Adaptive Hydrologic Design and Water Resources Management

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HYDROSYSTEMS RESEARCH LABORATORY

UNESCO Category II Centre on Integrated and Multidisciplinary Water Resources Management,

Thessaloniki, Greece (CIMWRM) Webinar, November 27 2020

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HRL

Water . Environment . Climate .

Committed to Understanding, Modeling and Managing Terrestrial Hydro-Environmental Systems

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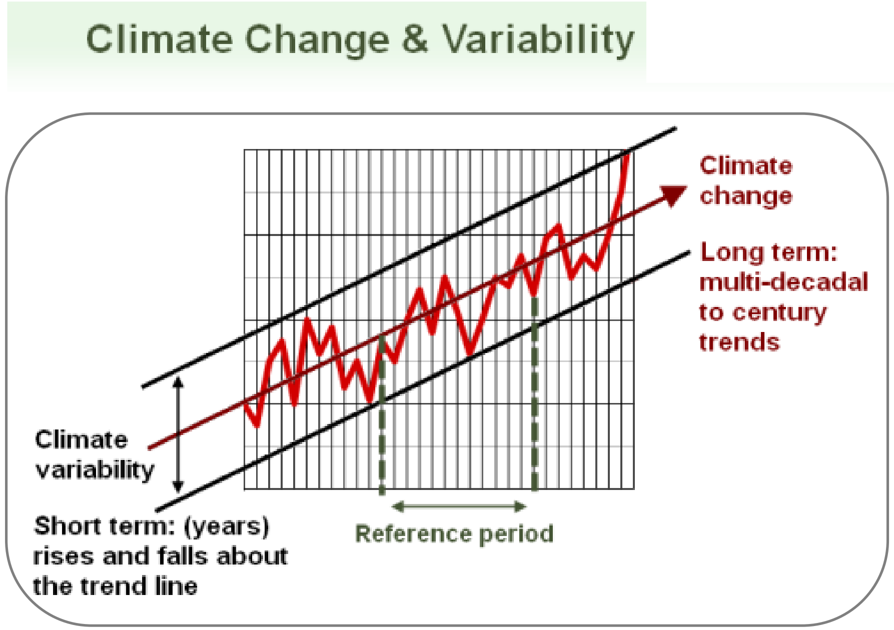
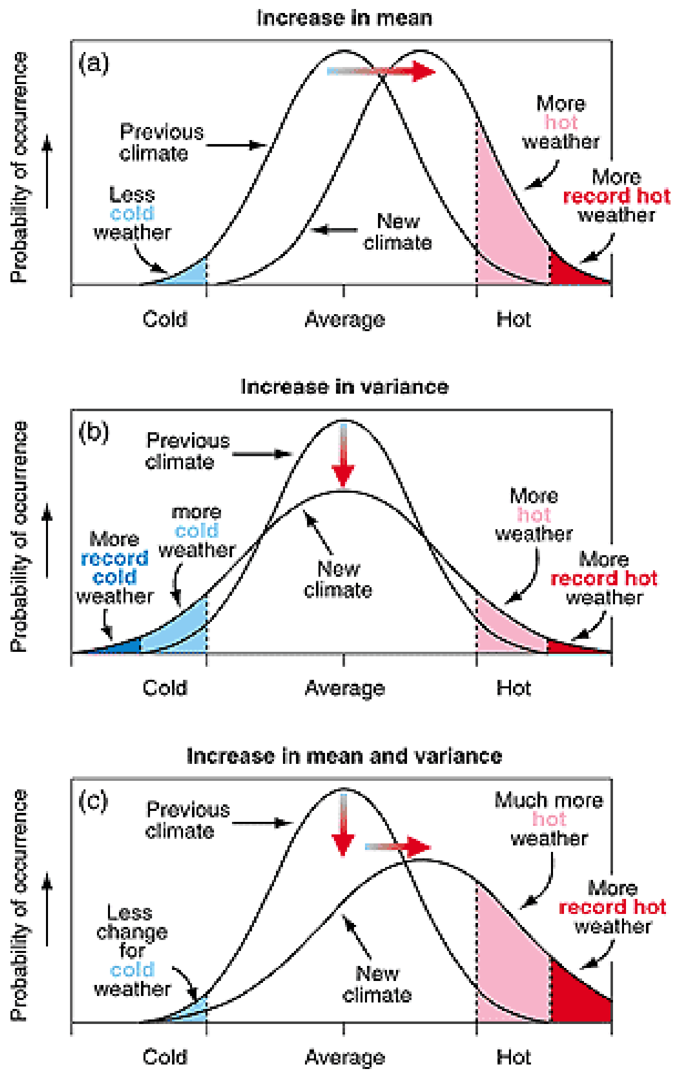
Climate Variability and Change



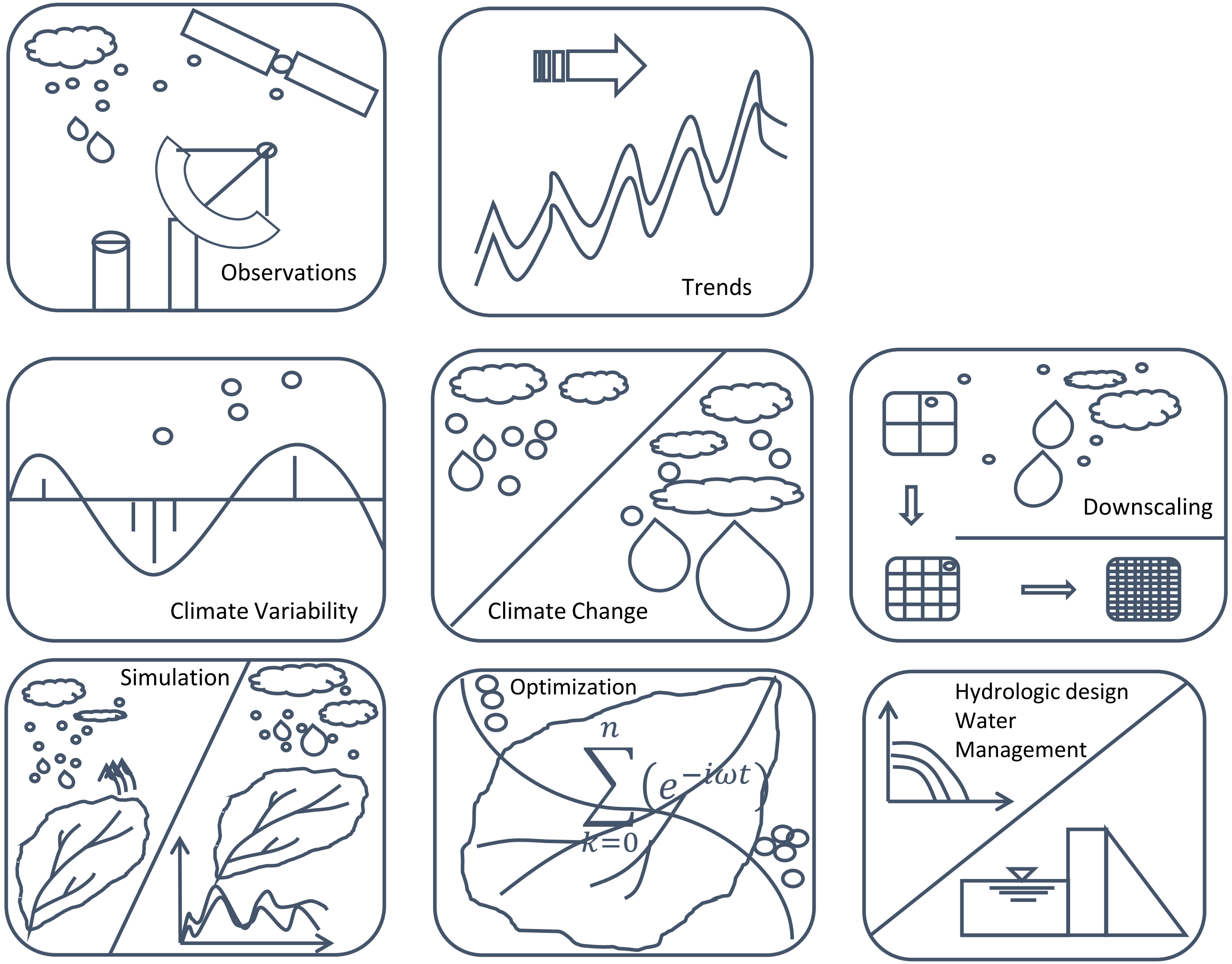


UNFCCC makes a distinction between "climate change" attributable to human activities altering the atmospheric composition, and "climate variability" attributable to natural causes.

United Nations Framework Convention on Climate Change

(Source: IPCC)

Addressing Evolving Climate



Teegavarapu 2013 and 2018

Coupled Oceanic Atmospheric Oscillations

- Natural internal processes within the climate system (internal variability): Oceanic-Atmospheric Oscillations and Teleconnections

- Major oscillations around the globe:
  - Atlantic Multi-decadal Oscillation (AMO)
  - El Niño Southern Oscillation (ENSO)
  - Pacific Decadal Oscillation (PDO)
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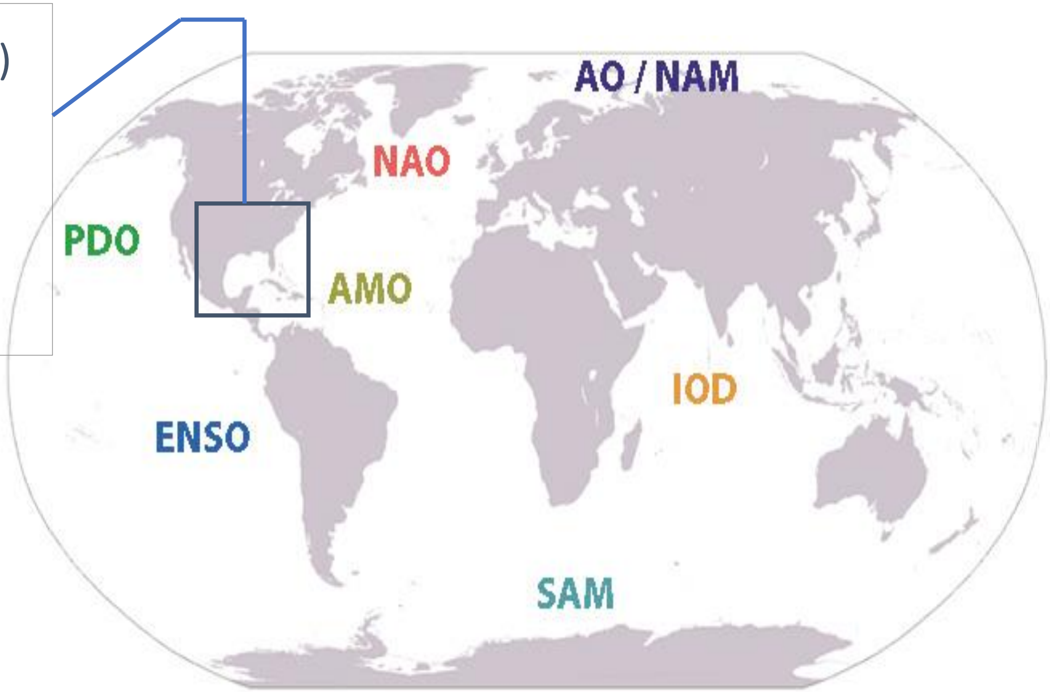
  - Southern Annular Mode (SAM)
  - Indian Ocean Dipole (IOD)
  - Artic Oscillation (AO)



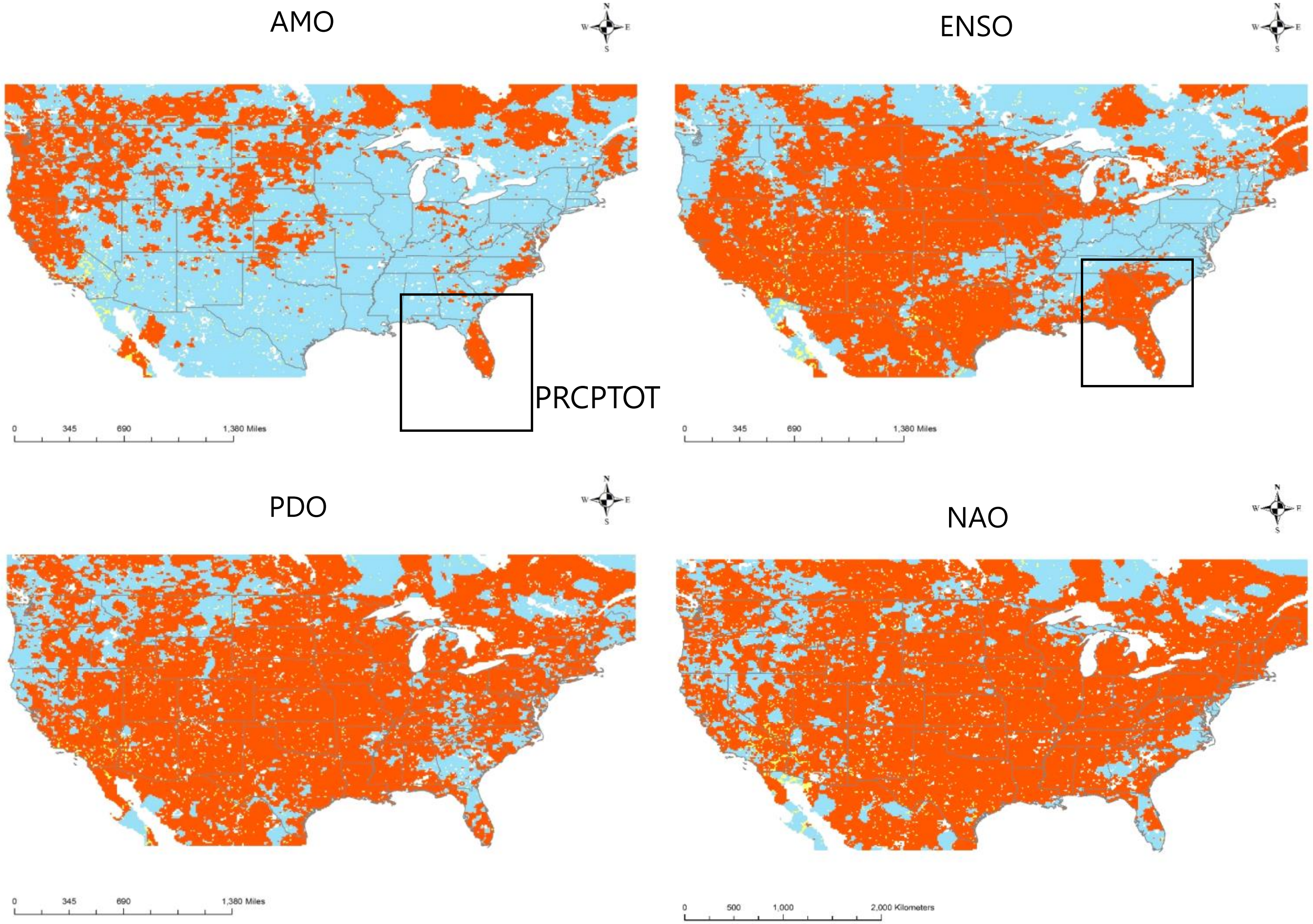
2015 El Niño Season

December 2015
Los Angeles

The latest rain has been significant so far since Sunday, pouring 1.3 inches in Laguna Hills, 1.39 inches on downtown L.A., 1.45 inches in San Juan Capistrano, 1.64 inches in Ventura, 1.75 inches in Beverly Hills, 1.79 inches in South Gate, 1.97 inches in San Onofre, 2.2 inches in Pasadena and 2.46 inches in Alhambra as of 2 p.m. Tuesday.

Source: LA Times

Precipitation Totals



Goly and Teegavarapu, 2013

- AMO: Influence of AMO is prominent in southeastern US (esp. Florida) and northwestern part of the US.
- ENSO: Unlike AMO, ENSO warm phase (El Niño) has more uniform affect on precipitation over entire U.S except parts of southeast and northwest.

