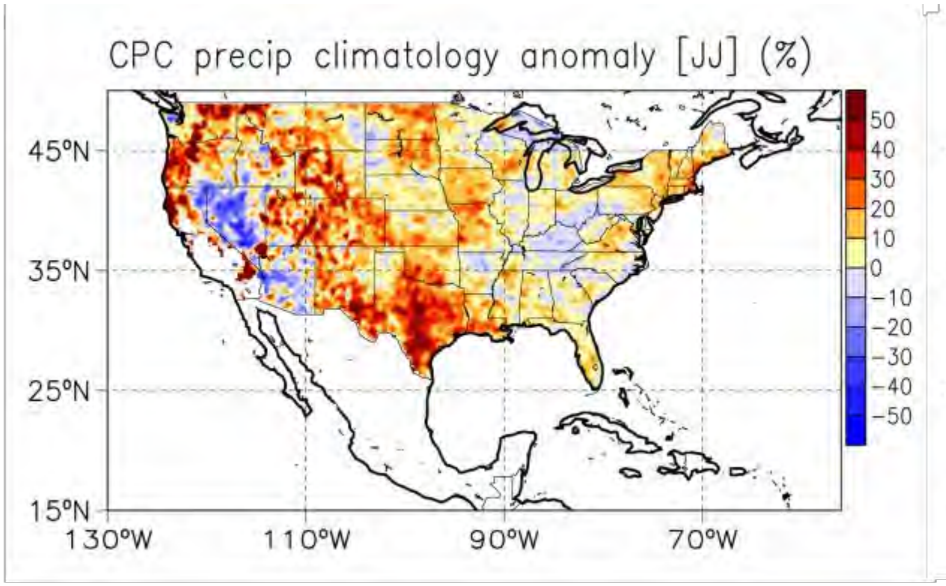
WRF-MPI

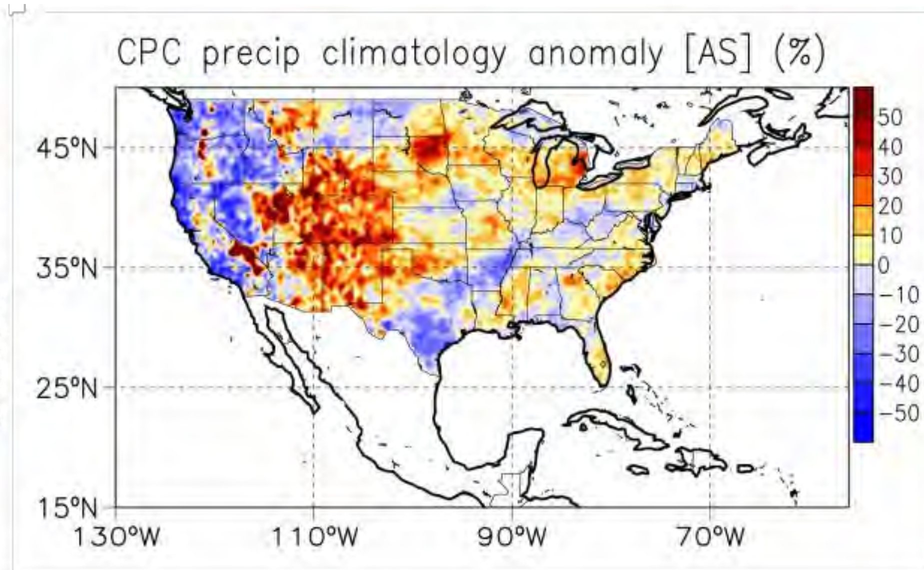


WRF-HadCM3

Observation climatology:
Trend of extreme precipitation is following the mean precipitation

Observed mean precipitation anomaly
([1981-2010]-[1950-1980] in percentage change)



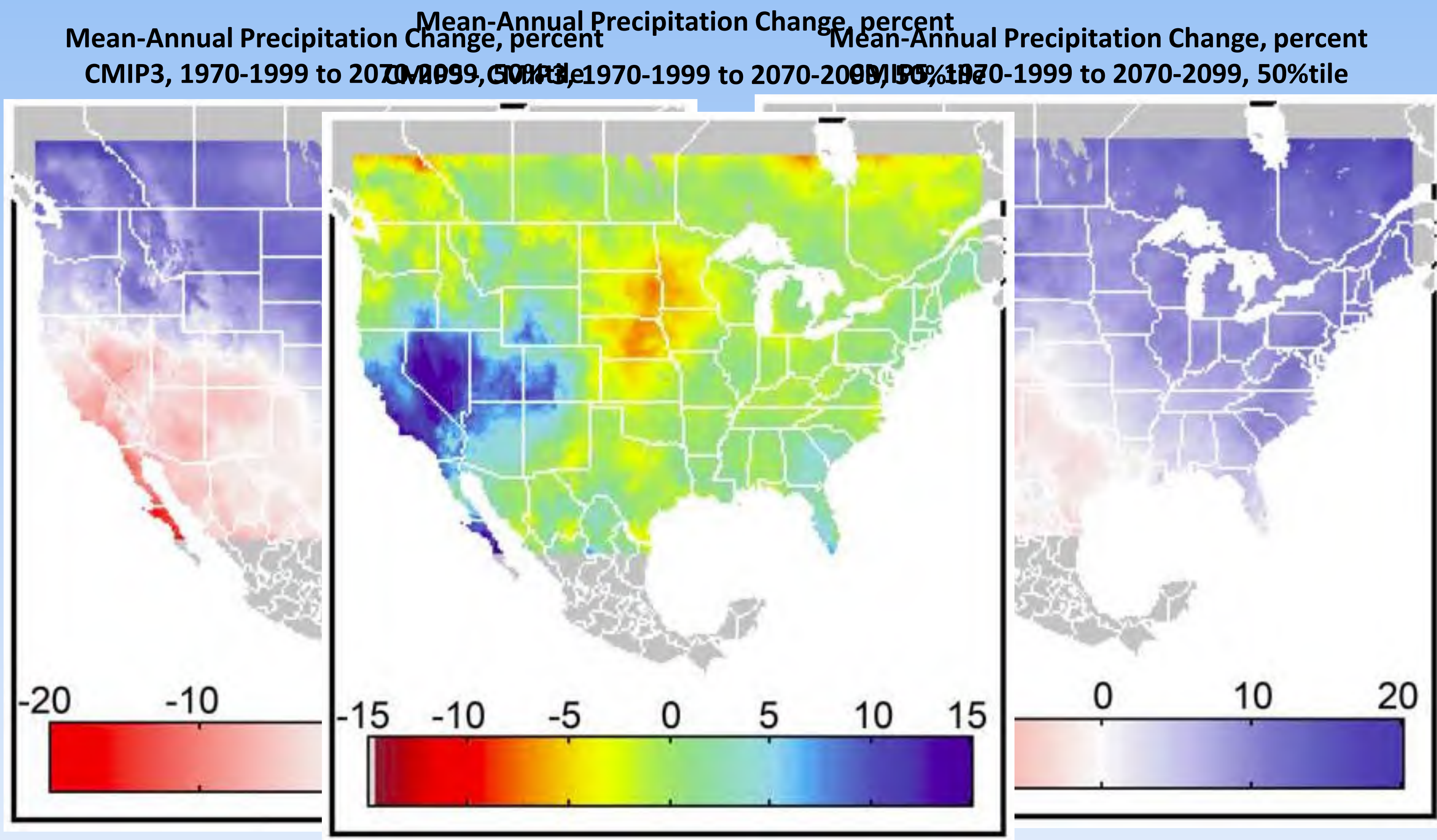


Early summer: Precipitation is climatologically higher over Central U.S. with drier Southwest

Late summer: Precipitation maxima move westward towards Western U.S.

(Chang et al. 2015)

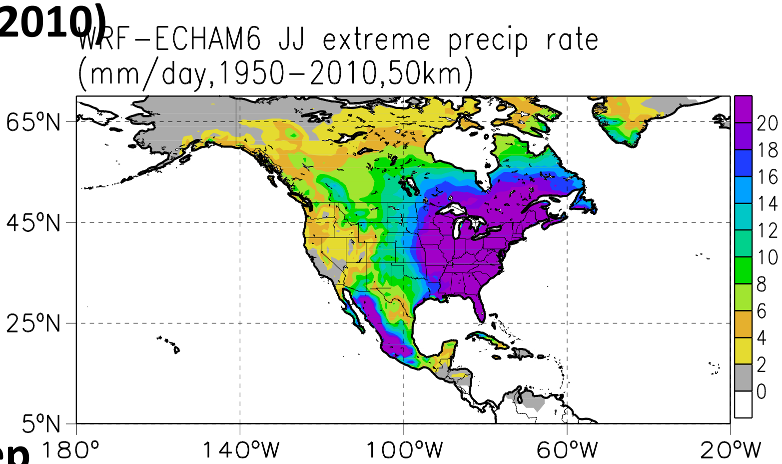
IPCC CMIP3 vs CMIP5 projections for the Southwest



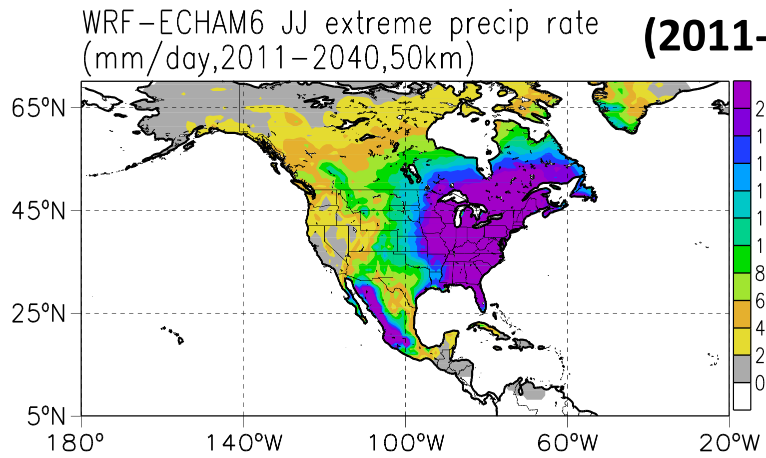
Projected Southwest drying trend is not as dire in AR5

Extreme precipitation rate: June/July vs Aug/Sep (WRF-CMIP5)

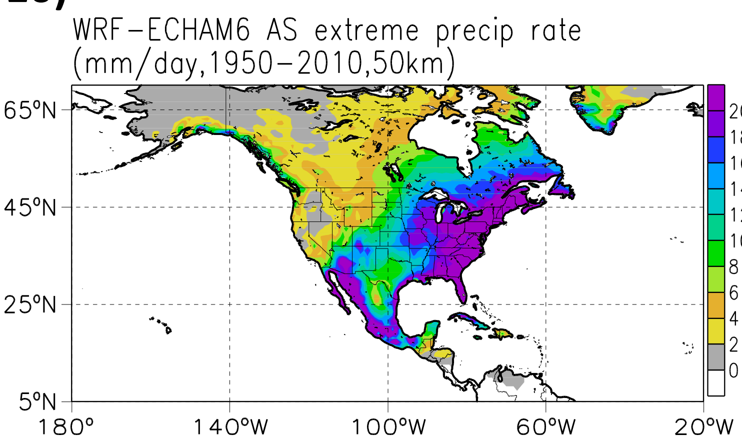
June/July
(1950-2010)



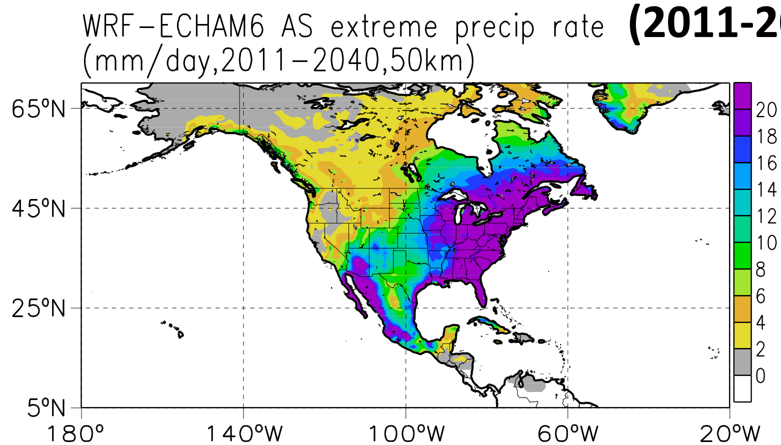
June/July
(2011-2040)



Aug/Sep
(1950-2010)



Aug/Sep
(2011-2040)



Mean and extreme precipitation difference: June/July vs Aug/Sep (WRF-CMIP5)

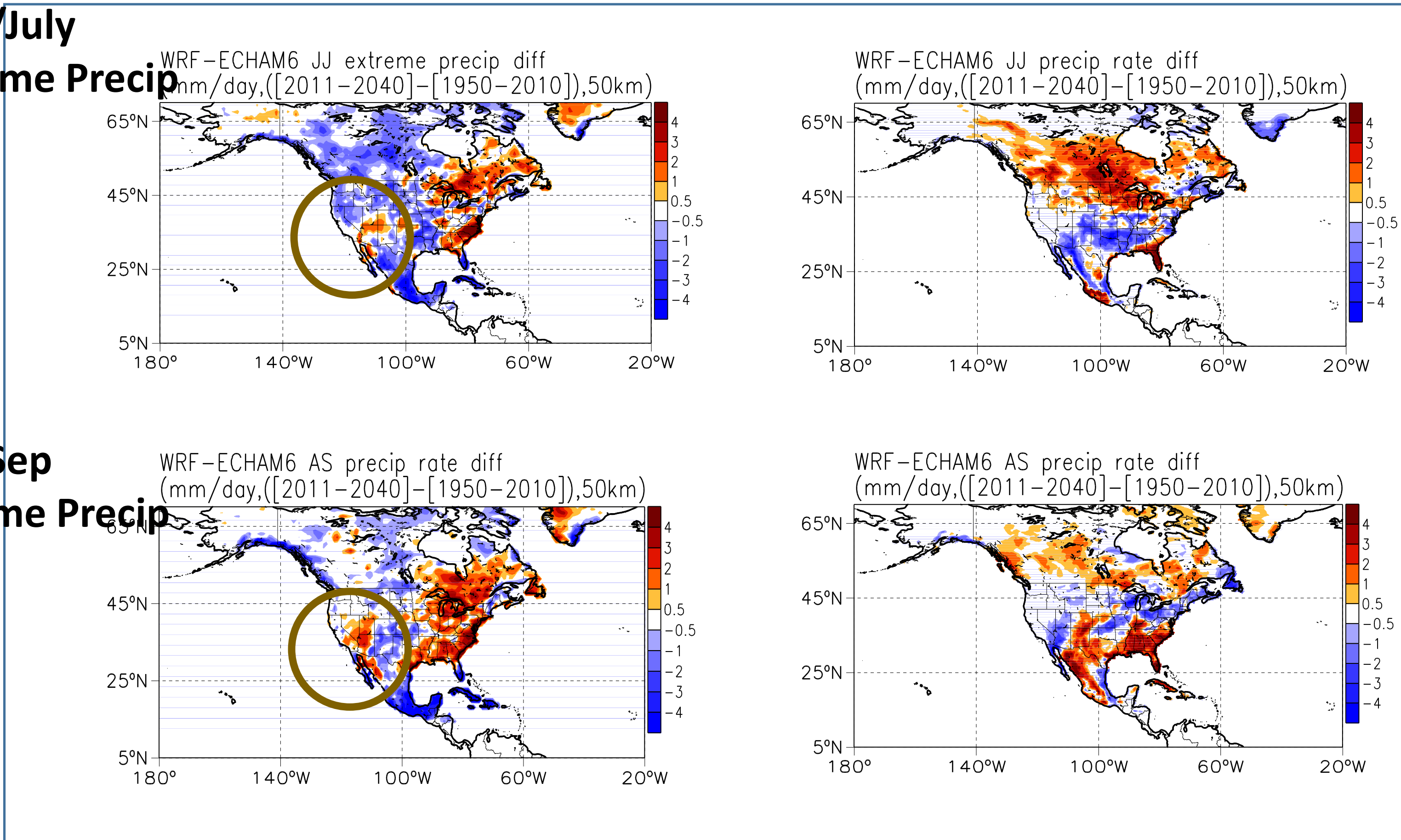
Trend of future extreme precipitation does not follow the mean precipitation ([2011-2040]-[1950-2010], mm/mo). <u>The pattern is similar to our convection-permitting scale simulation. Resolution matter!</u>

June/July Extreme Precip

June/July Mean Precip

Aug/Sep Extreme Precip

Aug/Sep Mean Precip



Climate extreme analysis:
Considering natural variability signal

Hypothesis: Increases in warm season precipitation and temperature extremes will be enhanced by natural variability.

Dry Gets Drier and Wet Gets Wetter

Trend in Global Monsoon Precipitation:

- **Wang et al. 2012: "….. enhanced global summer monsoon not only amplifies the annual cycle of tropical climate but also promotes directly a ''wet – gets – wetter'' trend pattern and indirectly a ''dry – gets – drier'' trend pattern through coupling with deserts and trade winds."**
- **Hsu et al. 2011: "results suggest that in the past 30 years with an increase in the global mean surface temperature, the global monsoon total precipitation is strengthened.**

Statistical analysis methods: mean, extreme, natural variability

- Dominant warm season precipitation climatology:
  - Standardized Precipitation Index (SPI)
  - Emprical Orthogonal Function/Principle Component Analysis (EOF/PCA)
- Climate extreme analysis
  - Top 10% extreme temperature and precipitation
- Natural variability and climate extremes
  - Combined Pacific Variability Mode (CPVM)

  Dominant precipitation modes that have statistically significant relationship to Pacific SST based on field significance test with permutated Pacific SSTA correlation maps (considering the area 40°S-60°N, 110°E-80°W)
  - Positive CPVM (PC >0.5): El Nino signal
  - Negative CPVM (PC <-0.5): La Nina signal

North American Monsoon dynamics: SST Interannual Variability and NAM Monsoon Ridge Positioning

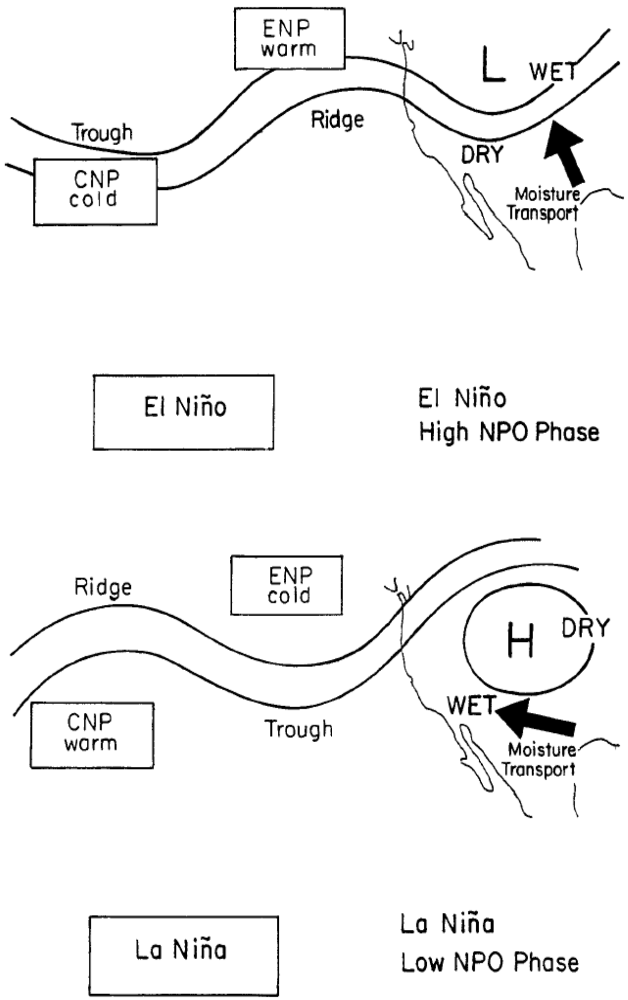
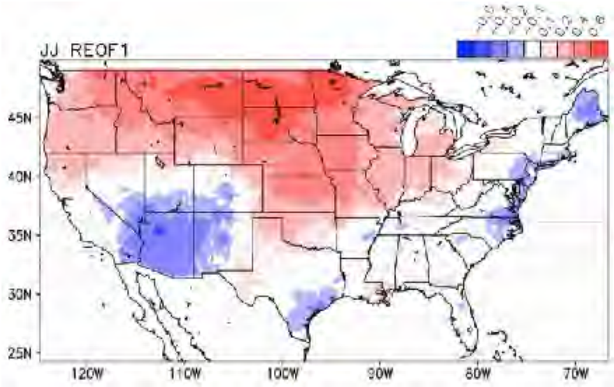


Fig. 14. Idealized relationship of monsoon ridge position and midlevel moisture transport to Pacific SSTs at monsoon onset.