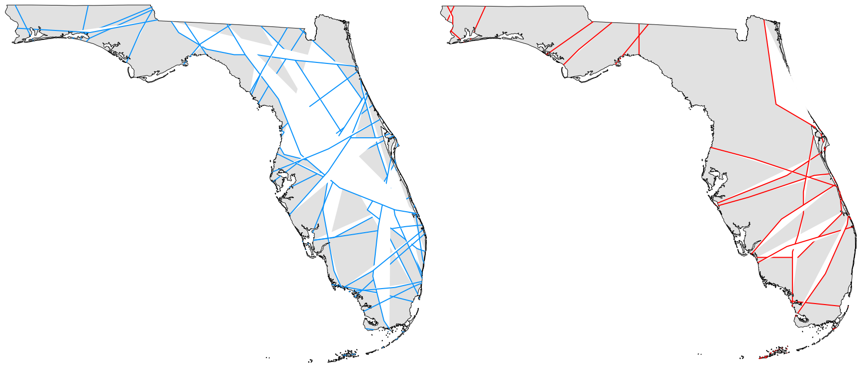
All tropical storms and Hurricanes since 1851 (Atlantic) and 1949 (Pacific)

E-mail: rteegava@fau.ed

Hurricanes

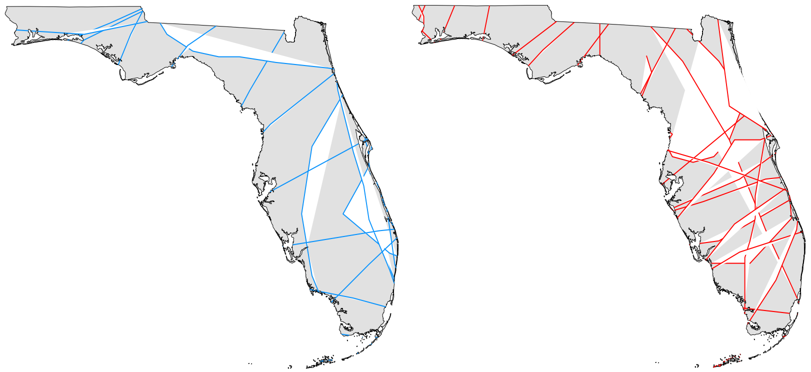
PDO

36 Storms 18 Storms



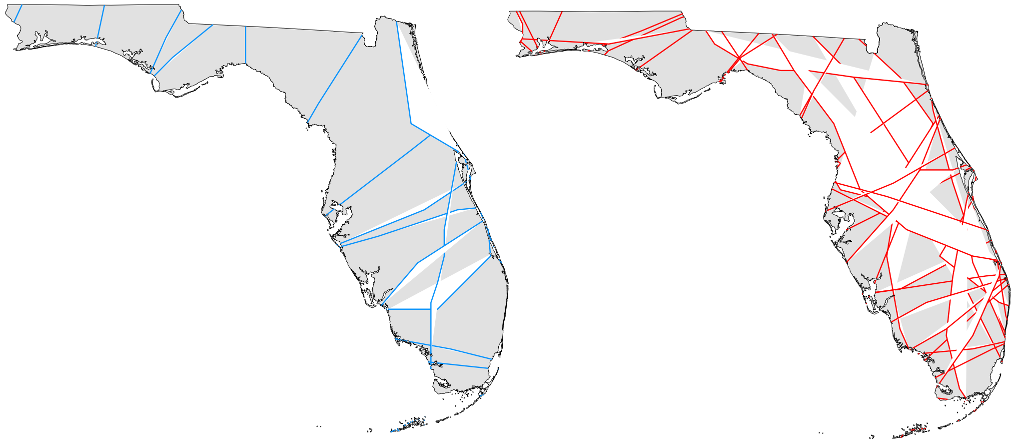
NAO

20 Storms 25 Storms



AMO

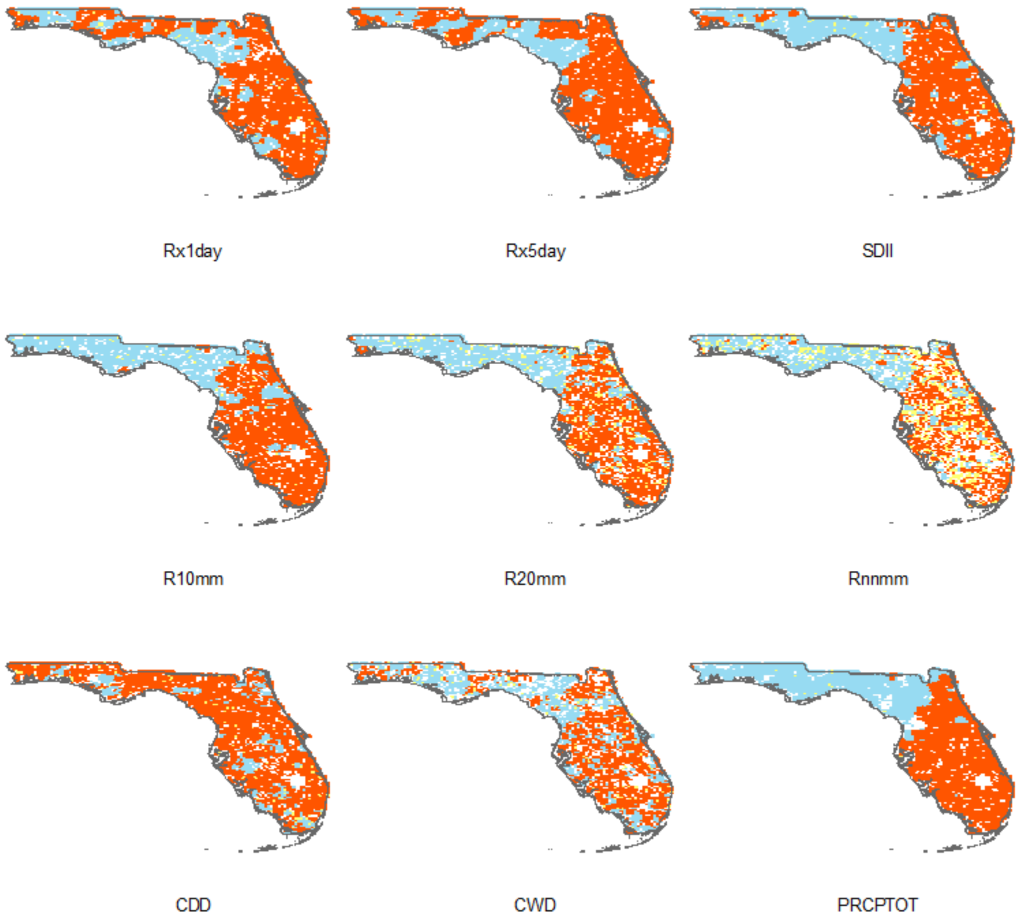
16 Storms 38 Storms



Red: Warm
Blue: Cool

Category 3 or more. Teegvarapu and Milla, 2013.

Variability of Precipitation Extremes



9 extreme precipitation Indices

Gridded Data
3270 grids
Spatial resolution : 6.5 km

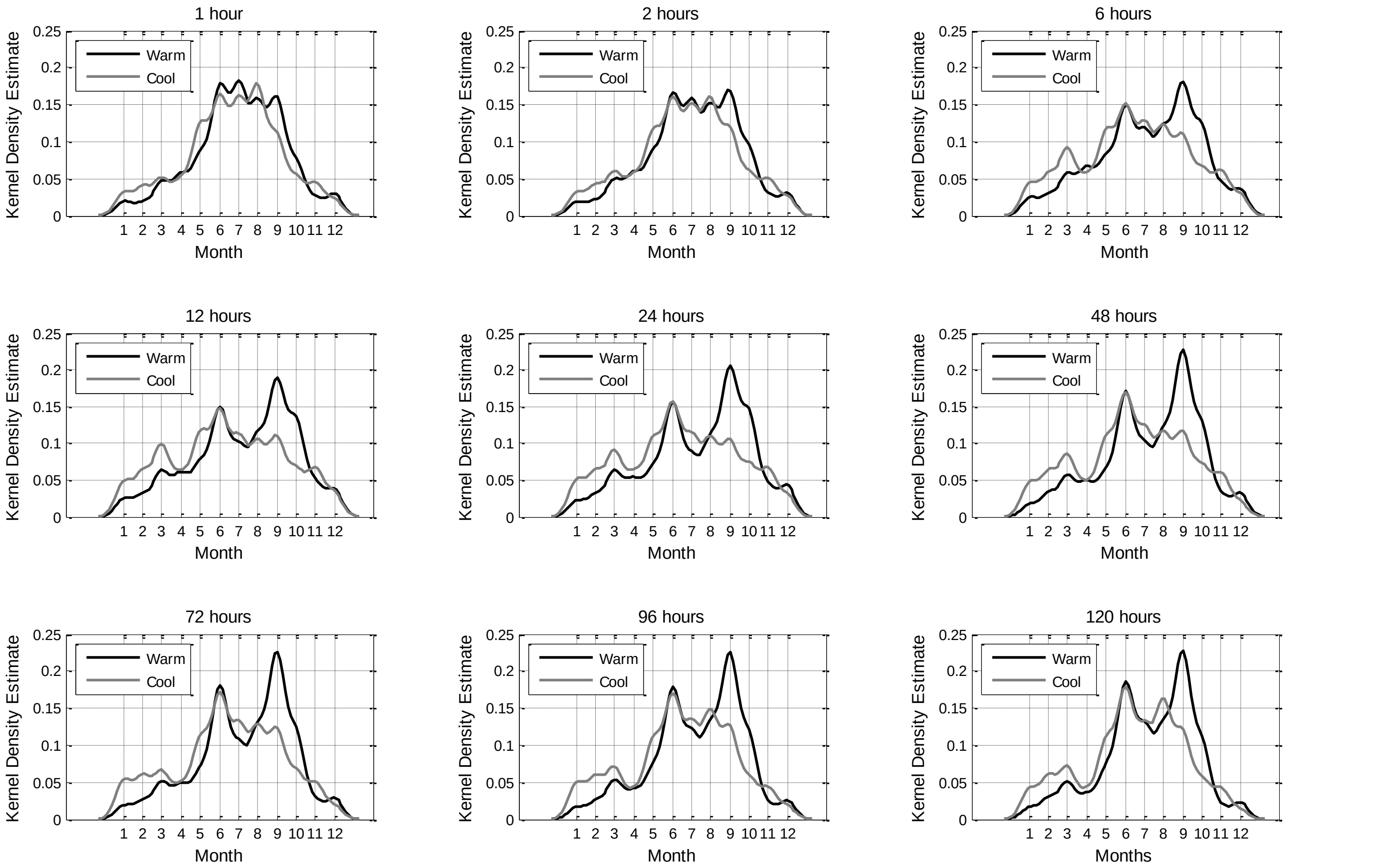
Statistical significantly changes

Thermic and hyperthermic (in continental and peninsular regions)

Goly and Teegavarapu, 2014, *Water Resources Research*

Temporal Shifts

Warm

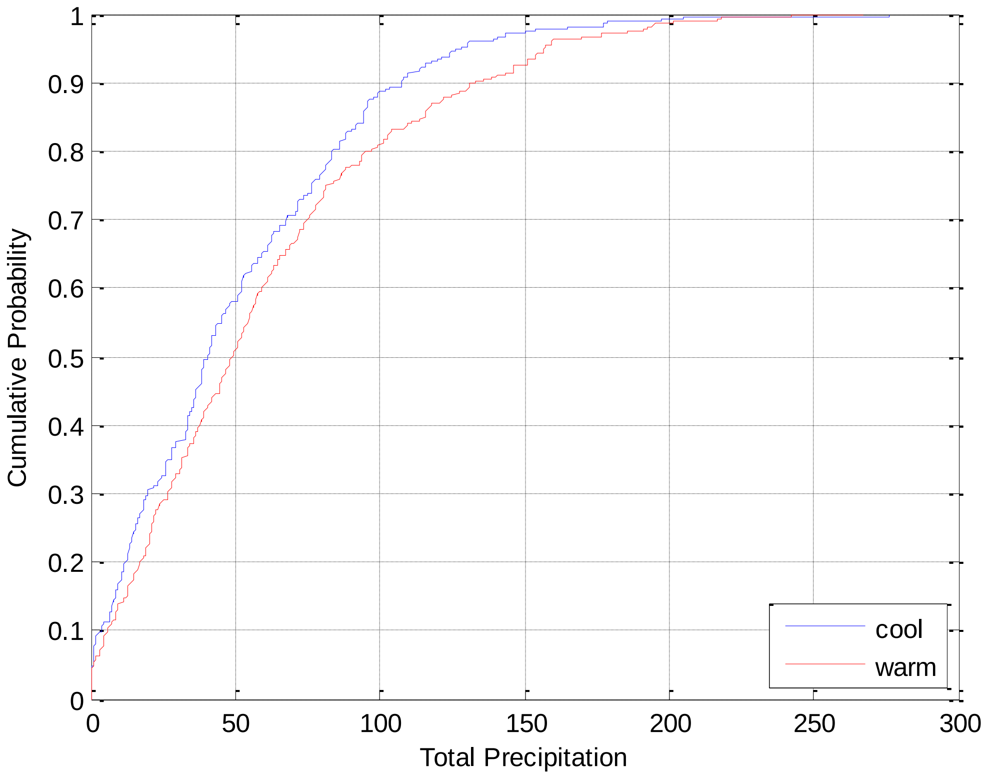


Cool

Teegavarapu, et al. 2013, Journal of Hydrology

Implications on Flood Control Management in the region, water storage

AMCs



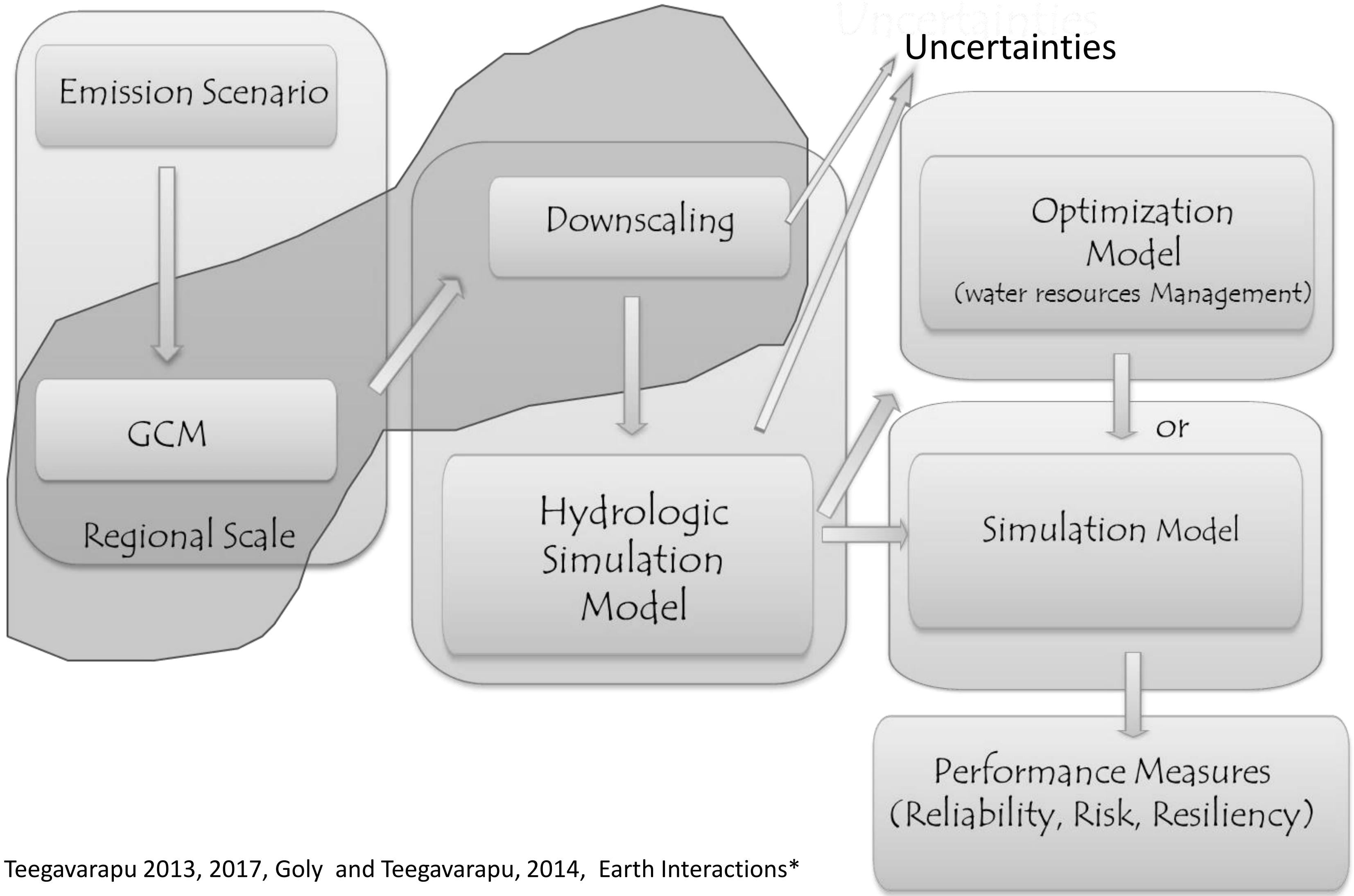
Antecedent moisture conditions preceding one day extremes are evaluated for AMO cool and warm phases.

10-day precipitation totals show more wetter moisture conditions for warm phase compared to cool phase.

Implications on design floods in the region.

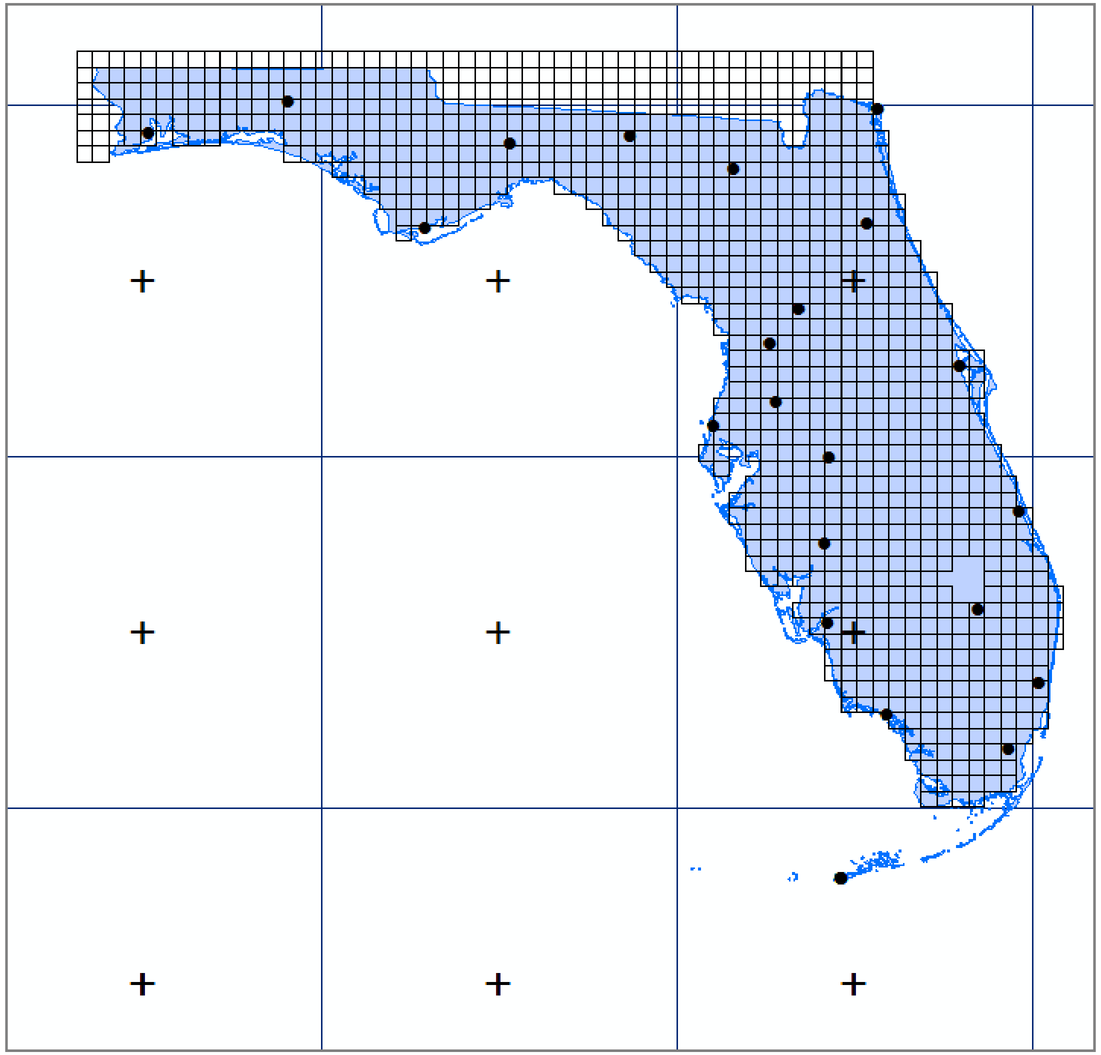
Goly and Teegavarapu, 2014, *Water Resources Research*