The onset and variability of North American Monsoon System (NAMS) is partly controlled by atmospheric teleconnections related to SST variability (El Niño Southern Oscillation (ENSO) and Pacific Decadal Variability (PDV))

North American Monsoon dynamics: (cont.)



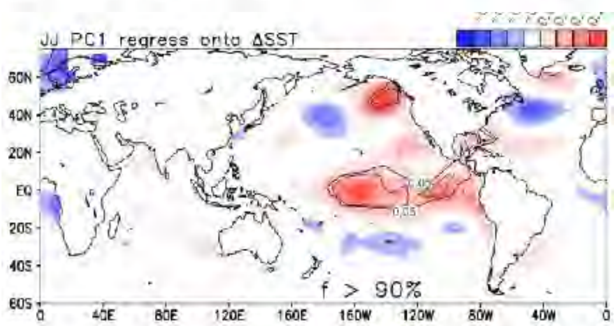
Dominant mode of early summer precipitation (1950-2000) PRISM-based JJ SPI

Antiphase relationship in early summer rainfall between Southwest U.S. and central U.S.

Relationship to atmospheric circulation anomalies

Teleconnection response

Quasi-stationary Rossby wave train



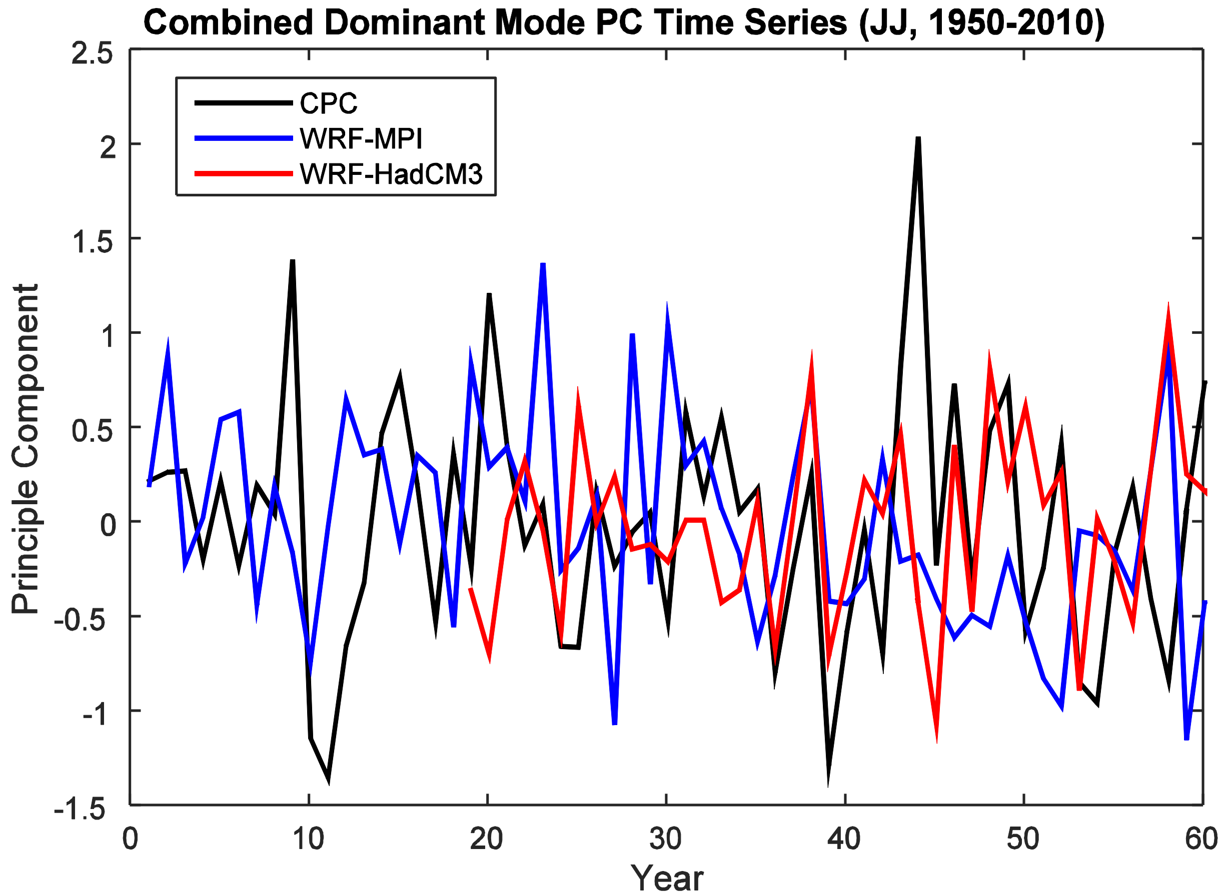
Relationship to sea surface temperature anomalies

ENSO, Pacific decadal variability drive variation in tropical convection

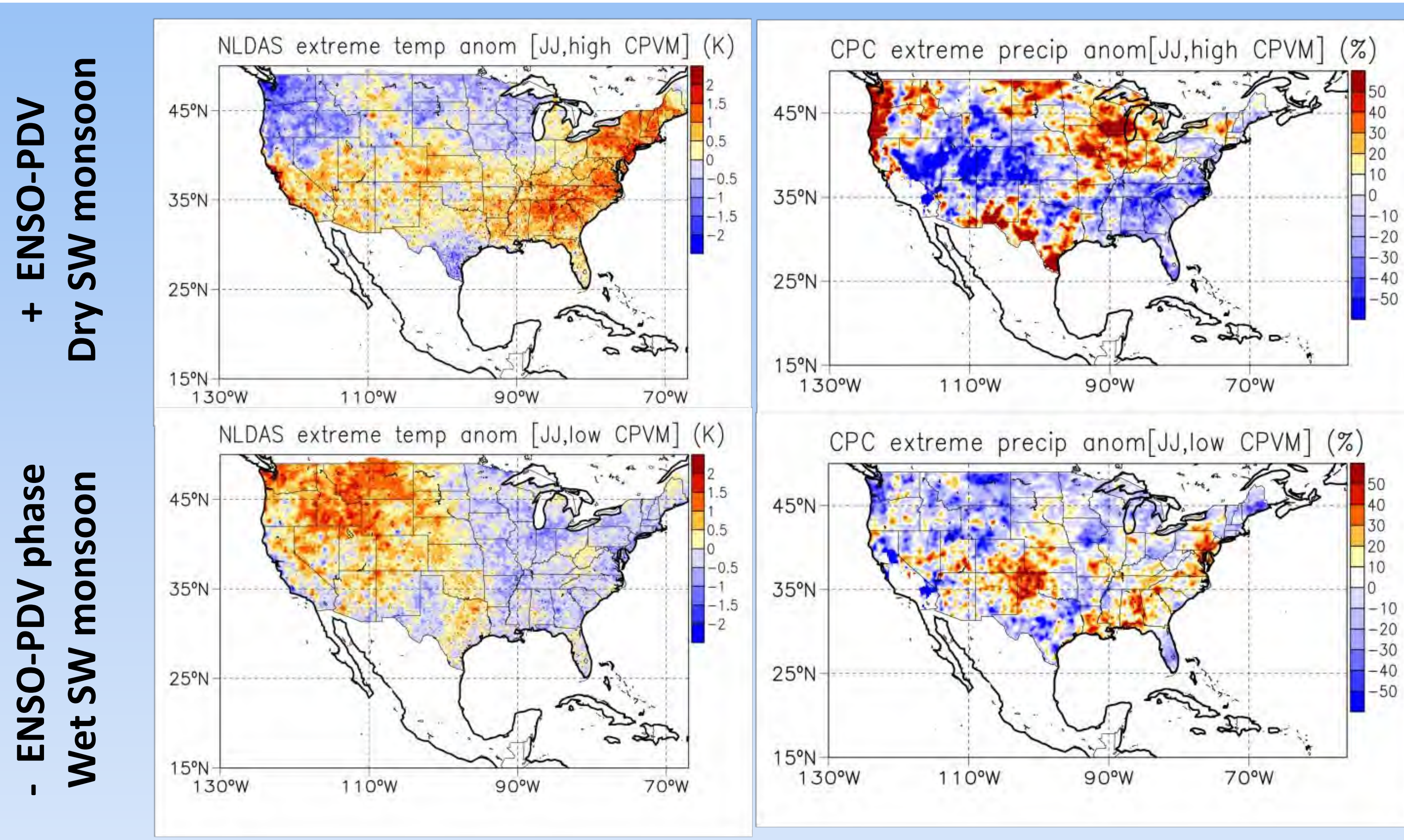
(Cianceralli et al. 2012)

CPVM dominant mode:
Precipitation principle component time series

Observation and RCM (WRF-CMIP) each has their own CPVM PC time series internannual variability



Change in observed extreme event precipitation at monsoon onset Considering years with strong ENSO-PDV signals (1980-2012) minus (1950-1980)



<u>WHAT INSTRUMENTAL RECORD SAYS:</u> When natural variability favors wet (dry) conditions in early summer, that is generally when increases in precipitation intensity (drought) become more apparent. Especially case for areas on the periphery of monsoon.

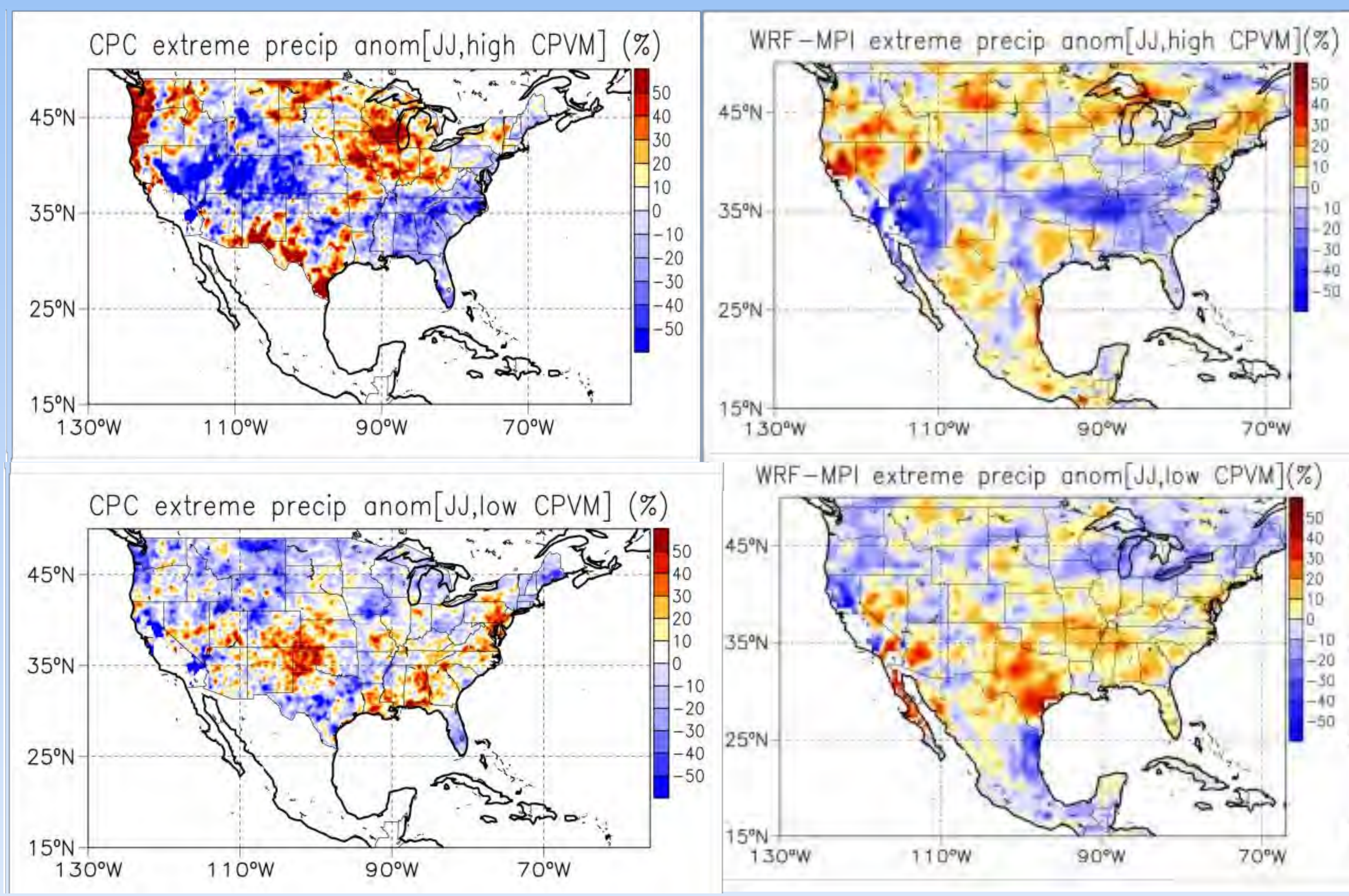
(Chang et al. 2015)

Change in extreme event precipitation at monsoon onset: under strong ENSO-PDV signals

(1980-2012) minus (1950-1980)

+ ENSO-PDV
Dry SW monsoon

- ENSO-PDV phase
Wet SW monsoon

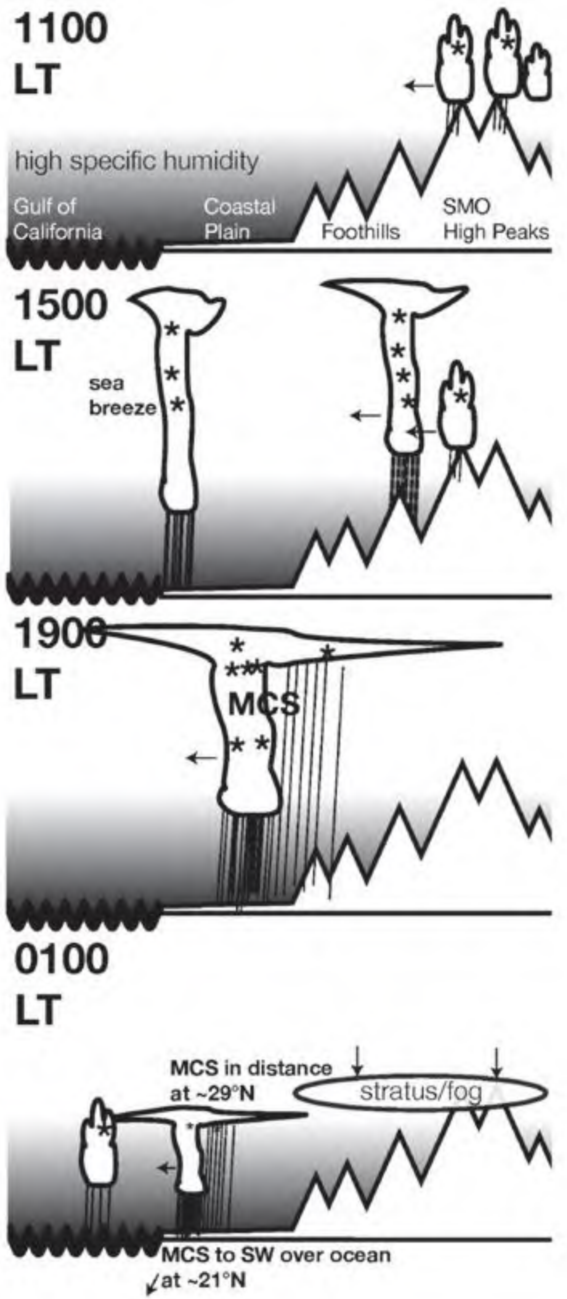


(Chang et al. 2015)

NAM-related convection: Is downscaling to meso-β scale enough?

Convection Permitting Models

What are the prerequisite meteorological conditions for strong monsoon thunderstorms?



Nesbitt et al. (2008)

Convective organization and propagation

- Convective clouds form over the mountains in the morning
- By afternoon and everning storms propagate to the west towards the Gulf of California where they can organize into mesoscale convective systems if there is sufficient moisture and instability.
- It's likely that a resolution less than 5 km is necessary to represent this process correctly in regional models. Global models pretty much fail.

Thermodynamic Criteria: Heat + Moisture

<u>Atmospheric Instability</u>

- Cool the atmosphere aloft, warm atmosphere below
- Facilitates development of vertically developed, cumuliform clouds
- *Convective available potential energy (CAPE)*

<u>Atmospheric moisture</u>

- Upper-level moisture: from easterly flow aloft
- Low-level moisture: typically from surges of moisture from Gulf of California
- *Column integrated precipitable water (PW)*

Dynamic criteria:

Monsoon ridge positioning

+

Upper-level disturbance (inverted trough)