Hydrosystems Management



Teegavarapu 2013, 2017, Goly and Teegavarapu, 2014, Earth Interactions*

Statistical Downscaling



- In-house (FAU) downscaling models*
- Bias Corrected Statistical Downscaling (BCSD)
- Observed Data Sets
- Resolution : 1/8^{o}
- Data Availability: 1940s – present Day

Goly and Teegavarapu, 2014, Earth Interactions*

Multi-Model Performances (temperature)

Correlations

Station \ Climate Model	BCCR-BCM2.0	CGCM	CNRM-CM	CSIRO-Mk	GFDL-CM	GISS-ER	INM-CM	IPSL-CM	MIROC	ECHO-G	ECHAM5	MRI-CGCM	CCSM3	PCM	UKMO-HadCM
1	0.92	0.91	0.92	0.91	0.92	0.92	0.92	0.92	0.92	0.91	0.91	0.92	0.92	0.92	0.91
2	0.92	0.91	0.92	0.92	0.93	0.93	0.93	0.92	0.92	0.91	0.92	0.92	0.92	0.92	0.92
3	0.91	0.90	0.91	0.90	0.91	0.91	0.91	0.91	0.90	0.90	0.90	0.91	0.90	0.91	0.91
4	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
5	0.93	0.92	0.92	0.92	0.93	0.93	0.94	0.93	0.93	0.92	0.93	0.93	0.93	0.93	0.93
6	0.90	0.89	0.89	0.89	0.89	0.90	0.90	0.90	0.89	0.89	0.89	0.90	0.89	0.89	0.89
7	0.92	0.91	0.92	0.91	0.92	0.92	0.92	0.92	0.91	0.91	0.91	0.92	0.91	0.91	0.91
8	0.91	0.90	0.91	0.90	0.91	0.91	0.91	0.91	0.91	0.90	0.90	0.91	0.90	0.91	0.90
9	0.93	0.92	0.92	0.92	0.93	0.93	0.93	0.92	0.92	0.92	0.92	0.92	0.92	0.93	0.92
10	0.94	0.93	0.93	0.93	0.94	0.94	0.94	0.94	0.93	0.93	0.94	0.93	0.94	0.94	0.93
11	0.94	0.94	0.93	0.93	0.94	0.94	0.94	0.94	0.94	0.93	0.94	0.93	0.94	0.94	0.94
12	0.93	0.92	0.92	0.92	0.93	0.93	0.93	0.93	0.93	0.92	0.92	0.92	0.93	0.93	0.92
13	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
14	0.90	0.90	0.90	0.89	0.90	0.90	0.90	0.90	0.90	0.89	0.90	0.90	0.89	0.89	0.90
15	0.92	0.91	0.92	0.92	0.93	0.93	0.93	0.92	0.92	0.91	0.92	0.92	0.92	0.93	0.92
16	0.94	0.94	0.94	0.93	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94	0.94
17	0.93	0.92	0.92	0.92	0.93	0.93	0.93	0.92	0.92	0.92	0.92	0.92	0.92	0.92	0.92
18	0.92	0.91	0.92	0.91	0.92	0.92	0.92	0.92	0.92	0.91	0.91	0.92	0.92	0.92	0.91

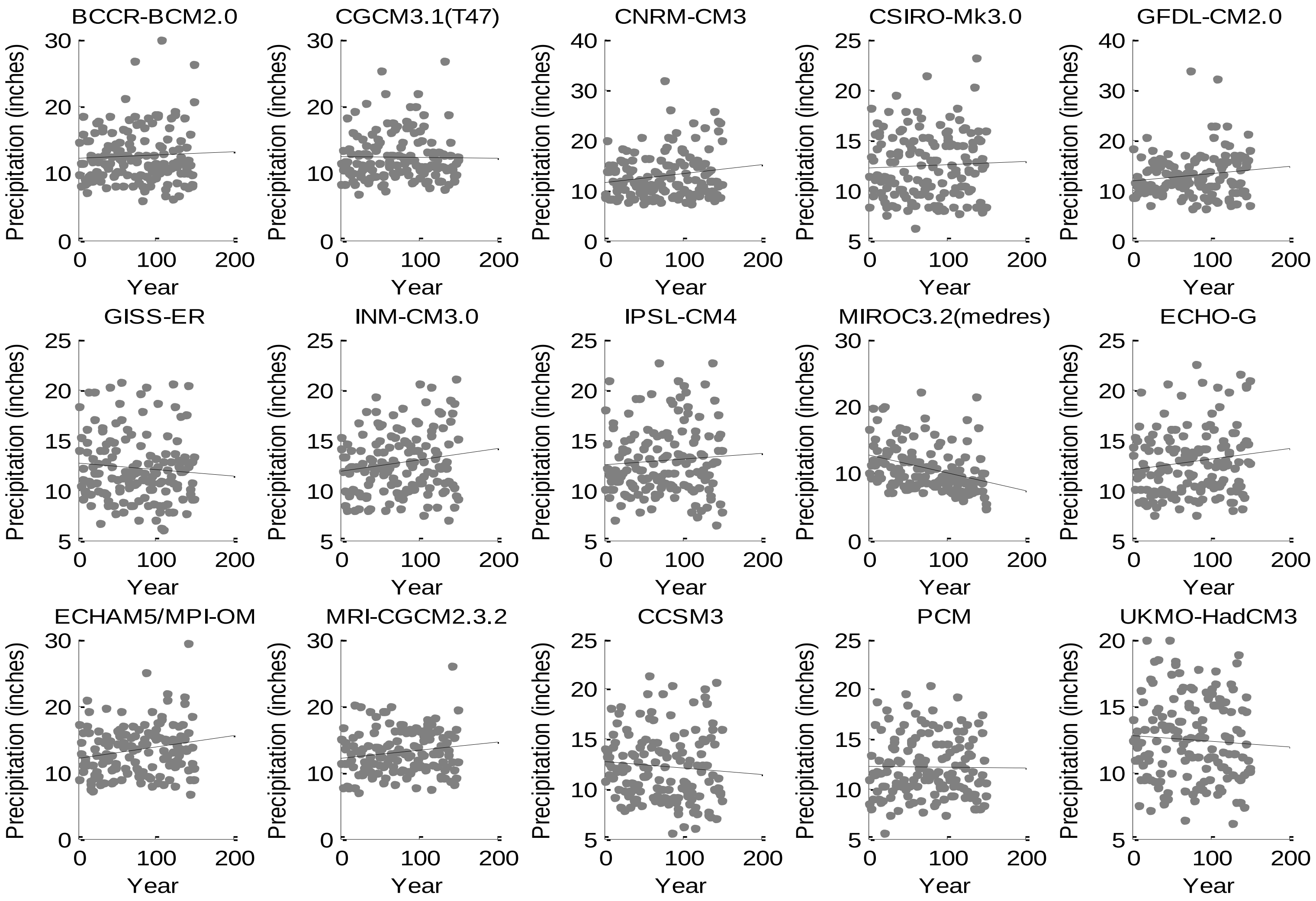
Multi-Model Performances (precipitation)

Correlations

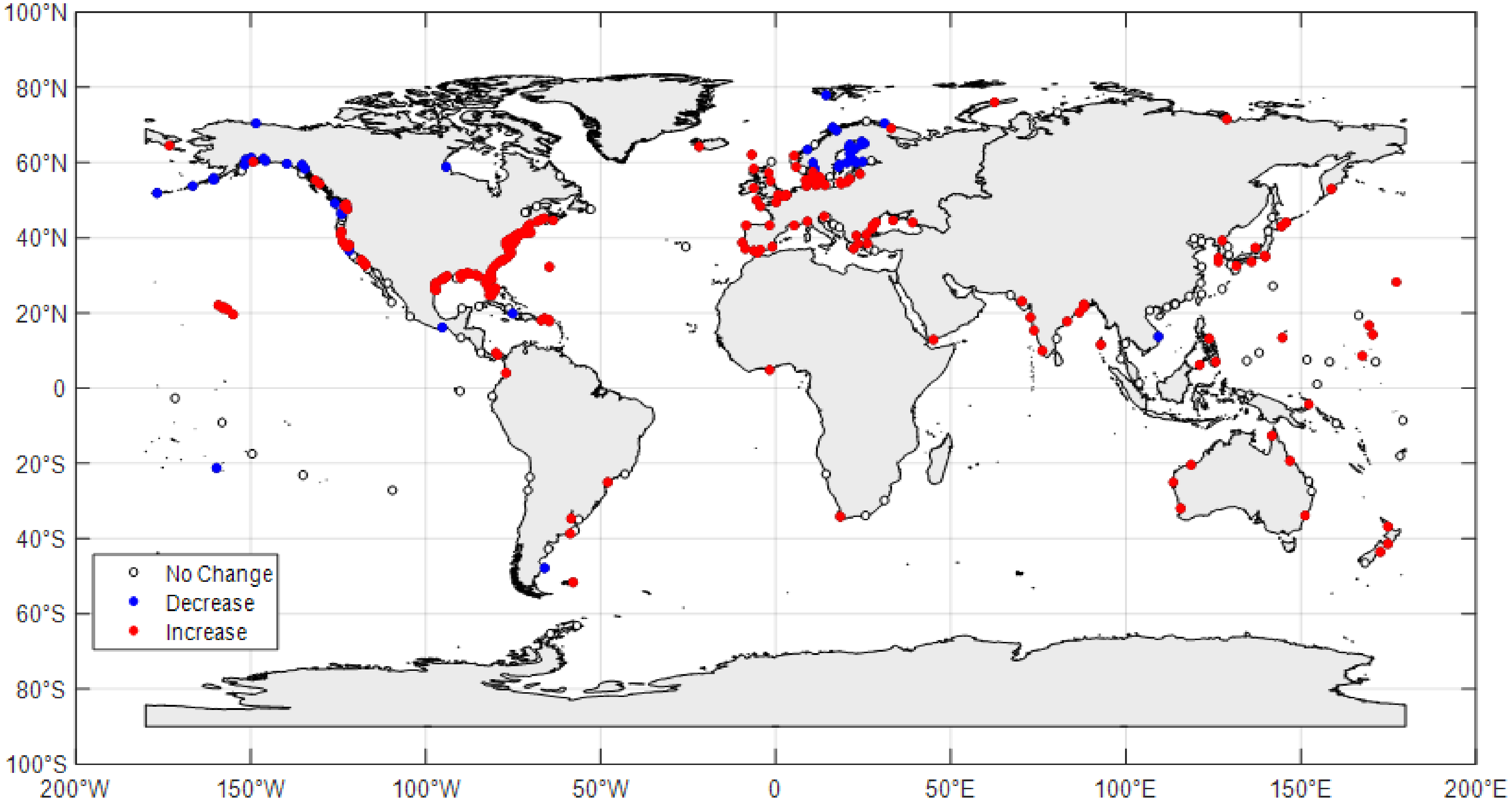
Station \ Climate Model	BCCR-BCM2.0	CGCM	CNRM-CM	CSIRO-Mk	GFDL-CM	GISS-ER	INM-CM	IPSL-CM	MIROC	ECHO-G	ECHAM5	MRI-CGCM	CCSM3	PCM	UKMO-HadCM
1	0.58	0.49	0.55	0.55	0.51	0.57	0.52	0.49	0.51	0.51	0.56	0.52	0.58	0.57	0.56
2	0.54	0.49	0.49	0.51	0.49	0.55	0.51	0.46	0.49	0.48	0.52	0.51	0.50	0.54	0.51
3	0.53	0.49	0.52	0.52	0.51	0.54	0.53	0.51	0.51	0.51	0.52	0.49	0.57	0.55	0.54
4	0.19	0.16	0.12	0.13	0.17	0.14	0.20	0.20	0.23	0.16	0.19	0.12	0.23	0.21	0.16
5	0.41	0.37	0.37	0.34	0.36	0.37	0.44	0.33	0.40	0.37	0.39	0.39	0.39	0.44	0.39
6	0.45	0.40	0.43	0.45	0.44	0.38	0.44	0.38	0.42	0.45	0.41	0.44	0.46	0.43	0.44
7	0.66	0.63	0.66	0.63	0.63	0.59	0.63	0.60	0.65	0.62	0.63	0.60	0.65	0.64	0.66
8	0.38	0.34	0.38	0.37	0.37	0.39	0.38	0.39	0.39	0.35	0.35	0.36	0.42	0.38	0.36
9	0.47	0.45	0.46	0.48	0.48	0.52	0.48	0.44	0.48	0.45	0.48	0.51	0.46	0.52	0.51
10	0.29	0.34	0.30	0.32	0.35	0.37	0.36	0.32	0.35	0.34	0.34	0.34	0.39	0.39	0.33
11	0.20	0.22	0.15	0.16	0.20	0.26	0.20	0.24	0.24	0.22	0.22	0.19	0.30	0.28	0.21
12	0.38	0.39	0.34	0.40	0.42	0.43	0.43	0.37	0.42	0.43	0.40	0.42	0.41	0.46	0.44
13	0.14	0.15	0.10	0.10	0.10	0.08	0.18	0.15	0.14	0.10	0.10	0.08	0.17	0.15	0.11
14	0.55	0.53	0.55	0.55	0.58	0.52	0.55	0.51	0.56	0.56	0.55	0.53	0.60	0.56	0.59
15	0.43	0.40	0.42	0.46	0.45	0.49	0.46	0.39	0.45	0.43	0.48	0.48	0.45	0.48	0.46
16	0.23	0.25	0.16	0.18	0.22	0.21	0.27	0.27	0.26	0.22	0.25	0.19	0.32	0.29	0.24
17	0.47	0.45	0.45	0.47	0.50	0.46	0.47	0.43	0.46	0.45	0.46	0.50	0.48	0.51	0.49
18	0.44	0.42	0.38	0.41	0.42	0.45	0.44	0.39	0.43	0.38	0.42	0.43	0.43	0.45	0.44

Future Projections

Multiple Models



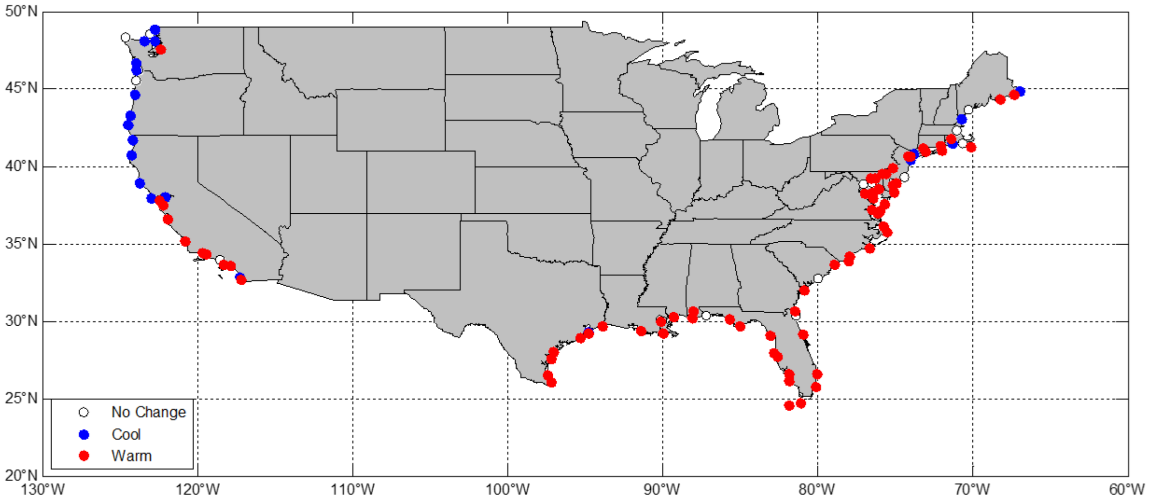
Global Sea levels



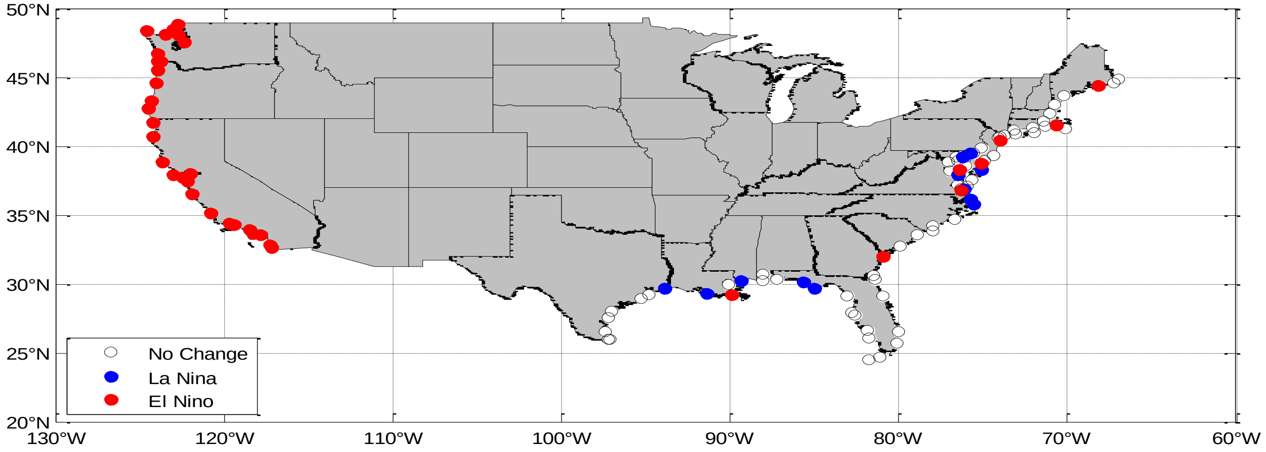
Teegavarapu, 2018; Teegavarapu and Schmidt, 2018