+

Gulf surge

=

Large-scale upward motion

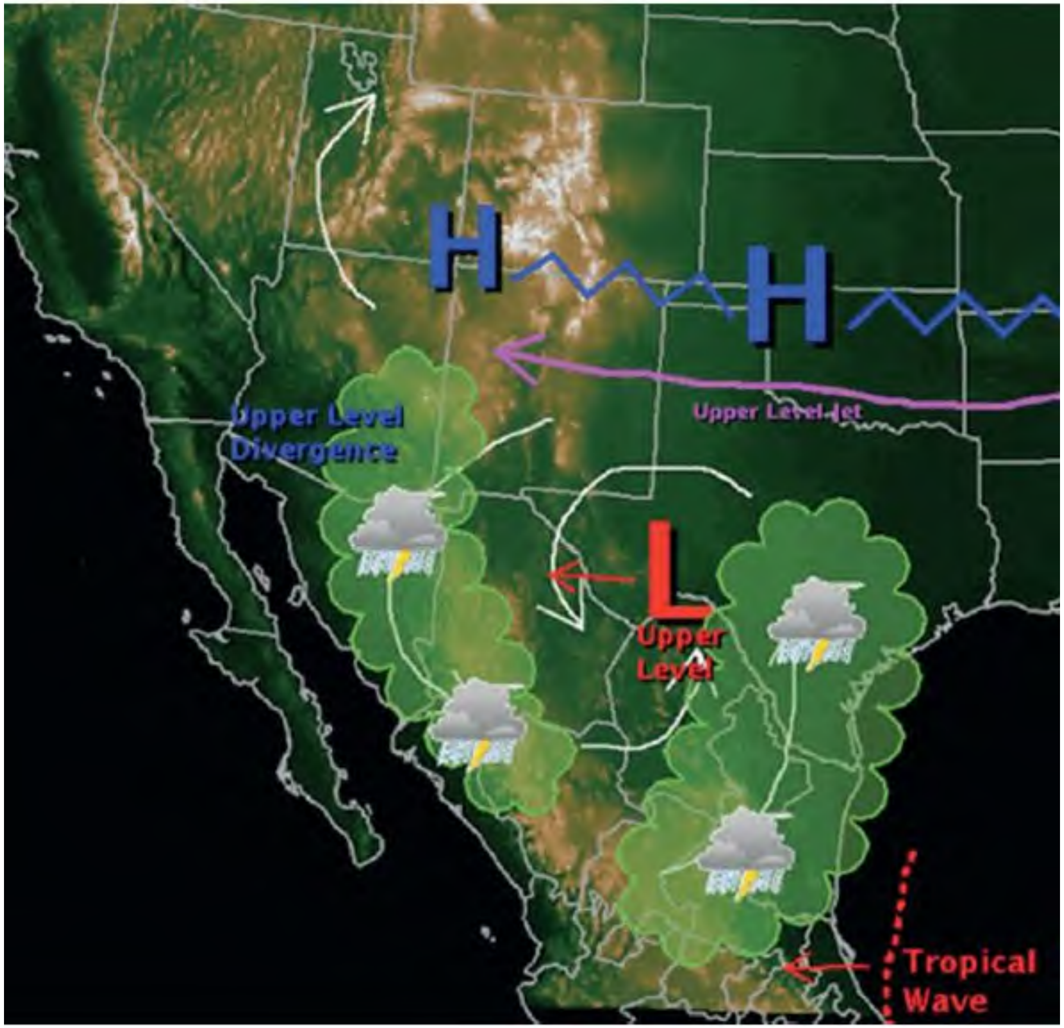
+

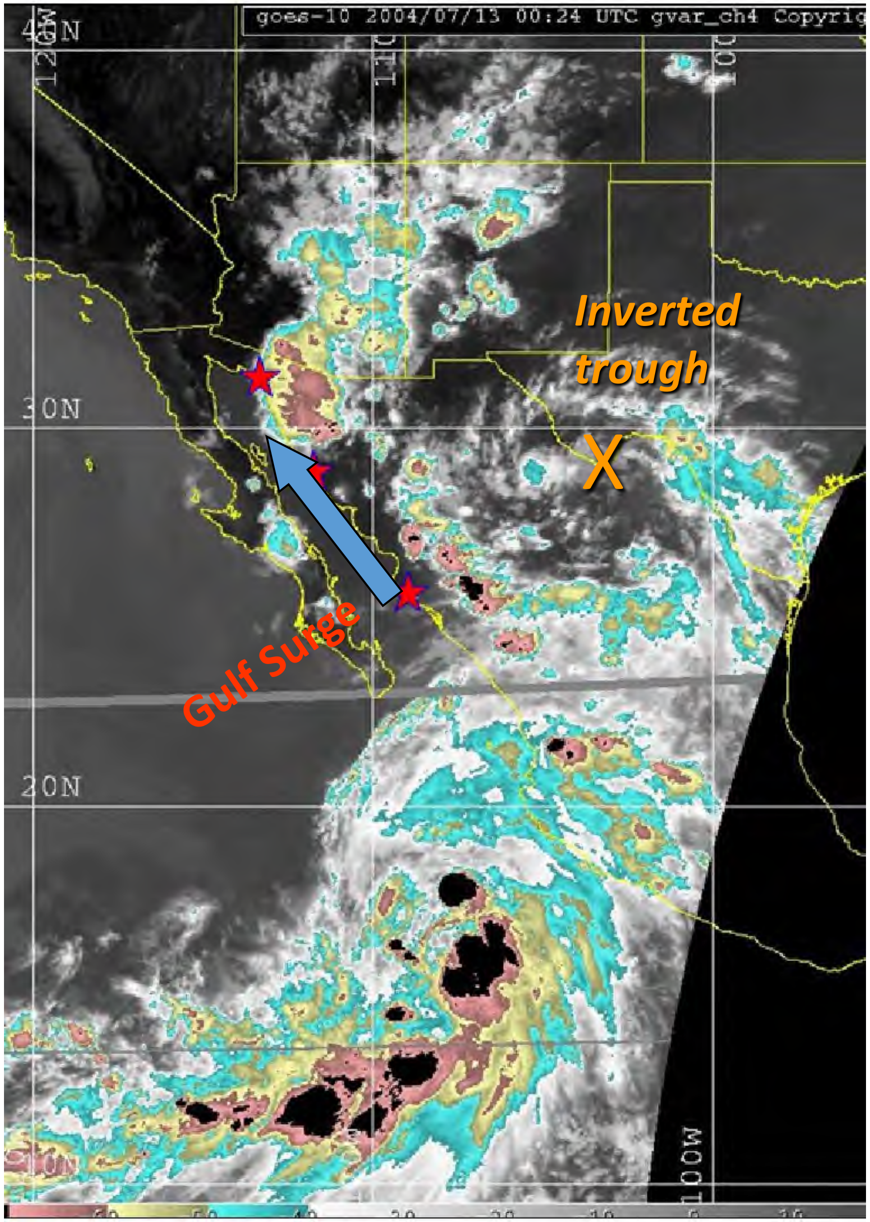
Vertical wind shear

+

Influx of low level moisture

Inverted trough: Favors upward motion and vertical wind shear





Conditions for enhanced monsoon thunderstorms

- An inverted trough (X) traveling around the monsoon ridge.
- Low level-moisture surging up the Gulf of California

RESULT

Thunderstorms which originate on the Mogollon Rim intensify and move westward toward low deserts and the Colorado River Valley.

AGU PUBLICATIONS

Reviews of Geophysics

REVIEW ARTICLE

10.1002/2014RG000475

A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges

Andreas F. Prein[1,2], Wolfgang Langhans[3], Giorgia Fosser[4], Andrew Ferrone[5], Nikolina Ban[6], Klaus Goergen[7,8,9], Michael Keller[6,10], Merja Tölle[11], Oliver Gutjahr[12], Frauke Feser[13], Erwan Brisson[14], Stefan Kollet[9,15], Juerg Schmidli[6,10], Nicole P. M. van Lipzig[16], and Ruby Leung[17]

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Key Points:
- Convection-permitting climate models reduce errors in large-scale models
- Added value in convective processes, regional extremes, and over mountains
- Discusses challenges/potentials of convection-permitting climate simulations

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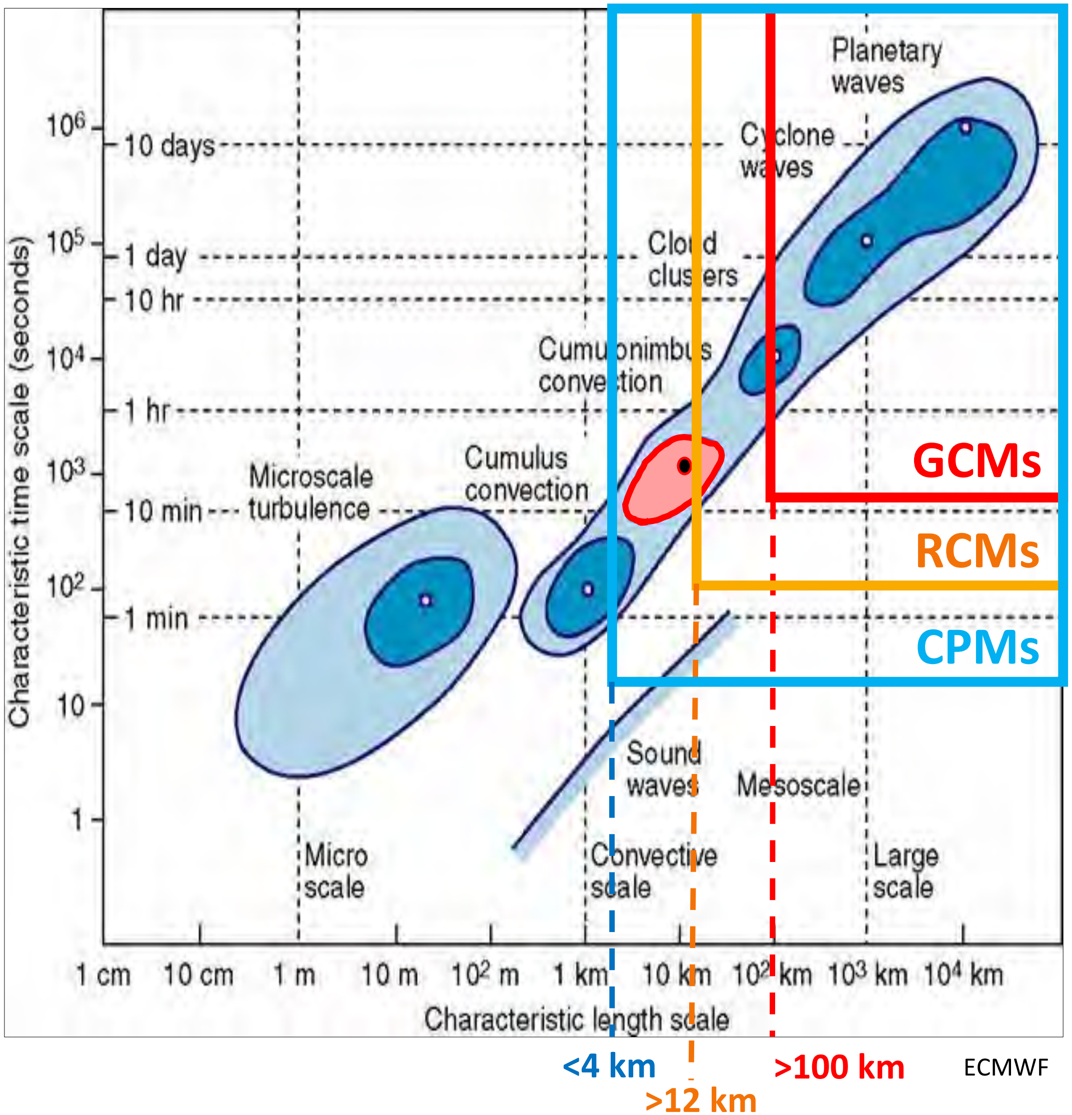
Abstract Regional climate modeling using convection-permitting models (CPMs; horizontal grid spacing <4 km) emerges as a promising framework to provide more reliable climate information on regional to local scales compared to traditionally used large-scale models (LSMs; horizontal grid spacing >10 km). CPMs no longer rely on convection parameterization schemes, which had been identified as a major source of errors and uncertainties in LSMs. Moreover, CPMs allow for a more accurate representation of surface and orography fields. The drawback of CPMs is the high demand on computational resources. For this reason, first CPM climate simulations only appeared a decade ago. In this study, we aim to provide a common basis for CPM climate simulations by giving a holistic review of the topic. The most important components in CPMs such as physical parameterizations and dynamical formulations are discussed critically. An overview of weaknesses and an outlook on required future developments is provided. Most importantly, this review presents the consolidated outcome of studies that addressed the added value of CPM climate simulations compared to LSMs. Improvements are evident mostly for climate statistics related to deep convection, mountainous regions, or extreme events. The climate change signals of CPM simulations suggest an increase in flash floods, changes in hail storm characteristics, and reductions in the snowpack over mountains. In conclusion, CPMs are a very promising tool for future climate research. However, coordinated modeling programs are crucially needed to advance parameterizations of unresolved physics and to assess the full potential of CPMs.

Convection Permitting Models (CPMs)



CPM grid spacing ≤ 4 km

Weather forecasting

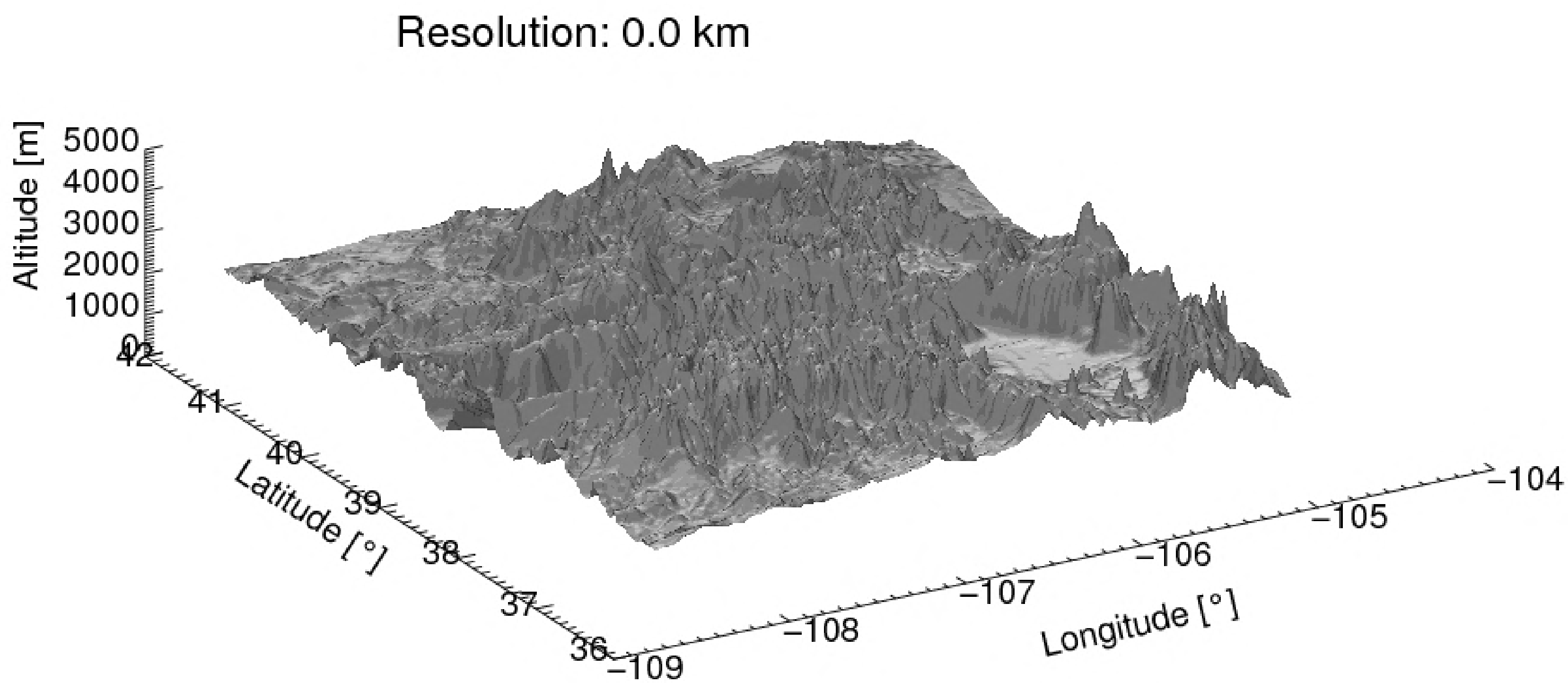
- Weisman et al. 1997
- Done et al. 2004

Climate

- Langhans et al. 2012

Courtesy Andreas Prein

Orography resolving scales



Model orography in the Colorado Rocky mountains from Δx=1 km → 100 km

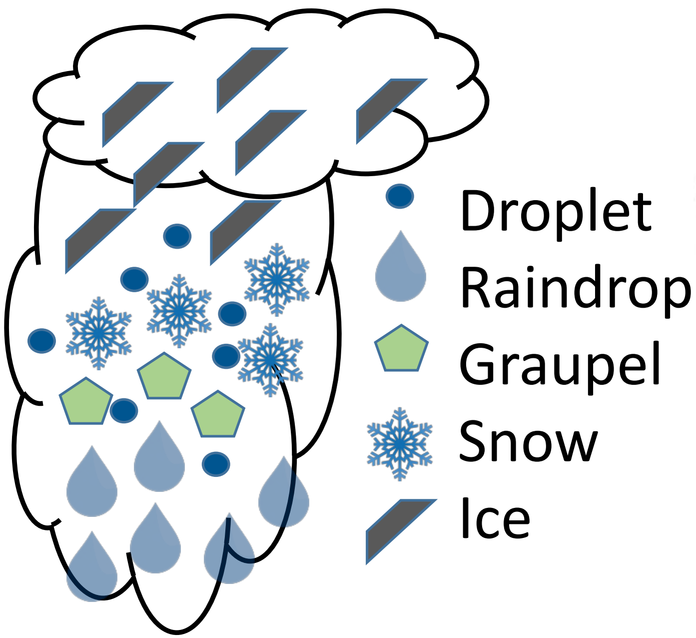
Improved representation of **orography** and **surface fields**

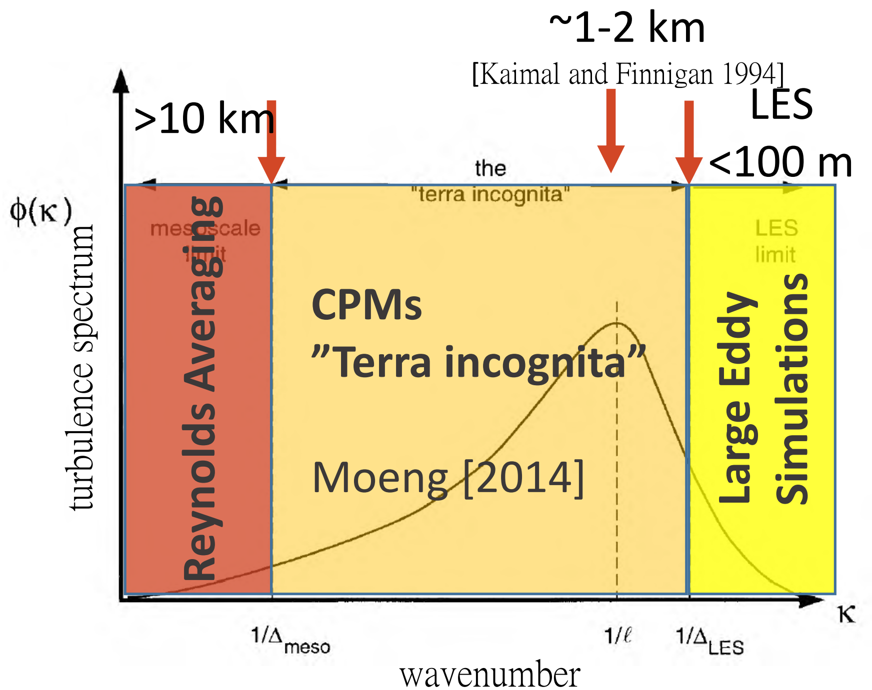
Courtesy Andreas Prein

Model Physics

Physics setup adapted from weather forecasting models → setups are not tested on climate time-scales

Clouds, Aerosols, and Radiation | **Turbulence** | **Soil-Vegetation-Atmosphere Coupling**



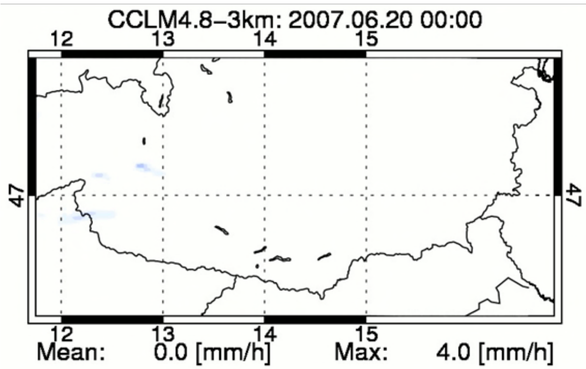


Courtesy Andreas Prein

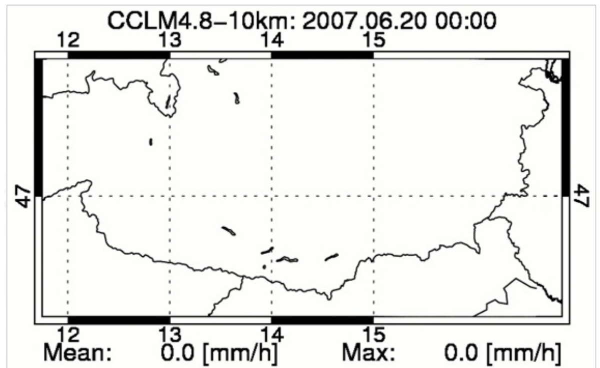
[Wyngaard, 2004, Copyright 2004 AMS]