Climate Variability Influences

- AMO



ENSO

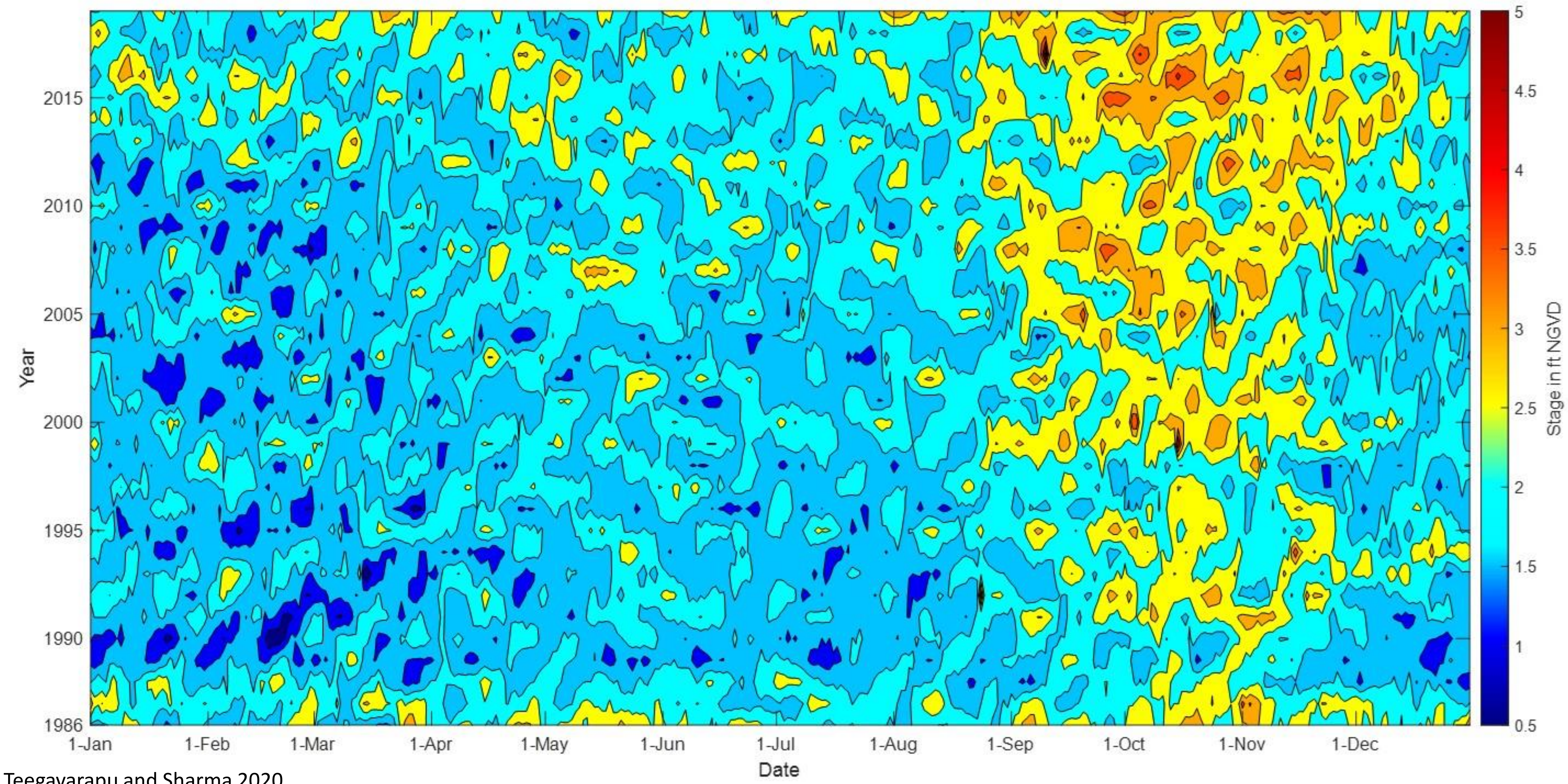


Nuisance Flooding

Image source acknowledgement : Steve Rothaus, Miami Herald)

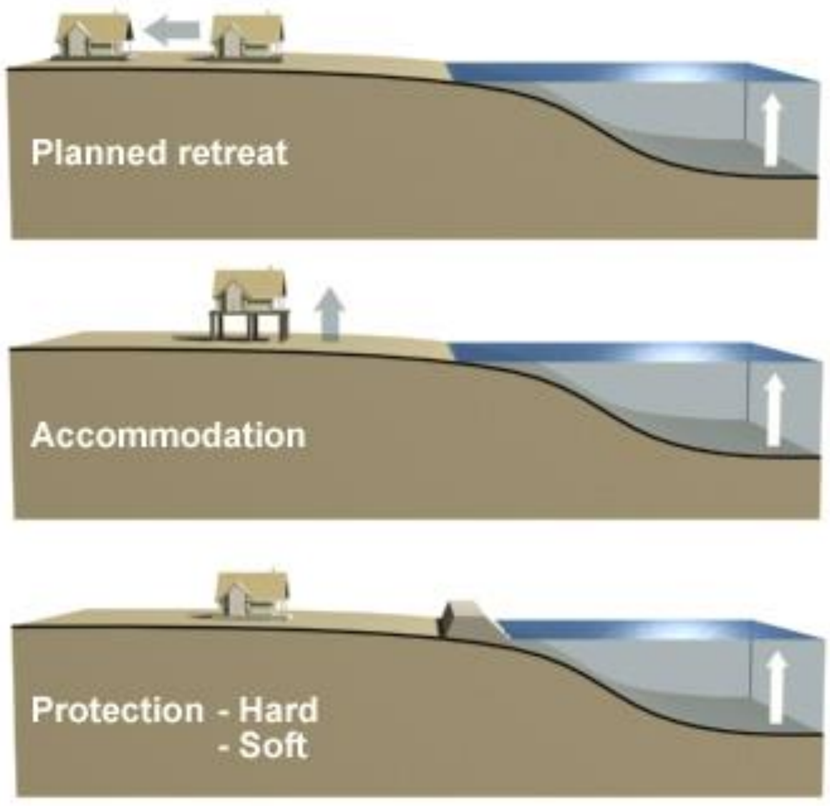
A king tide is no excuse not to pay for parking in Miami Beach.
Photo by Joe Raedle

Water levels at coastal structures



Teegavarapu and Sharma 2020

Adaptation



Source : Comet Program

Coupled Oceanic Atmospheric Oscillations

Japan

- Natural internal processes within the climate system (internal variability): Oceanic-Atmospheric Oscillations and Teleconnections

- Major oscillations around the globe:
  - Atlantic Multi-decadal Oscillation (AMO)
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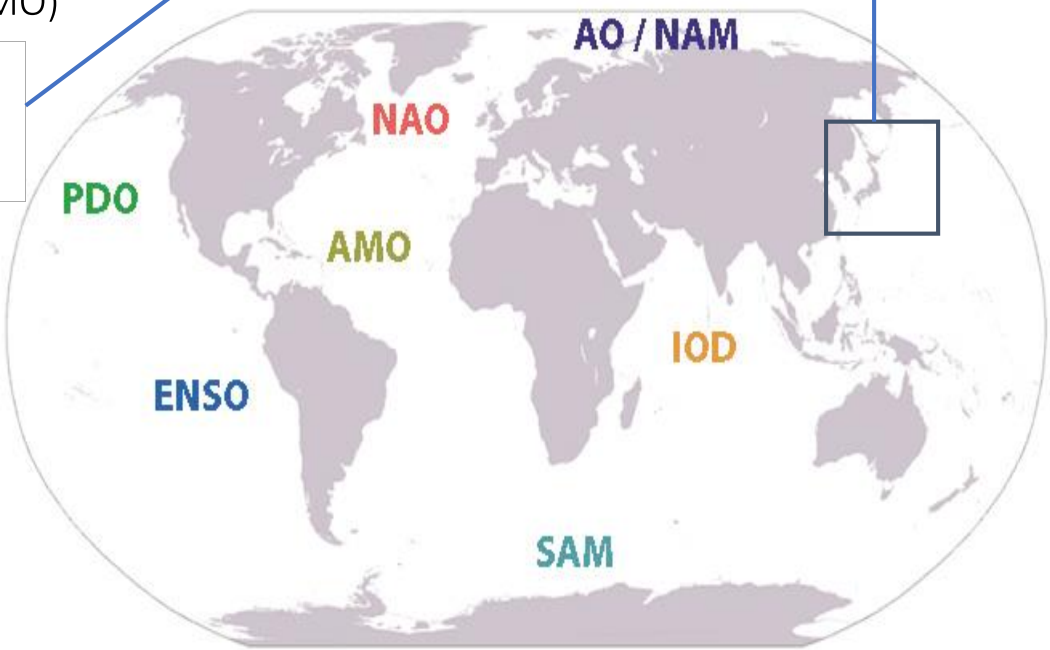
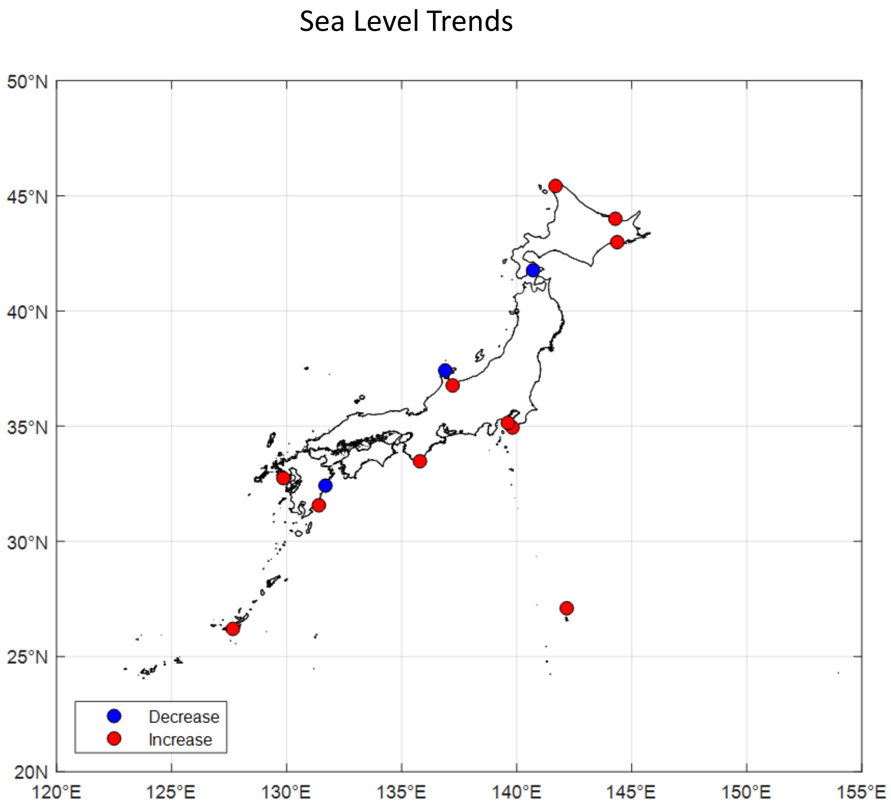
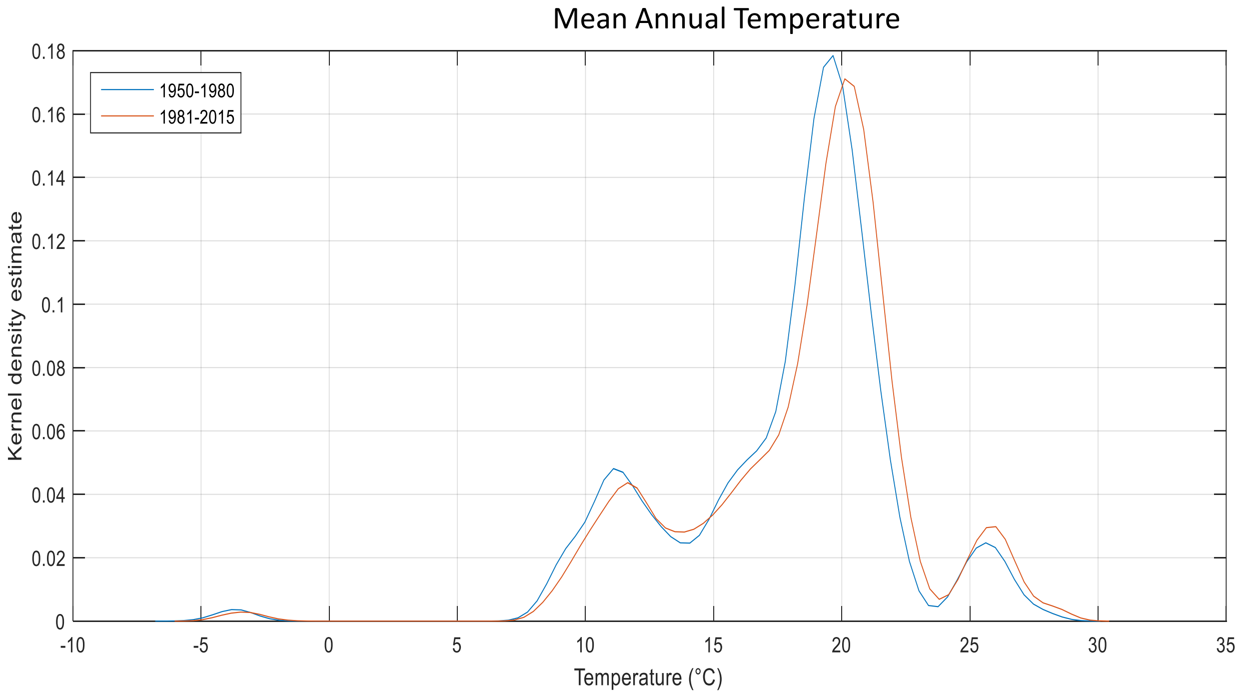
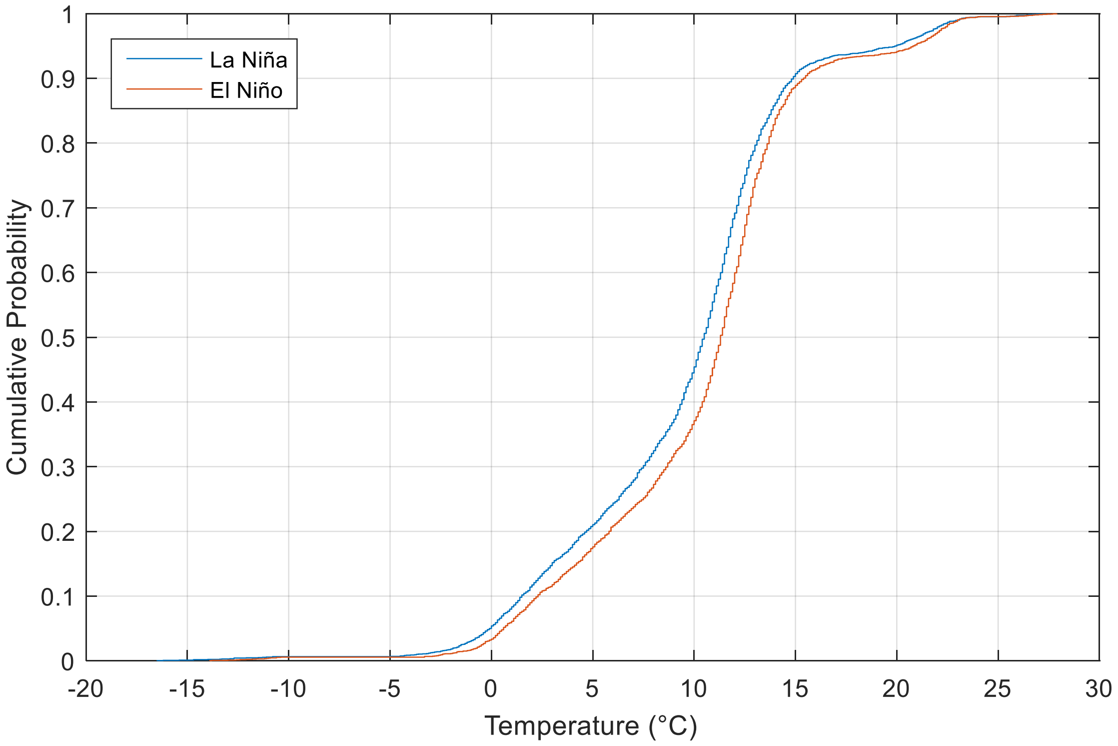
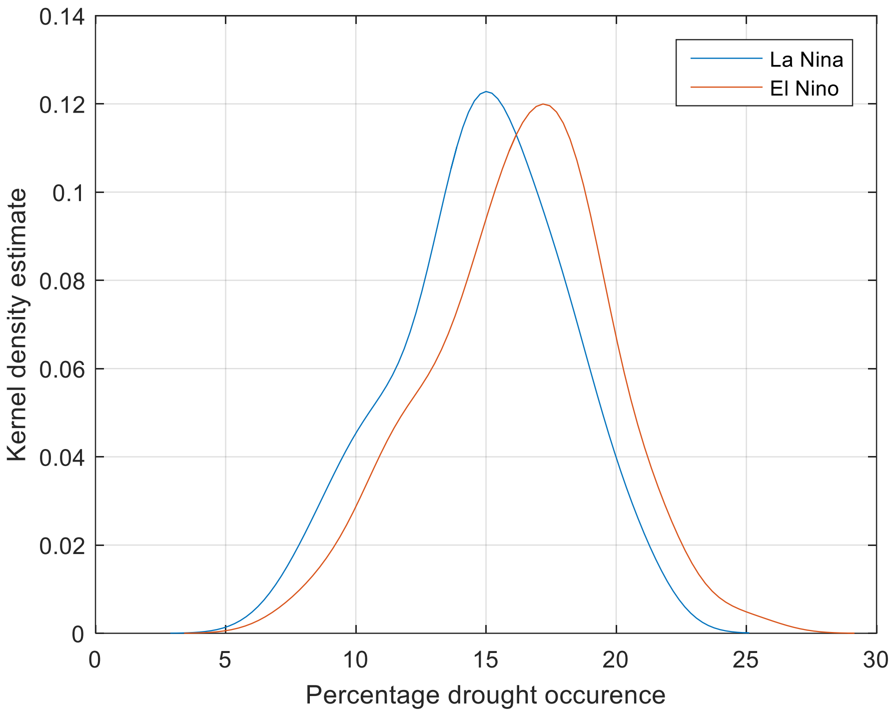


Trends & changes









Higher temperatures in December in El Niño as indicated by higher exceedance probabilities