Convective Precipitation

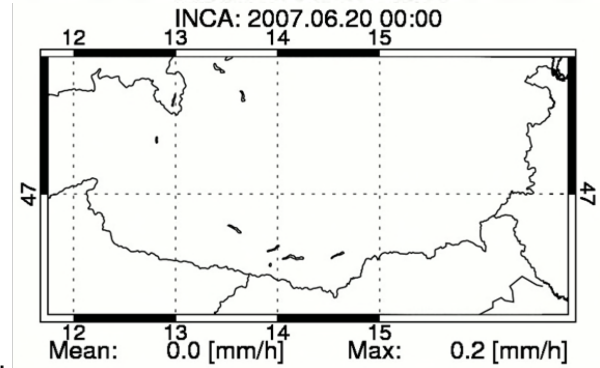
3 km Simulation

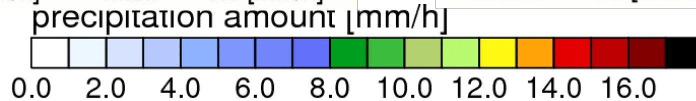


10 km Simulation

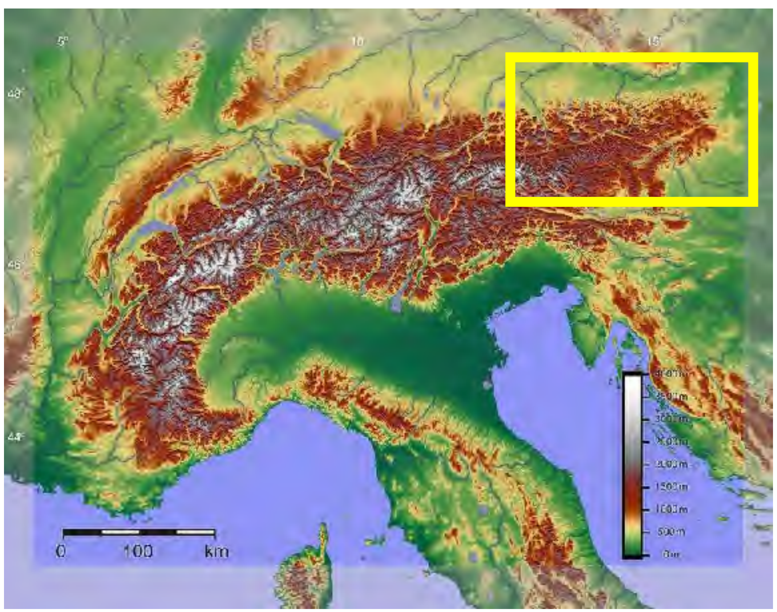


Observation: 1 km





[Prein et al. 2013]

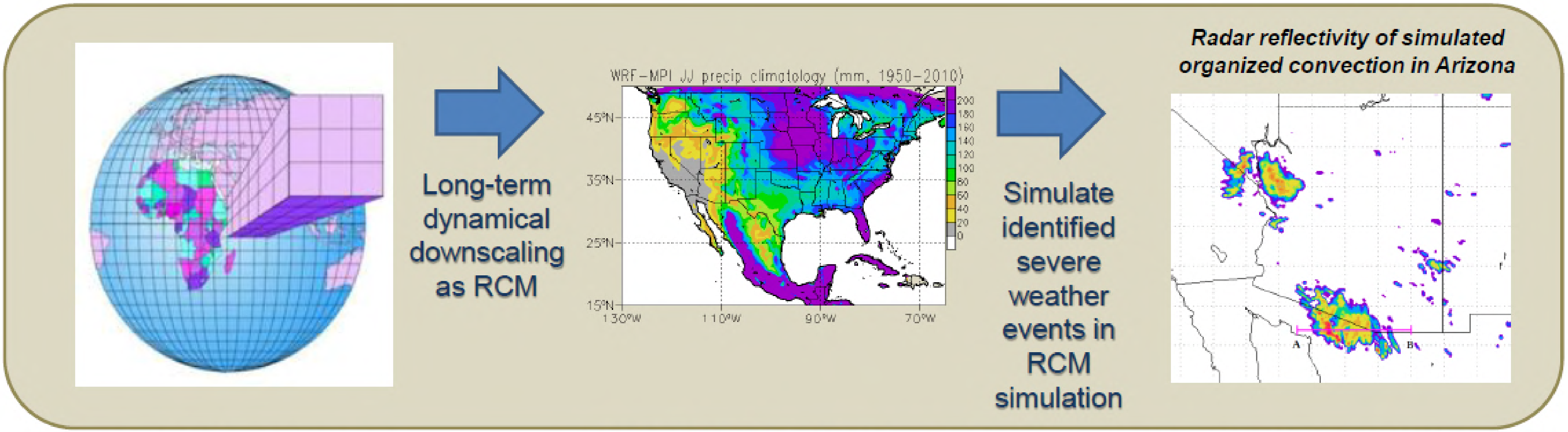


Improvements:

- Timing
  [e.g., Ban et al. 2014, Kendon et al. 2012, Langhans et al. 2013, Prein et al. 2013; Fosser et al. 2014]
- Intensities
  [e.g., Ban et al. 2014, Prein et al. 2013, Lind et al. 2016]
- Structures
  [e.g., Brisson et al. 2015; Prein et al. 2013 , Lind et al. 2016]

Courtesy Andreas Prein

Event-based convective-permitting dynamical downscaling



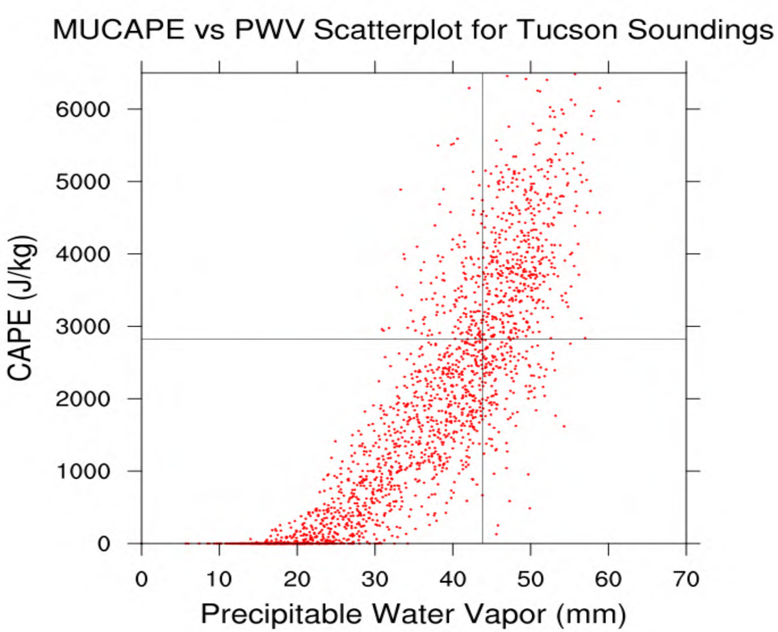
Selected CMIP3 and 5 models, global reanalysis
100 to 200 km resolution

Long-term simulations with WRF (1950 to 2100)
35-50 km grid spacing

Short-term NWP-type simulations
2.5 km grid spacing

Produces results that represent the possible changes in extreme events in a physically-based way, using the same paradigm as a short-term NWP forecast used by National Weather Service.

Extreme weather events selection criteria: Thermodynamic component

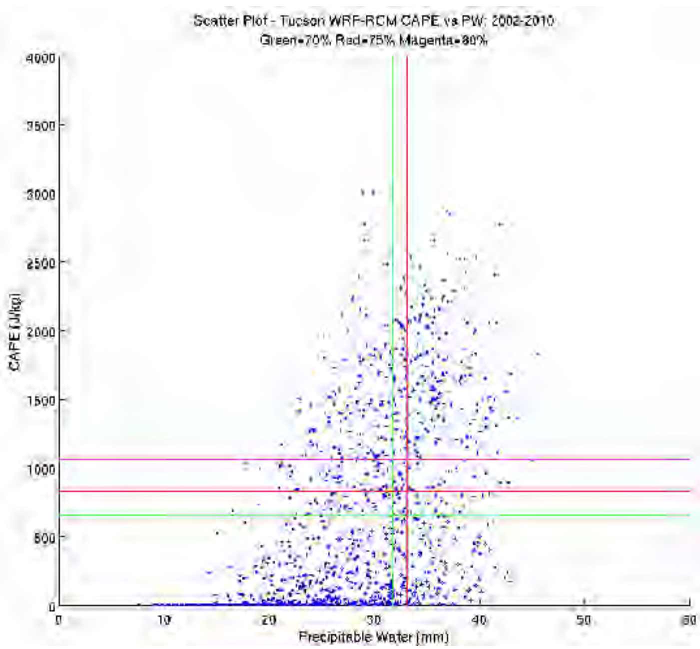


- Thermodynmic criteria
  - Instability (CAPE)
  - Precipitable water
- Extreme weather events can be identified in the highest portions of the joint distribution of CAPE and precipitable water.
- Average 200 days of extreme events identified over a 20-year period.
- **Captures ~70% of observed severe weather events (radiosonde)**

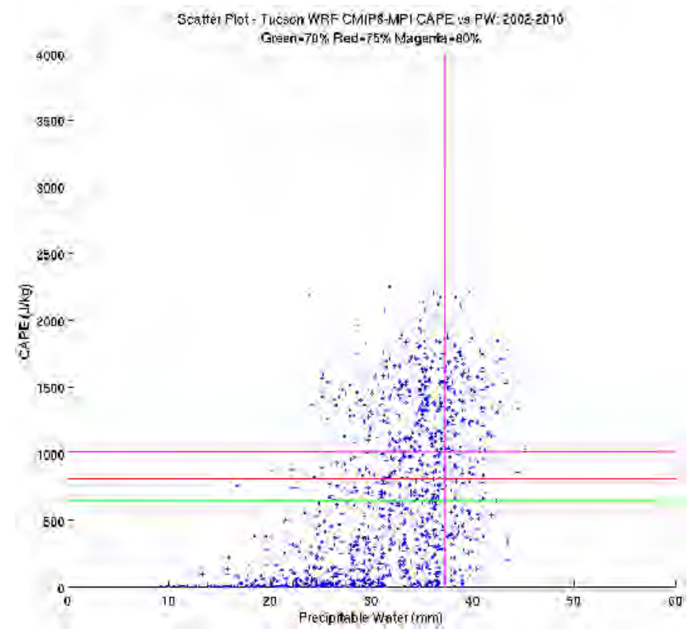
(Mazon et al. 2016)

Extreme weather events selection criteria: Thermodynamic component

WRF-NCEP Reanalysis



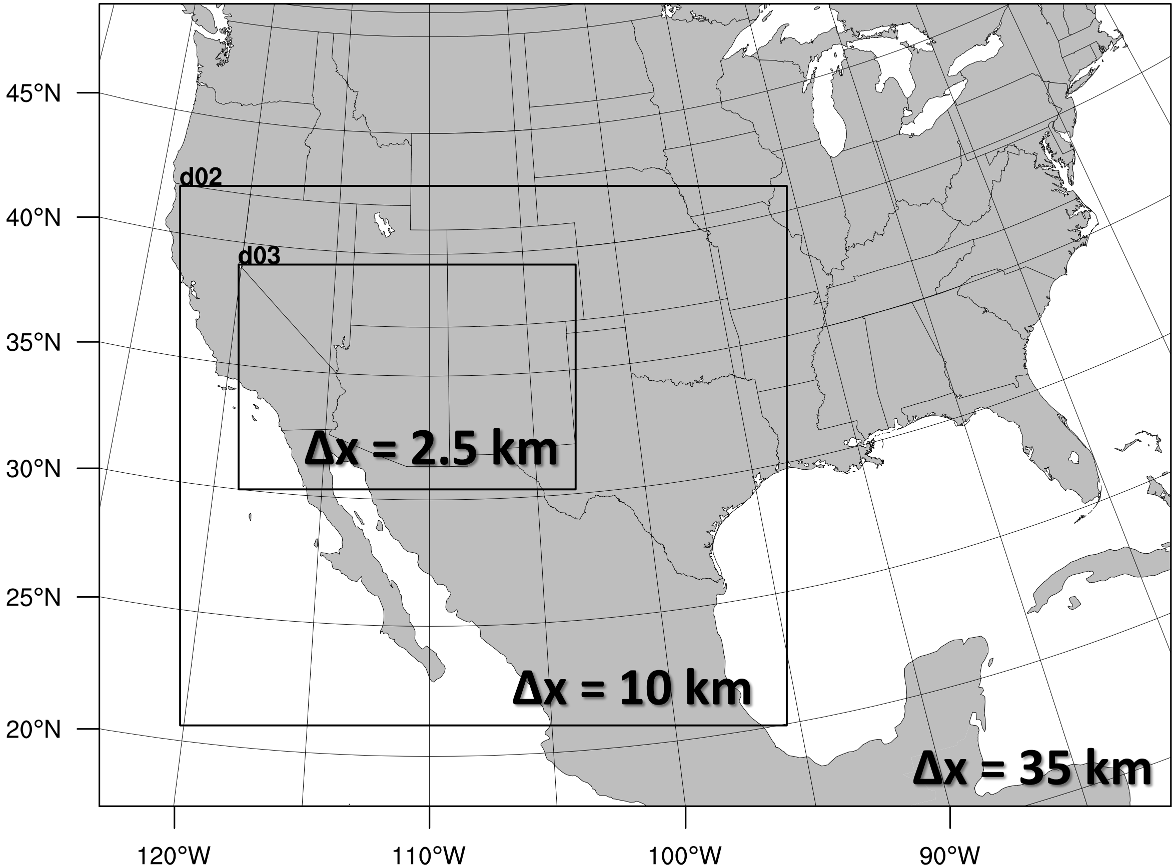
WRF-MPI-ECHAM5



Megan Jares, M.S.

- **A positive relation between CAPE and precipitable water.**
- **The behavior of instability and precipitable water is very coherent across the Southwest U.S. region.**

WRF nested grid structure

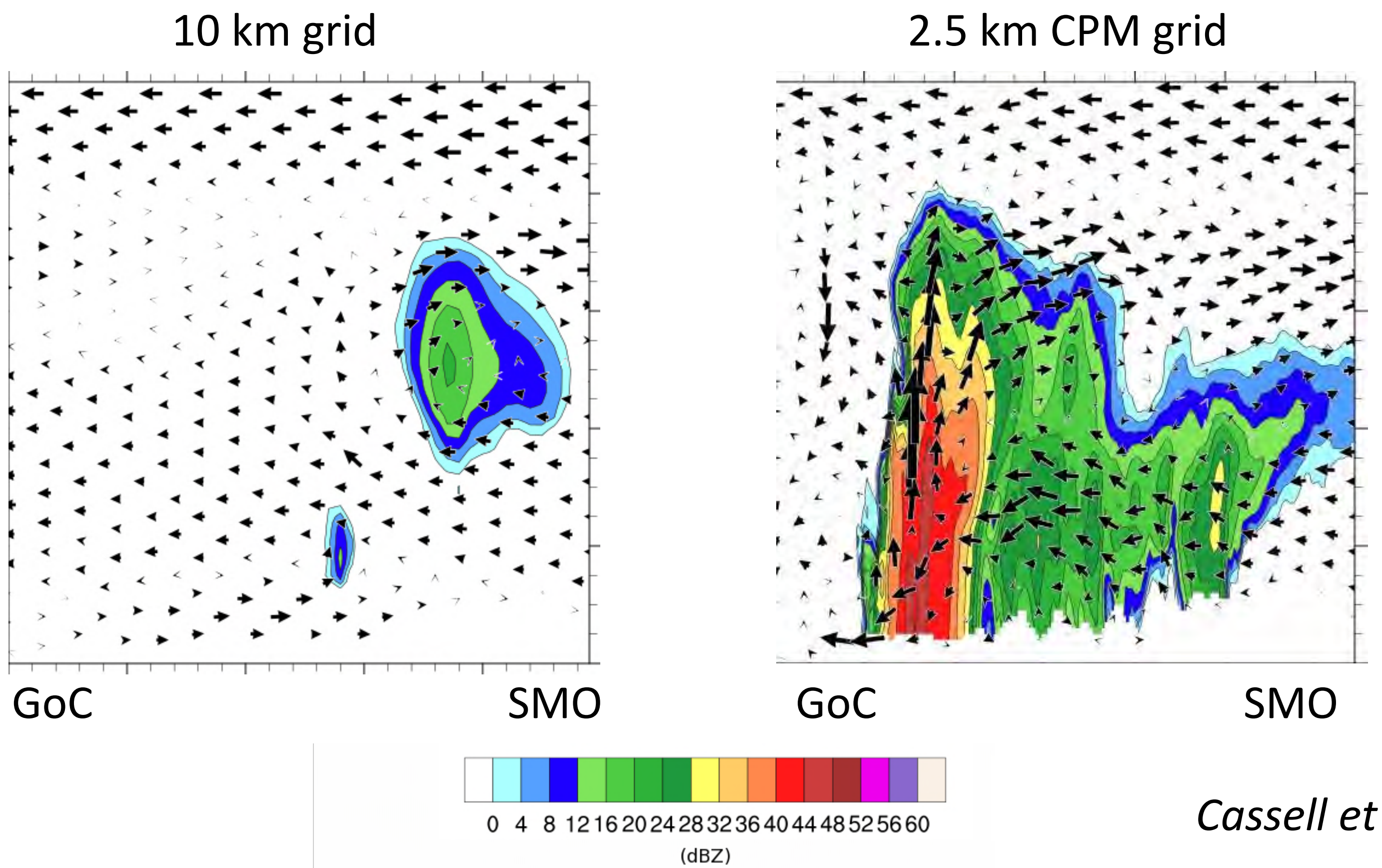


Domain setup:
<u>D1: </u>35km, U.S./Mexico
<u>D2: </u>10km, Western U.S.
<u>D3: </u>2.5km, Southwest U.S., only to simulate the most favorable severe weather event days according to the thermodynamic criteria.

Parameterizations: operational numerical weather prediction at University of Arizona, with no parameterized convection on D3.

Difference in WRF model simulated radar reflectivity for NAME IOP2 case: 03 UTC 14 July 2004

Vertical cross section through model depth from Sierra Madre Occidental to Gulf of California at 29.5°N



Cassell et al. (in revision)

Wind vectors scale with ratio of 10:1 in horizontal to vertical.

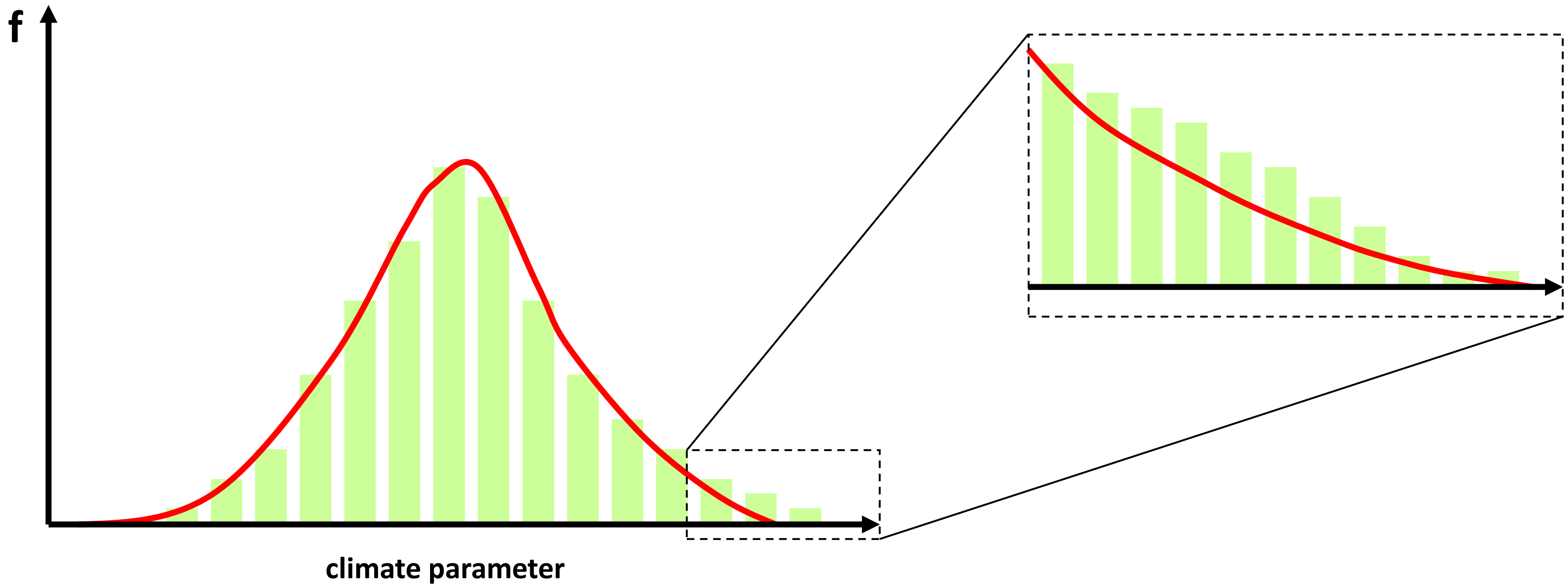
Extreme Event Study Application: Severe Thunderstorm Analysis – Frequency, Intensity, Distribution

Past DOD project (December 2016):

Assessing climate change impacts for DoD Installations in the Southwest United States during the warm season

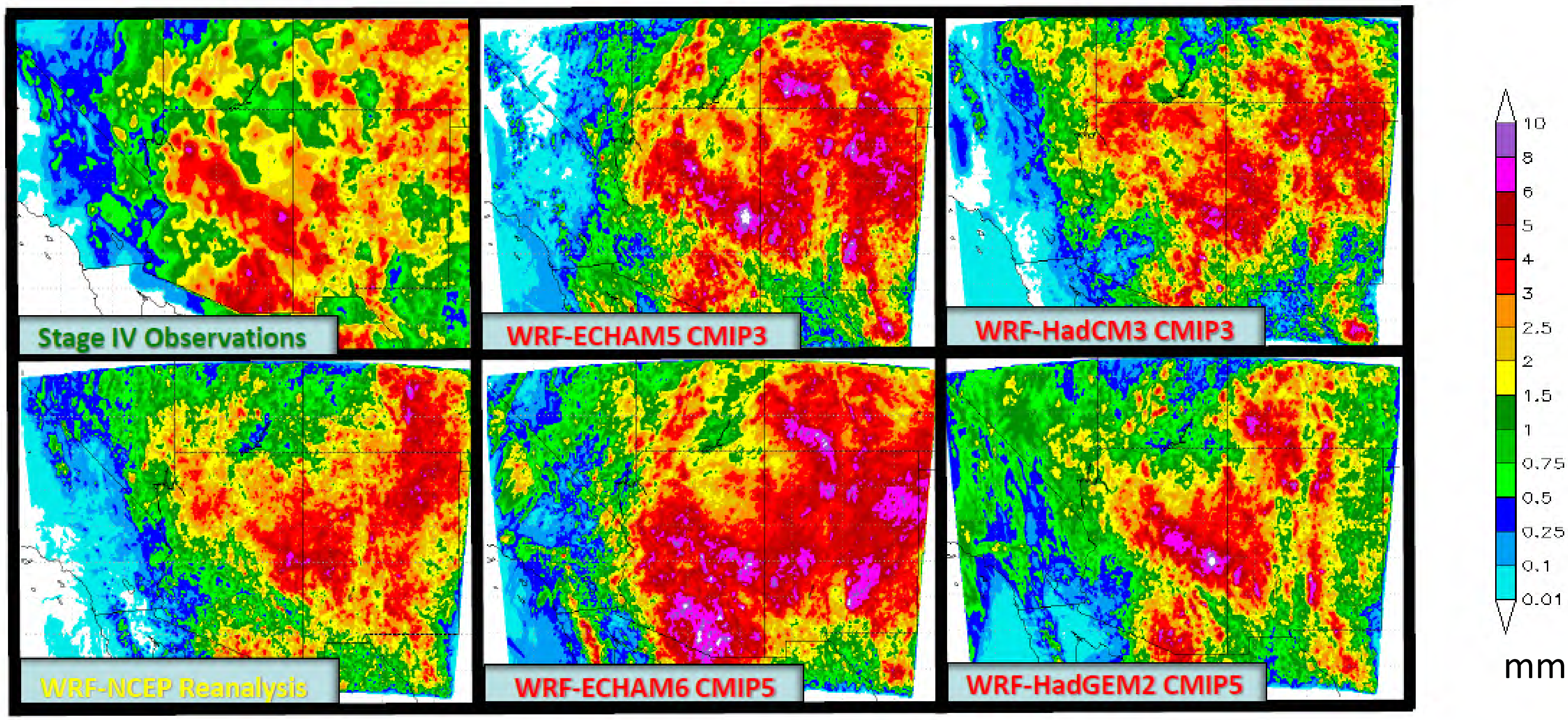
Strategic Environmental Research and Development Program

Statistical evaluation of precipitation extremes using Generalized Extreme Value Theory - GEV



- Conceptual idea is that extreme climate values (e.g. for precipitation or wind speed) in the tail of the distribution may not necessarily fit well to a theoretical PDF that applies to the whole lot of data.
- Solution is to fit generalized Pareto distribution, a peak-over-thereshold method, to better describe the behavior in the tail (Rivera et al. 2014)
- Addess statistical uncertainty by boostrap resampling of the distribution.

Daily averaged modeled precipitation in comparison to observations for thermodynamically favorable severe weather event days (2002-2010)

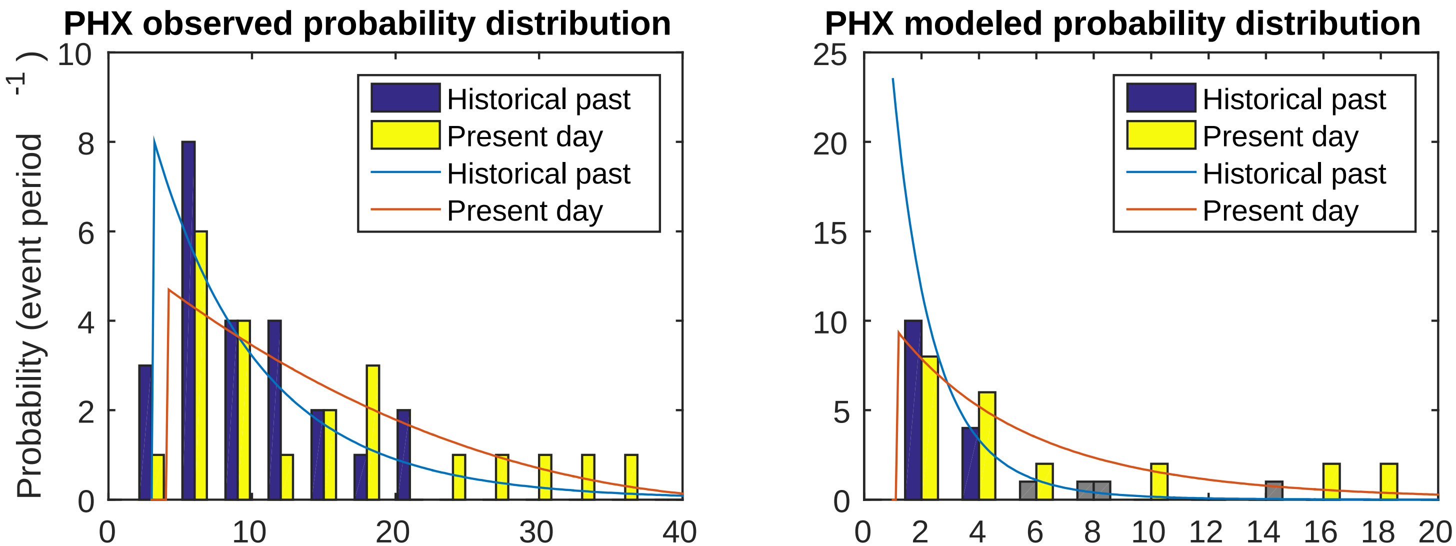


Precipitation across the Southwest U.S., with maximum values centered on mountains. CMIP paradigms behave well in comparison to Stage IV product. Diurnal cycle is reasonable too.

(Luong et al. 2017)

Extreme rainfall (>90%) intensity analysis

historic past: 1950-1970; present day: 1990-2010



- The distribution of extreme events in the present-day period ***is broader and flatter.*** The change in the distribution is statistically significant in rain gauge observations and also in the CPM.

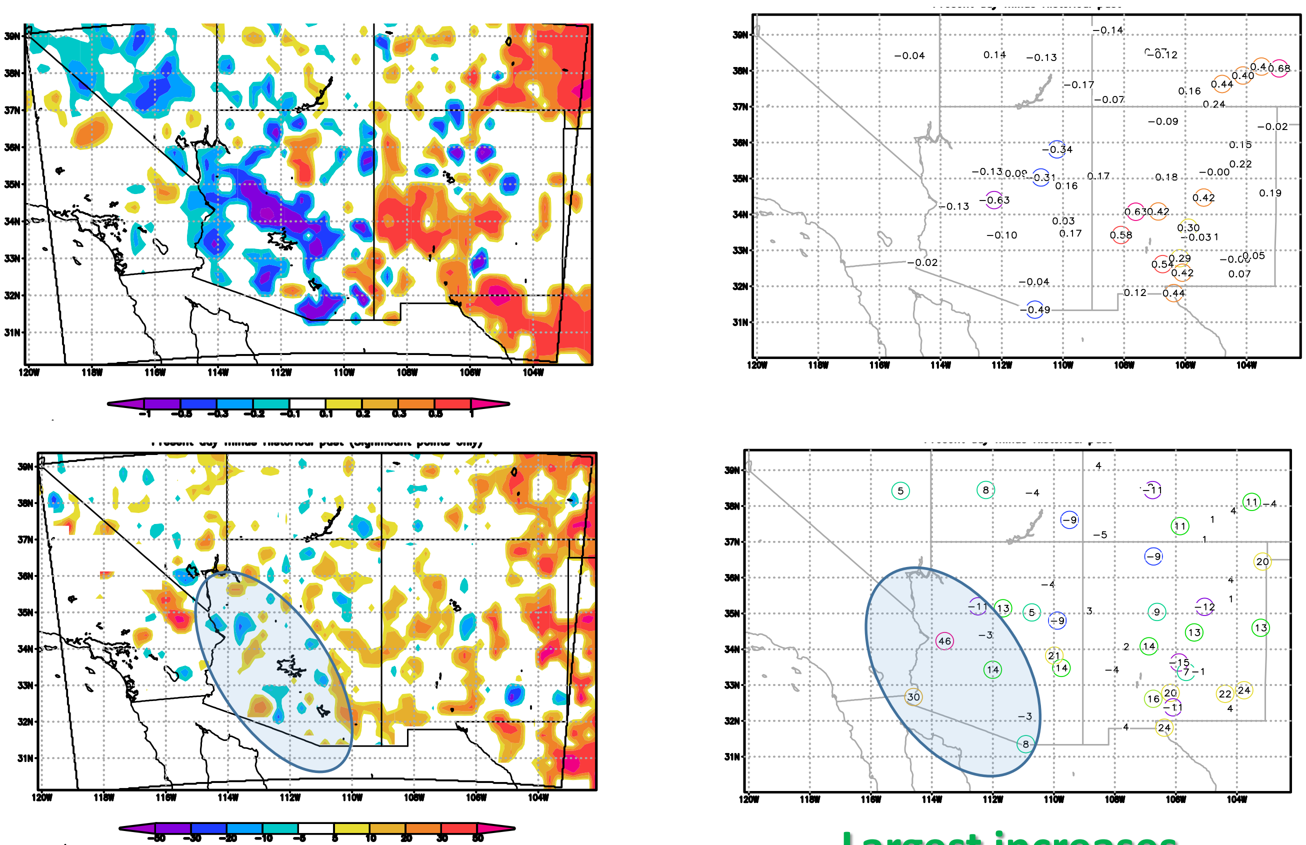
- ***Therefore, the frequency of extreme precipitation is less, but the precipitation during those events is more intense***

Daily precipitation changes (JA) from observations (mm day^{-1}) (1990-2010) minus (1950-1970)

CPC Product | **COOP Station observations (rain gauge)**

Mean changes

Extreme changes



Increases do not exist!

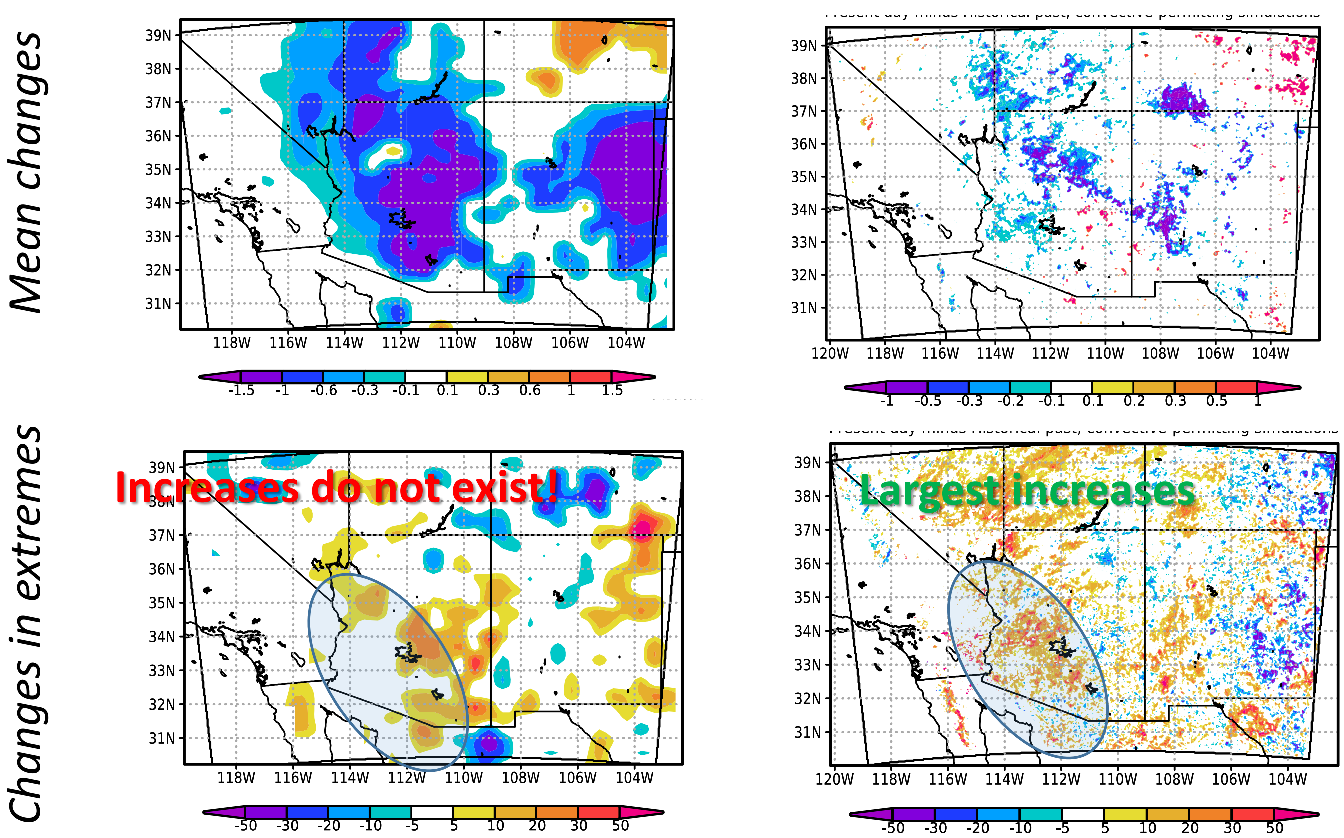
Largest increases

The changes in extreme events are different from mean changes. The COOP station observations indicate that the largest changes occur in the southwest part of Arizona—and these are the ''ground truth'' data.

Luong et al. (2017)

Daily precipitation (JA) in WRF-NCEP Reanalysis model results (mm day^{-1}) (1990-2010) minus (1950-1970)

Δx = 35 km | **Δx = 2.5 km (CPM)**

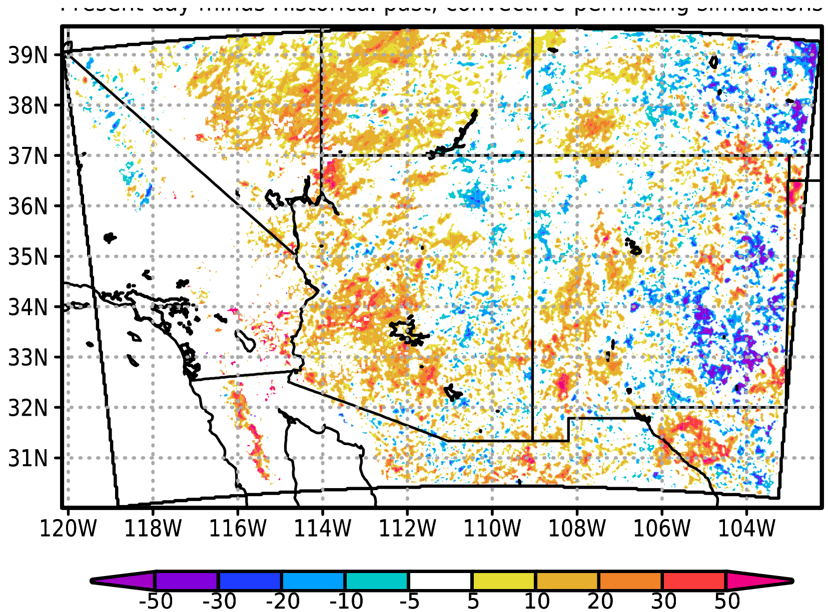


With the use of CPM, we can represent extreme precipitation changes in the exact region that corresponds to where they occur in rain guage station observations.

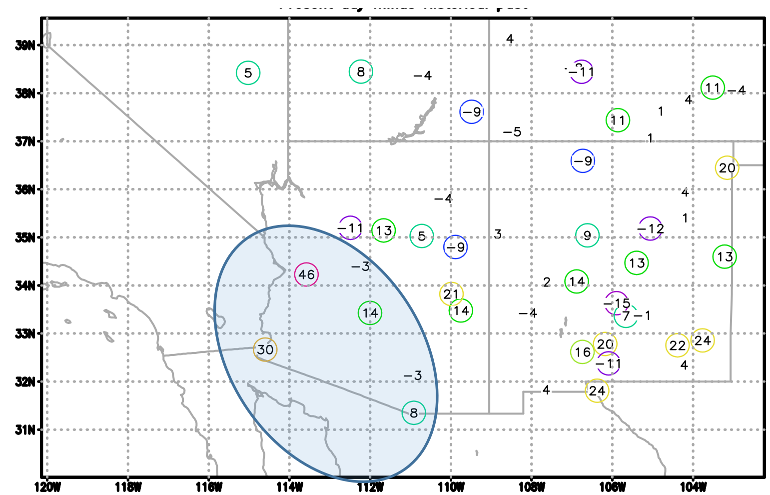
(Luong et al. 2017)

Value added using CPM to simulate changes in extreme precipitation events in the Southwest U.S.

WRF model: Δx = 2.5 km (CPM)



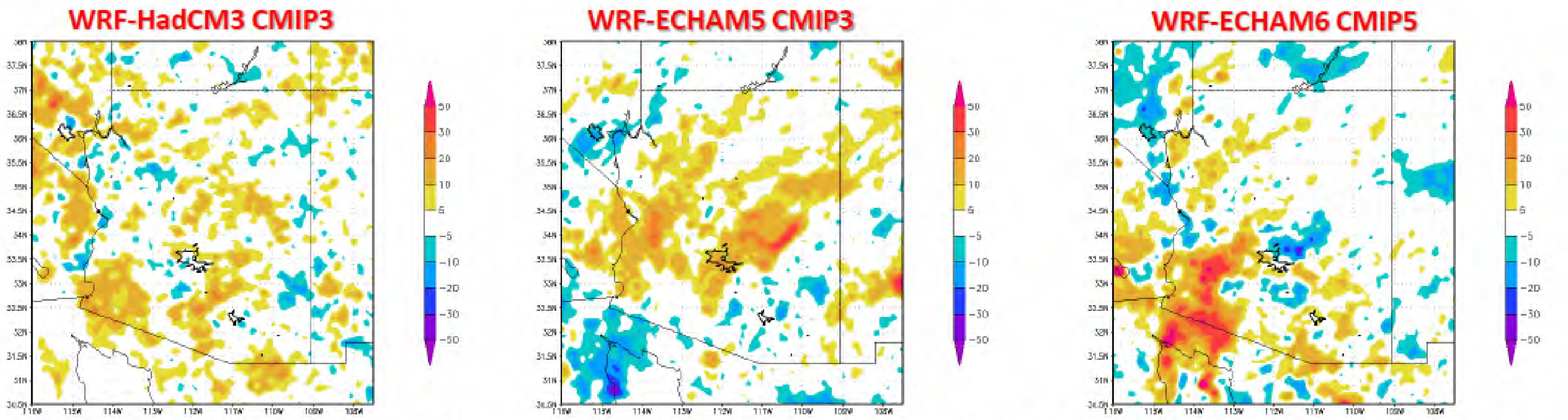
Station observations



The largest increase in extreme precipitaiton occurs in the southwest part of Arizona where MCSs account for most monsoon precipitation and where there are the larges increases in precipitable water.