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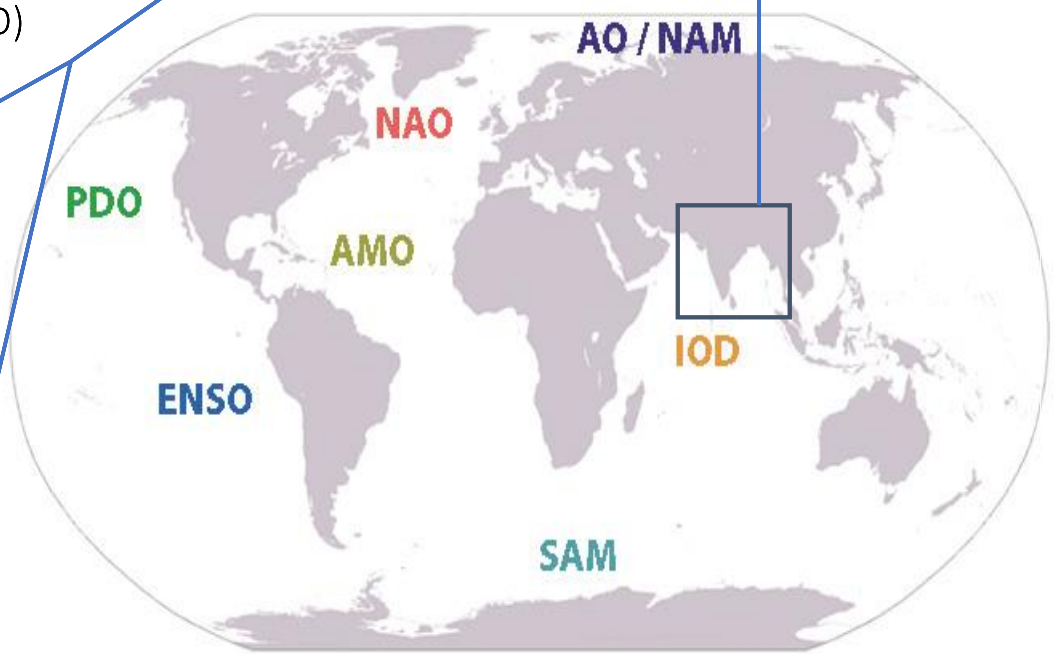
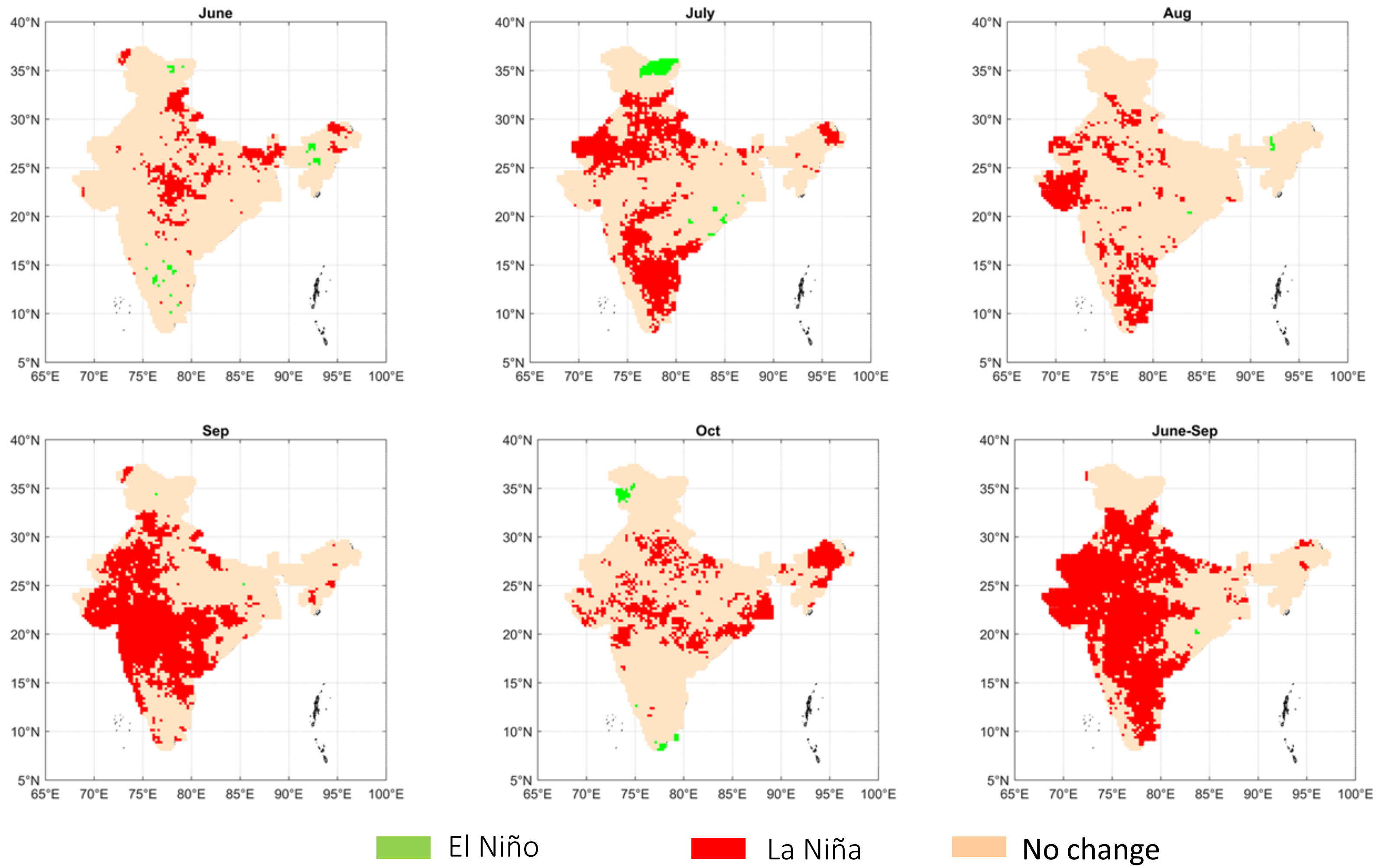
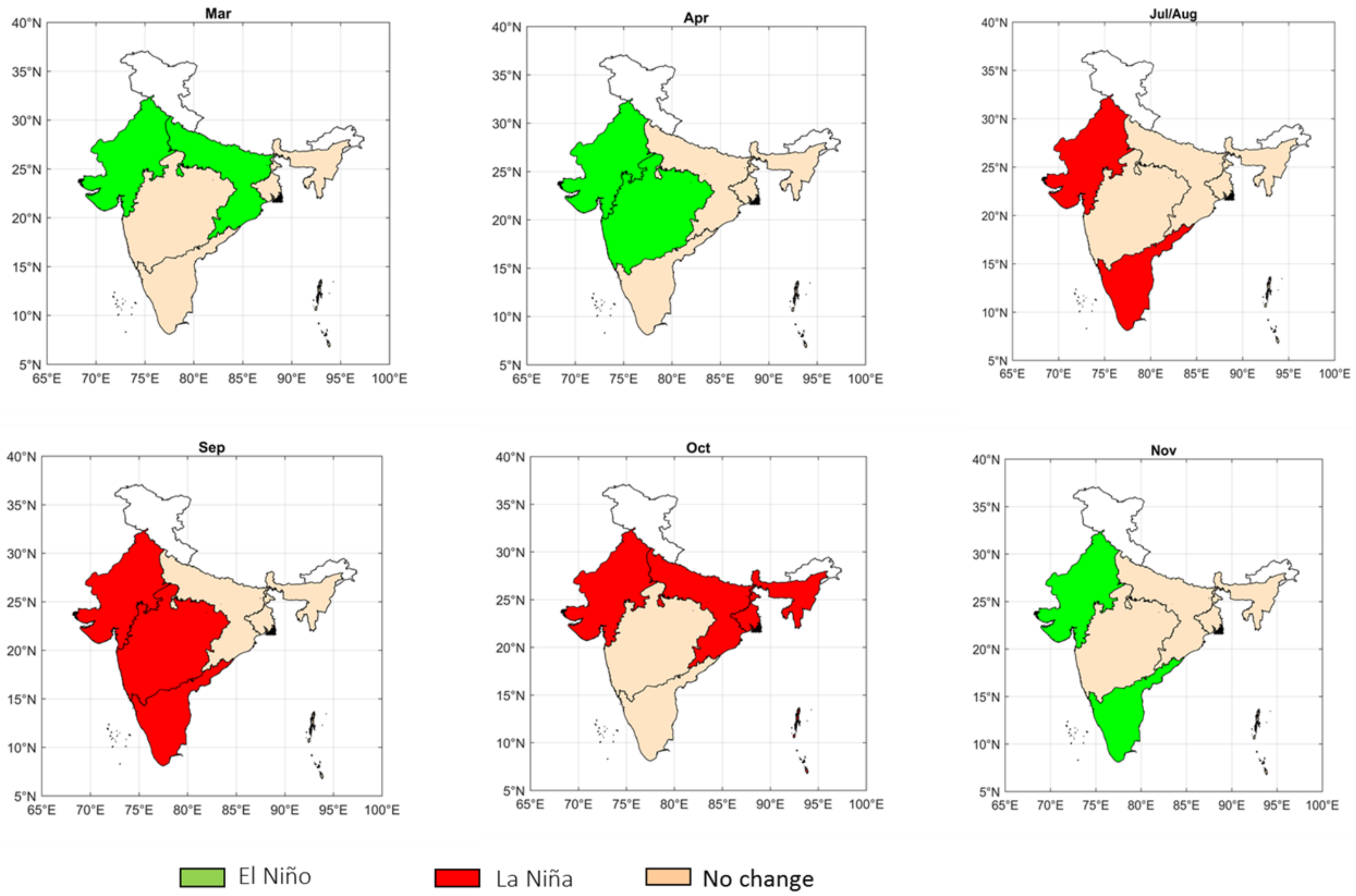


India



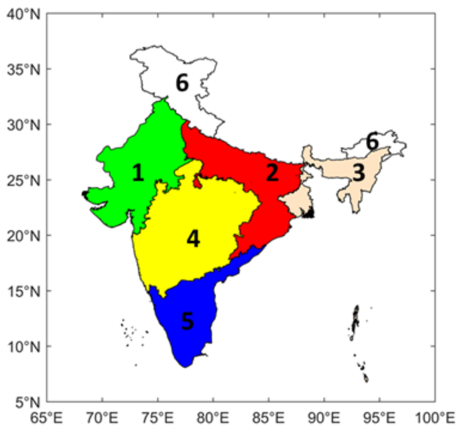
Teegavarapu, 2019 on going work

ENSO Influences



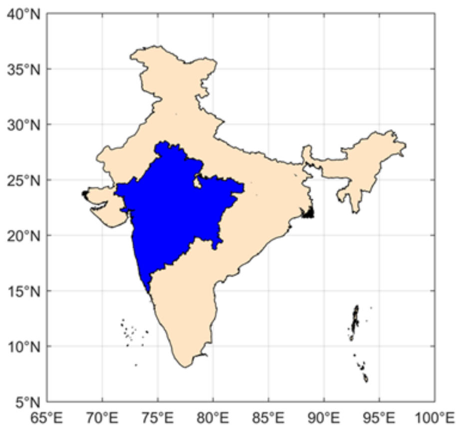
Teegavarapu, 2019 on going work

Statistically significant changes, nonparametric test results

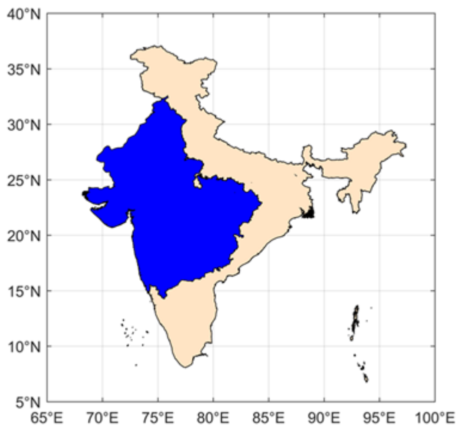


Homogeneous Monsoon Regions

1: Northwest 2: Central Northeast 3: Northeast
4: West Central 5: Peninsular
6: Hilly Regions



Core Monsoon Region



Homogenous Indian Monsoon Region

	Region							
Statistic	India	HM	CM	NW	WC	CNE	NE	PEN
Mean	La Niña	La Niña	La Niña	La Niña	La Niña	La Niña	La Niña	La Niña
Median	-	-	-	-	-	-	-	-
Maximum	La Niña	La Niña	La Niña	La Niña	La Niña	-	La Niña	La Niña
Minimum	-	El Niño	El Niño	El Niño	-	El Niño	-	-
Variance	La Niña	La Niña	La Niña	La Niña	La Niña	-	-	La Niña
Skewness	El Niño	El Niño	El Niño	El Niño	El Niño	El Niño	-	-
Kurtosis	El Niño	El Niño	El Niño	-	El Niño	El Niño	-	-
Autocorrelation	La Niña	La Niña	La Niña	La Niña	La Niña	La Niña	-	-

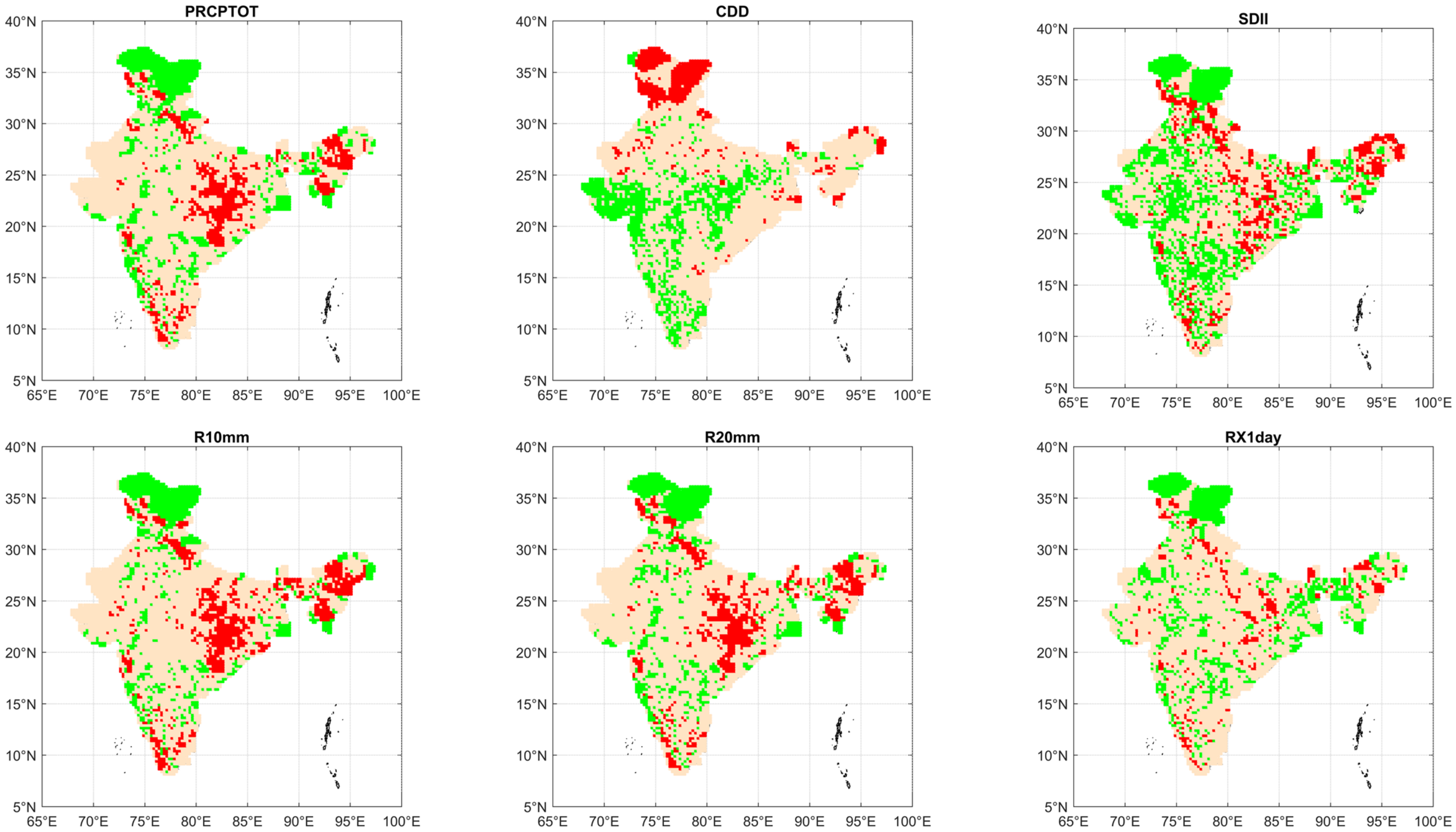
HM: Homogeneous Monsoon NW: Northwest CNE: Central Northeast PEN: Peninsular

CM: Core Monsoon WC: West Central NE: Northeast

Teegavarapu, 2019

Statistically significant changes, nonparametric test results

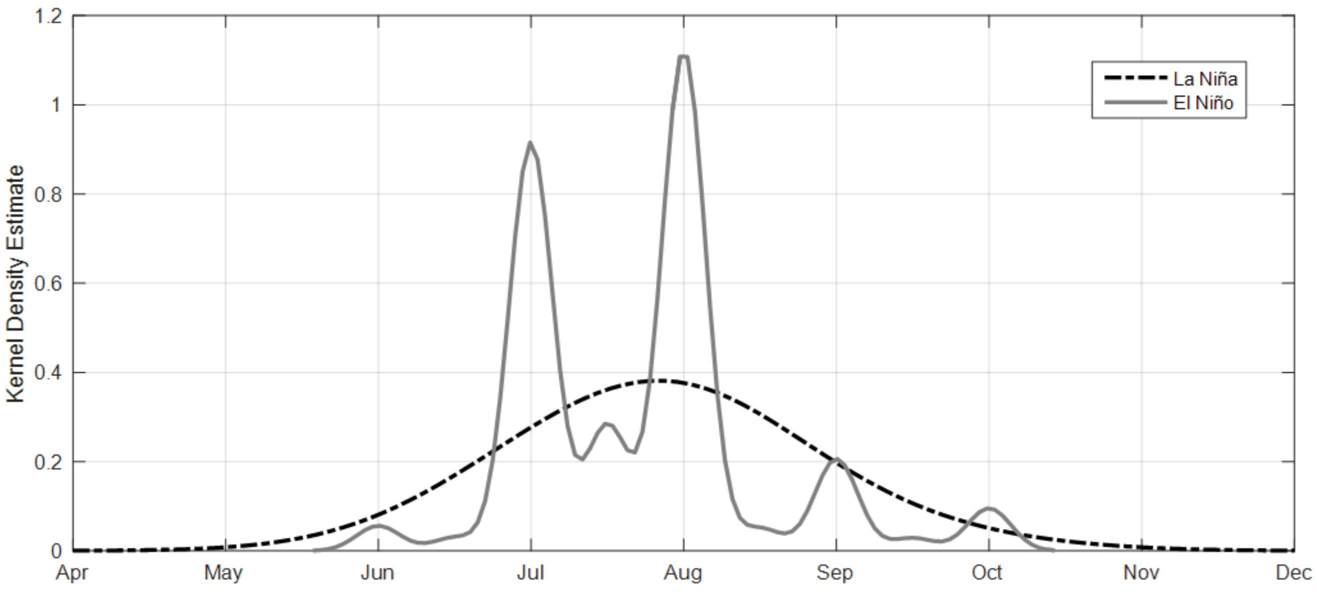
Trends

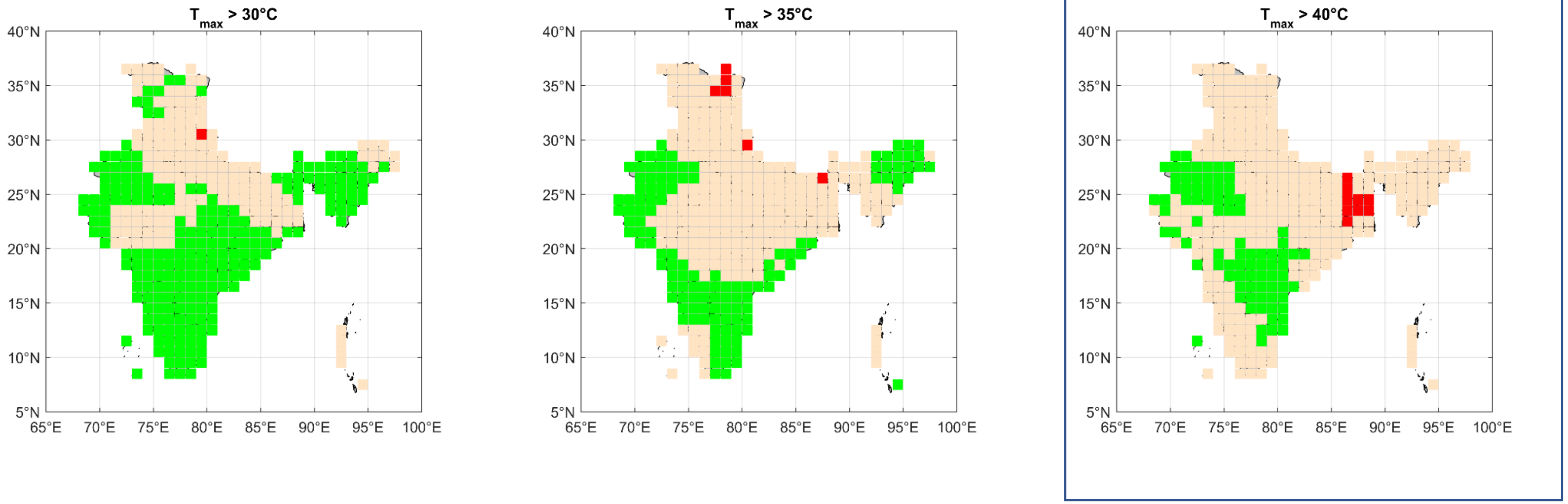


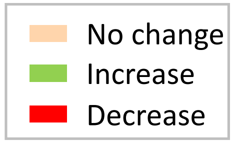
Teegavarapu, 2019 on going work

Increase Decrease No change

Temporal Occurrences of Extremes - ENSO

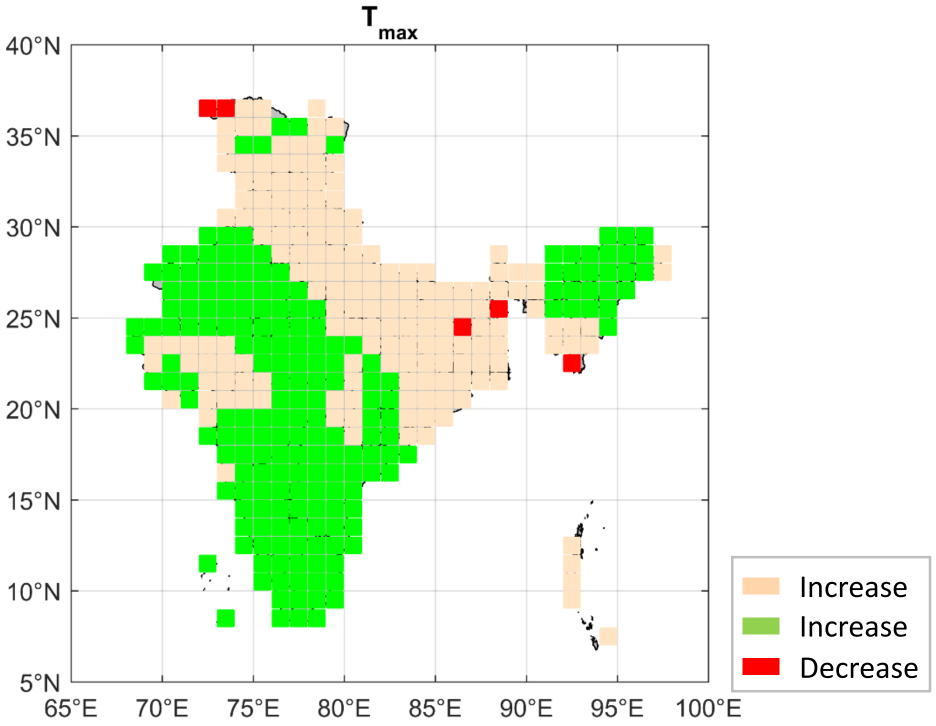






Summer Days : SU : Number of days above a specific threshold temperature

1951-2013



Trends

A 1.8 degree Fahrenheit temperature rise reduced a crop's duration by about one week, causing losses in the overall weight of harvest*(Swaminathan, 1980)

Teegavarapu, 2017 on going work

Projections of Precipitation Extremes - Challenges

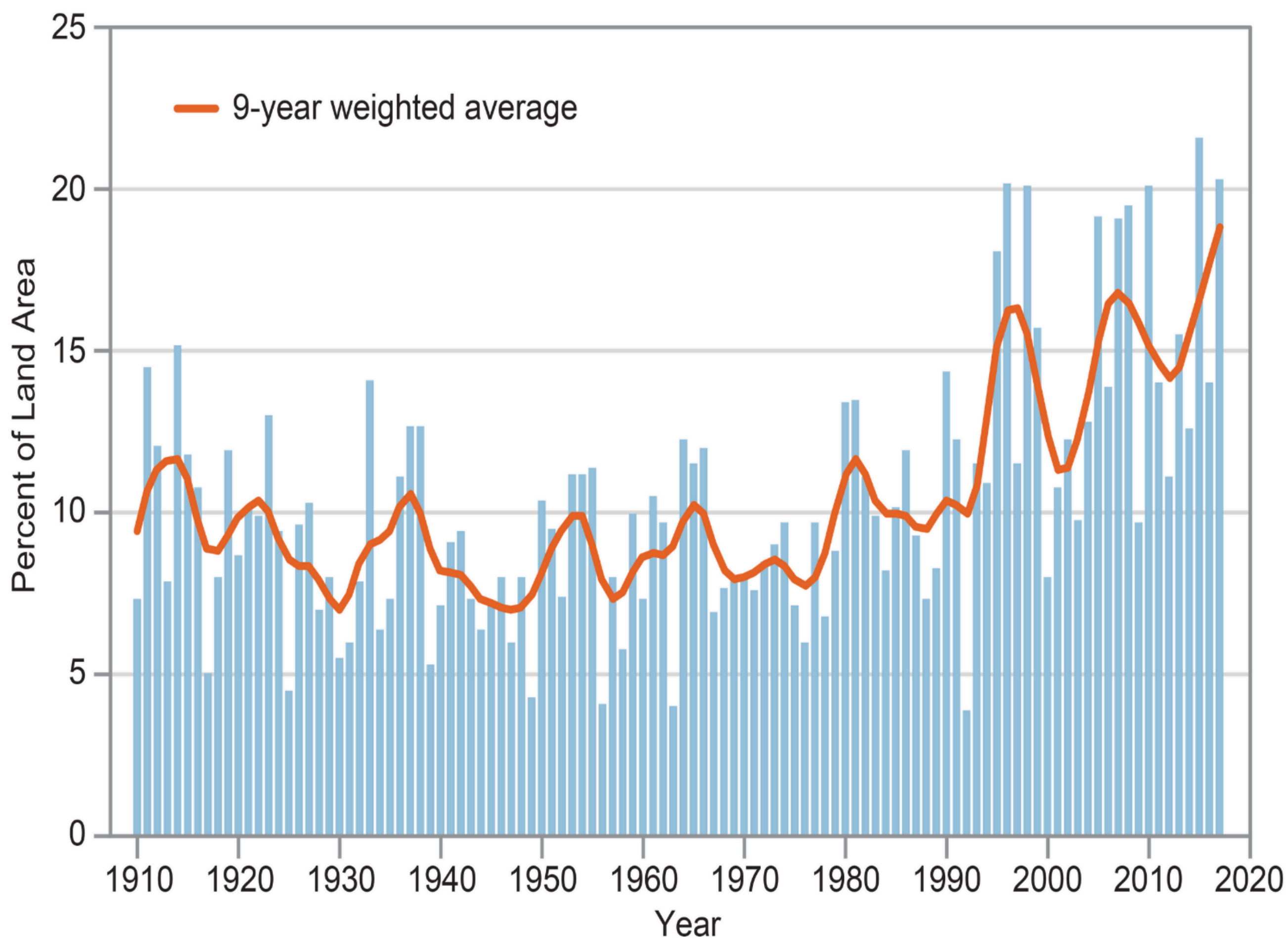
- Climate change models suggest an increase in global average annual precipitation during the 21st century, although changes in precipitation may vary from one region to another.

- Urban drainage design practices are continuously revisited by:
  - Incorporating climate change factors
  - Analyzing trends in precipitation extremes and their frequencies
  - Evaluating impacts of changing extremes using downscaled precipitation data from GCMs
  - Designing frameworks for risk and uncertainty management
- The inabilities of climate change models in reproducing precipitation extremes accurately and limitations of downscaling models in replicating the spatial and temporal variability of the same

- Temperature can be downscaled with more skill than precipitation. Emission scenarios and limited skills of multi-model GCM-based projections of future are considered to be the first and second sources of uncertainty respectively.

- Many sources of uncertainties in the models, including forcing uncertainty, initial condition uncertainty, and climate modeling uncertainties.

Spatial variation of precipitation extremes



The percent of land area in the contiguous 48 states experiencing extreme one-day precipitation events between 1910 and 2017.

Data source: EPA 2017

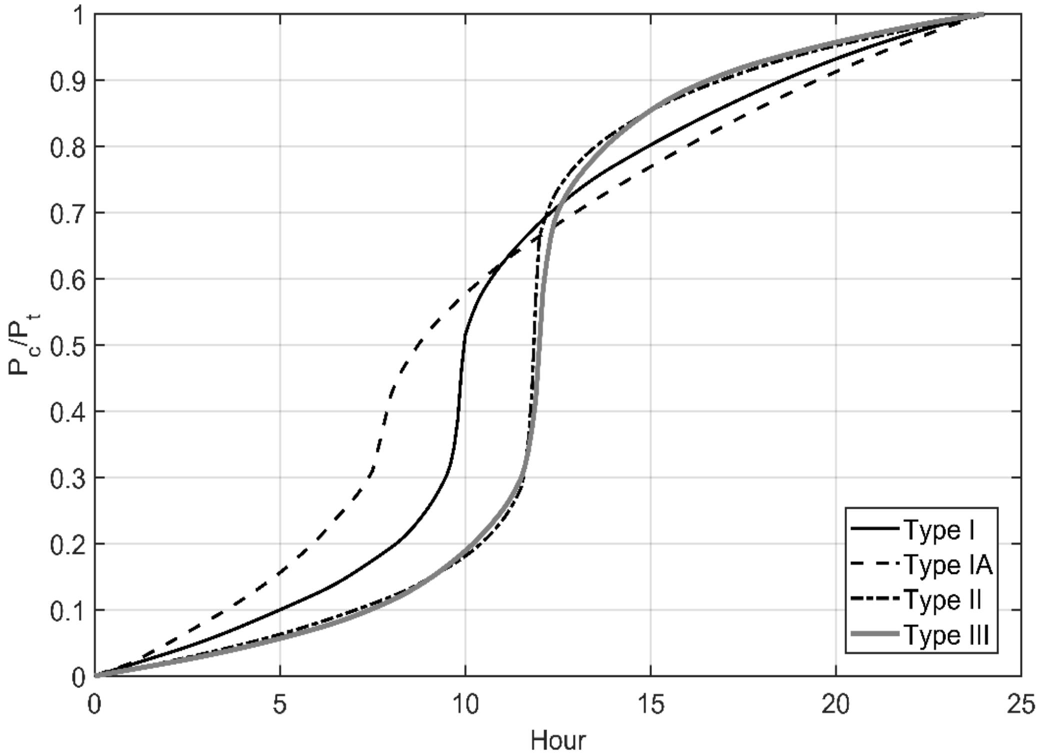
Precipitation Regimes

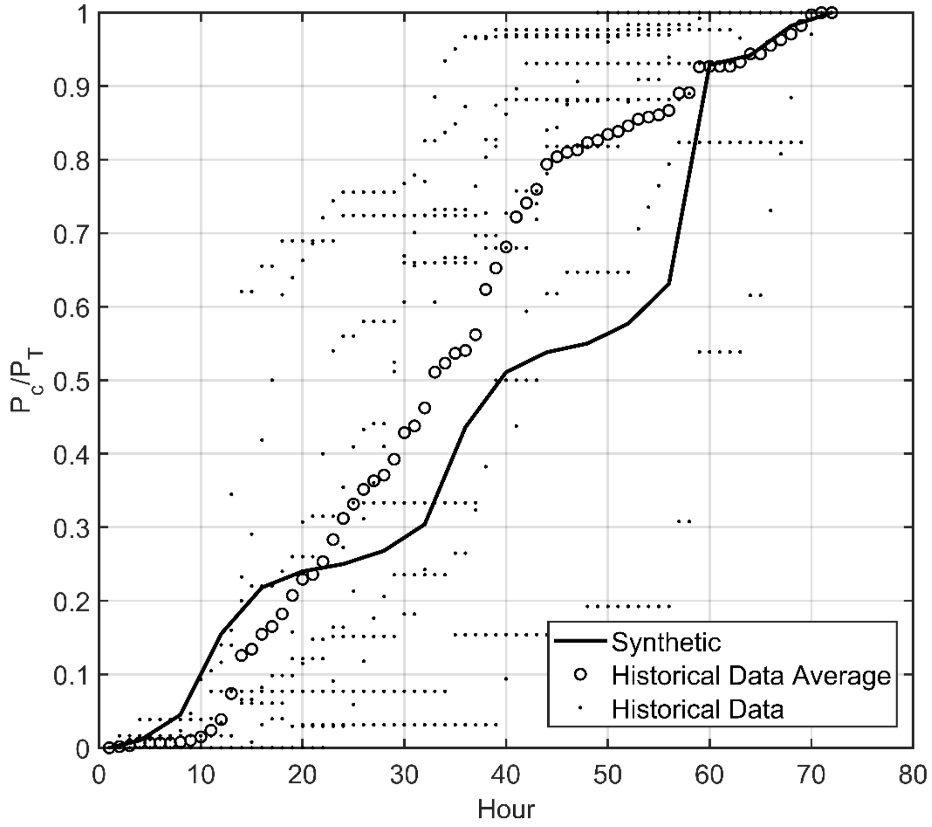
- How precipitation regimes are altered by natural climate variability and climate change ?

    - Inter-annual and Intra-annual variations
    - Seasonality
    - Spatial and temporal variability of extremes
    - Nature of extremes
    - Transition states [as defined by dichotomous events]
    - Persistence
    - Intra-event temporal distribution of precipitation
    - Antecedent moisture conditions preceding extreme events
    - Temporal occurrences of extremes
    - Number of extremes over a specific threshold
    - Inter-event time definition [IETD] –based events
    - Individual and coupled influences of internal modes of climate variability

Rainfall Distributions

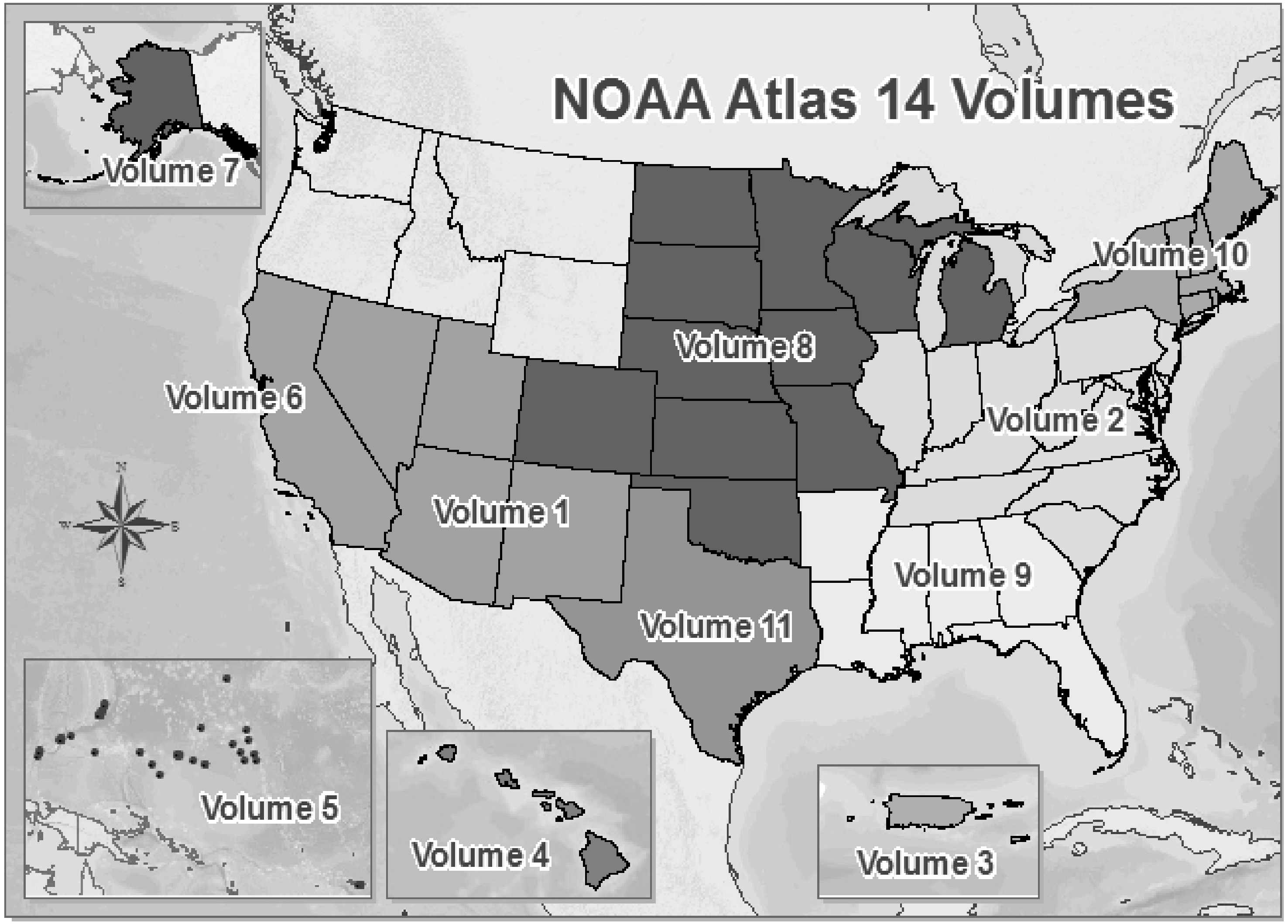
- Changes to Rainfall distributions used in design hydrology