CANNOT capture these type of changes in a coarser resolution model because it would not have an adequate physical representation of MCSs

Significant changes in extreme precipitation using CMIP3 and CMIP5 global climate models and CPM (2021-2040) minus (1991-2010)



<u>Figure 9</u>: Near future projected extreme (top 5%) precipitation trends (2021-2040 minus 1991-2010) [mm day^{-1}] from downscaled CMIP3 HadCM3 (left), CMIP3 ECHAM5 (middle), and CMIP5 ECHAM6 (right)

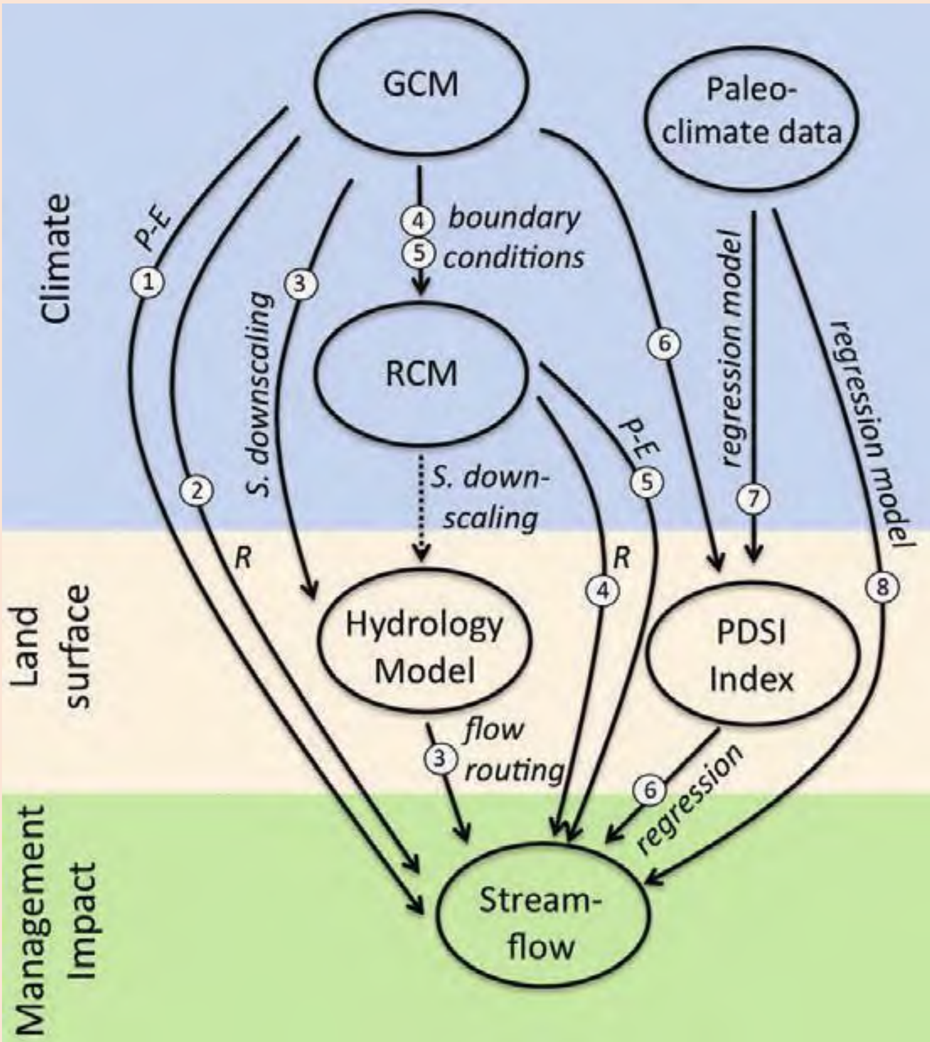
Generally, the changes in precipitation extremes correspond to the results downscaling a global reanalysis and observations we saw previously

Summary: CPM-type simulation

- The use of CPM now is possible with the rapid increase in computational capacity.
- CPMs can better represent physical processes of convective precipitation, particularly organized convection like MCSs .
- Results with CPM generally correspond better with precipitation observations, with respect to amount, intensity, duration, and timing, and we found this to be true for Southwest U.S.
- In the Southwest US, long-term increases in precipitation intensity are realized principally by organized convection (MCSs). For that reason, use of CPMs adds much value in climate modeling for forecasts and projections.

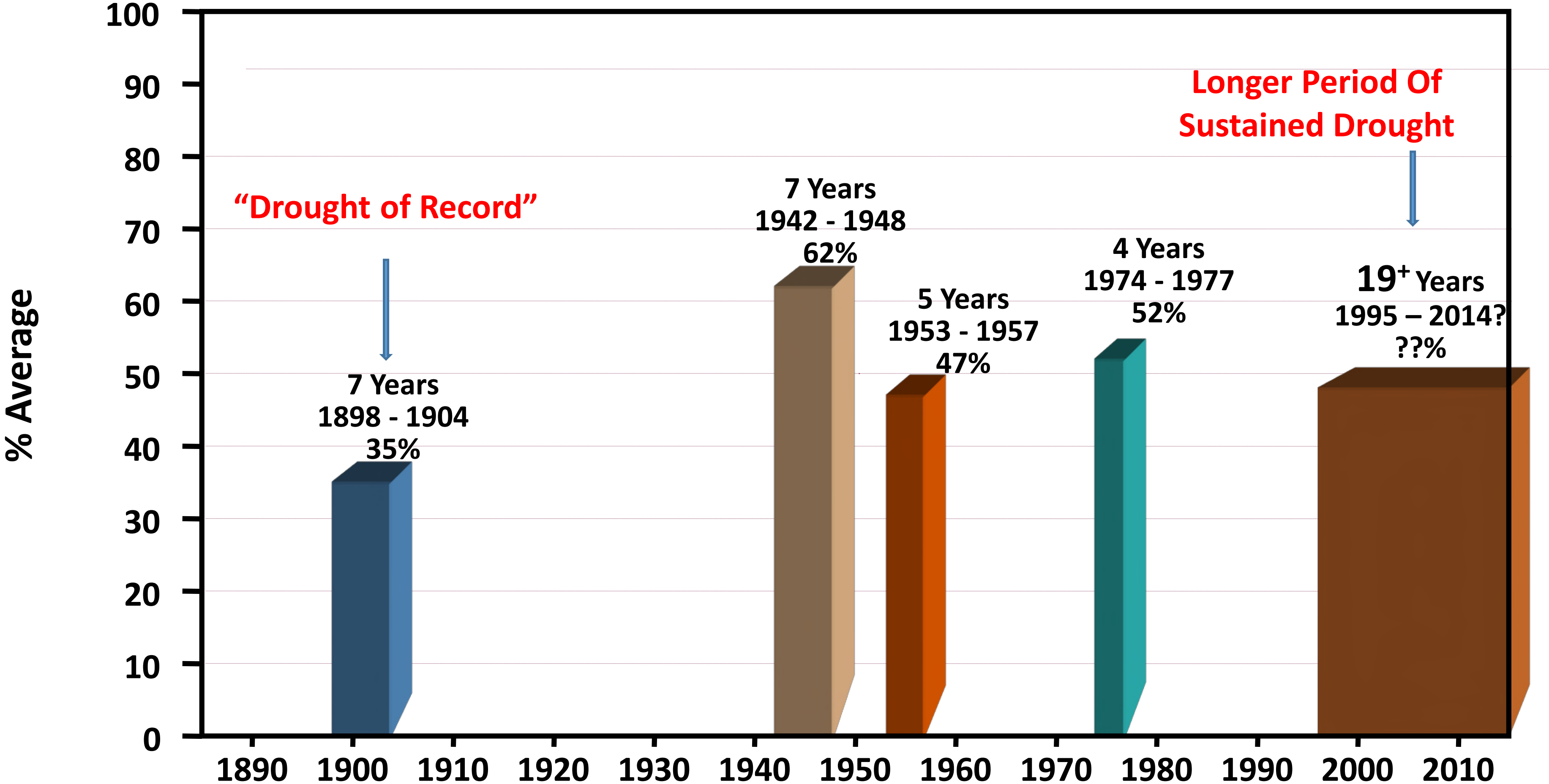
Extreme Event Study Application: Colorado River Streamflow Hydrology

Understanding uncertainties in climate and streamflow projections (BAMS, 2014)



- Sources of climate projection uncertainty for Colorado River:
  1. GCM and emission scenarios used
  2. Spatial scale and topography dependency
  3. How land surface hydrology represents precipitation and temperature change
  4. Downscaling methodologies

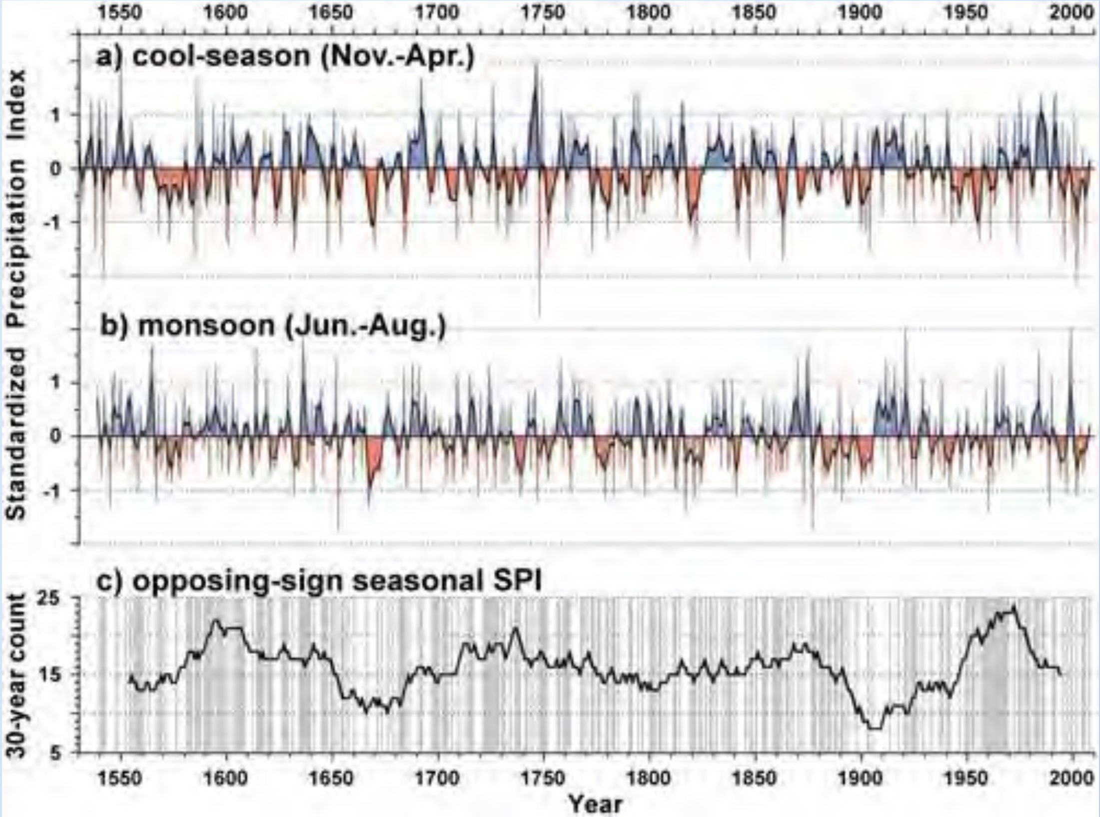
Historic Drought Record – Runoff % change



Salt River Project Historic Drought Periods

(Average Runoff 1913–2010 = 1,198,536 AF)

Tree-Ring study for seasonal precipitation

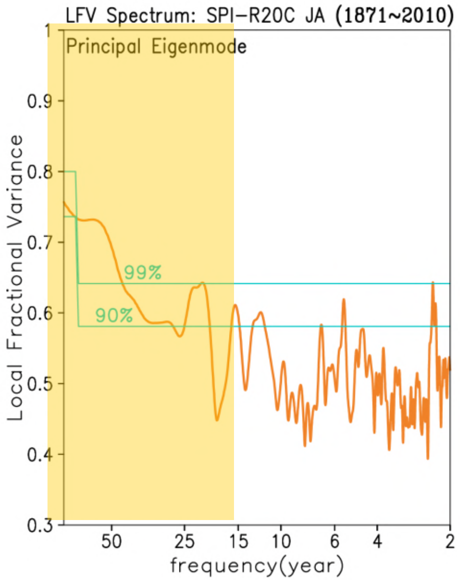


Time-series graphs of reconstructed SPI
Vertical gray bars denote years with opposing-sign SPI anomalies and the black line represents a centered 30-year running count of these events (c).

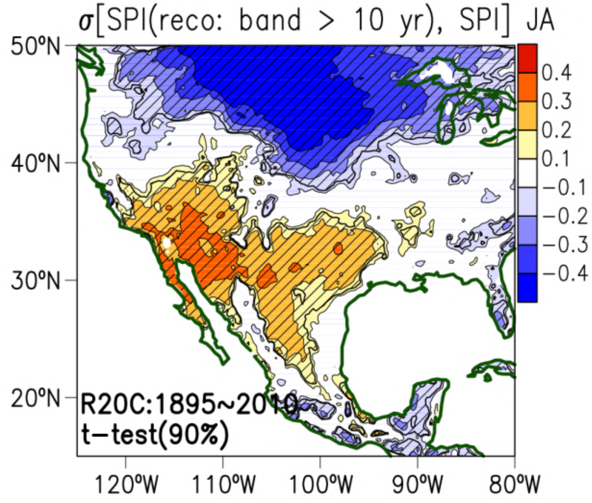
A dual summer-winter season coherence co-variability characterizes simultaneous cool-season precipitation deficit and failure of summer monsoon precipitation.

(Griffin et al., 2013)

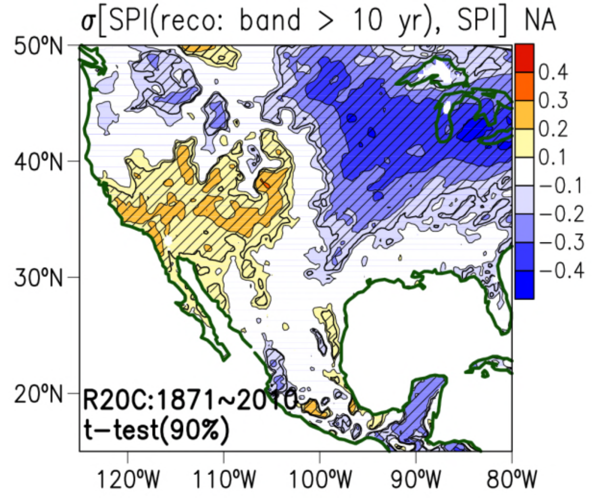
Preccipitation low-frequency (band > 10 years) mode (WRF-Reanalysis, 1895-2012)



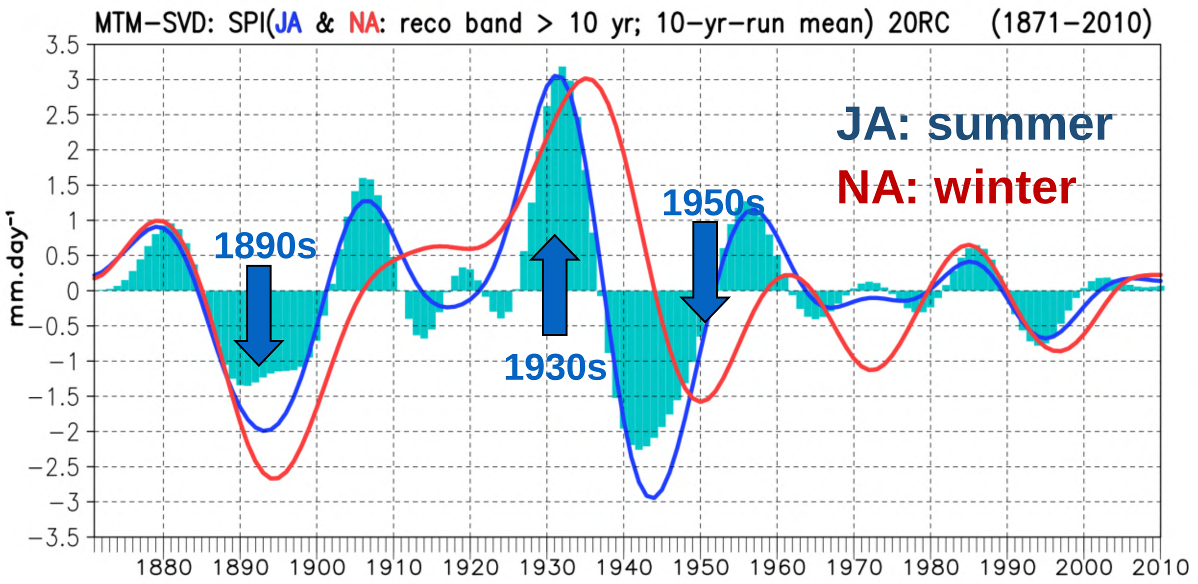
JA: summer



NA: winter



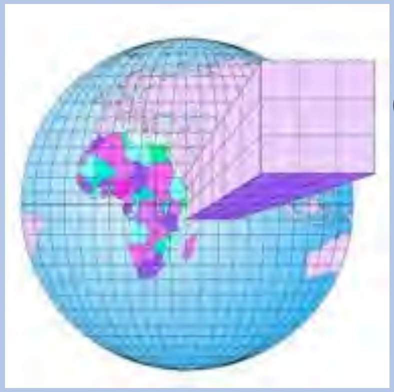
In-phase Winter and summer spatial pattern



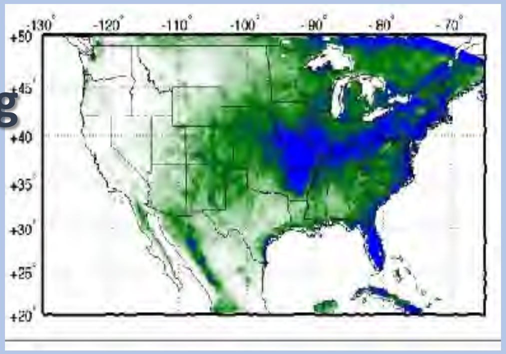
In-phase winter and summer temporal pattern

(Carrillo et al. 2017)

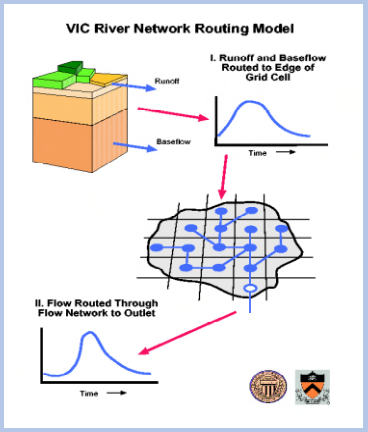
How precipitation variability from anthropogenically-influenced climate change affects streamflow in Colorado River



Dynamical downscaling



Bias correction



Global IPCC climate projections (1-2°)

Regional climate simulations (25 km to 3 km)

Basin-scale simulations

Statistical Downscaling (BCSD)

COLORADO RIVER BASIN

Operationally used statistically downscaled climate data: Bureau of Reclamation

CMIP3 GCMs	No. of BCSD SRES A2 runs
MPI3	3
HadCM3	1
CGCM3	5
GFDL	1
CCSM	4
Total number of ensemble members	14

Dynamically downscaled climate data:

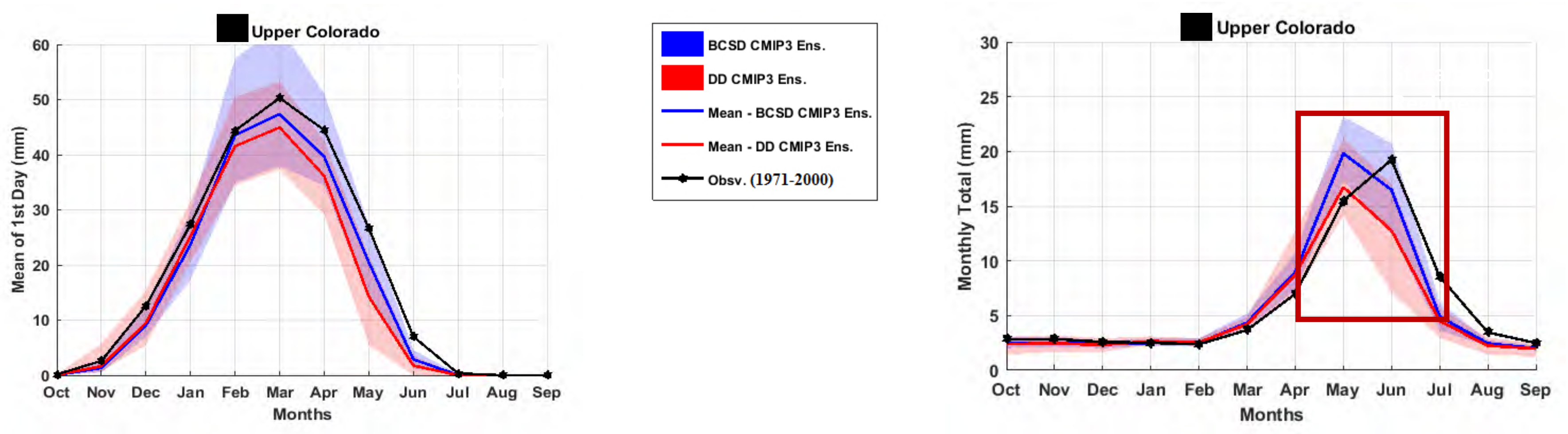
		NARCCAP Database						University of Arizona	No. of DD models for corresponding GCMs
	RCMs	CRCM	ECP2	HRM3	MM5I	RCM3	WRFG	WRF	
CMIP3 GCMs									
MPI3								WRF-MPI3	1
HadCM3								WRF-HadCM3	1
CGCM3		CRCM-CGCM3				RCM3-CGCM3	WRFG-CGCM3		3
GFDL			ECP2-GDFL	HRM3-GDFL		RCM3-GDFL			3
CCSM		CRCM-CCSM			MM5I-CCSM		WRFG-CCSM		3
						Total number of ensemble members			11

Bias Correction Statistical Downscaling (BCSD) Methodology

- **Bias Correction**: Performed on monthly GCM variables at 2° resolution against Maurer et al., 2002 observed dataset for the historic (1950-1999) and scenario (2000-2099) period a using non parametric quantile mapping technique.
- **Spatial Disaggregation**: A modified inverse-distance-squared interpolation method to disaggregate the monthly variables from 2° to 1/8° resolution.
- **Temporal Disaggregation**: Generating daily variables by preserving sequences of daily values from a sample historical month.
- The bias corrected daily climate variables are used as forcings on **Variable Infiltration Capacity (VIC)** model v. 4.0.7 to generate hydrologic projections for Upper Colorado, Salt and Verde Basins.

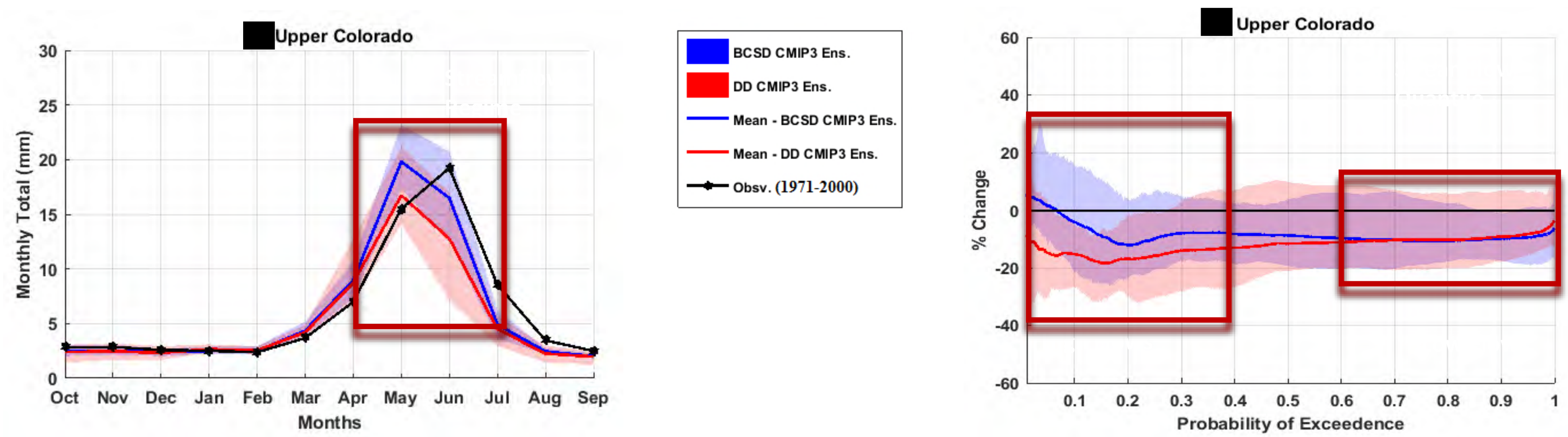
(Swietanek et al. 2017)

Upper Colorado Basin
Projections in Scenario Period (2041-2070)



- Projected increase in spring (Mar-May) streamflow and reduction in summer (Jun-Aug) streamflow as compared to observations from both dynamical and statistical downscaling Ens.
- Both Ens. also projects a shift in hydrograph peak from June to May.
- With lower winter/spring precipitation and reduced April 1st SWE, dynamical downscaling Ens. mean projects a reduced streamflow amount during May and June, the months when the hydrograph peaks, as compared to statistical downscaling Ens

Upper Colorado Basin
Projections in Scenario Period (2041-2070)



- The mean of dynamical downscaling Ens. projects a greater reduction in high flows and flows during moist condition (PE<0.4) as compared to statistical downscaling Ens., as the former projects a decrease in hydrograph peak during May and June.
- Low flows and flows during dry conditions (PE>0.6) shows similar projections for both dynamical and statistical downscaling Ens. means.

Pseudo global warming

- Key interest: Sequencing of drought and wet event projection
- Can we have a modeling framework that is possible to represent the sequencing and duration of dry and wet periods that's consistent to observation record?
- CMIP3 doesn't get the long-term drought (CMIP5 may not get it either, Sheffield et al 2013)
- Ault et al (2013): Swap the higher modes of variability from CMIP5 and replace it with paleo climate record. Weakness: does not account for dynamical features.
- Dynamically downscaled 20C reanalysis gets the long-term drought record! Apply for the future climate projection.

Summary:
Colorado River Streamflow Hydrology

- Lower winter and early spring (Jan-Apr) precipitation is projected in mid 21st century
- Lower future April 1st snowpack – indication for spring streamflow recharge
- Earlier snowmelt – shift in hydrograph peak from June to May
- Greater reduction in high flows and flows during moist condition ($PE<0.4$), and lower streamflow during peak season.
- **Most significant hydrologic impact is found in high flows**

Another Extreme Event Study Application: Dust Storms

Image: Mike Oblinski

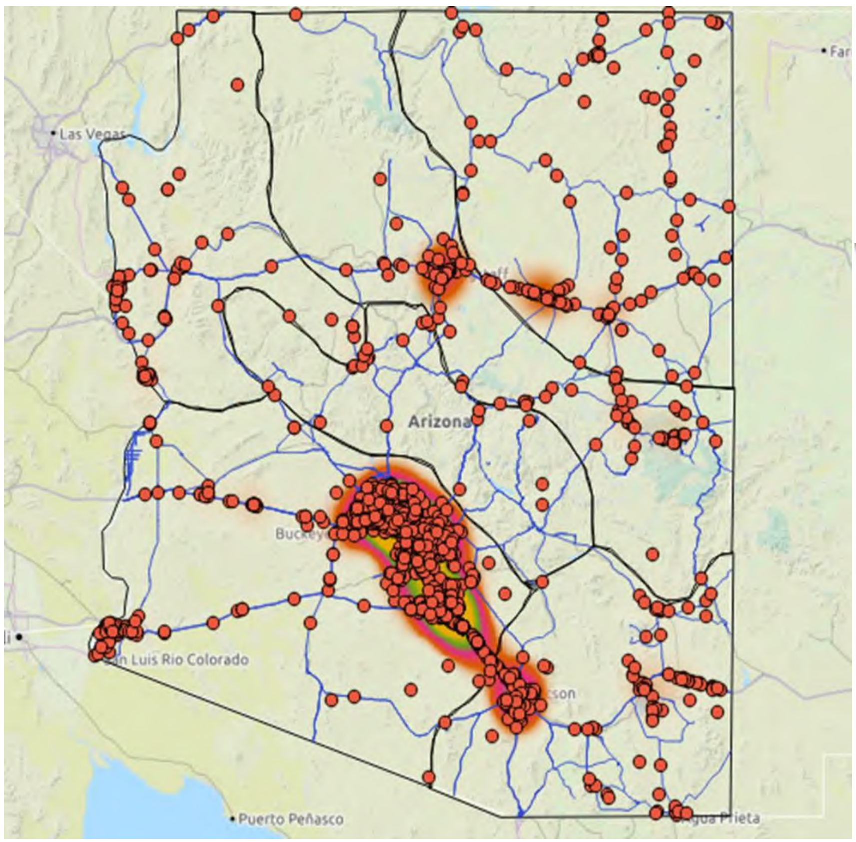
July 5th, 2011
Massive Haboob Hits Phoenix

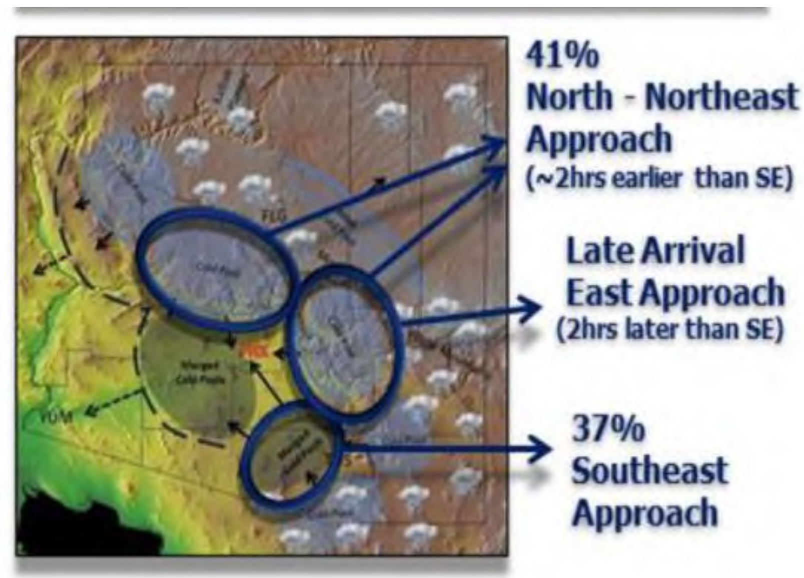
2011 Phoenix Dust Storm/Haboob

- Dust storm: Common natural hazard during summer monsoon in Southwest U.S.
- July 5th, 2011: once-in-100-year dust storm event
- Peak vertical height: ~ 1 mile (1.6 km)
- Horizontal area covered: leading edge stretched nearly 100 miles (160 km)
- Travel distance: 150 miles (average 25-50 mile)
- Damages: Airport/highway closure, power outage, public health

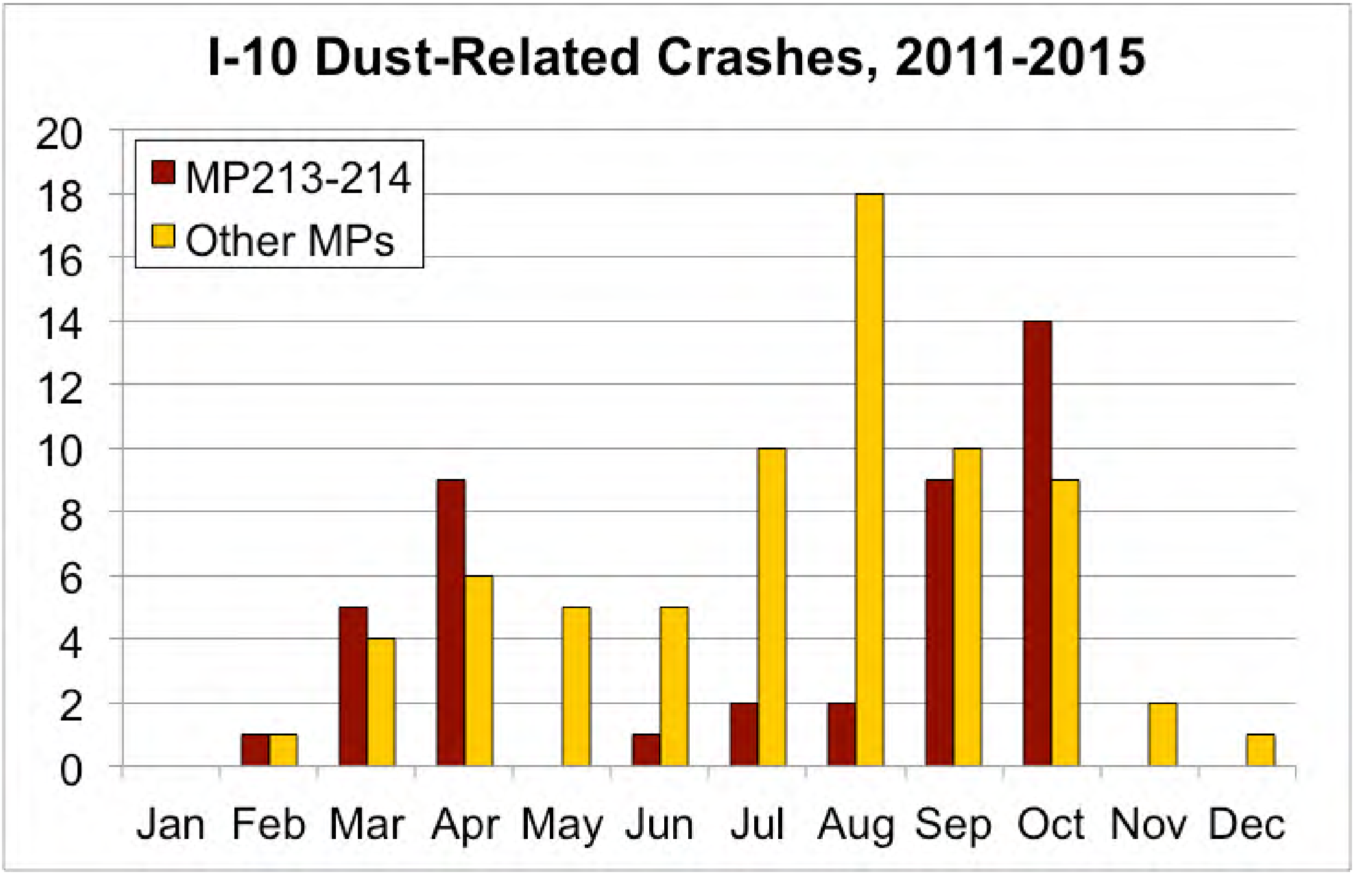
Dust Storm Hotspots: Tucson, Phoenix, Yuma, Flagstaff, Winslow, Willcox

[*National Centers for Environmental Information (NCEI) Storm Data, 1955-2011]*





Assessing highway crash patterns

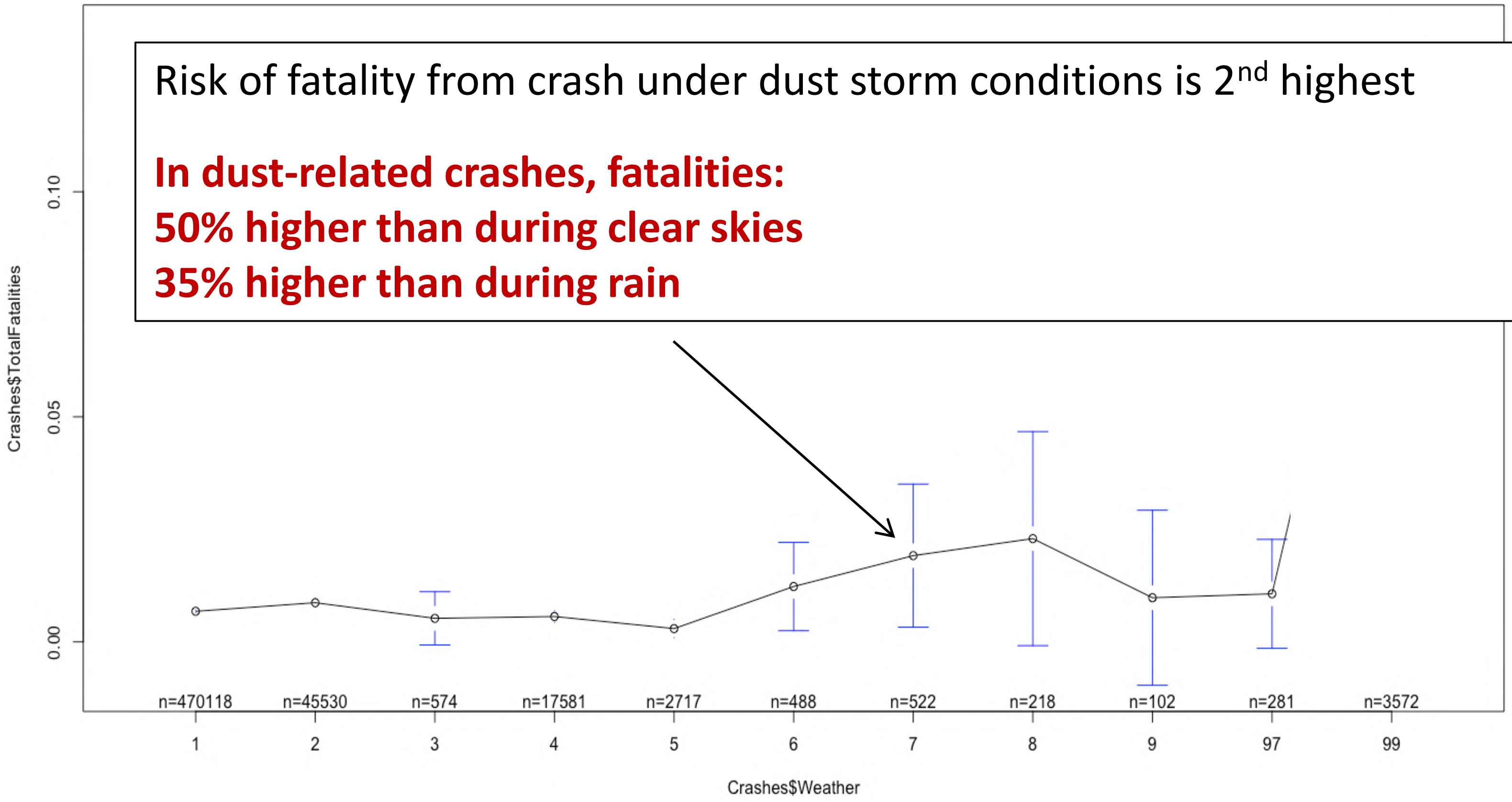


Preliminary Results

Evaluating crash risks

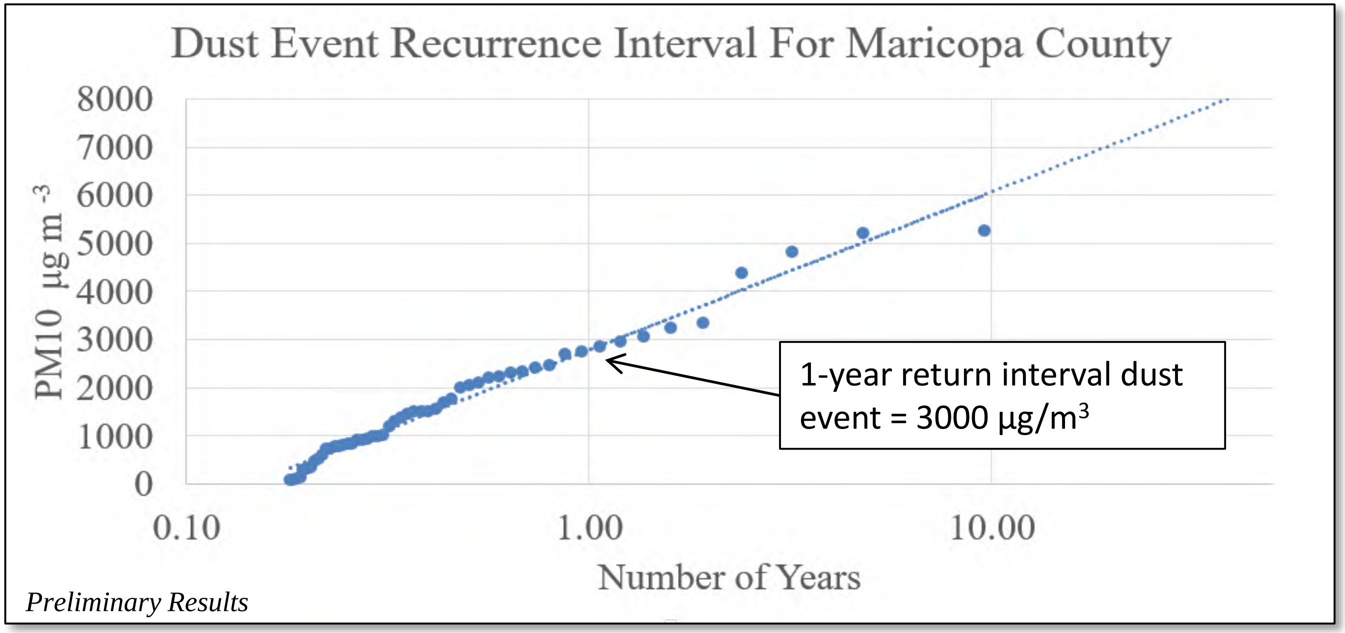
Risk of fatality from crash under dust storm conditions is 2nd highest