Teegavarapu, 2019, 2020

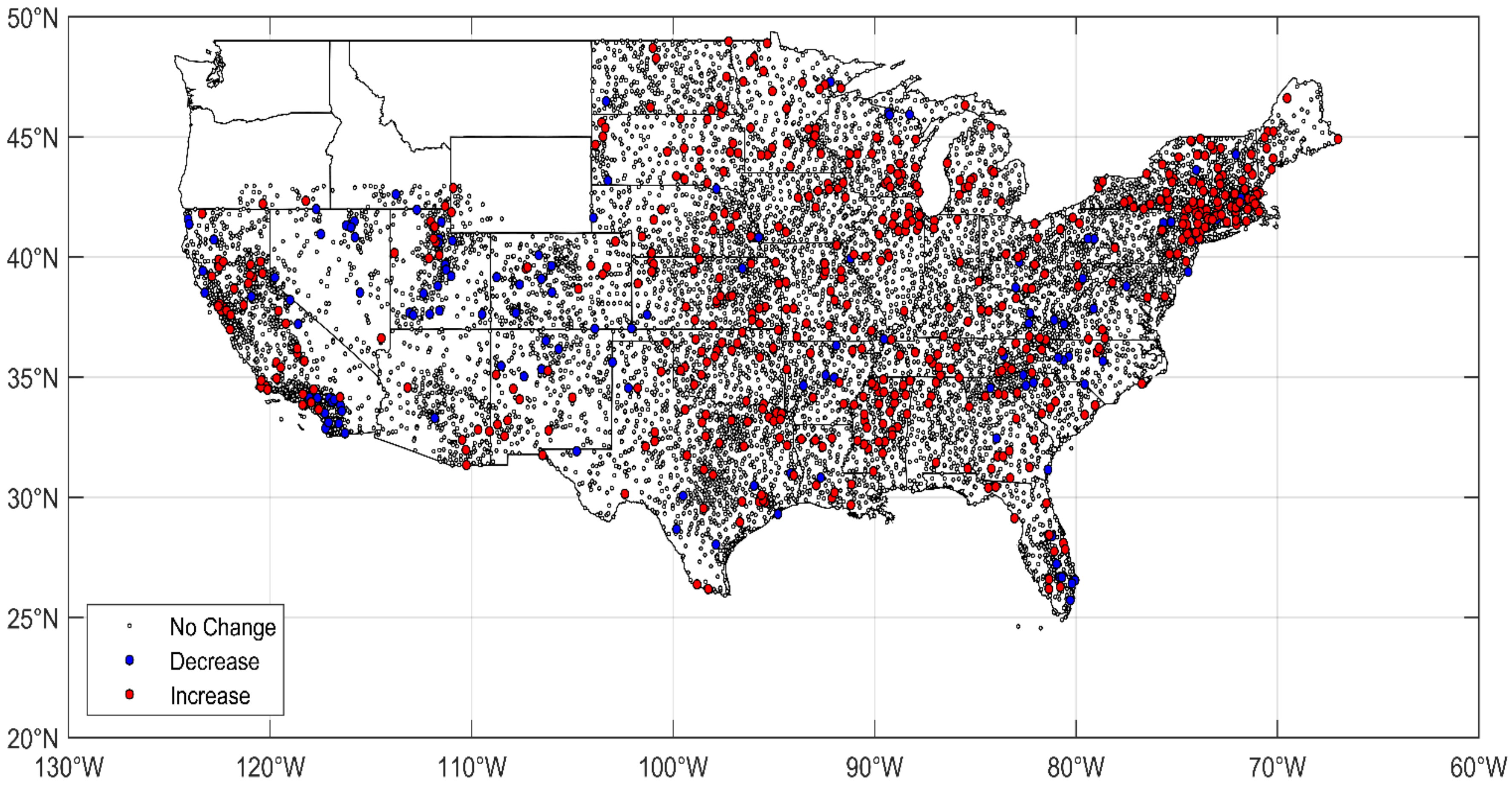
NOAA Atlas 14 efforts - Update



Frequency analyses were carried out on Annual and partial duration series for the following nineteen durations:

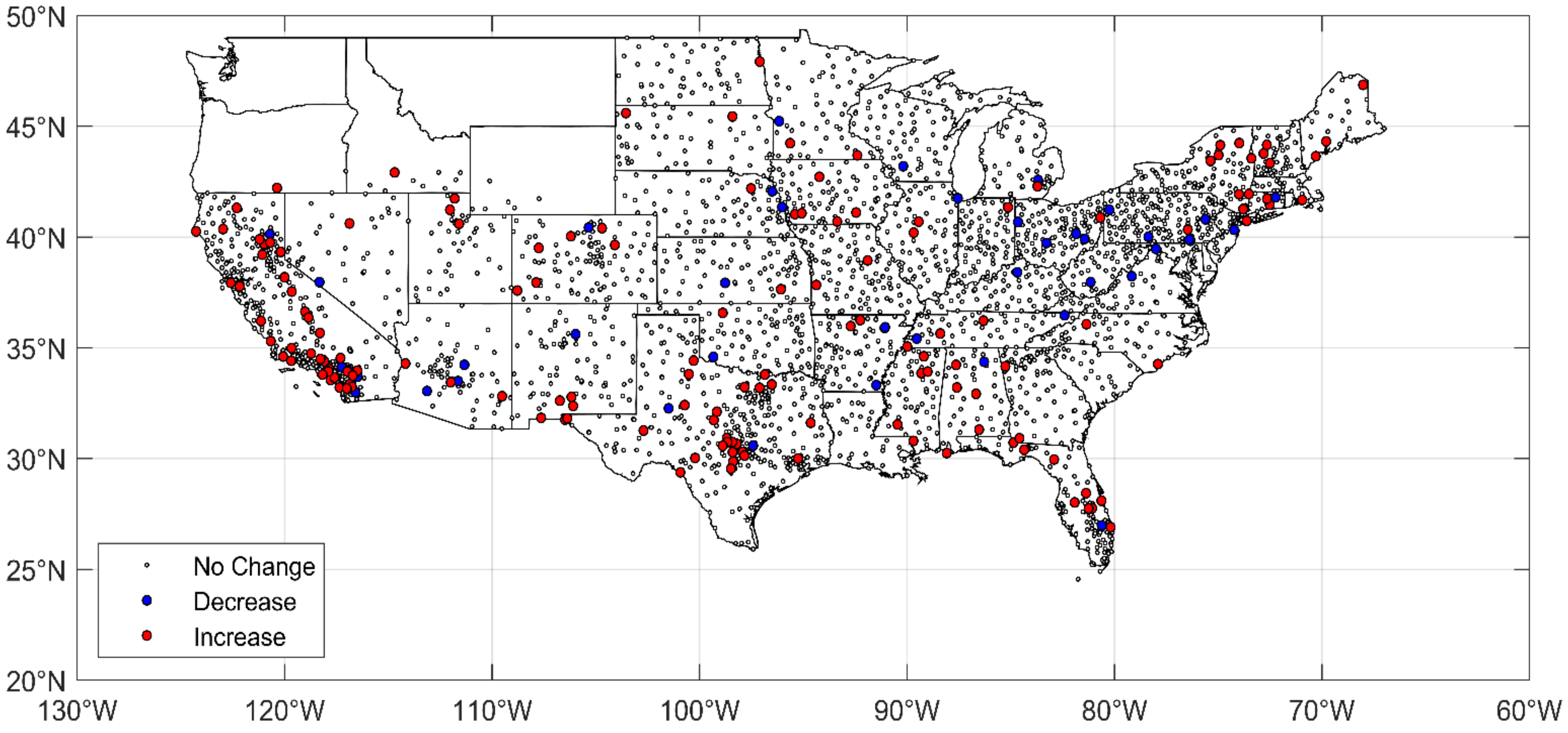
5-minutes, 10-minutes 15-minutes, 30-minutes, 1-hour, 2- hour, 3-hour, 6-hour, 12-hour, 1-day, 2-day, 3-day, 4-day, 7-day, 10-day, 20-day, 30-day, 45-day, and 60-day.

Trends in Rx1day



Teegavarapu, 2019, 2020

Annual Hourly Maximum



Teegavarapu, 2019, 2020

Implications

- Future changes in climate that may alter precipitation intensity or duration would likely have consequences for urban stormwater discharge, particularly where stormwater detention and conveyance facilities were designed under assumptions that may no longer be correct.
- The social and economic impact of increasing the capacity of undersized stormwater facilities, or the disabling of key assets because of more severe flooding, could be substantial

- Rising sea levels along different coasts of different countries are serious cause of concern. This is mainly due **coastal flooding** and inundation of low lying areas close to the coastal regions. Erosion of beaches and **storm-surge based flooding** will be common.
- Non-uniform spatial and temporal variations of temperatures due to natural variability will result in changes in agricultural production in different regions. Increasing temperatures as seen by trend analysis and climate change models suggest that impacts on rice and other agricultural products in several regions of the world.
- Non-uniform spatial and temporal variations of precipitation across many regions may introduce water stress, increased urban flooding, episodic extreme events and drainage issues.

Teegavarapu, 2020

Recommendations

- Evaluation of historical and climate-change model projection-based precipitation extremes
  - Historical precipitation data needs to be checked for any issues
    - Duplicate records, missing data, homogeneity issues related to station/site relocation, or instrumentation changes).

- Spatially and temporally downscaled general circulation model-based outputs considering different scenarios are needed.

- Suitability of one or more models to a specific region needs to be conducted.

- Exhaustive evaluation of different GCM models need to be conducted for their capabilities in replicating the characteristics of historical extremes.

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- Appropriate statistical and dynamic downscaling model for a specific region needs to be selected by using several performance metrics

- Although daily precipitation extremes for specific return periods are often used for hydrologic infrastructure design, sub-daily precipitation values are also critical for many applications.

- Disaggregation models are required to obtain precipitation extremes at a finer temporal resolution based on coarse-resolution future projections.

- Appropriate disaggregation approaches need to be selected by exhaustive evaluation of their capabilities in resolving precipitation at finer temporal resolution with the help of historical data.

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- Regional assessments of recent changes in precipitation extremes based not only on data from rain gauge observations but also weather radar and satellite-based quantitative precipitation estimates are needed.

- Use of weather radar is recommended to assess and confirm the existence of rare precipitation extremes. Radar-based quantitative precipitation estimates (QPEs) can also help in probable maximum precipitation (PMP) estimates.

- Periodical updates to available precipitation extreme databases and revisions to IDF relationships are required to support hydrologic design by incorporating changes occurring in evolving extremes.

- The upper limit of the 90% confidence interval estimates of precipitation magnitudes provided by agencies (e.g., NOAA, USA) can be used to develop conservative hydrologic designs.

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- The development of new approaches (e.g., Bayesian inference approach) that can consider non-stationarity of the precipitation extremes and adoption of these approaches by regional water management agencies is recommended.

- Regional IDF relationships do not provide adequate information about changing precipitation extremes at sub-regional scale. Local IDF relationships need to be developed based on available rain gauge observations and QPEs from other estimation sources.

- Rainfall extremes are not the only drivers of floods. Recent research studies have focussed on the development of IDF curves which consider both snowmelt processes and climate non-stationarity.

- These curves are referred to as next-generation IDF curves in multiple research studies and these focus on available water available for runoff generation. More research studies are needed to understand snowmelt runoff generation mechanisms and rain on snow conditions that lead to catastrophic floods.

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- The future hydrologic design should use the concept of inter-event times via an inter-event time definition (IETD) that can identify extreme runoff generation scenarios for better design of hydrologic and hydraulic infrastructure.

- Long-duration precipitation extremes with different return periods need to be estimated considering the storm events that last over a day in many regions in the world including the U.S. that experience events that are cyclonic with slow-moving hurricanes over the land (cyclones or typhoons).

- Hydrologic design procedures not only require extreme precipitation depths for the pre-specified return period but also need the intra-storm temporal distribution of precipitation when hydrologic simulation models are used.

- In changing climate, the standard synthetic distributions (for e.g., in the U.S Soil Conservation Service (SCS) or Natural Resources Conservation Service (NRCS) synthetic rainfall distributions) are no longer valid. Therefore, there is a need for developing region-specific temporal distributions of extreme storm events based on local precipitation data.

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- A strong association between temperature and precipitation extremes when quantified regionally, will be beneficial in specifying the spatial and temporal variation of precipitation extremes in hydrologic simulation models used for design.

- Develop compromise sustainable climate change-sensitive hydrologic design approaches. These approaches can model the uncertainties associated with multi-model multiple-scenario-based future climate projections.

- Atmospheric rivers (ARs) are known to be responsible for the occurrences of rare precipitation extremes in many parts of the U.S. and the world in the past decade. A clear understanding of these systems and modelling approaches for evaluating these systems are required to forecast events in short-term and historical observations of extremes caused by such processes should be considered for precipitation frequency analysis.

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- Close collaboration among climate scientists, practicing engineers, hydrologists and agencies that oversee and regulate hydrologic design need to work on addressing climate change in design standards.

- Climate change impacts on urban drainage systems can be reduced by using green infrastructure (GI) for both mitigation and adaptation efforts.

- Approaches that consider incorporation of GI for stormwater management, performance evaluation of existing urban drain systems and adoption of emerging technologies to assist low impact development (LID) are required.

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Water Resources Management

- Long-term planning for water resources management heavily depends on reliable estimates of water available in space and time based on future climate change projections.
- Evaluations of potential climate change scenarios and suitability of an appropriate GCM model and downscaling procedures are required before the projections can be used for assessments of changes in water availability in the future.
- Short-term planning for water resources management will require approaches that consider forecast-informed operations that rely on seasonal forecasts and consideration of climate variability.
- Forecasts of temporal lengths of the coupled ocean and atmospheric oscillation phases are essential for planning purposes.
- Adaptive short-term operation of water resource systems conditioned on seasonal forecasts of water availability is possible.

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- Water resources management models should adopt approaches to address uncertainties in future projections of climate, a trade-off between long- and short-term modifications to operating rules for hydrosystems is needed.
- Rules that can be referred to as compromise climate change-sensitive operating policies are required.
- Hydrosystems cannot be managed based on single or multiple objectives but rather developing approaches that consider the nexus between multiple sectors that influence operations of hydrosystems that are impacted by changing climate.

- Climate change-sensitive water resources management should not only focus on water but also evaluate the impacts on ecosystems, water quality in streams and natural bodies, social, economic and urban systems with an emphasis on food, health, water, energy, and several other important sectors.