In dust-related crashes, fatalities:
50% higher than during clear skies
35% higher than during rain



Preliminary Results

Categorizing dust events (PM10)



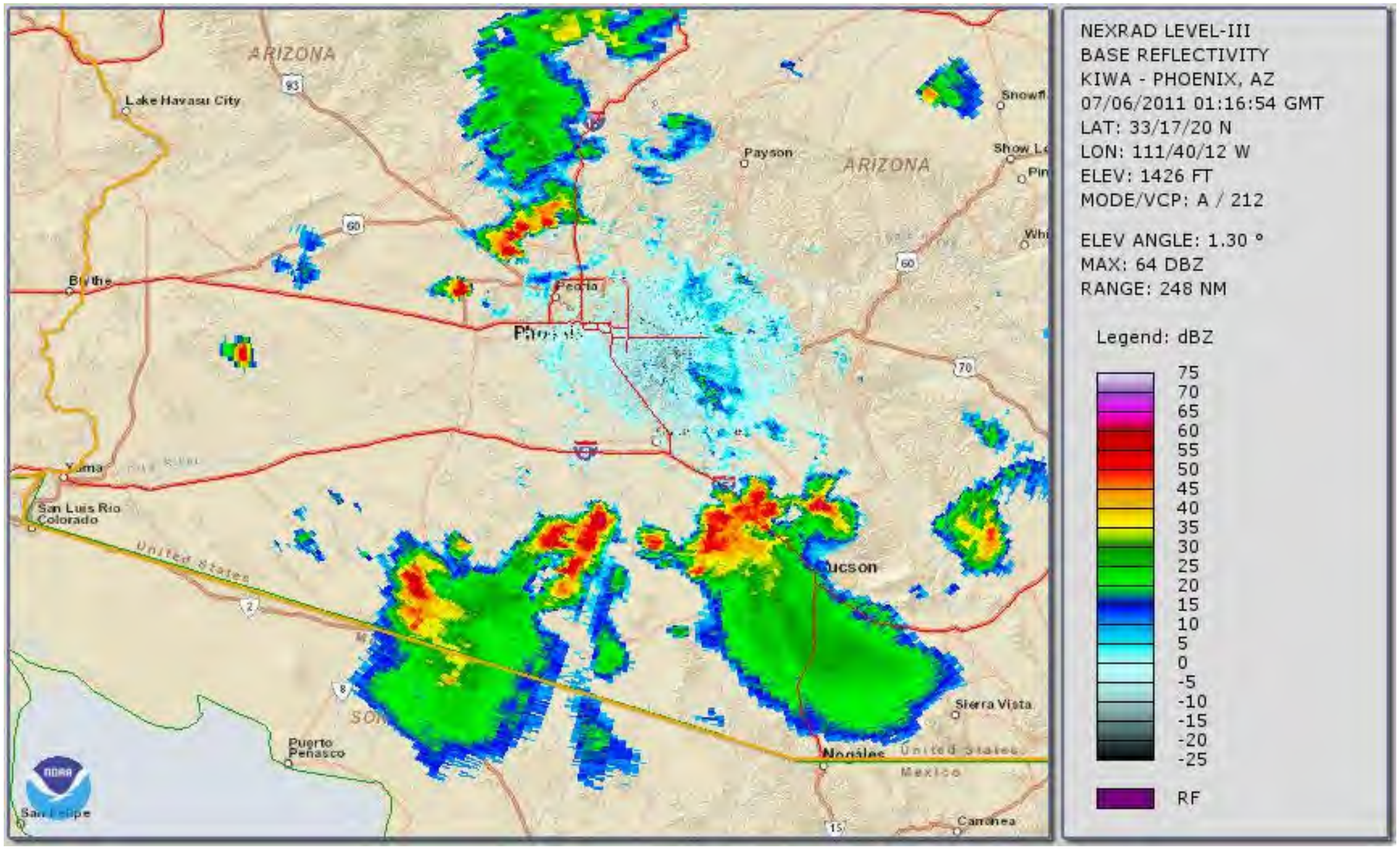
Can we catch dust signature with model?

- Arizona Dust Storms
  - Summer Dust storms form from monsoon thunderstorms (July and August)
  - Spring Dust storm is cold-front related
- Case Study presented
  - July 5th, 2011, a powerful dust storm swept through Phoenix, Arizona.
- Cases identified with dust-related highway fatality and major property damage between 2011-2016: 16

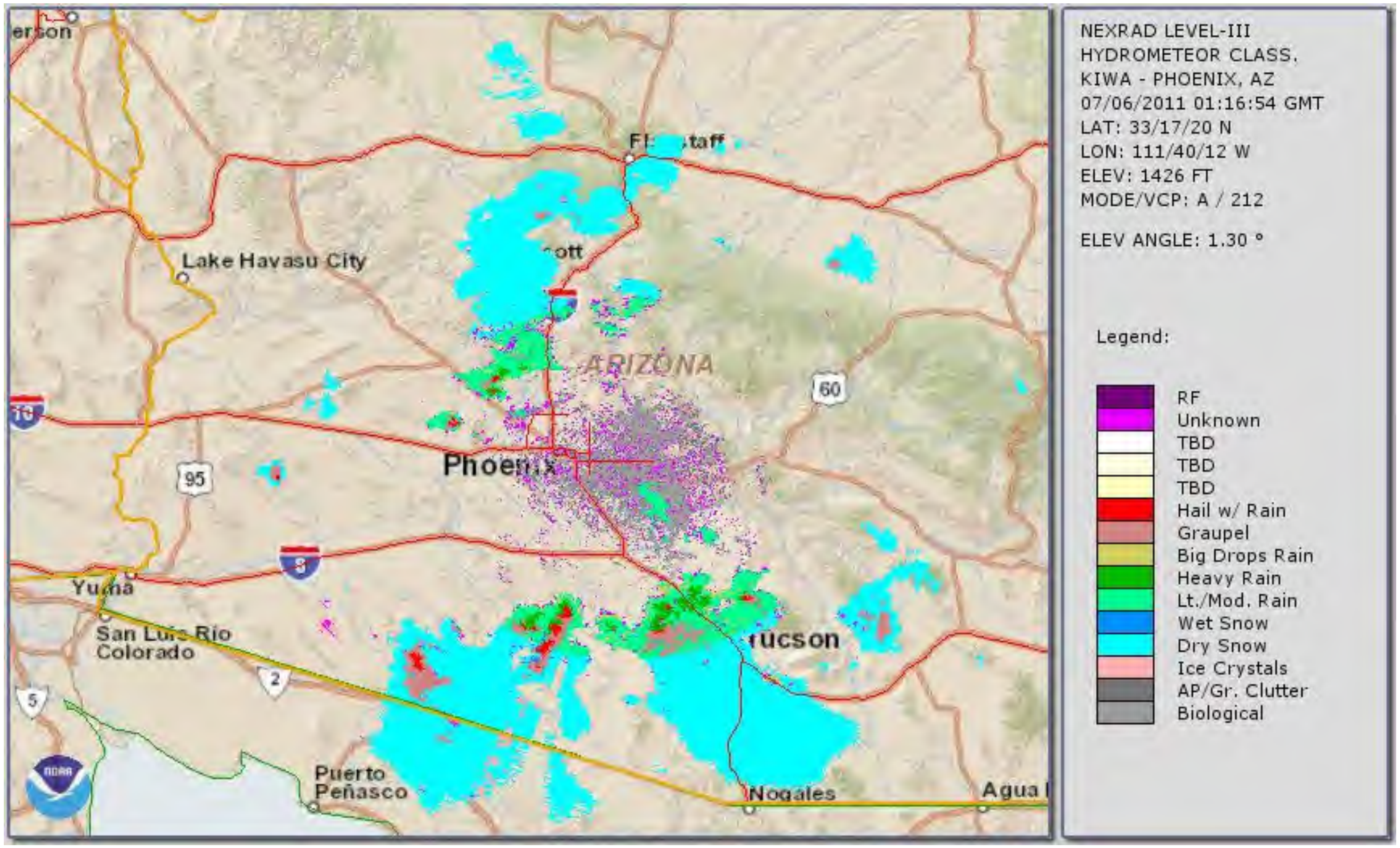
Month	%
January	2%
February	3%
March	5%
April	13%
May	13%
June	7%
July	28%
August	17%
September	6%
October	4%
November	1%
December	1%

Arizona Recorded Dust Storms
1/17/1996 - Present

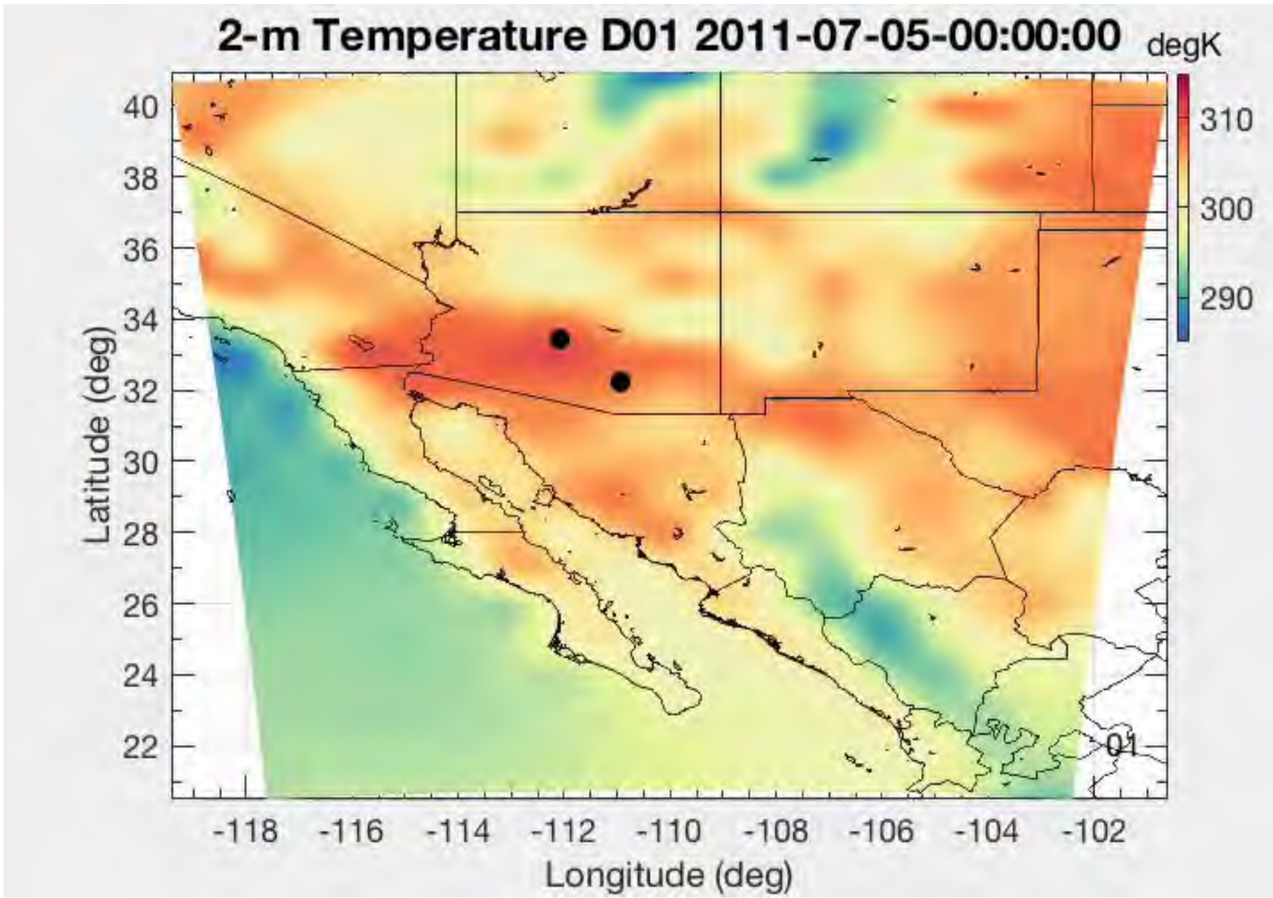
Radar Observed Reflectivity (NEXRAD)



Radar Observed Hydrometer (NEXRAD)



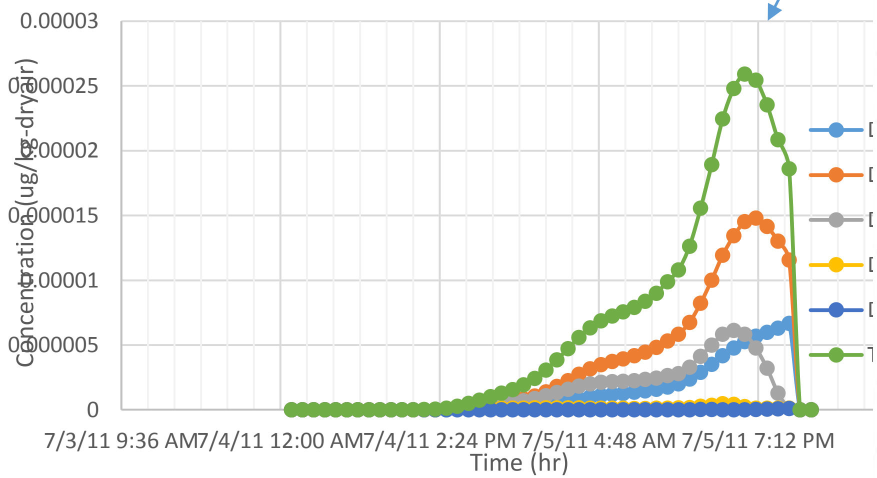
July 11, 2011 case with operational WRF model

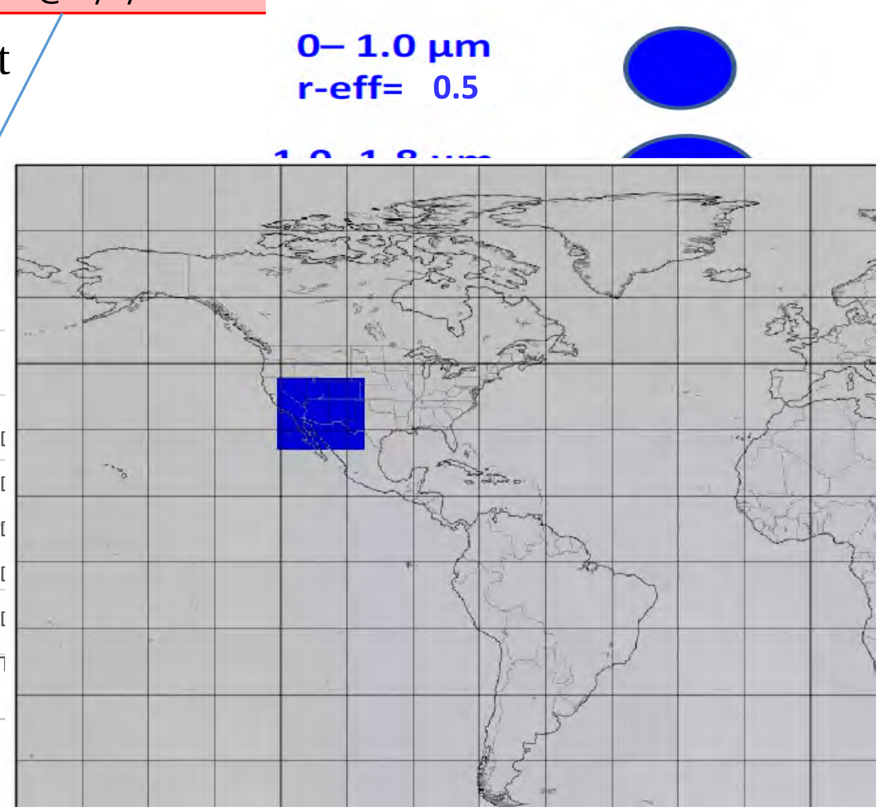


Dust concentration from WRF-Chemistry

Recorded 7/5/2011 19:50~20:45
Modeled Peak @ 7/5/2011 18:00

- Peak is a function of latitude, longitude, height
- Mostly dust with radius < 1.4 μm





Dust storm – related highway fatality prevention
Arizona Department of Transportation (ADOT)

- New dust storm detection protocol on Interstate I-10
  - Doppler radar for dust storm detection (10-mile radious)
  - Real-time dust sensors
  - Immediate highway patrol response for road closure

ADOT Weather Brief 01.23.17 158PM MST By ADOT Meteorologist Ray Greely: Forecast Valid 01.22.17 through 01.24.17

An increase in precipitation this morning and afternoon in central areas and then in the northwest after a relatively quiet night. Snow levels were running mostly in between 5000-6000 ft. This type of activity will continue but with a noticeable increase through the afternoon hours. A front is expected to traverse the area today and ahead of this feature there will be an increase in of rain and snow activity. The peak for the heaviest precipitation will be mid afternoon through the evening for the northwest areas, late afternoon through late evening for the central areas the this evening through tomorrow morning for the much of the east, the White Mountains, and into the southeast. Snow levels will fall back to 5000 ft level by late afternoon for areas west of the 17 with slightly lower levels north of I40 and then down to about 4500 ft by morning but the core of the precipitation should be passed this area by then. Further east snow levels will likely hold in 5500 -6500 ft level until this evening when levels will drop to about 5000 ft and then to about 4500-5000 ft by morning for most areas but lowering to all but the lowest valley floors in far north central and northeastern areas approaching the Utah Border. Snow fall accumulations tonight will range from a dusting to a couple of inches from 5000-6000 ft, 6-12 inches from 6000 ft -8000 ft inches and 10-15 inches above that level. Note that the highest accumulations will be from the Flagstaff area and then extending southeastward through the rim and areas outside of this zone will see snow totals on the lower end of this scale. Temperatures will hold steady through most of the afternoon with most areas in the mid to upper 30s from 5000-6000 ft and mid 20s to near 30 for elevations of 6000-8000 ft. By later this evening temperatures will range

- Include dust-storm forecast in daily ADOT weather report
- Provide additional dust detection criteria: atmospheric condition favorable for dust initiation
- Real-time report of dust source from highway patrol

Take Home Messages

- Long-term climate-type downscaling simulations requires careful selection criteria before hitting the 'go' button!
- We should look beyond the average of mean and extreme climatology when considering anthropogenically influenced climate change on decision making
- **For monsoon-active regions with complex terrain (Southwest U.S., Taiwan), climate simulation at CPM spatial scale can add significant value**
- The applicability of CPM-type simulation is extensive across spatial and temporal time scale

Acknowledgement

- Christopher Castro, University of Arizona
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- Amin Mohebbi, Nothern Arizona University
- Andreas Prein, NCAR
- Daniel Lein, National Weather Service