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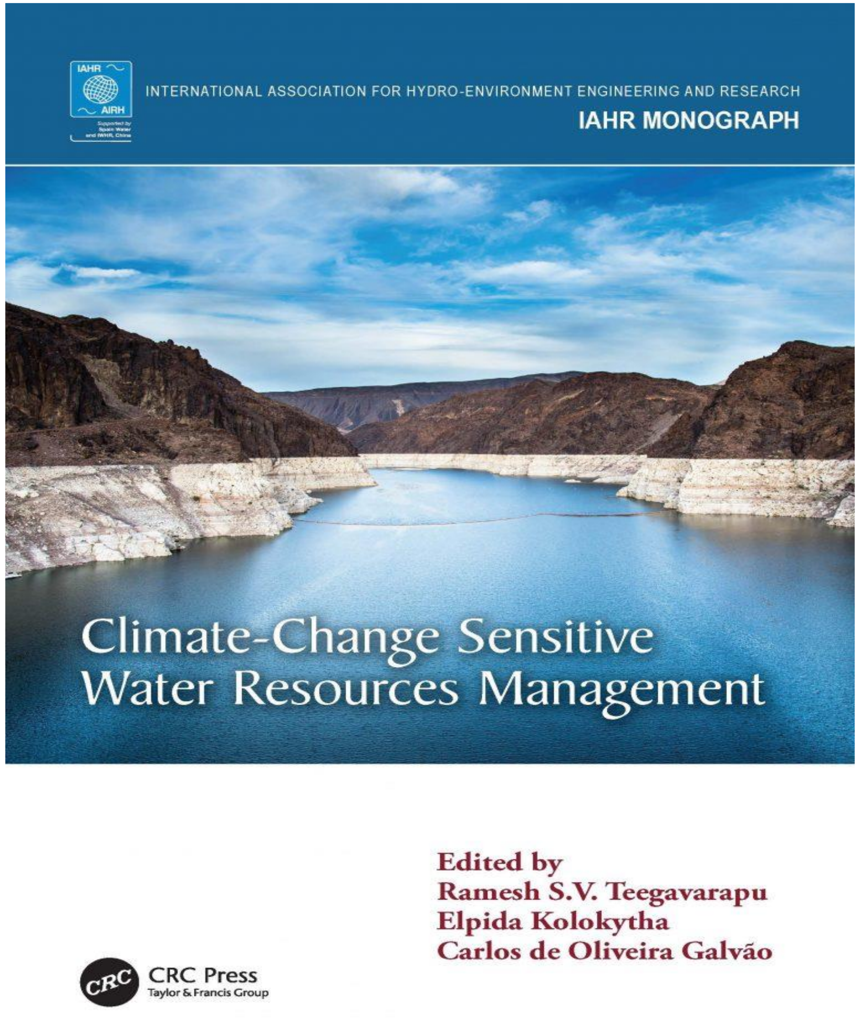
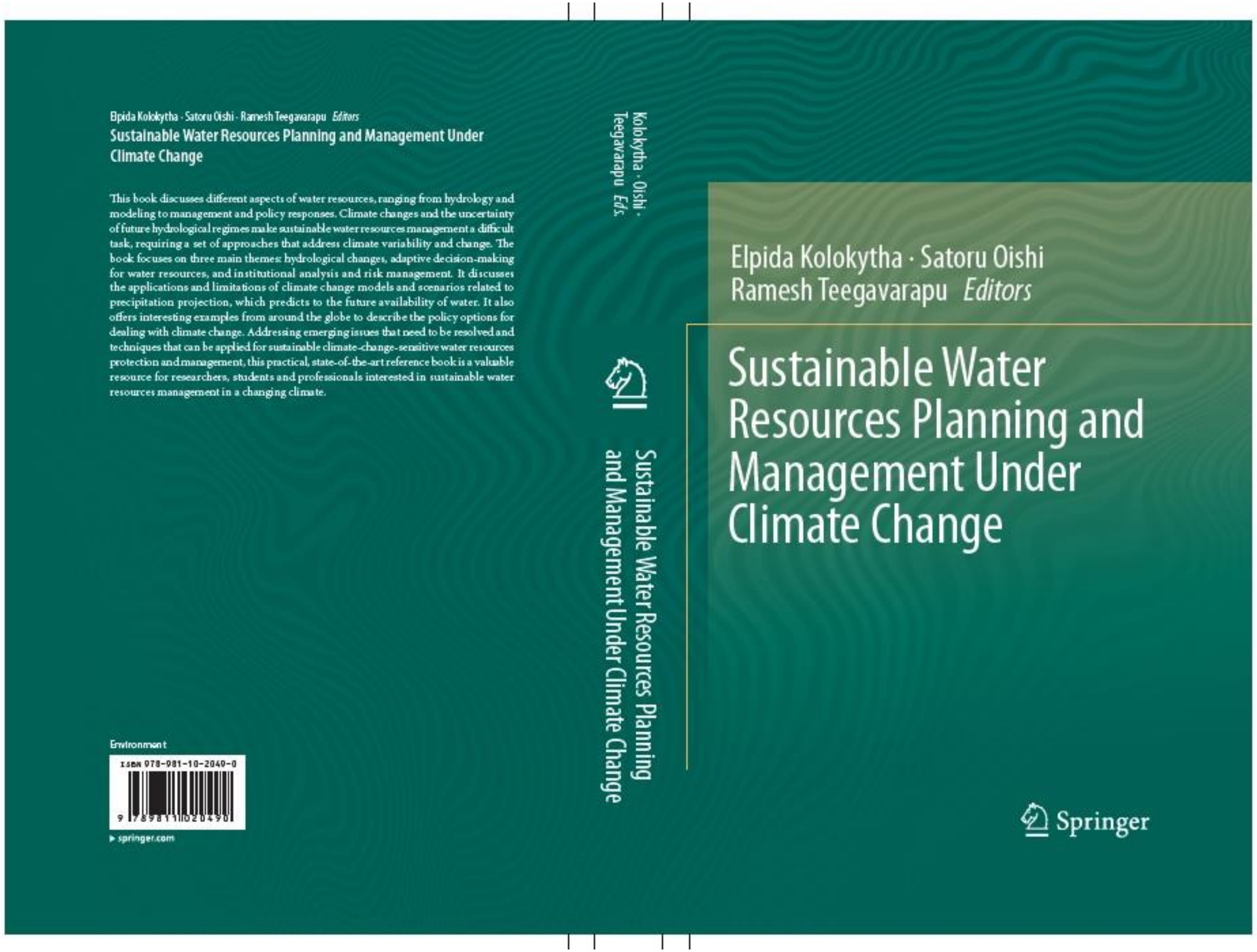
- Forecast Informed Reservoir Operation (FIRO) approach has gained attention in the U.S. for improving flood-control reservoirs based on the use of quantitative precipitation forecasts for adaptive short-term or real-time operation.
- Concepts of probabilistic analytical approaches that consider inter-event precipitation storm characteristics are recommended for urban stormwater management.
- Ensemble streamflow forecasting approaches are appropriate to develop multiple scenarios of input to models that simulate operations to address issues related to input, model and any other uncertainties.
- Considering uncertainties associated with the projections of future climate based on climate change models, dynamic simulation models to replicate system behaviour (i.e., operations) and to assess resiliency, reliability, and vulnerability of systems are needed. New metrics need to be developed to assess the level of service (LOS) provided by different hydrosystems.

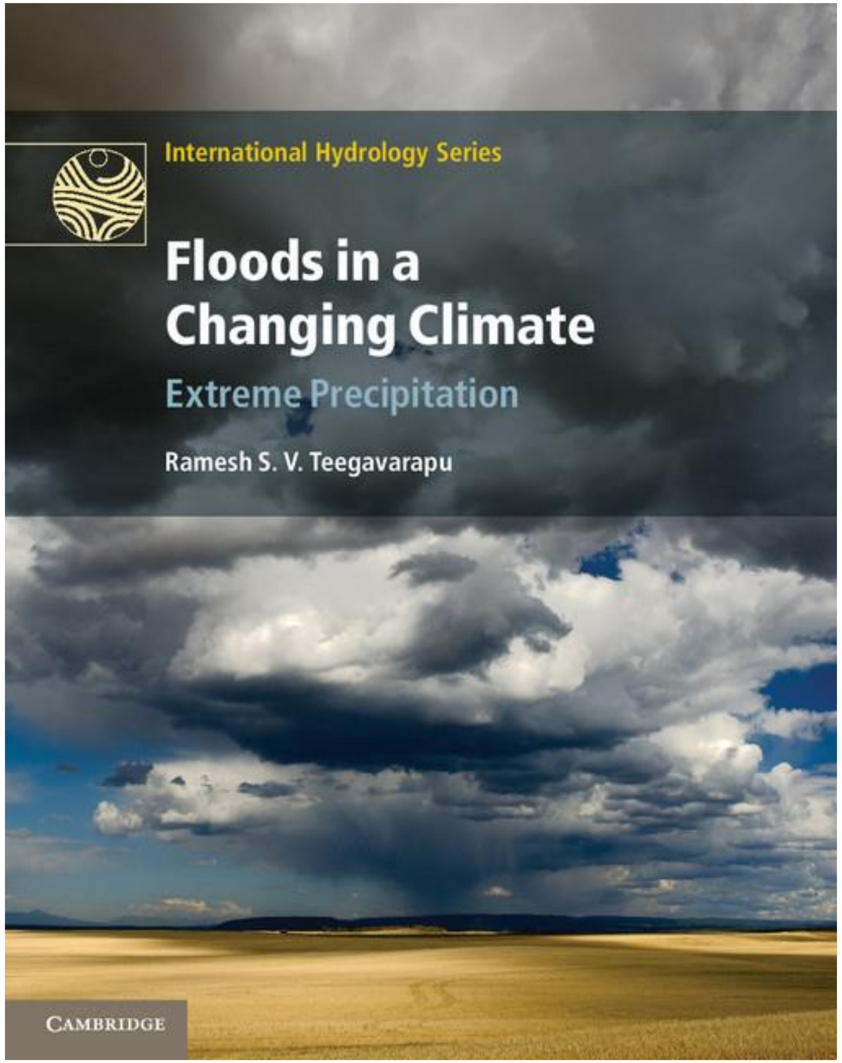
Teegavarapu, 2020

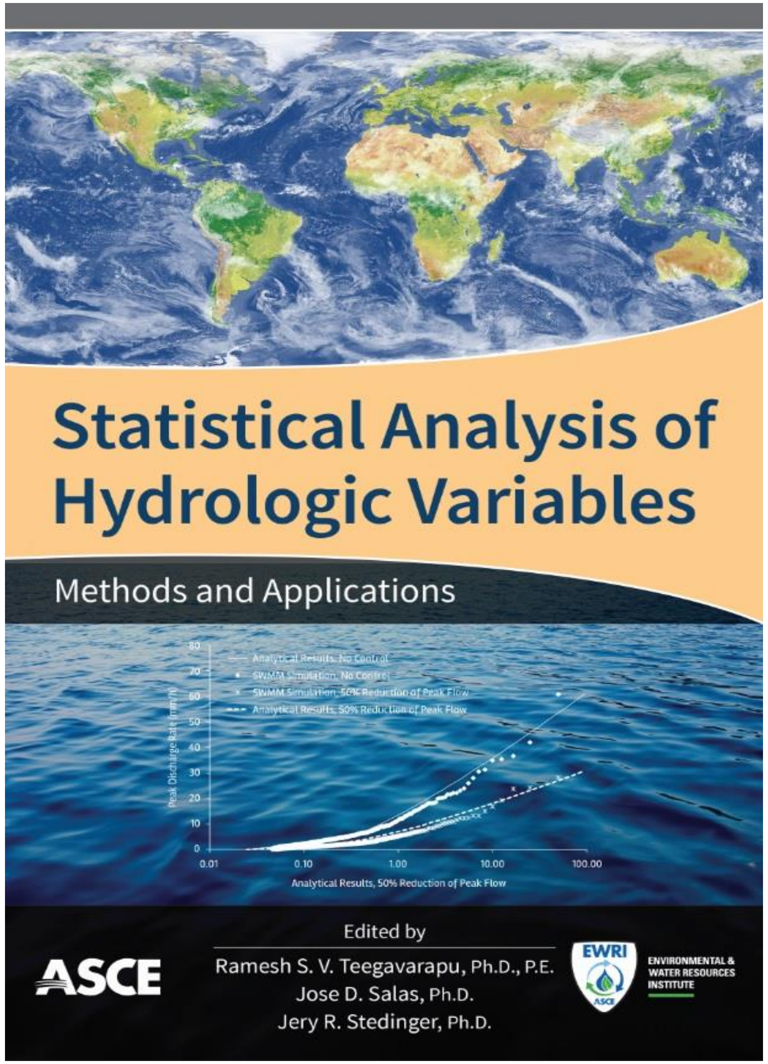
Books from HRL group





Books


International Hydrology Series
Floods in a Changing Climate
Extreme Precipitation
Ramesh S. V. Teegavarapu
CAMBRIDGE


Statistical Analysis of Hydrologic Variables
Methods and Applications
Edited by
Ramesh S. V. Teegavarapu, Ph.D., P.E.
Jose D. Salas, Ph.D.
Jery R. Stedinger, Ph.D.
ASCE
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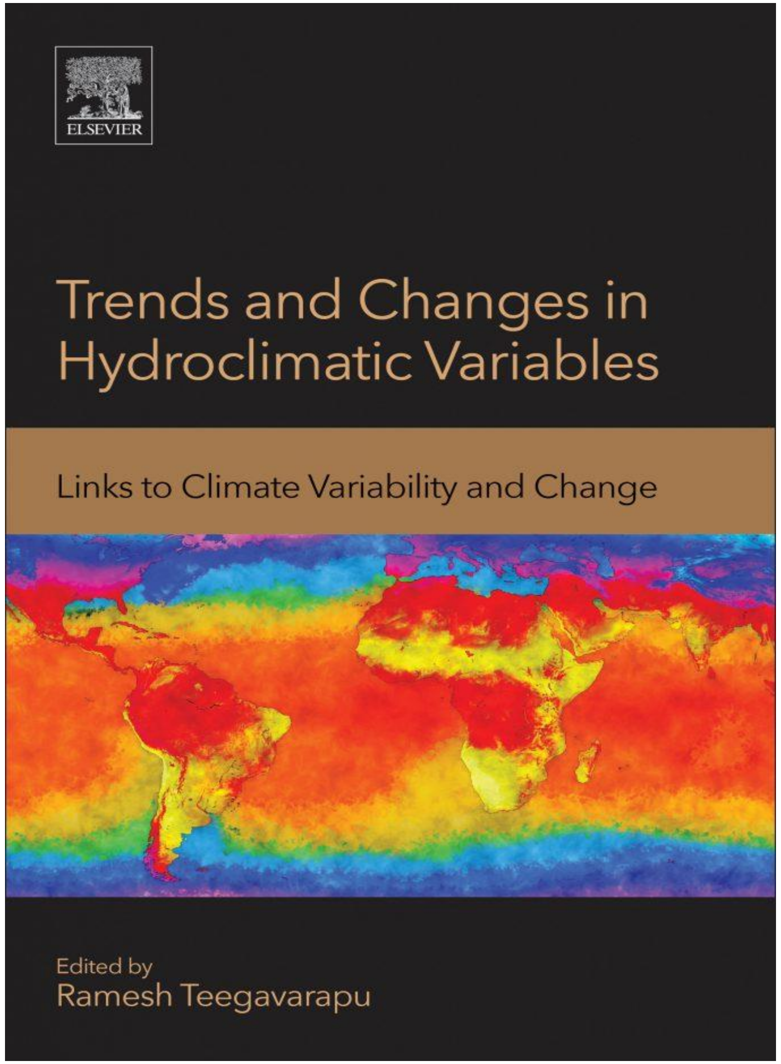
ENVIRONMENTAL & WATER RESOURCES INSTITUTE


ELSEVIER
Trends and Changes in Hydroclimatic Variables
Links to Climate Variability and Change
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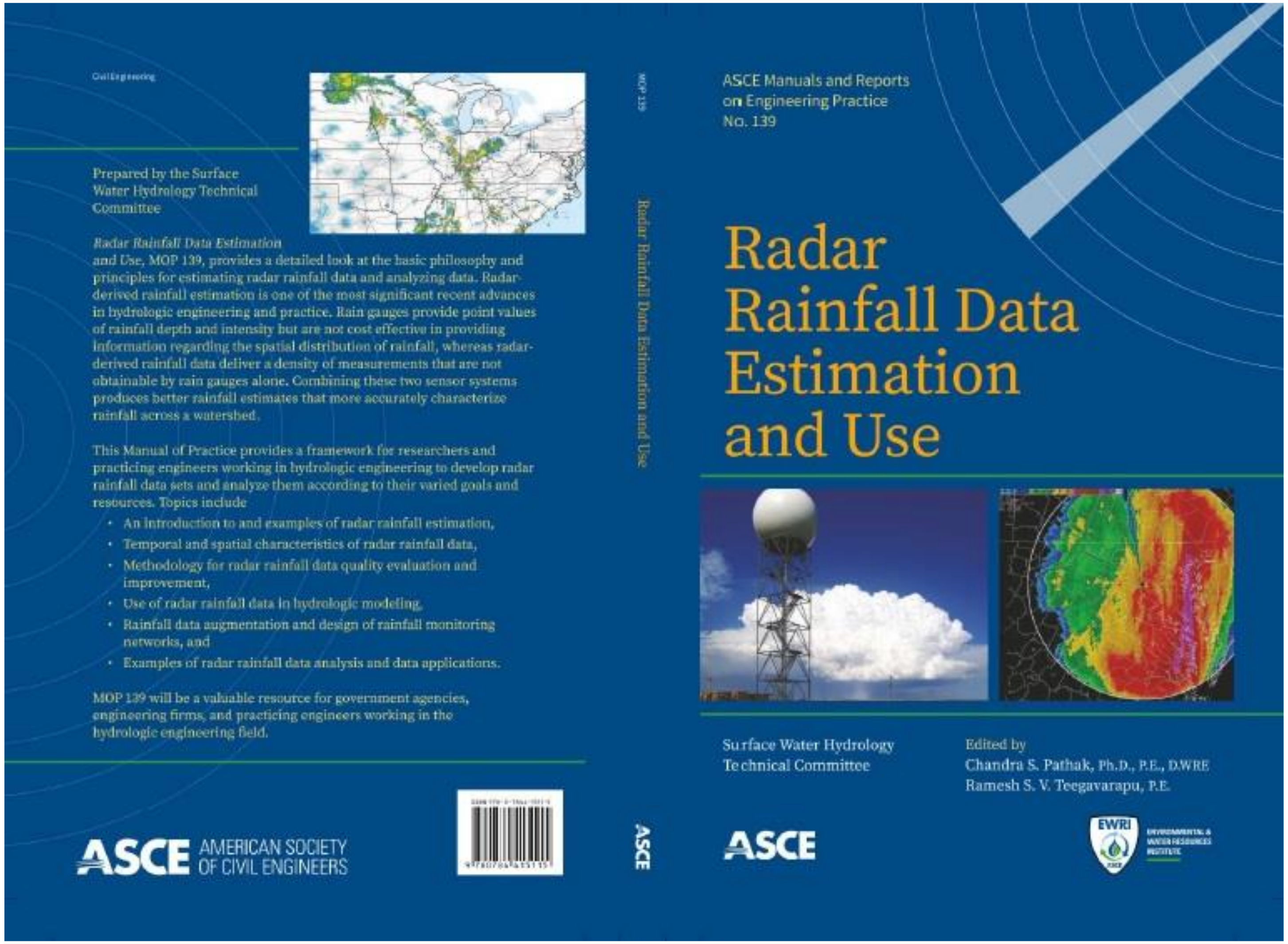
Books


Prepared by the Surface Water Hydrology Technical Committee
Radar Rainfall Data Estimation and Use, MOP 139, provides a detailed look at the basic philosophy and principles for estimating radar rainfall data and analyzing data. Radar-derived rainfall estimation is one of the most significant recent advances in hydrologic engineering and practice. Rain gauges provide point values of rainfall depth and intensity but are not cost effective in providing information regarding the spatial distribution of rainfall, whereas radar-derived rainfall data deliver a density of measurements that are not obtainable by rain gauges alone. Combining these two sensor systems produces better rainfall estimates that more accurately characterize rainfall across a watershed.
This Manual of Practice provides a framework for researchers and practicing engineers working in hydrologic engineering to develop radar rainfall data sets and analyze them according to their varied goals and resources. Topics include
• An introduction to and examples of radar rainfall estimation,
• Temporal and spatial characteristics of radar rainfall data,
• Methodology for radar rainfall data quality evaluation and improvement,
• Use of radar rainfall data in hydrologic modeling,
• Rainfall data augmentation and design of rainfall monitoring networks, and
• Examples of radar rainfall data analysis and data applications.
MOP 139 will be a valuable resource for government agencies, engineering firms, and practicing engineers working in the hydrologic engineering field.
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Radar Rainfall Data Estimation and Use
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ASCE Manuals and Reports on Engineering Practice No. 139
Radar Rainfall Data Estimation and Use
Surface Water Hydrology Technical Committee
Edited by
Chandra S. Pathak, Ph.D., P.E., D.WRE
Ramesh S. V. Teegavarapu, P.E.
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- Thank you

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Committed to Understanding, Modeling and Managing Terrestrial Hydro-Environmental Systems